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16. Abstract

The purpose of the study reported herein was to characterize the sediments of Lake Okeechobee through field and laboratory studies, with special emphasis on the fine sediment regime. Continuous seismic profiling information, involving side-scanning and shallow reflection apparatus, was obtained. Despite the exceptionally shallow water depths in the lake, compounded by the presence of gas in the superficial muds, good quality data revealing the lake bed stratigraphy and indicating suitable sites for later sampling were derived. The sampling program was designed to establish the complete succession with special emphasis on the superficial muds. The underlying geological bedrock succession is consistent in terms of overall thickness and numbers of thin calcareous deposits with that already established onshore.

Overlying the bedrock, around the southern and northeastern periphery at least, is a thick in situ peat bed. The peat dates from 5,490 yr BP to 2,670 yr BP, a time when proto-Lake Okeechobee had a much more restricted extent than at present. Extending over much of the northern part of the lake and overlying the peat in places is a thin fan of quartz sand. The sand is most recently of fluviatile origin and its extent and variation in thickness imply input by streams and rivers from the north.

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The shallowest deposit and the one of greatest interest in respect of nutrient cycling in the lake is a black, carbonate and organic rich mud. As with the sand, the mud is restricted to the northern end of the lake, occupying about one third of the area of the lake bed. It contains $\sim 193 \times 10^6 m^3$ of material and is offset slightly to the northeast of the central deep of the lake. As a result its surface slopes towards the southwest at a low angle. Mud depths range from a few centimeters at the periphery to in excess of 75 cm in the deep center of the lake. The deposit has been accumulating for a long period ($\sim$ 6300 yr). Its distribution suggests input of some components from the same northern rivers which supplied the sand. Variation in deposition rate with time remains to be investigated.

Internally the deeper, central mud area shows slight lithological variations interpreted to imply that deposition commenced here. The upper and more extensive part of the mud succession looks less differentiated in cut section, but high resolution X-radiography of thin vertical slices showed that the lower horizons exhibit a microscopic interlamination of dark and light bands, thought to arise from periods of algae blooming, death and sedimentation of skeletal debris, alternating with more normal periods of deposition of organic floc material. The microscopic internal primary fabric is clear evidence that the deeper layers of the mud patch are not susceptible to frequent reworking. The X-radiographs also show that there appear to be spherical gas bubbles in the mud in some areas.

In situ density profiles of the upper part of several cores revealed a relatively thin (0-10 cm), fluid mud veneer. This material is believed susceptible to resuspension on occasions. Between the submillimeter lower zones and the top-most fluid mud upper zone is often a broad (up to 25 cm) zone apparently with poorly developed internal primary fabric. This zone is slightly problematical because whereas shear strength profiles imply the zone to be too strong to be regularly resuspended, the presence of gas within the zone could lead to considerably enhanced susceptibility.

The present results need to be considered along with the nutrient profile data to assist the understanding of the relationship between sediment entrainment and nutrient cycling. It is concluded that the role of gas merits further close scrutiny.

UFL/COEL-89/009

FINE SEDIMENT REGIME OF LAKE OKEECHOBEE, FLORIDA

by

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SUMMARY

The purpose of the study reported herein was to characterize the sediments of Lake Okeechobee through field and laboratory studies, with special emphasis on the fine sediment regime. Continuous seismic profiling information, involving side-scanning and shallow reflection apparatus, was obtained. Despite the exceptionally shallow water depths in the lake, compounded by the presence of gas in the superficial muds, good quality data revealing the lake bed stratigraphy and indicating suitable sites for later sampling were derived. The sampling program was designed to establish the complete succession with special emphasis on the superficial muds. The underlying geological bedrock succession is consistent in terms of overall thickness and numbers of thin calcareous deposits with that already established onshore.

Overlying the bedrock, around the southern and northeastern periphery at least, is a thick <u>in situ</u> peat bed. The peat dates from 5,490 yr BP to 2,670 yr BP, a time when proto-Lake Okeechobee had a much more restricted extent than at present. Extending over much of the northern part of the lake and overlying the peat in places is a thin fan of quartz sand. The sand is most recently of fluviatile origin and its extent and variation in thickness imply input by streams and rivers from the north.

The shallowest deposit and the one of greatest interest in respect of nutrient cycling in the lake is a black, carbonate and organic rich mud. As with the sand, the mud is restricted to the northern end of the lake, occupying about one third of the area of the lake bed. It contains $\sim 193 \times 10^6 m^3$ of material and is offset slightly to the northeast of the central deep of the lake. As a result its surface slopes towards the southwest at a low angle. Mud depths range from a few centimeters at the periphery to in excess of 75 cm in the deep center of the lake. The deposit has been accumulating for a long period ($\sim$ 6300 yr). Its distribution suggests input of some components from the same northern rivers which supplied the sand. Variation in deposition rate with time remains to be investigated.

Internally the deeper, central mud area shows slight lithological variations interpreted to imply that deposition commenced here. The upper and more extensive part of the mud succession looks less differentiated in cut section, but high resolution X-radiography of thin vertical slices showed that the lower horizons exhibit a microscopic interlamination of dark and light bands, thought to arise from periods of algae blooming, death and sedimentation of skeletal debris, alternating with more normal periods of deposition of organic floc material. The microscopic internal primary fabric is clear evidence that the deeper layers of the mud patch are not susceptible to frequent reworking. The X-radiographs also show that there appear to be spherical gas bubbles in the mud in some areas.

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The present results need to be considered along with the nutrient profile data to assist the understanding of the relationship between sediment entrainment and nutrient cycling. It is concluded that the role of gas merits further close scrutiny.

1 INTRODUCTION

Lake Okeechobee provides many functions for south-central Florida, including drainage, water supply, flood relief and recreation. The water quality of the lake has deteriorated over thirty years or more as evidenced by its chemical and biological properties. During this period farming practices and various other changes in the lake's watershed have occurred. Should water quality continue to decline, it is likely that plankton blooms will become more extensive, frequent and severe with the ultimate threat of eutrophication of the system. Steps need to be taken to reduce nutrient input to the system, but at present the major factors influencing the deteriorating water quality are not well documented or understood.

One scenario envisages that increasing input of nutrient to the inflowing waters are largely or entirely responsible for deteriorating water quality and that steps need to be taken to reduce these. Should this turn out to be the case, it requires a clearly defined course of action. A different scenario, however, envisages that, notwithstanding present nutrient loads, a large proportion of nutrients are sorbed onto fine sediment particles, which are periodically resuspended leading to partial nutrient release. According to this internal loading dependent scenario, decreasing the fresh nutrient input will have little short-term impact, because nutrient releases will continue to be dominated by fine sediment entrainment and nutrient leaching.

The study reported here is aimed at characterizing the bottom sediment regime in the lake. This has been approached by undertaking a continuous seismic profiling survey followed by a coring survey to characterize the various acoustic reflectors recognized by the geophysical instruments. The coring survey involved sampling with a small hand-held vibracorer. The vibracorer permitted the complete succession to be penetrated, except where indurated rock is exposed directly at the lake bed. The undisturbed samples were returned to the Coastal Engineering Laboratory at the University of Florida (UF) for the following sedimentological and geophysical testing to characterize the deposits. a) cutting, preparation and photography to determine the sedimentary succession, b) measurement of down-core density and shear strength profiles to determine erosion potential, and c) cutting of thin slices from the axis of cores for X- radiography to show the primary sedimentary fabric of mud deposits.

In addition to these laboratory studies, where very loosely consolidated "fluid mud" type deposits were observed to overlay the more consolidated muds in the field, in situ density profiles of these top-most deposits were performed on board ship at the time of collection with a vibrating tube-type densimeter. Such in situ measurement was essential as the loosely consolidated fluid mud deposits would otherwise have dewatered during transport and been impossible to measure in the laboratory.

Some of the measurements carried out under this study, e.g. core density and shear strength measurements, were also useful to a companion study on lake sediment resuspension and deposition (Hwang, 1989). Those measurements therefore are reported in detail in that study and only summarized in what follows.

2 METHODS

2.1 Field Techniques

Classical geological/sedimentological investigations of the type required in this study demand application of a particular suite of techniques which must be deployed in a set order. Firstly, continuous seismic profiling techniques must be applied. These include two basic types of instruments. A side-scan sonar allows the surface topography and acoustic character of sediments exposed at the lake bed to be mapped. At the same time, penetrating acoustic devices of some kind must be deployed to map the subsurface reflectors. See Appendix A for a report on the geophysical field operation.

The maps prepared from these two types of system then provide the input and basis upon which sample localities are chosen to characterize each reflector type and the sedimentary succession. Arising from this heirachy of techniques it is clearly essential to complete the geophysical surveys before moving on to the bottom sampling program.

In this case the extremely shallow nature of the lake (maximum depths 4-5 m depending on water level, see Fig. 1), together with the suspected presence of gas in the sediments, imposed certain requirements upon the type of seismic device used. Arising from its known high resolution it was decided to use an E.G. & G side-scan sonar. The extremely shallow water depth and mud layer thickness indicated that a short pulse-length, variable frequency pinger was the best high-resolution, shallow-penetration device to chose. By the use of these devices continuous seismic profiles of a better caliber than any previously available from the lake have been obtained.

The E.G. & G SMS-960 side-scan sonar employs a towed torpedo-shaped fish with 105 kHz transducers on either side. It produces a fan- shaped pulse of sound (in the vertical plane with the transducer forming the axis or hinge of the fan). Foreward movement of the fish ensures that successive strips of the bed are scanned. By this technique two swathes of the lake bed extending from directly under the survey vessel out to a nominal range of

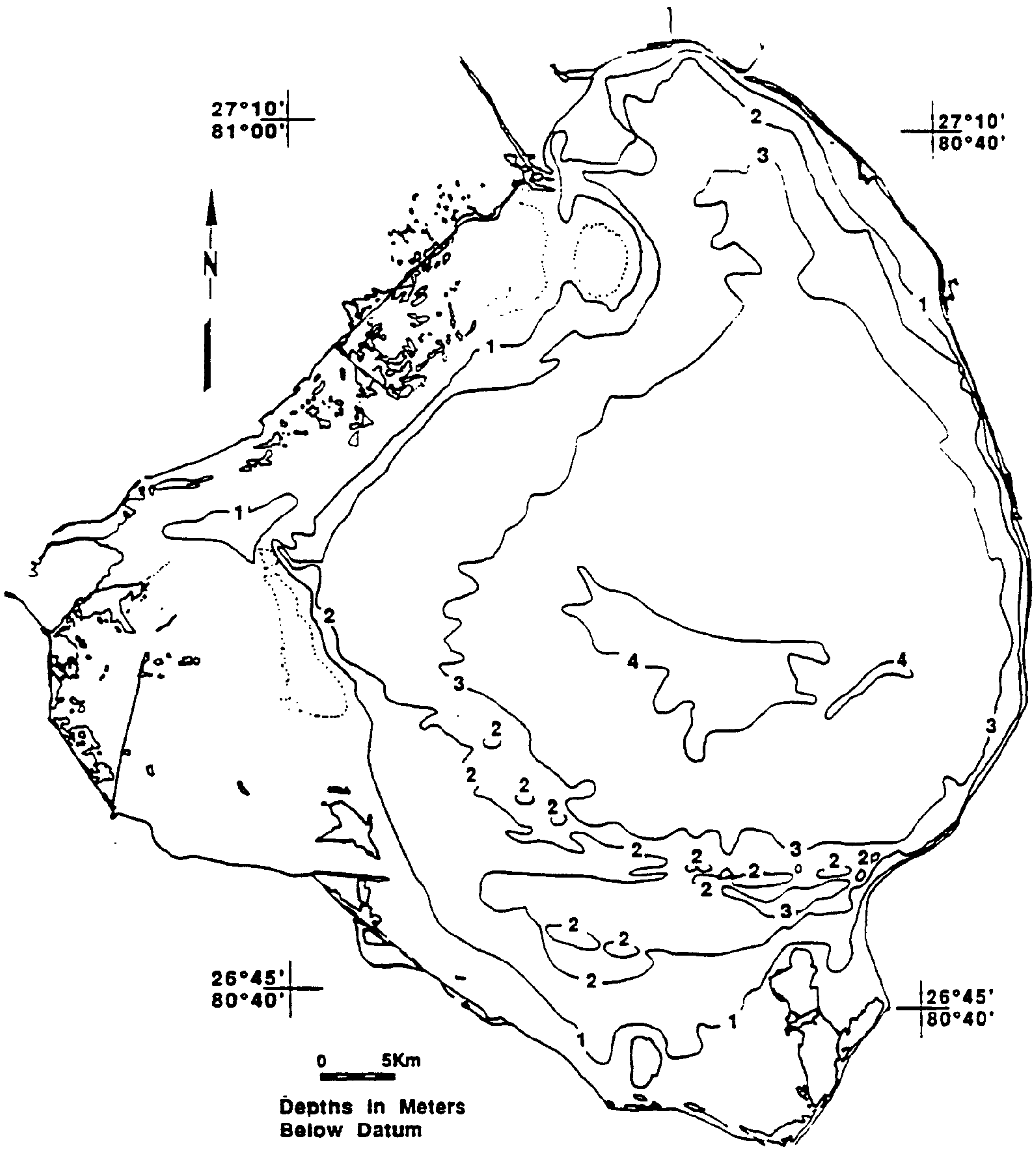

Fig. 1. Bathymetric map of Lake Okeechobee. Depths are relative to a datum which is 3.81 m above msl.

100 m on either side are covered. The E.G. & G SMS-960 employs a signal conditioning unit which produces digital records are scale corrected to provide an undistorted image.

The Datasonics SBP-5000 pinger employs a piezo-electric crystal to produce the acoustic pulse which is directed down through the lake bed. A receiving hydrophone collects the returning acoustic signals from sub-surface reflectors. In addition to the variable frequency (3.5, 5 or 7 kHz) pinger a high frequency (200 kHz) echo sounder was operated in parallel. The high and low frequency systems are complementary, permitting precise bottom tracking and good penetration, respectively.

To complete the mapping a small mechanical vibracorer was developed and deployed from a davit on the UF research vessel Silver Bullet. The vibracorer basically has a concrete vibrator powered through a flexible drive from a gasoline motor on board the survey vessel. The concrete vibrator was clamped onto the top of the drill barrel. The drill barrel was 1.83 m in length and had an i.d. of 9.4 cm. It was fitted with a transparent liner to contain the sample. To permit core penetration and retention, a steel cutting shoe, plastic, petal-type core catcher and a non– return valve were fitted. A threaded collar on the top of the corer permitted a guide tube to be fitted. This was attached after the vessel had anchored and the corer had been hung over the side and into the water. The guide tube allowed the vertical position of the corer to be maintained during drilling operations (Fig. 2) as well as permitting visual monitoring of bed penetration. Sample sites were chosen at localities where the geophysical records indicated that particular topographic or lithological features occurred at the surface or within reach of the vibracorer, but below the mud surface. See Appendix B for a brief report on coring survey.

On recovering the vibracorer, the transparent liner was capped at its base and removed from the core barrel. The sample was then measured and described on board ship. In circumstances where the upper surface of the mud deposits was very loosely consolidated a Paar (DMA 35) densimeter was used in the field to measure the density structure of the upper, lowly consolidated horizons. The Paar densimeter is a small, battery operated device

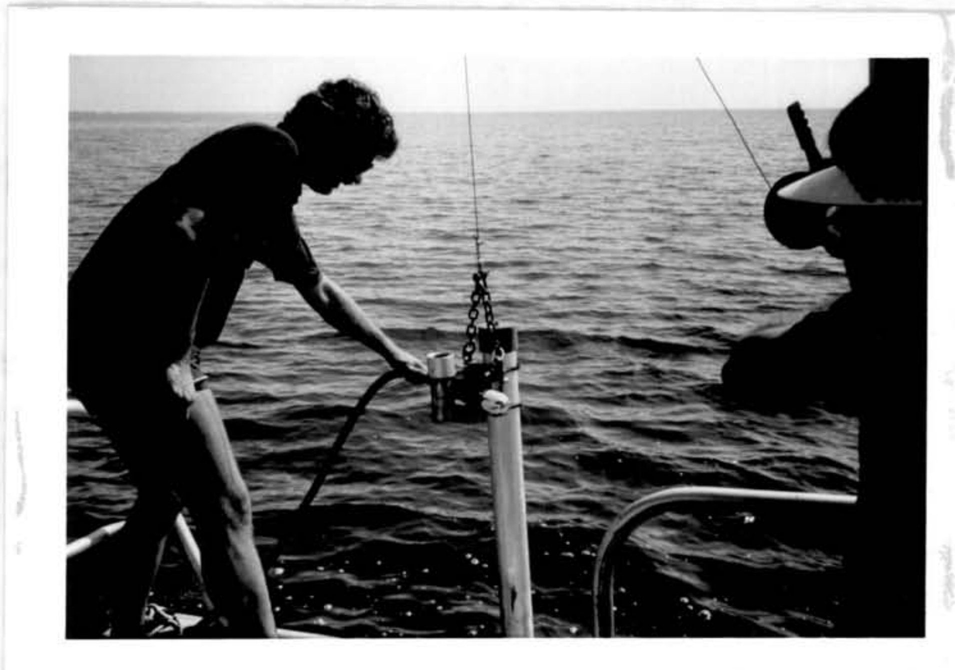

Fig. 2. Vibracorer being deployed for core collection.

for accurate measurement of the density of slurries. It operates on the principle of a vibrating glass U-tube. The frequency of the vibration is directly influenced by the slurry, which is converted to density in the instrument and displayed digitally. The core liner was then capped at the top and numbered before being stored in an upright position for transport to the laboratory.

2.2 Laboratory Techniques

In the laboratory the cores were laid in a clamp and the liner only was cut down opposite sides with an electric saw. The core was then halved by drawing a cheese wire down the cuts and through the sample. The bisected core was then opened so that both halves could be described and photographed. Illustrative core photographs are included in Figs. 3, 4 and 5. Core locations are shown in Fig. 6.

No further studies were made on quartz sand, peat or beach rock, but attention was concentrated on the upper muddy zone, where this was present. Shortly after cutting and before the sample could dry to any extent, vertical profiles of density and shear strength were made.

The density profiles were made gravimetrically and the shear strength profiles were measured with a small calibrated vane (Wykeham Farrance, Model 100). Cone penetrometer tests were also carried out. Measurements were made at 5 cm increments of depth and the vane was inserted sideways into the axial (thickest) part of the halved core. This procedure disrupted the sample, rendering it inappropriate for later non-destructive testing.

The other half of the core was then tipped gently out of the liner to rest with its diameter flat on a board. The upper, curved section was then removed with the cheese wire and a palette knife to leave behind a constant thickness (5 mm) undisturbed slice from the maximum diameter of the core. This slice was then X- radiographed using a standard X-ray machine with a low powered (75 kV, 550 mA) head. The X-ray films were then processed to show the very small scale and detailed primary fabric of the mud layers. Illustrative examples are shown in Figs. 7a, 7b and 8.

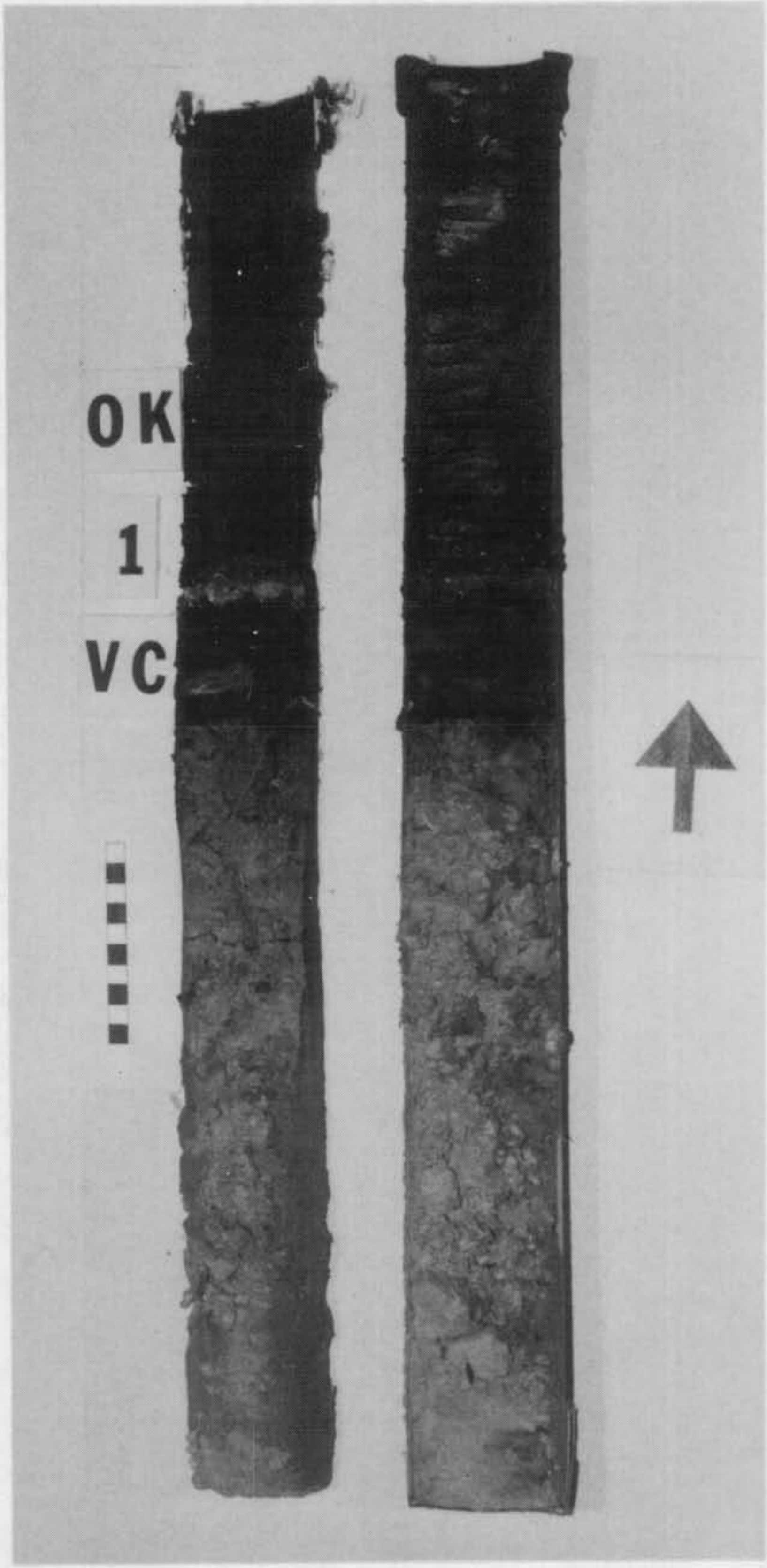

Fig. 3. Core OK1 VC.

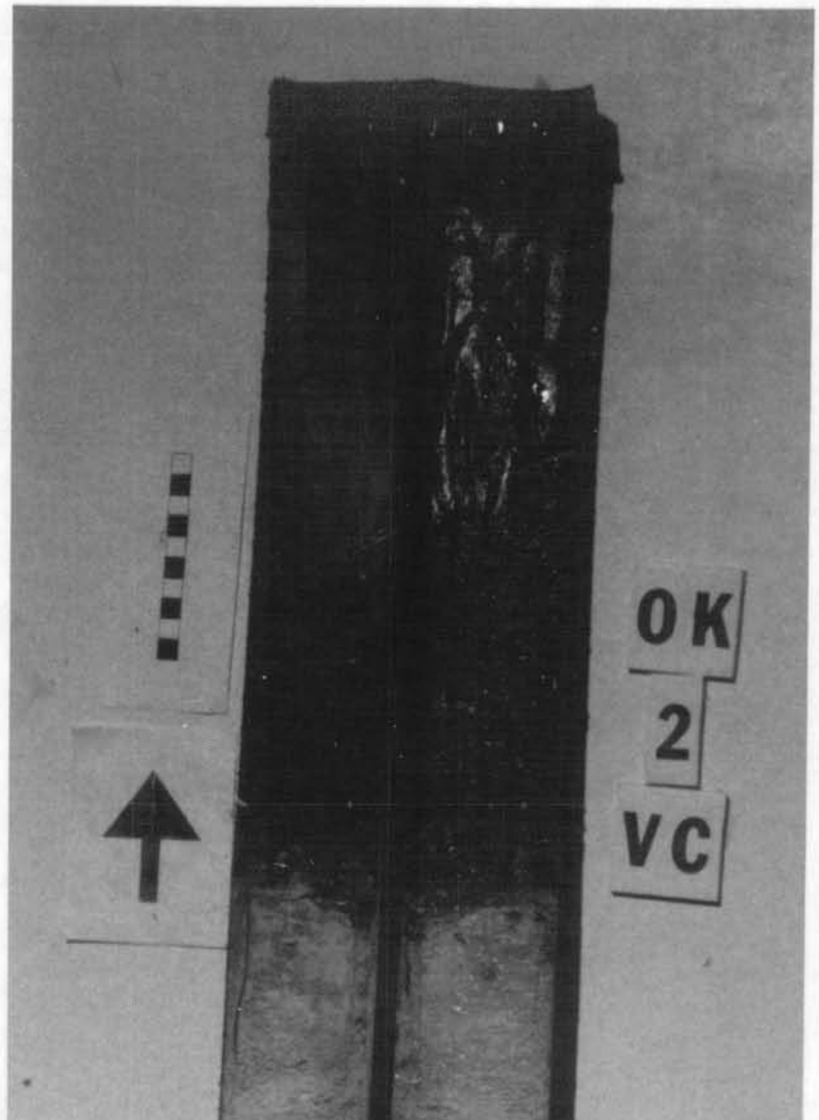

Fig. 4. Core OK2 VC.

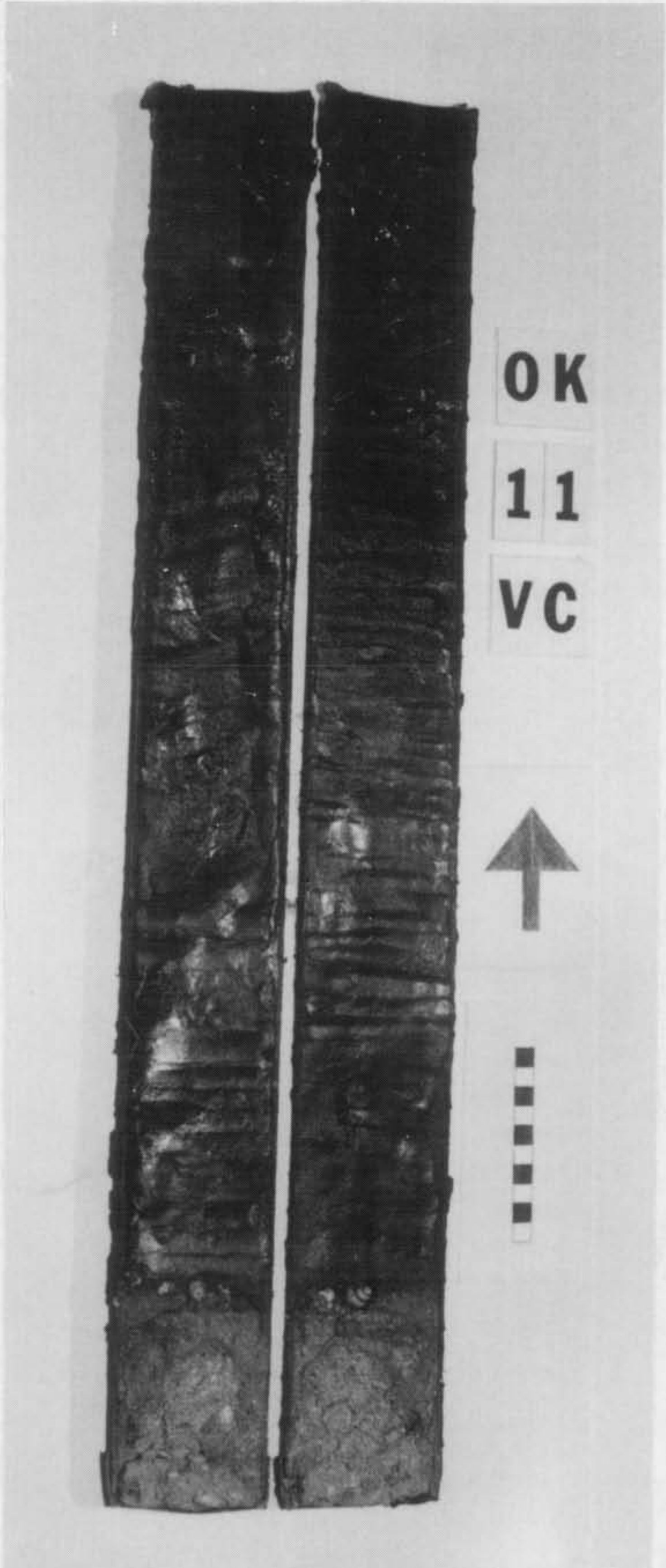

Fig. 5. Core OK11 VC.

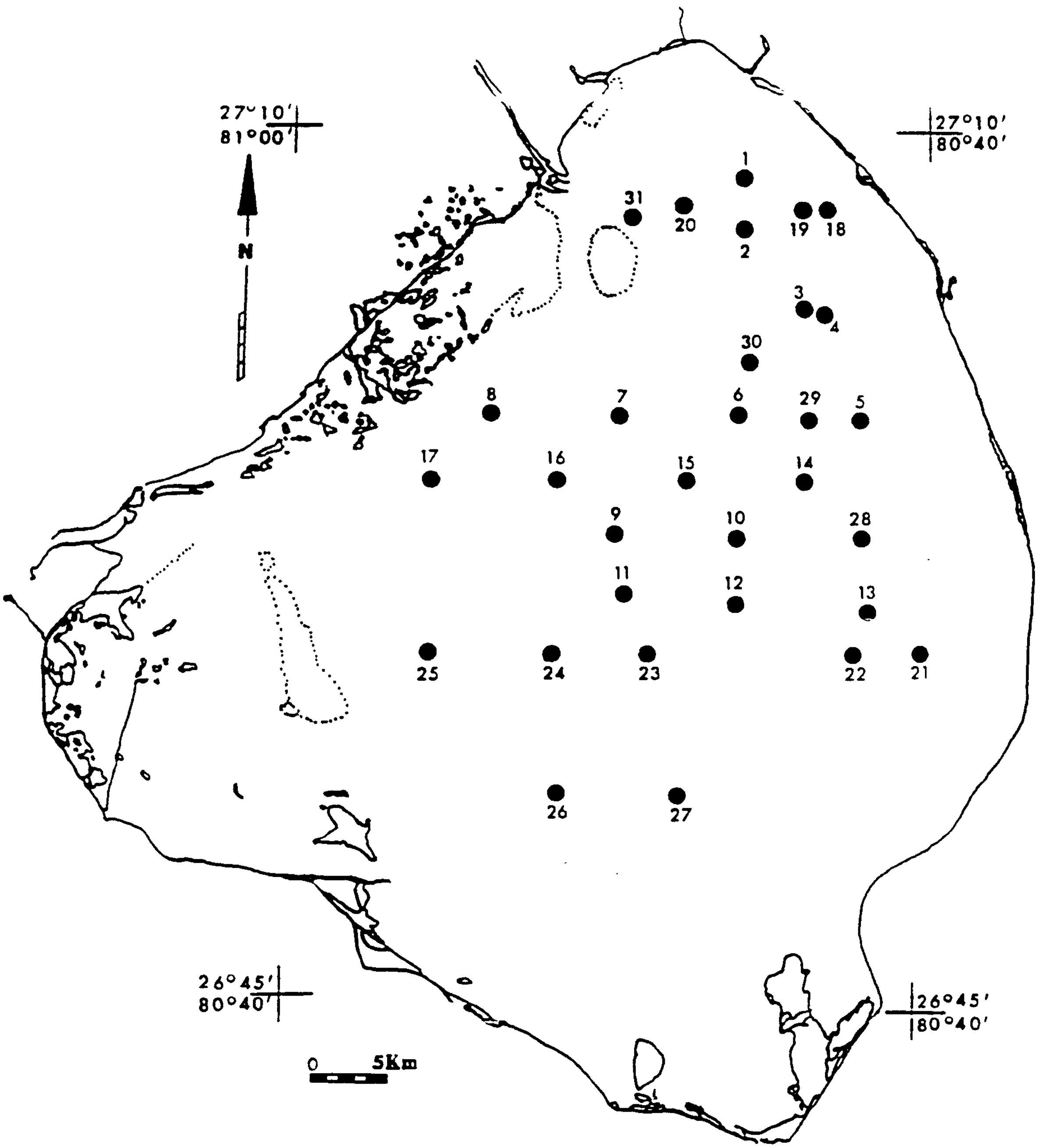

Fig. 6. Vibracore sampling locations.

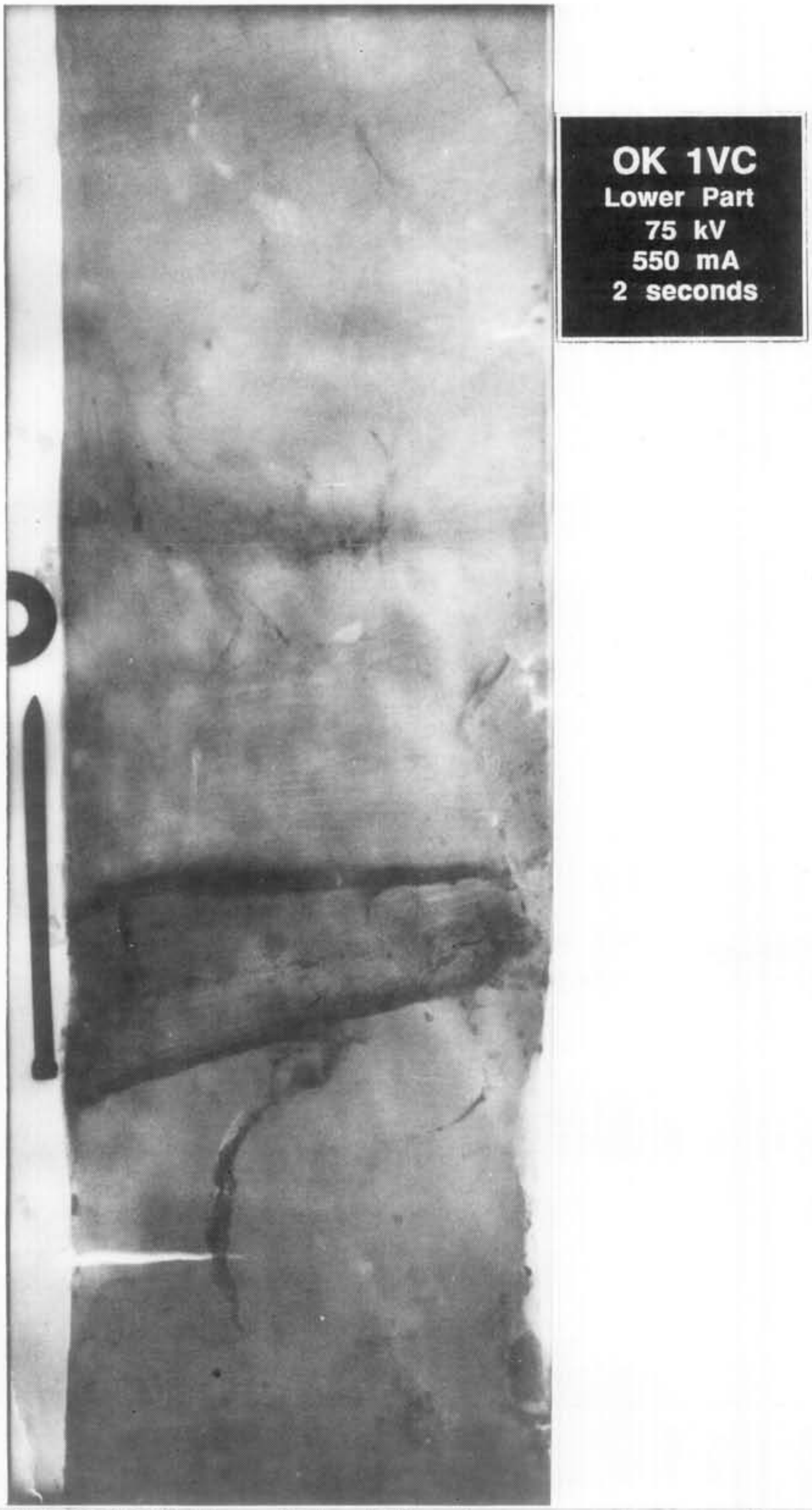

Fig. 7 (a). Core X-radiograph. X-ray (7 kv; 550 ma) exposure time was 2 seconds. Lower part of core OK1 VC. Nail image is 5.1 cm in length.

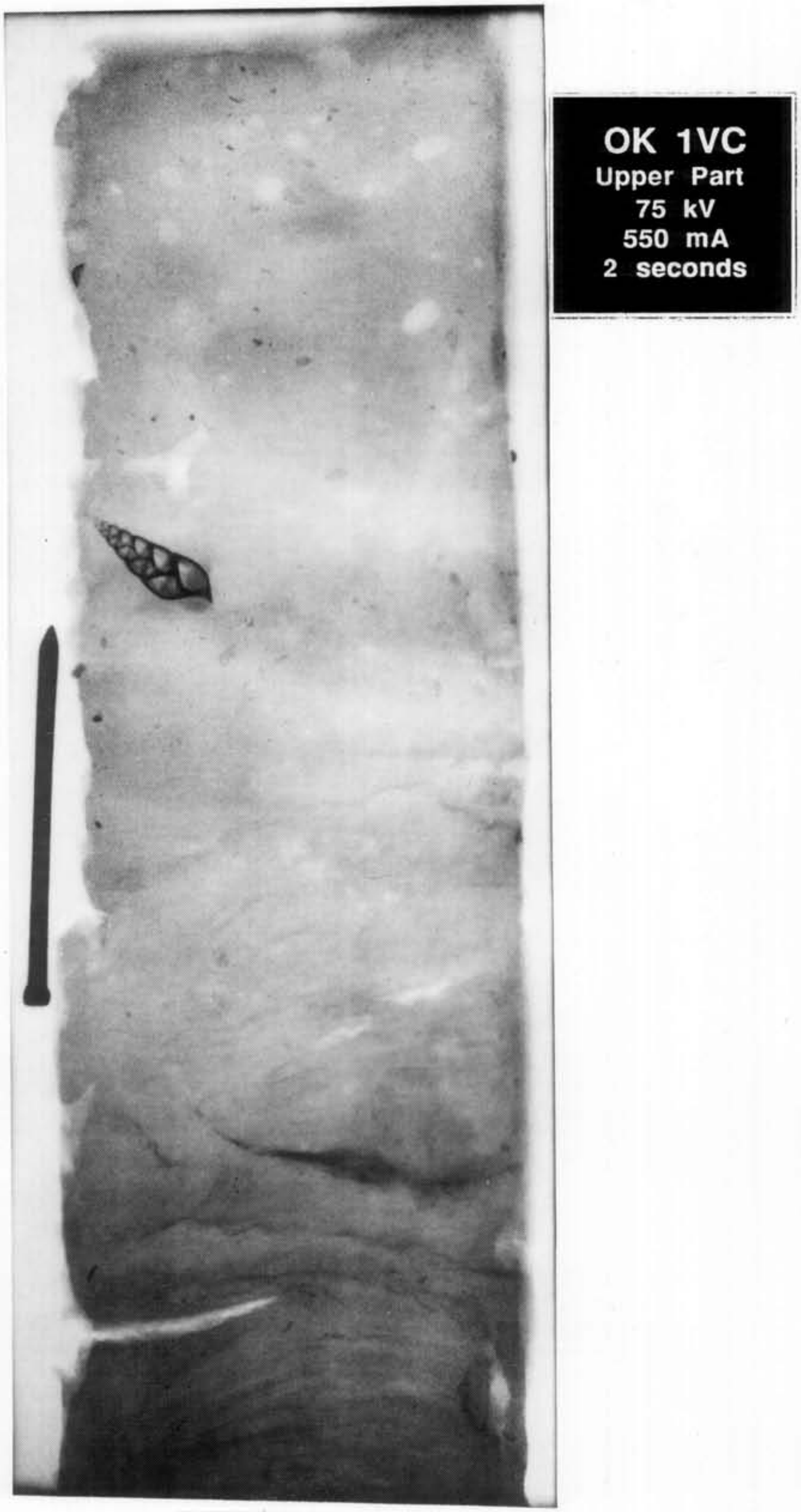

Fig. 7 (b). Core X-radiograph. X-ray (7 kv; 550 ma) exposure time was 2 seconds. Upper part of core OK1 VC. Nail image is 5.1 cm in length.

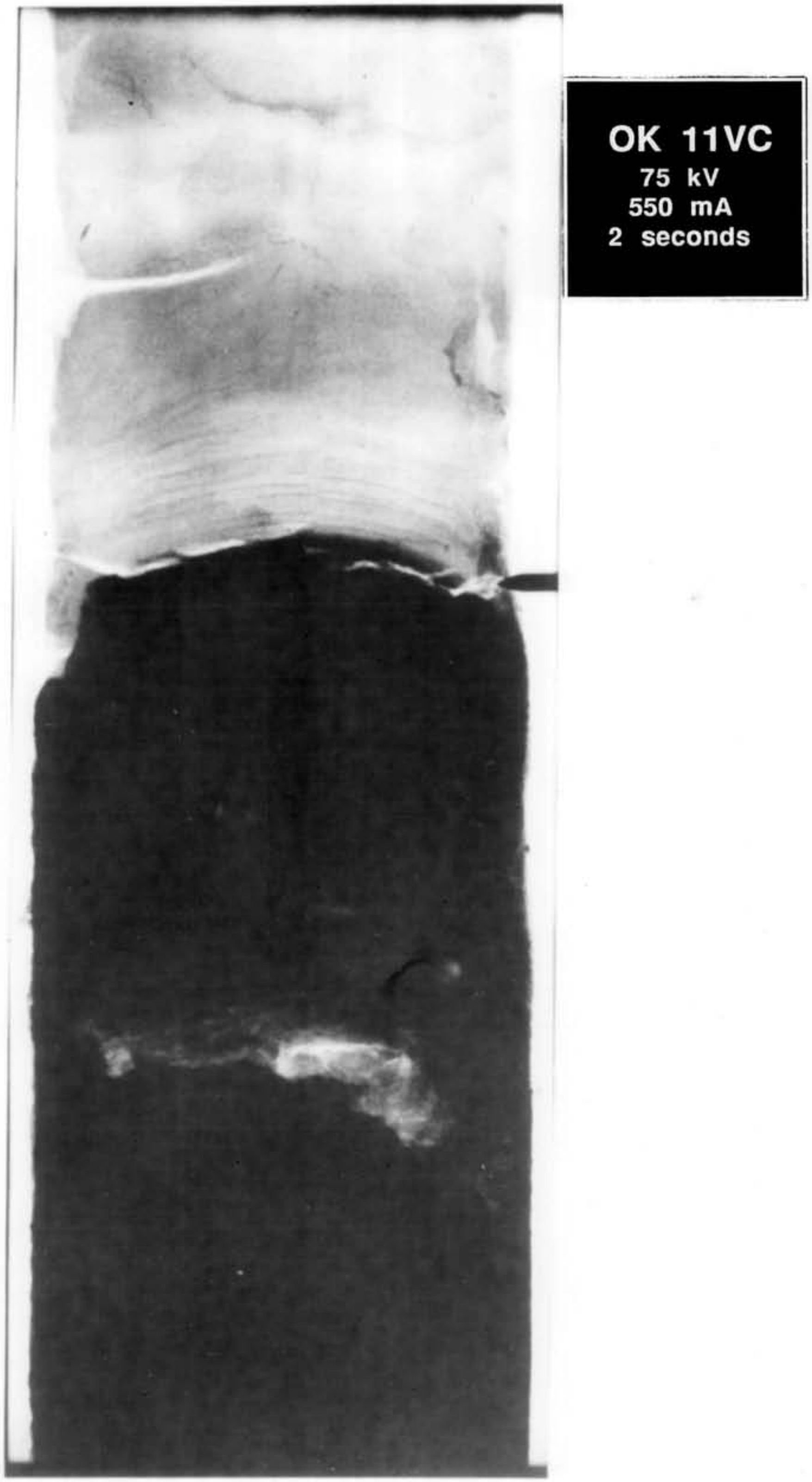

Fig. 8. X-radiograph of core OK11 VC.

3 RESULTS

3.1 Introductory Note

Part of the task of characterizing the sediments is to map their areal and vertical extent. A map showing the surface sediment distribution is presented as Fig. 9; illustrative core descriptions are provided as Appendix C. For all core descriptions see Hwang (1989). These form the basis upon which the geological history is established.

3.2 Geophysics

Sub-bottom profiles were of variable quality, possibly being strongly influenced by weather conditions experienced during the survey. Some records, i.e. those from lines 2, 3 and especially Line 4, were particularly good.

The geological history revealed by the continuous seismic profiling records is of well defined, if shallow, limestone (?) bedrock basins or swallow holes. 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 is difficult to establish owing to the variable record quality.

The origin of the basins is not clear from the geophysics records alone. In addition to these series of basins the bedrock surface, at least in the west on Line 4, where record quality was excellent, is quite irregular and shows a large number of steep, often V- shaped, valleys or channels which criss-cross the margin of the basin. Similar channels are also incised into the bed of the basin. The abundance and shape of the channels gives rise to the tentative suggestion that they may be infilled, possibly tidal, channels.

More recent calcareous deposits overlie much of this ancient topography with the result that the more accentuated, if low, relief has become muted. In the basins themselves the overlying calcareous deposits are generally of a sheet-like and extensive nature. In the more central areas of the lake up to 5 separate layers can be resolved, whereas towards the edge of the lake it is generally the case that only two layers are present. The depth of the

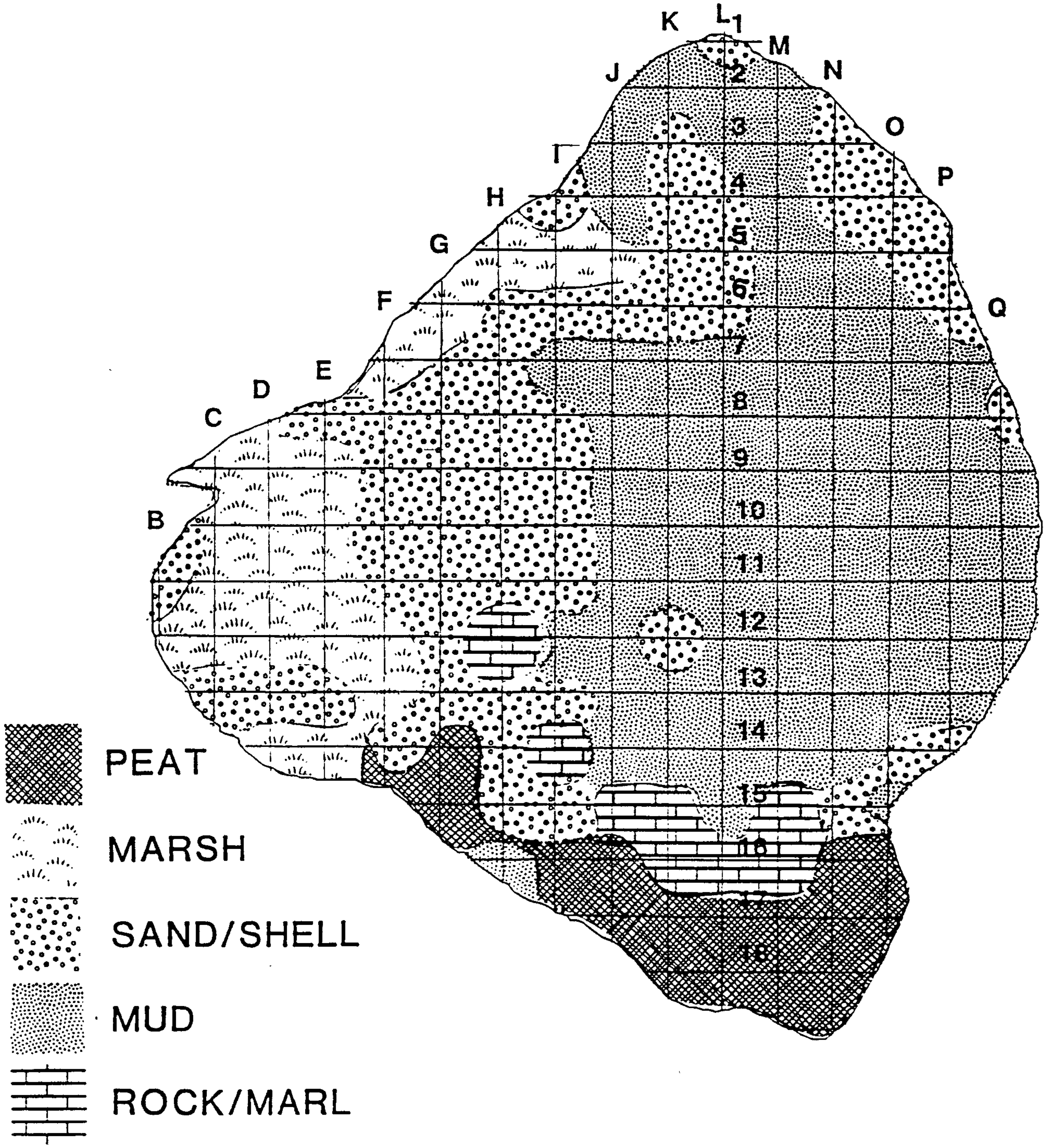

Fig. 9. Surface sediment distribution in Lake Okeechobee including coring grid pattern (courtesy Ramesh Reddy and Don Graetz, UF Soil Science Department). Compare with sediment distribution map produced in this study (Fig. 10).

deposits ranges up to a maximum of 4 m, but is more generally in the range 1.5 - 2.5 m. The complex history of the deposits is illustrated from the fact that deeper layers of these calcareous rocks are themselves cross-cut by later channels and the channels, in turn, have been infilled. 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 calcareous layered deposits.

The vibracorer nowhere reached down more than 30-40 cm into these indurated calcareous rocks, which are referred to here by the generic term "beach-rock." The highly cemented nature and presence of marine shell species in samples (e.g. see Fig. 7a) suggests they are likely to be in part old shallow marine sediments of possible Plio-Pleistocene age. As a result the deeper layers remain unexplored, other than by these seismic techniques.

Overlying mud deposits are difficult to isolate from the underlying beds on the geophysics records. Signals from the mud zone are often "acoustically turbid" - possibly indicating the presence of dispersed gas. At some sites deep-lying strong reflectors may be from shelly layers, e.g. on Line 7 in the south. Elsewhere, for example on Line 4, in addition to the acoustic turbidity the signal from the upper horizon showed strong surface or near-surface reflectors and a phase reversal of the signal. Initial inspection might suggest the presence of coral boulders at the surface, but the 200 kHz record clearly showed a planar lake bed and the parabolic reflectors diagnostic of rock debris are absent from the record. Instead it seems more likely that these signals are due to the presence of gas accumulations in the sediment. This is also suggested by the weak reflectance of the surface seen on the side- scan records.

These zones of phase reversal are at times several tens of meters in extent on the pinger records and would undoubtedly be picked up on the side-scan records if there were patches of shell or rock at the surface. The side-scan records did, however, show a multitude of small (< 1 m) point-source strong reflectors at the lake bed (see e.g. Fig. 7a). These strong reflectors could have several origins.

To investigate the character of the unconsolidated sediments at the lake bed and interpret the geophysics, samples had to be taken.

3.3 Samples

The accessible part of the geological succession is rather straightforward. The entire lake appears to be founded on a whitish, calcareous marine "beach rock" type material. Almost all cores penetrated into this although in some cases, especially in the south, the beach rock is so indurated that the vessel could either not anchor or the corer was unable to penetrate. In a few cases the deposits overlying the beach rock are sufficiently difficult to drill and have a thickness such that they were not completely penetrated by the corer. Over part of the area the beach rock is overlain by a peat layer. Above the peat and not quite coincident with its preservation is a quartz-sand horizon. The shallowest deposit is a blackish, organic-rich clay layer, which shows both macroscopic and microscopic primary layering. The peat, sand and mud occur chiefly at the northern end and in the center of the lake, whereas the southern end is largely free from unconsolidated sediment. The extent and thickness of the various horizons are shown in the bed sediment distribution map (Fig. 10).

Much of the margin of the lake, especially on the west side, is extremely shallow and difficult to gain access to as a result of extensive beds of vegetation. This zone could not be investigated during this survey, but has been investigated by UF's Soils Science Department in a companion study. The various formations are discussed in the following sections.

3.3.1 Beach 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. These deposits are of variable lithology and include indurated lime muds, nodular limestones, calcareous sands and sandstones and shelly horizons. In places the upper zone shows signs of weathering and the penetration by rootlets from the overlying peat. The shelly fauna consists of gastropod and bivalve species and has not been specifically identified. These basal deposits were considered by Gleason and Stone (1975) and Brooks (1984). The calcareous deposits are probably the complete succession of the Caloosahatchee-Fort Thompson formation (Plio-Pleistocene).

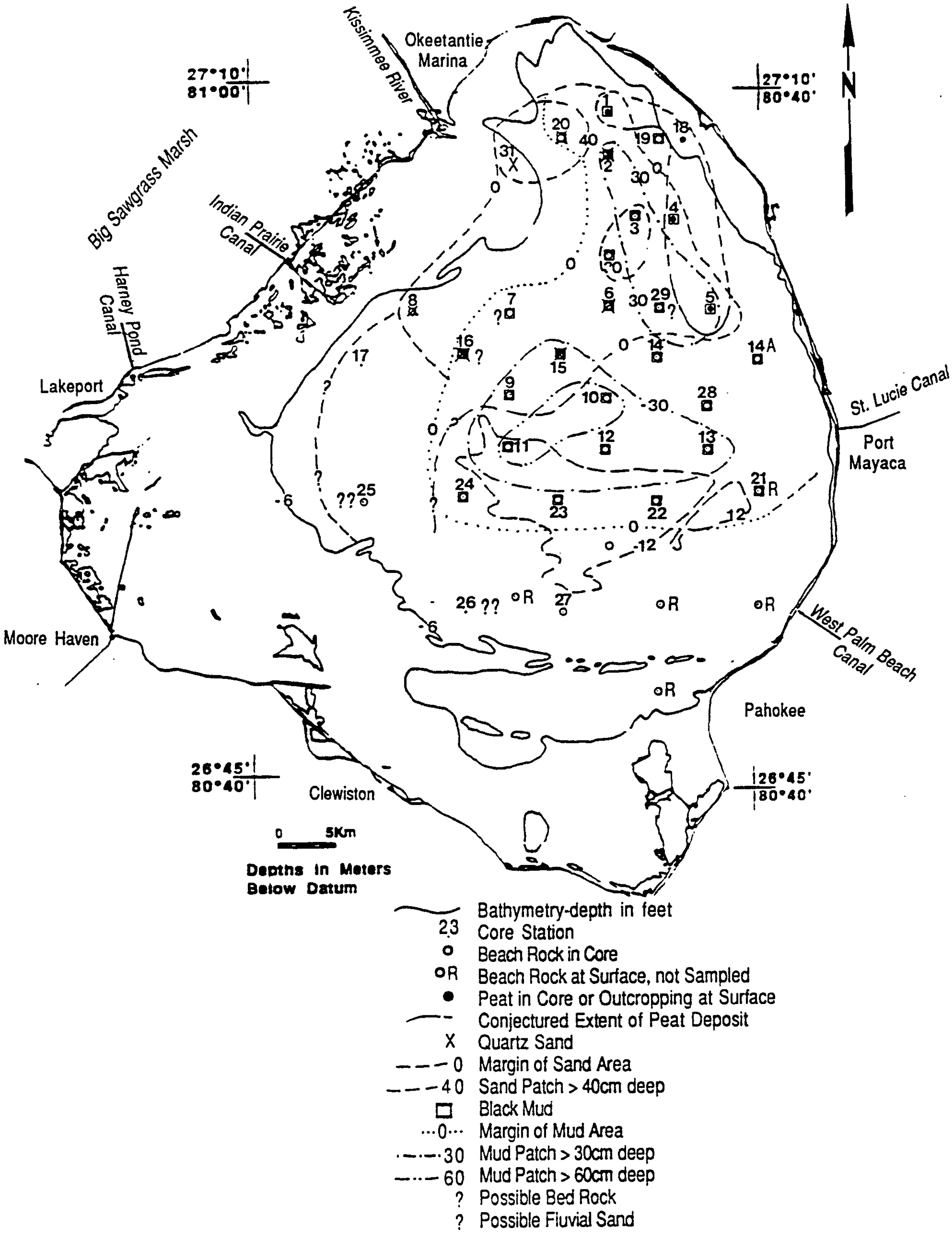

Fig. 10 Sediment Distribution Map of Lake Okeechobee.

3.3.2 Peat

One of the more unexpected discoveries of the sampling campaign is the depth and geographical extent of peat deposits at the northern end of the lake. The authors are not aware that peat deposits have been recognized at the northern end of the lake before.

The peat deposits are believed to lie in situ. In a number of cases the beach rock upon which they invariably rest is penetrated by rootlet beds from the vegetation which originally grew upon the beach rock surface. The fact that the peat is in places layered and shows a variety of textural features may also support the view that it is in situ and if the need arose could be sampled for pollen and other evidence of the past environment around Okeechobee. The relatively thick and layered peats hint at a quite prolonged period of sub-aerial exposure during which a variety of climatic or environmental changes occurred. No attempt was made in this study to carry out pollen dating, radiocarbon dating or any identification of macroscopic plant remains.

Being organic, peat layers are known to generate and hold gas. As such they present particular difficulties to seismic devices, which generally will characterize them as strong reflectors, producing a phase reversal of the acoustic signal. Peat layers are thus difficult for seismic devices to "see through" to what is underneath. In this case what is below is the beach rock and is of little direct interest to this study.

The extent of the peat suggests that at some stage the entire basin may have been a peat bog or at least that the water may have occupied a smaller area in the deep center of the present lake. The oldest previously known peats are 5,490 yr BP and range up to 2,670 yr BP (Gleason and Stone, 1975).

3.3.3 Sand

In those few cores where the succession is complete the peat is overlain by a grayish quartz sand. The sand occupies a broader zone than the peat at the northern end of the lake, although it is generally thin (< 10.0 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-sizes and shell content overlie each other. In the west the sand layers are exposed at the lake bed and not entirely covered by the more recent black muds.

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 terrestrial peat, are all indicative of a fluviatile sand supplied by the Kissimmee River drainage basin, as opposed to a marine beach sand.

At the southern extremity of the fan of sand thin sand layers are interbedded with the overlying black muds at two sites. This suggests that the sand sheet originally had a rather greater southerly extent and was reworked back onto the proximal mud deposits at a much later date.

The sand layer is indicative of a change in source rocks or deposits in the hinterland compared to that which is presently supplied. The Kissimmee River watershed constitutes more than 50% of Okeechobee's drainage basin and the Plio-Pleistocene deposits are more sandy in the north. The sand layer is not directly relevant to the present investigation.

3.3.4 Mud

Black, organic-rich muds form an extensive veneer in the northeast quadrant of the lake, possibly covering a third of the entire bed. Why the mud should be absent from the southern end and western sector of the lake is unclear, especially because the western side of the lake is heavily vegetated and thus provides both more sheltered and possibly more nutrient enriched waters. Possibly the distribution is linked in some way with inputs of nutrients or inorganic fine sediment from Taylors Creek or the Kissimmee River in the north. Equally it is not immediately apparent why the mud is absent in the south, other than to observe that the distribution of sand and mud are similar in this respect. Maps showing both bathymetric contours and the extent of the mud patch (Figs. 1 and 10) reveal that the mud patch is offset to the north-east such that its surface is inclined to the south-west. This is presumed to reflect a hydrodynamic control. The mud layer is generally less than 30 cm thick, although in two areas it exceeds 30 cm and approaches 75 cm in one. The area of maximum thickness of mud is almost coincident with the area of deepest water, possibly indicating a link.

The general outline of the edge of the mud patch is closely coincident with that mapped in greater detail with more samples by UF's Soil Science Dept. (Fig. 9). Most discrepancies are comparatively minor and probably accounted for by the poor repeatability of the LORAN positioning system (see Appendix A), added to the fact that the mud area thins to a feather edge at its margins and probably is patchy. There is a greater discrepancy in the south where seven stations were attempted during this survey. At five the vessel could not anchor or the vibracorer would not penetrate, indicating the presence of rock at the surface. The anchors came up clean. At the remaining two stations the corer produced rock samples. Clearly any black mud here must be thin and very soft. The southerly limit of mud is probably about 26° 54′N whilst the Soil Sciences map shows a greater southerly extent down almost to 26° 49′N.

Whereas the boundary of the mud area as mapped by Soil Sciences and this vibracoring survey are generally coincident the thickness of the mud patch sometimes appeared rather different. This is largely accounted for by the fact that Soil Science mapped the mud depth by measuring core length in the field. In contrast, in this study the length is measured from opened cores. The peat and sand layers omitted from this study result in a smaller mud thickness. To facilitate core retention the vibracorer used a petal-type core catcher. In the very lowly consolidated muds encountered this could have given rise to a certain amount of loss at the top of the sample. Other evidence (below) shows that the amount of disturbance caused to the sample by the vibration, core-catcher, recovery or removal and capping of the core was, however, generally slight. In Fig. 11, a mud contour map is presented to highlight the variability of mud thickness. This variability appears to be considerably greater than that suggested by Gleason and Stone (1975), although their observations regarding mud distribution in the lake are confirmed in a qualitative sense. Four sources of information were integrated in preparing this map: 1) geophysical profiling reported here, 2) vibracoring reported here, 3) core data derived from sampling undertaken by UF's Soil Science Depart-

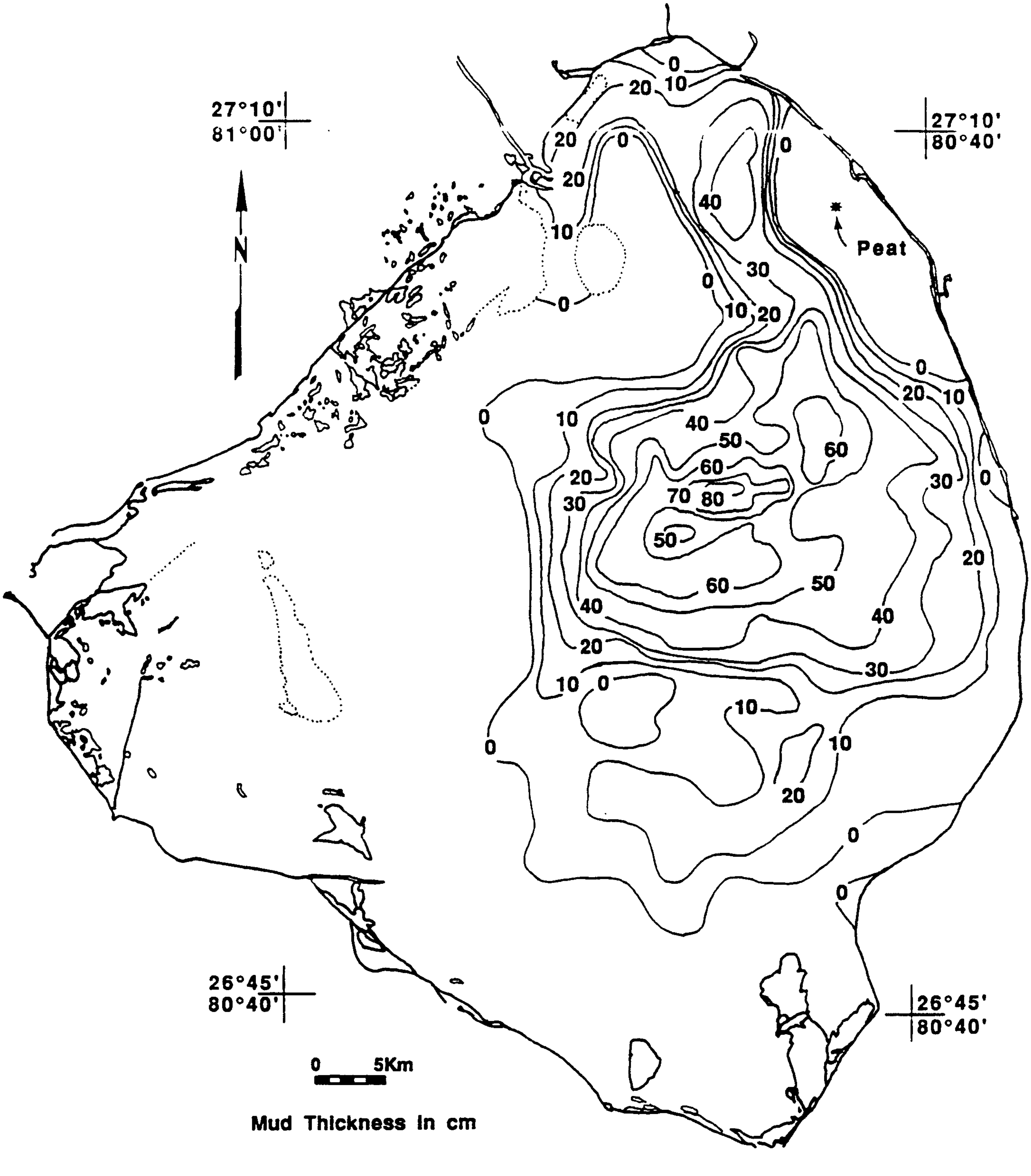

Fig. 11. Mud thickness contour map of Lake Okeechobee.

ment in Summer, 1988, and 4) Coastal and Oceanographic Engineering Department's data collection effort in Spring, 1988 (Appendix D). Using the values of mud thickness and area from this study, of the order of 193 x $10^6 m^3$ of mud lie on the bed of Lake Okeechobee.

Cutting the cores revealed the primary fabric of the black, organic-rich muds. The muds have little by way of a benthic invertebrate fauna; living organisms were largely confined to an occasional rare and small, highly ribbed, fresh water bivalve. Arising from this the samples were expected to show a well- preserved primary fabric, although there was little in the uncut cores to reveal any evidence of any significant change in lithology with depth.

Once the cores were cut the internal structure was more readily apparent and some lithological contrasts were apparent. Samples OK2, 6, 9, 10, 11 (?), 14, 15, 28 and 29 showed zones of different colored clay and thin beds of shell or sand. These lithological variations are important confirmation that the cores are largely undisturbed. These samples with a more complex stratigraphy occur in the deepest mud zones, suggesting that these are the earliest deposits, which accumulated slowly and possibly reflect major climatic perturbations in the lake or hinterland, such as hurricanes (shell and sand layers), forest fires or other short term events (clay layers). Brooks (1984) has dated these lower muds at as early as 6300 yr BP.

The upper part of the mud zone is invariably formed by a more homogeneous, black silty clay of wider extent. It appears that following the deposition of varied lithologies and beds in the deeper areas a period of more uniform, widespread and faster (?) deposition has commenced. These apparently homogeneous beds can be examined using X-radiography.

3.3.4.1 X-radiography

Unlike sand deposits, which frequently show a variety of internal primary depositional features in cut section, mud deposits generally appear massive and homogeneous in cut sections of cores. Such apparent homogeneity hides much of the evidence for how the muds were deposited and their 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, or it could have been only an artefact of the small size of the sediment grains and uniformity of the sediment supply over a prolonged period.

To throw light on these issues the 5 mm thick slabs of core were X-rayed. The preparation technique employed ensured that any primary fabric was displayed with very high resolution. Arising from the fact that X-radiography was only applied to selected cores as a check on sample quality only a limited study of the internal primary sedimentary fabric could be accomplished.

Two features of the few X-radiographs (see Figs. 7a, 7b and 8 as illustrative examples) completed are worthy of note. These are that in most cases, especially towards the base of the mud layer, a distinctive alternating sequence of dark and light bands, or layers, is present on a submillimeter scale. A second significant feature is the apparent presence of gas. These two features are discussed in turn below.

The very delicate small scale layering is important at two levels. Firstly, it provides unequivocal evidence that the core samples obtained are largely undisturbed, despite the vibration process and the poorly consolidated nature of the deposits. This is very consistent with evidence of this kind of sample from elsewhere. Secondly, the layering shows in preserved form the history of individual sedimentary events in the lake waters stretching back in this case over several thousand years. The alternating light and dark bands clearly represent algal blooms and the detritus resulting from them, (skeletal secretions etc.) interbedded with organic deposits of more normal sedimentary processes, deposition of inorganic clays, precipitation of organic flocs etc.

The recognition of the layering has another implication relevant to nutrient cycling too, namely that any repeated resuspension and re-deposition, on whatever timescale it occurs, must only affect those sections of the bed deposits which do not show the submillimeter alternations. Any large-scale entrainment, for example during hurricanes, might be expected to give rise to single or infrequent graded units, as opposed to the alternations. Regrettably the frequency and distribution of dark and light alternations in the upper, massive and widespread shallow mud deposits could not be ascertained owing to the absence of X-radiographs of these materials.

In this study no attempt was made to date the deposits by radiocarbon techniques, or to examine the succession to discover whether algal blooms have become more common, more prolific giving rise to thicker bed deposits, or whether the species of algae involved have remained unchanged.

In the few X-radiographs available for examination there is apparent evidence that the submillimeter intercalculations become less well defined towards the top of the cores. There are several reasons why this might be so, core disturbance, lack of consolidation to form distinctive layers and the generation and expulsion of gas being just three of the possibilities.

One X-radiograph, OK1 VC (Fig. 7a), shows a series of circular or elliptical voids (light areas). This provides possible evidence of the presence of gas in the sediment. No strong smells of gas were detected at any time suggesting that H_2S (hydrogen sulphide) was largely absent and that any gas was likely to be in the odorless form of CH_4 (methane). The apparently spherical nature of the voids makes it unlikely that the voids were artefacts of the cutting and preparation process.

3.3.4.2 Evidence of Gas in Mud Deposits

The 7 kHz pinger records showed phase reversals of the acoustic signal consistent with the presence of gas in the sediment. In addition, the surface of muddy deposits shown by the side-scan sonar show many point-source reflectors (Fig. A.2). The abundance of these point-source reflectors is unusual for a mud area. The origin of the reflectors is problematical. They could arise from weed at the lake bed or could be debris and litter jettisoned from pleasure craft. An alternative possibility is that they could represent gas-seeps. This possibility has not been investigated further.

In addition to the acoustic evidence for the presence of gas, several of the cores showed signs of being gassy. Gas generation in recently collected cores can be difficult to distinguish from expulsion of air from voids created during handling. In this case recognition of the gas is made more difficult by the fact that the change in pressure from the lake bed to atmospheric is so small. In general terms such physical evidence for gas generation and presence in the cores was limited. This seems to be borne out by the rather undisturbed nature of the cores themselves. However, further evidence for the presence of gas seems to be found in the X-radiographs of some of the muddy cores.

Furthermore, rather strong evidence for the presence of gas in sediment was first obtained during a sediment sampling cruise in Spring, 1988 (Salkield, 1988). Table 3.1 provides a brief description of the type of material found at the different sites using a small piston core (with 5 cm dia. PVC pipes varying in length from 0.6 to 1.8 m) or a clamshell grab sampler, and whether gas was present in the sediment. Site locations are shown in Fig. D.1. Gas was detected by bubbles which broke the water surface when the clamshell was dropped at the bottom. Should there be significant gas in the muddy sediment, it could have a measure of importance in terms of its effect on erosion potential of the muds. This matter is believed to merit closer scrutiny.

3.3.4.3 Density and Shear Strength Profiles

A most important aspect of characterizing the physical properties of the muddy deposits was to determine their density and shear strength characteristics with a view to calculating their erosion potential. Many of the cores had a very loosely consolidated upper zone of fluid mud in which in situ measurements of density were made. These zones range from a few to eight centimeters in depth and have densities of 1.01 to 1.03 g cm^{-3}. No shear strength readings are available for these low strength upper zones, firstly because shear strength measurements were only made in the laboratory and secondly because the strengths were below the resolution of the instrument. Illustrative core descriptions are provided in Appendix C. For a more complete description of measurements see Hwang (1989).

The distribution of the low strength fluid mud zones showed no systematic pattern other than a slight possible tendency for the fluid mud zone to be deeper and more frequent in the south. In the firmer muds the density and shear strength measurements were generally

Table 3.1: Core/Clamshell Sample Description

Site No.	Material description	Water depth[a] (m)	Presence of gas
1	Muddy over soft marl	4.6	Gas released
2	Muddy with small shells	4.6	Gas released
3	Muddy[b]	4.6	Gas released
4	Muddy, no core	4.9	Gas released
5	No core, not much mud	5.2	No gas
5A	No core, not much mud, hard bottom	4.3	No gas
6	No core, fine sand and small shells over hard bottom	—[c]	No gas
7	Mud over hard bottom	4.9	Gas released
8	Mud over hard bottom	4.6	Gas released
9	Mud with some sand and shell	4.6	Gas (large quantity) released

[a]Water depths were about 1.2 m above the chart datum (reported to be 3.81 m above msl in NOS Chart No. 11428) at the time of measurement.
[b]Core penetrated about 0.3 m of mud, hit a relatively hard "lens," and then broke through into the mud below.
[c]Not recorded.

closely related. In unlayered deposits, such as OK2 VC, the density and shear strength values showed a steady increase with depth consistent with a normally consolidated, undifferentiated substrate. Other samples with a more complex stratigraphy of interbedded weak and strong clays or clays, sands and shelly clay layers showed a general gross increase in density and strength with depth but a detailed profile which shows a series of sharp density and strength reversals. Again the strength and density peaks and troughs generally were coincident (e.g. OK10 VC). In this core, however, whilst the shear strength increased with depth the density of the weak mud layers was lower at 50 cm than at 2 cm below the surface. This type of behavior arises from the fact that density is not an unambiguous analog for strength, which, among other factors, depends strongly on mud composition.

Mud densities were in the range that might be expected, ranging up to 1.2 g cm^{-3} and a maximum of 1.3 g cm^{-3}. Sand densities were higher, reaching 1.8 g cm^{-3}. Shear strengths reached almost 6 kN m^{-2} at times. Even close to the surface the shear strengths were generally up to three times the critical shear stress for erosion. A heuristic explanation for this difference is provided by Hwang (1989).

A plot of shear strength versus density based on measurements from a large number of cores (Fig. 12) shows the expected scatter of data points. A best fit curve for the data intercepts the density axis at 1.065 g cm^{-3}. At density values below 1.065 g cm^{-3} the shear strength becomes zero, implying that the mud essentially behaves as a fluid.

The evidence seems to indicate that the fluid mud layers could be regularly resuspended during windy weather, whilst the underlying mud is relatively resistant to erosion. The intricate and small scale lamination of the deeper mud layers supports this observation. In addition, resuspension work carried out by Hwang (1989) as well supports the same observation, indicating a depth of reworking under storm wave action on the order of 10 cm.

3.3.5 Problematic Substrate

In the west at depths less than $\sim$ 2 m the black mud and peat deposits are absent and at several OK localities (Fig. 6), 8, 17, 25 and 26 and possibly also at 7, 9, and 16, a

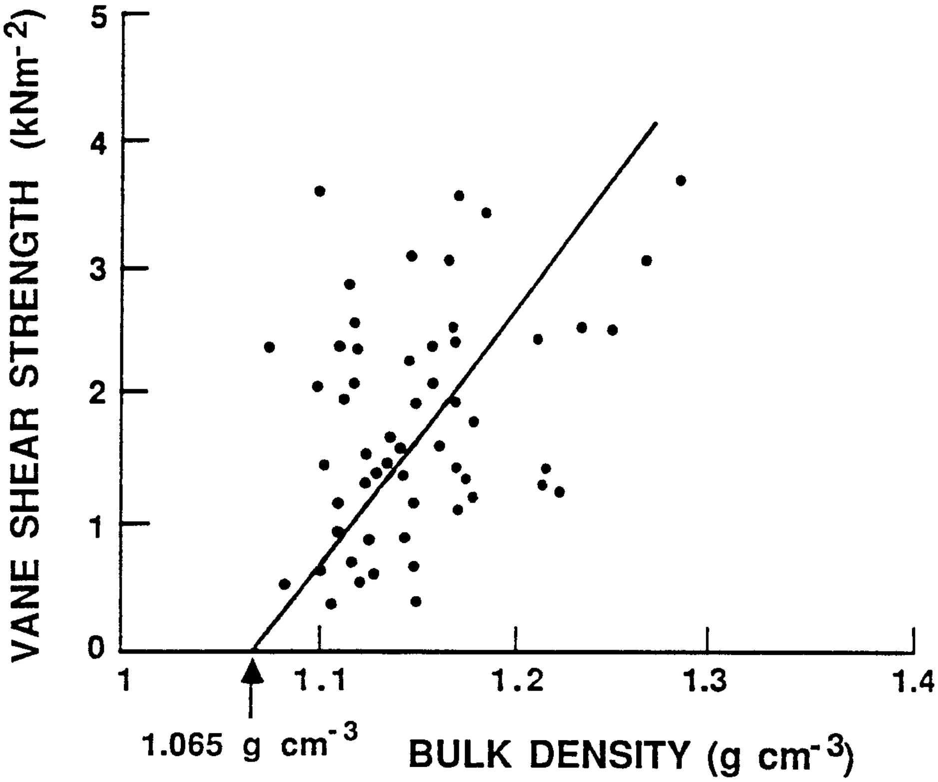

Fig. 12. Mud vane shear strength variation with density (after Hwang, 1989).

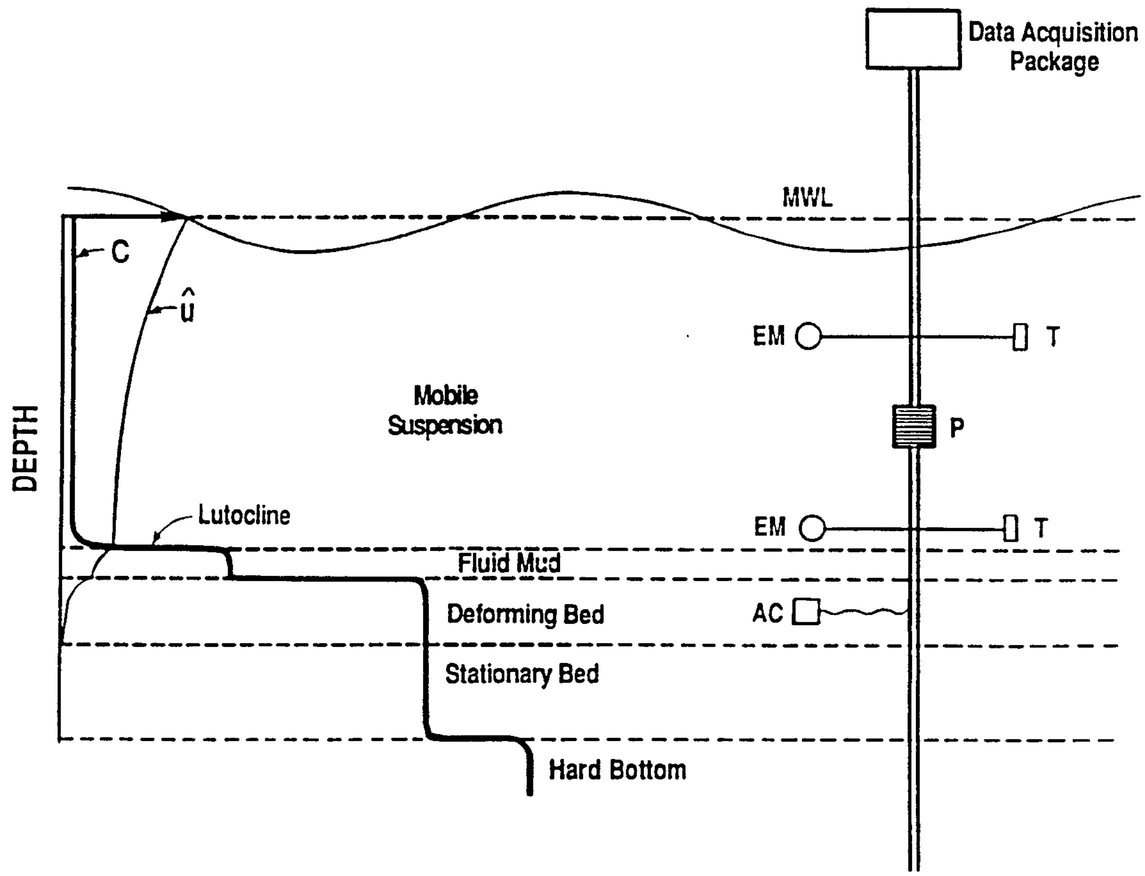

Fig. 13. Schematic showing velocity and concentration fields under wave action and suggested instrumented tower.

variable, generally whitish or grayish sand or shelly clay occurs. The layer is believed to represent either the weathered top of the beach rock or the fluviatile sand. It is unclear whether sediments of this zone should be considered as the ancient marine foundation of the lake, as later fluviatile deposits or whether they are a mixture. The latter is considered unlikely owing to the absence of a mixing mechanism. The geophysical evidence suggests that the underlying bedrock is exposed in the west. It is unlikely that these materials play a significant role in nutrient cycling and they are not considered further here.

4 GEOLOGICAL STRUCTURE

Lake Okeechobee lies in a stable part of the earth's crust in which the overall configuration of the basin has not changed since the early Pleistocene. 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. The other controlling influence on the geological history has been the pattern of deposition of clastic sediments during Plio-Pleistocene periods of high sea level (Brooks, 1984).

The Okeechobee Area is underlain by a sequence of Tertiary/Pleistocene Deposits as follows (Table 4.1):

Table 4.1: Lake Okeechobee Deposit Sequence

Deposit	Age
Lake Flirt Formation (confined to the headwaters of the Caloosahatchee River)	Late Pleistocene
Caloosahatchee-Fort Thompson Formation (5 or more lithological horizons one of which is the Coffee Mill Hammock Formation. Marine limestones and fresh water marls, 220,000 - 120,000 yrs)	Plio-Pleistocene
Tamiami Formation (white-grey sandy limestone to clayey marl and fossiliferous sands)	Mid-late Pliocene
Hawthorn Formation (olive green and grey clays with phosphatic sandy clays > 200 m thick and controls lake position)	Miocene
Tampa Limestone	Lowest Miocene
Suwannee Limestone	Oligocene
Ocala Limestone	Upper Eocene

Only the Caloosahatchee-Fort Thompson Formation is of relevance to this study, as the sub-bottom profiling data presented here shows an earlier eroded basin within the lake possibly of Tamiami limestones and marls, which has been progressively infilled by a complex sequence of calcareous deposits at least 4 in number. 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 in areas surrounding the lake. Brooks recognized 5 typical Caloosahatchee-Fort Thompson units in canals excavated in the construction of Hoover Levee on the north eastern section of the lake. Brooks traced these formations over a 24 km distance. In the north the units were predominantly sand and shelly sands of the "Pipecrest Beds." Southwards, massive but discontinuous cap rocks, usually sandy freshwater limestones with solution pipes and laminated caliche crusts occurred at the top of each marine unit. The Coffee Mill Hammock Formation does not occur around the margins of the lake and may be absent from the lake bed deposits. The thickness of the Caloosahatchee-Fort Thompson Formation on shore is generally of the order of 3 m which compares closely with continuous seismic profiling evidence for the thickness in the lake itself. These 5 units could not be penetrated during the vibracoring exercise undertaken during this study, but these descriptions from marginal locations around the coast serve to characterize the deposits. Brooks recognized a bed of Rangia cuneata overlying the Fort Thompson deposits in South Bay and extending out into the lake reaching 1 m in thickness. The Rangia beds are estuarine deposits more than 25,000 yr in age. Brooks 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.

At Belle Glade, just southeast of the lake, peat deposits have an oldest ages of 4,400 yr BP (McDowell et al., 1969). It has long been considered that the lacustrine plain of the Florida peninsula represents in unmodified form the seabed surface at the time of its latest emergence (Heilprin, 1887; Brooks, 1984).

The northern and eastern margins of the lake are enclosed by a series of beach ridges, finding their best development between Taylor's Creek and Chauncy Bay. The lowest part of the oldest ridge has been dated by ^{14}C on fresh water clams at 1,685 $\pm$ 75 yr BP, presumably at this recent date these were fresh as opposed to salt water beaches formed around the lake itself.

From dates on the fresh water calcitic muds in the lake of 6,300 yr BP (Brooks, 1984) and from dates on peats determined by Gleason and Stone (1975) showing ages ranging from 5,490 $\pm$ 90 yr BP to 2,670 $\pm$ 80 yr BP we can imply that a lake has been present extending back many millennia. Brooks suggests to at least 12,000 years BP. At around 6,300 yrs ago the lake was small and the fresh water organic-rich muds were being deposited in the deepest, central part of the lake. Penecontemporaneously vegetation was growing which ultimately decayed to form the peats now exposed widely along the southern and north eastern margins on the exposed Caloosahatchee-Fort Thompson carbonates around the margin.

From this remnant the modern lake, with an ever increasing elevation, resulting from organic deposition along its southern rim, began to develop just over 4,000 yrs ago (Brooks, 1984). From the beach ridges, Brooks concludes a historic maximum level shortly after 265 AD. Speculative evidence dates the latest of the beach ridges at 900-1200 AD, a warm, hurricane-prone climatic interval. The organic sill rising at the southern end of the lake and blocking drainage to the south ponded the lake waters. The sill reached a maximum of 6 m above present sea level. During periods when the lake reached the 6.8 m stage, 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.

This pattern of steady and progressive ponding, accompanied by episodic overtopping, may have been typical of the last millennium and continued until the major interference by man to alter a coastline and canalize and divert the drainage during the present century.

The geophysical and sampling data obtained during this program thus support and contribute more detail on this topic of the evolution and characterization of the bed sediments.

5 RECOMMENDATIONS FOR FURTHER WORK

Three aspects of the mud deposits of Lake Okeechobee merit further study. First, both the continuous seismic profiling records and the samples show evidence for the presence of a certain amount of gas in the sediment. The continuous seismic profiling records are not adequate to map the areal distribution of gas and neither are core samples adequate to determine the vertical distribution of gas. The gas may be relevant to the erodibility of the mud in two ways, either directly through the entrainment of sediment by gas seeping from the sediment spontaneously, or indirectly through a weakening of the cohesion of the mud bed, for example during periods when large waves occur on the lake. Wave cycling at the bed leads to pressure fluctuations which will be quite large in relative terms in such shallow water. Arising from this it may be that muds of apparent strength above that normally considered stable and resistant to erosion could be entrained, should widespread gas liberation occur. A small scale project definition study is required to investigate these issues further and possibly indicate any field or laboratory tests which could throw light on the matter.

Second, the recognition of the microfabric of the cores and specifically the submillimeter lamination was a bonus to the investigation and indicates the value of applying X-radiographic monitoring. Its importance is that the alternating black and while bands of the elemental primary lamination are likely to be skeletal debris from algal blooms and organic-rich muds, respectively. As such they represent the day by day history of the lake bed and could provide a longer time record of the evolution of the eutrophic state of the lake.

This could be evaluated by such techniques as Scanning Electron Microscopy to reveal the small scale lamination in greater detail and to identify algal species present. In addition to species the thickness and frequency of bloom deposits would also be apparent. The mineralogy could be studied at the same time using XRF and XRD methods. Such a study would be enhanced if it could be interpreted in the light of radiocarbon date profiles in the mud. At shallower depths in the samples any evidence for disruption by gas or for the presence and source of gas microbubbles would also be deduced.

Third, it is important to recognize that under wave action, the top ~ 10 cm of the bottom mud appears to fluidize regularly but does not entrain easily into the upper water column (Hwang, 1989). Fluidization essentially implies destruction of the structural integrity of the porous solid mud matrix, which may mean new pathways for upward diffusion of soluble phosphate. A careful study of the response of mud to wave action would require a combined field/laboratory effort addressing a number of experimental components. A key field test would involve simultaneous measurements, during periods of significant wave action, of wave properties (height, period and induced orbital velocities) in the water column, sediment-related turbidity and bottom mud motion.

Fig. 13 depicts the likely variation of the horizontal wave velocity amplitude ($\hat{u}$), the corresponding concentration (C) profile and a suggested field tower for examining the flow field and bed response. The significance of the division of the concentration profile into identifiable sublayers ranging from mobile suspension to hard bed has been discussed elsewhere (Hwang, 1989). It sufficies to note that one is interested in investigating flow conditions which lead to the fluidization of the mud bed by waves, and bed reformation by dewatering after wave action is over. This objective can be achieved by monitoring wave orbital velocities (using electromagnetic current meters, EM), mud accelerations (using accelerometer, AC), water surface variation (using pressure gage, P), and turbidity (using electro-optic meters, T).

6 CONCLUSIONS

The geophysical and vibracoring survey has permitted the sediment of Lake Okeechobee to be characterized. Where the succession is most complete a variable thickness of black mud overlies a thin veneer of fluviatile sand. The sand rests in the north-east of the lake bed on an in situ peat deposit, which is rooted into the white, calcareous beach rock forming the foundation of the lake.

Unconsolidated deposits mainly are found at the northern end of the lake, suggesting a close affinity with the Kissimmee River. Some 193 x 10^6 m^3 (0.3 km^3) of organic-rich mud are distributed mainly at the northern end of the lake. It is evident that the earliest mud deposits infill the deeper central portion of the lake, a fact which may indicate the control on distribution exerted by waves. Modern mud deposits are progressively spreading wider and covering more of the lake floor. The deposits are focussed in the northeast sector of the lake and form an inclined deposit extending into shallower water on the northeast margin of the lake. This eccentric distribution and sloped surface must be controlled by the hydrodynamics of the lake. This could influence internal phosphorus cycling. The reason for this eccentric distribution is unclear. It could be entirely controlled by the input point in the Kissimmee River or it could be, in part, influenced by a more energetic regime at the southern end of the lake. However, there is no apparent reason why the southern end of the lake should be more energetic, either in the past or today. The depth and distribution of the mud could influence internal phosphorus cycling and the development of blooms, although the location or intensity of algal blooms is not known to the authors.

The shear strength profiles indicate that only the upper, low- strength fluid mud zone on the order of 10 cm thickness is susceptible to resuspension, whereas the deeper sections of core samples, which exhibit submillimeter lamination, confirm that the lower sediment layers do not participate in any sediment resuspension. An intermediate zone of apparently rather undifferentiated black mud occurs towards the tops of cores and is of widespread extent in the lake. This is the zone which could be influenced by gas-induced resuspension and there has been inadequate opportunity in this study to investigate this important zone in detail.

If internal phosphorus cycling in the lake is linked merely with fluid mud resuspension it will be a much smaller scale process than if part of the upper, more consolidated portion of the cores could possibly be involved. For this reason investigation of the upper part of the cores and of the gas content may be instructive.

It is noted that several other lakes may provide evidence relevant to understanding and managing Lake Okeechobee. For example, "pock- marks" created by gas-seeps are known to occur in Lake Superior, whilst severe phosphorus enrichment is a problem in several lakes in Northern Ireland. In Lough Erne, County Fermanagh the phosphorus is mainly from two sources, fish farms and sewage. Great progress in improving water quality has been achieved by a phosphorus extraction plant in the local sewage works.

7 REFERENCES

Cited

BROOKS H K 1984 Lake Okeechobee. In: Patrick J Gleason (ed) Environments of South Florida, Present and Past II. Miami Geological Society, p36-68.

GLEASON P J and STONE P A 1975 Prehistoric trophic level status and possible cultural influences on the enrichment of Lake Okeechobee. Unpublished Report, South Florida Water Management District, West Palm Beach, 133pp.

HEILPRIN A 1887 Explorations on the west coast of Florida and in the Okeechobee wilderness. Wagner Free Institute of Science of Philadelphia, 134pp.

HWANG K-N 1989 Erodibility of fine sediment in wave- dominated environment. M.S. thesis, University of Florida.

McDOWELL L L, STEPHENS T C and STEWARD E H 1969 Radiocarbon chronology of the Florida Everglades peat. Soil Sci Soc America Proc, 33, p743-745.

SALKIELD A P 1988 An evaluation of bottom sediment mapping methodologies: Task 1.6 of the Lake Okeechobee phosphorus dynamics study. Report submitted to the University of Florida, Gainesville.

Additional

GLEASON P J, COHEN A O, BROOKS H K, STONE P, GOODRICK R, SMITH W G and SPACKMAN W 1984 Environmental significance of Holocene sediments from the Everglades and saline tidal plain. In: Patrick J Gleason (Ed) Environments of South Florida, Present and Past II. Miami Geological Society, p1-67.

HOVELAND M and JUDD A G 1988 Sea bed pockmarks and seepages: Impact on Geology, Biology, and the Marine Environment. Published by Graham and Trotman.

KAPLAN I R (Ed) 1974 Natural gases in marine sediments. Marine Science, Vol 3, Plenum Press, NY. 324pp.

MOTHERSILL J S 1975 Lake Chad: Geochemistry and sedimentary aspects of a shallow polymictic lake. J. Sed. Pet., vol 45, No 1, p295-309.

OTSUBO K and MURAOKA K 1987 Field studies on physical properties of sediment and sediment resuspension in Lake Kasumigaura. Japanese Journal of Limnology, vol 48, Special Issue pS131-138.

RAKOCZI L 1983 Resuspension studies in the near-shore zone of Lake Erken, p101-112.

REEBURGH W S 1972 Processes affecting gas distribution in estuarine sediments. Geol. Soc. of America Memoir 133, p383-389.

SOMLYODY L 1983 Major features of the Lake Balaton Eutrophication problem: Approach to the analysis pp9-44 In: Eutrophication of Shallow Lakes Modelling and Management: The Lake Balaton Case Study. Hungarian Acad. Sci., 367pp.

TIPPETT R 1964 An investigation into the nature of the layering of deep-water sediments in two eastern Ontario lakes. Can. J. Bot. 42, p1693-1709 (from West 1968 Pleistocene Geology and Biology).

APPENDIX A

REPORT ON GEOPHYSICAL FIELD OPERATION

A.1 Introduction

Field operations began aboard the University of Florida's R/V Silver Bullet on October 11, 1988 and continued on the 12th, 13th, and 18th. Primary equipment was a Datasonics SBP-5000 Sub-Bottom Profiling System which utilizes a Datasonics SBT-220 transceiver, the transducer set removed from a TTV-120 Transducer Vehicle and remounted in a specially fabricated catamaran surface tow vehicle, and an EPC-3202 Graphic Recorder. The transducer set consisted of four, ganged, tunable transducers for sub-bottom profiling and a single 200 kHz transducer for bottom tracking. The other major instrument systems were an EG&G SMS-960 side-scan sonar and an EG&G Model 290 side-scan sonar field access unit as well as an EPC-4800 Graphic Recorder. Both side-scan systems were operated with the same 105 kHz EG&G Model 272 tow fish. The SMS-960 provides slant-range corrected and speed adjusted, thus near planimetrically correct, records in real time. The Model 290 yields conventional, i.e. uncorrected, sonographs.

Navigation was by the ship's Micrologic 7500 LORAN-C. Locations were recorded manually in field logs each five minutes (except on Line 1, see Fig. A.1, where the interval was two minutes) and at selected other times. All logged location fixes are coincident with annotated marks on the graphic records. Table A.1 is a listing of the navigation data. The LORAN was programmed to display an internally calculated latitude and longitude. Empirically, these geographic coordinates disagree with chart data, albeit unsystematically, the error sometimes approaching 2 km. As no method with which to adjust or correct the LORAN derived coordinates could be developed, we have used the position data as recorded in the field.

During the course of the study, we collected data over nine separate lines, Line 9 being an extension of Line 5 (Table A.2). The length of the lines total 177 km (95.5 nautical miles).

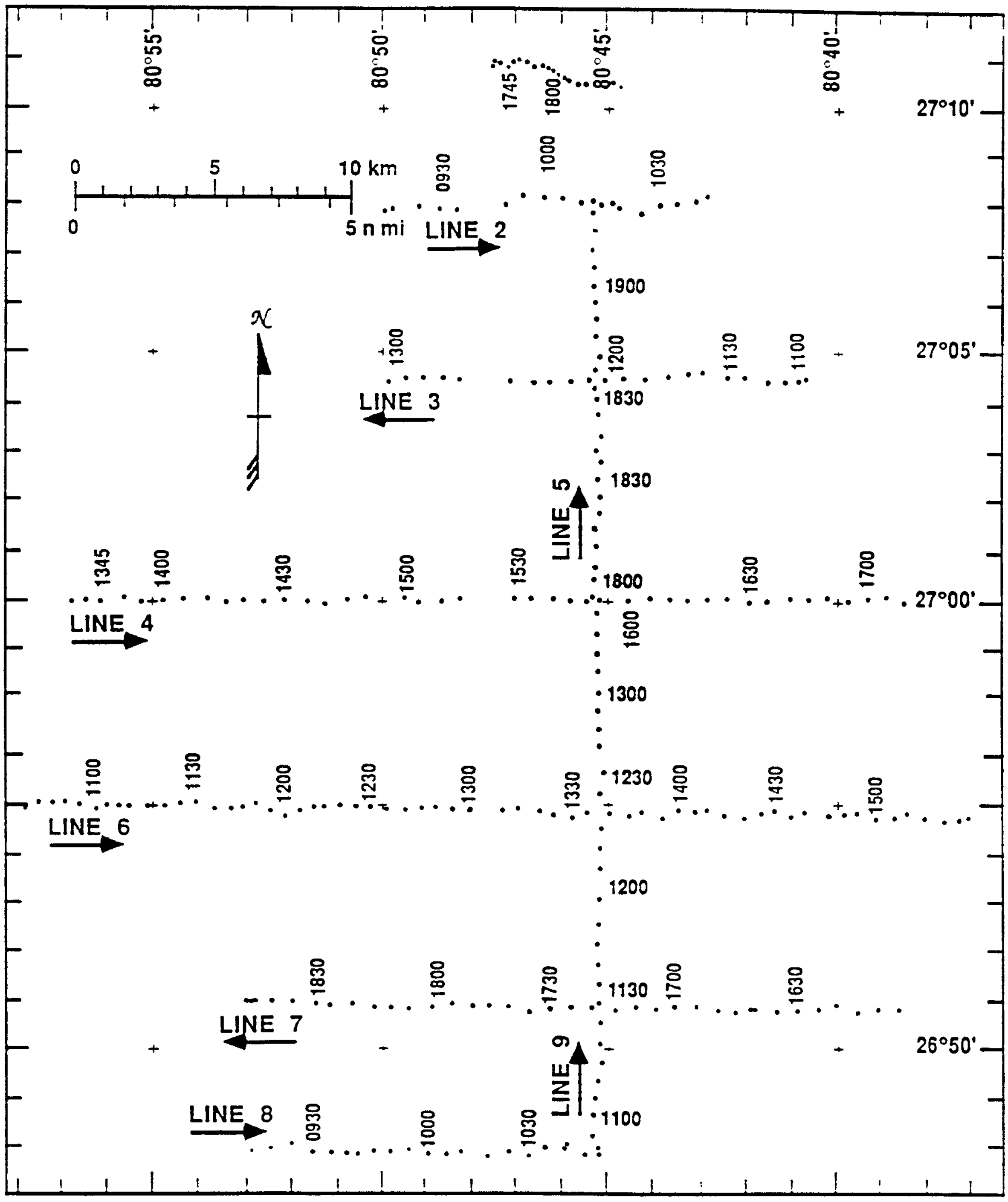

Fig. A.1. Geophysical lines with measurement time markers.

Table A.1

LATITUDE AND LONGITUDE AS DISPLAYED BY MICROLOGIC 7500 LORAN-C

Time	Longitude		Longitude		Comment	
1731	27	10.99	80	47.80	SOL 1	OCT 11, 88
1733	27	10.96	80	47.69		
1735:30	27	10.96	80	47.58		
1737	27	10.96	80	47.44		
1739	27	10.95	80	47.29		
1741:20	27	10.90	80	47.13		
1743	27	10.89	80	47.00		
1745	27	10.87	80	46.84		
1747	27	10.88	80	46.71		
1749	27	10.91	80	46.56		
1751:10	27	10.85	80	46.36		
1753	27	10.79	80	46.29		
1755	27	10.80	80	46.09		
1757	27	10.79	80	45.96	LONGITUDE 2.8 KM OFF	
1759	27	10.67	80	45.86		
1800	27	10.64	80	45.73	ABEAM TAYLOR CK LOCKS	
1802	27	10.61	80	45.60		
1804	27	10.54	80	45.45		
1806	27	10.47	80	45.32		
1808	27	10.48	80	45.15		
1810	27	10.47	80	45.00		
1812	27	10.46	80	44.85		
1814	27	10.49	80	44.69		
1816	27	10.46	80	44.56		
1818	27	10.48	80	44.42	EOL 1	EOD OCT 11, 88
0913:30	27	07.86	80	49.89	SOL 2	OCT 12, 88
0915	27	07.94	80	49.79		
0920	27	08.14	80	49.43		
0925	27	08.03	80	49.02		
0930	27	07.98	80	48.58		
0935	27	07.92	80	48.18		
0940	27	07.94	80	47.74		
0945	27	07.99	80	47.34		
0950	27	08.04	80	46.92		
0955	27	08.13	80	46.53		
1000	27	08.12	80	46.09		
1005	27	08.11	80	45.68		
1010	27	08.02	80	45.25		
1015	27	08.00	80	44.83		
1020	27	07.94	80	44.40		

Table A.1

LATITUDE AND LONGITUDE AS DISPLAYED BY MICROLOGIC 7500 LORAN-C

(continued)

Time	Longitude		Longitude		Comment
1025	27	07.85	80	43.97	
1030	27	07.96	80	43.57	
1035	27	08.04	80	43.16	
1040	27	08.08	80	42.72	
1042:30	27	08.15	80	42.54	EOL 2
1108	47	04.56	80	40.34	SOL 3
1110:30	27	04.47	80	40.53	
1115	27	04.45	80	40.89	
1120	27	04.48	80	41.30	
1125	27	04.51	80	41.75	
1130	27	04.53	80	42.15	
1135	27	04.63	80	42.66	
1140	27	04.55	80	43.00	
1145	27	04.53	80	43.43	
1150	27	04.44	80	43.84	
1155	27	04.48	80	44.28	
1200	27	04.47	80	44.69	
1205	27	04.45	80	45.10	
1210	27	04.43	80	45.53	
1215	27	04.40	80	45.97	
1220	27	04.39	80	46.39	
1225	27	04.41	80	46.83	
	27	04.49	80	47.34	NAV TOWER
	27	04.48	80	47.63	DATA TOWER
1240	27	04.46	80	48.10	
1245	27	04.46	80	48.53	
1250	27	04.52	80	48.96	CHANGE SIDE-SCAN PAPER
1255:15	27	04.46	80	49.38	SIDE-SCAN ON LINE
1300	27	04.41	80	49.75	EOL 3
1337	26	59.94	80	56.83	SOL 4
1340	26	59.97	80	56.57	
1345	26	59.98	80	56.11	
1350	27	00.03	80	55.66	
1355	26	59.98	80	55.21	
1400	26	59.99	80	54.77	
1405	27	00.02	80	54.33	
1410	27	00.02	80	53.89	
1415	26	59.99	80	53.45	
1420	26	59.97	80	53.00	

Table A.1

LATITUDE AND LONGITUDE AS DISPLAYED BY MICROLOGIC 7500 LORAN-C

(continued)

Time	Longitude		Longitude		Comment
1425	26	59.98	80	52.58	CHANGE EPC PAPER
1430	27	00.02	80	52.14	SMALL CHANNEL
1435	27	00.05	80	51.67	
1440	26	59.95	80	51.23	
1445	27	00.07	80	50.78	
1450	27	00.07	80	50.38	
1455	27	00.01	80	49.91	
1500	27	00.02	80	49.48	
1505	27	00.00	80	49.02	
1510	26	59.96	80	48.58	
1515	27	00.04	80	48.15	
1520	27	00.03	80	47.73	
1525	27	00.01	80	46.85	
1530	27	00.01	80	46.85	
1535	27	00.00	80	46.42	
1540	26	59.97	80	45.99	
1545	26	59.98	80	45.58	
1550	26	59.98	80	45.16	
1555	26	59.96	80	44.70	
1600	26	59.98	80	44.30	
1605	27	00.01	80	43.87	
1610	27	00.02	80	43.46	SIDE-SCAN DOWN
1615	27	00.01	80	43.03	
1620	27	00.04	80	42.60	
1625	27	00.05	80	42.17	
1630	26	59.94	80	41.70	
1635	26	59.98	80	41.29	
1640	27	00.07	80	40.81	
1645	27	00.01	80	40.31	
1650	27	00.04	80	39.98	
1655	27	00.01	80	39.46	
1700	27	00.07	80	39.03	
1705	27	00.10	80	38.60	
1710	27	00.07	80	38.15	
1715	27	00.06	80	37.72	
1716:45	27	00.00	80	37.56	EOL 4

Table A.1

LATITUDE AND LONGITUDE AS DISPLAYED BY MICROLOGIC 7500 LORAN-C

(continued)

Time	Longitude		Longitude		Comment	
1754	27	00.03	80	45.05	SOL 5	
1755	27	00.09	80	45.05		
1800	27	00.43	80	45.03		
1805	27	00.76	80	45.01		
1810	27	01.12	80	45.08		
1815	27	01.44	80	45.01		
1820:30	27	01.75	80	44.96		
1825	27	02.13	80	44.97		
1830	27	02.42	80	44.92		
1835	27	02.80	80	44.89		
1840	27	03.07	80	44.98		
1845	27	03.33	80	44.94		
1850	27	03.71	80	44.95		
1855	27	04.02	80	45.02		
1900	27	04.36	80	44.98	SUNSET 1857	
1905:06	27	04.62	80	45.00		
1910	27	04.95	80	44.99		
1915	27	05.37	80	45.00		
1920	27	05.72	80	45.00		
1925	27	05.99	80	45.01		
1930:30	27	06.40	80	45.04		
1935	27	06.72	80	45.02		
1940	27	07.09	80	45.03		
1945	27	07.46	80	45.03		
1950	27	07.85	80	45.05		
1954	27	08.11	80	44.99	EOL 5	EOD OCT 12, 88
1036:02	26	54.90	80	57.93	SOL 6	OCT 13, 88
1040	26	55.02	80	57.69		
1045	26	55.06	80	57.37		
1050	26	55.04	80	57.03		
1055	26	55.01	80	56.71		
1100	26	54.93	80	56.35		
1105	26	55.01	80	56.01		
1110	26	55.00	80	55.63		
1115	26	55.02	80	55.25		
1120	26	55.01	80	54.86		
1125	26	55.07	80	54.52		
1130	26	55.06	80	54.18		

Table A.1

LATITUDE AND LONGITUDE AS DISPLAYED BY MICROLOGIC 7500 LORAN-C

(continued)

Time	Longitude		Longitude		Comment
1200	26	54.87	80	52.12	
1136	26	54.96	80	53.74	
1140	26	54.98	80	53.47	
1145	26	54.96	80	53.11	
1150	26	55.01	80	52.78	
1155	26	54.95	80	52.45	
1205	26	54.93	80	51.79	
1210	26	54.97	80	51.50	
1215	26	55.04	80	51.19	
1220	26	55.06	80	50.85	
1225	26	55.05	80	50.52	
1230	26	55.04	80	50.15	
1235	26	54.99	80	49.79	
1240	26	54.99	80	49.39	
1245	26	55.02	80	49.04	
1250	26	55.08	80	48.67	
1255	26	55.02	80	48.27	
1300	26	55.00	80	47.90	
1305	26	54.98	80	47.63	
1310	26	54.97	80	47.13	
1315	26	55.01	80	46.77	
1320	26	54.97	80	46.37	
1325	26	54.94	80	45.98	
1330	26	54.90	80	45.61	
1335	26	55.00	80	45.25	
1340	26	54.99	80	44.86	
1345	26	54.95	80	44.47	
1350	26	54.97	80	44.11	
1355	26	54.94	80	43.68	
1400	26	55.04	80	43.35	
1405	26	55.02	80	42.96	
1410	26	55.07	80	42.62	
1415	26	54.95	80	42.25	
1420	26	54.93	80	41.85	
1425	26	55.02	80	41.49	
1430	26	55.06	80	41.11	
1435	26	54.96	80	40.73	
1440	26	55.04	80	40.36	
1445	26	55.00	80	39.96	
1450	26	55.00	80	39.58	
1455	26	55.05	80	39.24	

Table A.1

LATITUDE AND LONGITUDE AS DISPLAYED BY MICROLOGIC 7500 LORAN-C

(continued)

Time	Longitude		Longitude		Comment	
1500	26	54.99	80	38.83		
1505	26	55.00	80	38.44		
1510	26	55.09	80	38.08		
1515	26	54.98	80	37.66		
1520	26	54.96	80	37.26		
1525	26	55.00	80	36.87		
1530	26	55.05	80	36.72	EOL 6	MARKER 22
1602:45	26	51.02	80	38.24	SOL 7	
1605	26	51.04	80	38.39		
1610	26	51.02	80	38.86		
1615	26	50.96	80	39.30		
1620	26	51.03	80	39.75		
1625	26	51.00	80	40.18		
1630	26	50.99	80	40.65		
1635	26	50.97	80	41.09		
1640	26	51.02	80	41.53		
1645	26	50.98	80	41.98		
1650	26	50.96	80	42.42		
1655	26	51.03	80	42.86		
1700	26	51.02	80	43.34		
1705	26	50.97	80	43.79		
1710	26	51.03	80	44.25		
1715	26	50.96	80	44.68		
1720	26	51.00	80	45.16		
1725	26	50.96	80	45.62		
1730	26	51.00	80	46.08		
1735	26	50.93	80	46.51		
1740	26	51.01	80	46.98		
1745	26	51.05	80	47.43		
1750	26	51.03	80	47.89		
1755	26	51.04	80	48.32		
1800	26	51.02	80	48.76		
1806	26	50.93	80	49.38		
1811	26	50.96	80	49.77		
1815	26	50.98	80	50.11		
1820	26	50.99	80	50.58		
1825	26	50.96	80	51.01		

Table A.1

LATITUDE AND LONGITUDE AS DISPLAYED BY MICROLOGIC 7500 LORAN-C

(continued)

Time	Longitude		Longitude		Comment	
1830	26	51.04	80	51.49		
1835	26	51.04	80	51.95		
1840	26	51.04	80	52.38		
1845	26	51.03	80	52.84		
1846:37	26	51.00	80	53.00	EOL 7	EOD OCT 13, 88
0914	26	47.98	80	52.87	SOL 8	OCT 18, 88
0920	26	48.03	80	52.40		
0925	26	48.11	80	51.94		
0930	26	47.97	80	51.48		
0935	26	47.97	80	51.03		
0940	26	47.95	80	50.64	CHANGE STYLUS BELTS	
0941:30	26	47.93	80	50.43	FINISH CHANGE	
0945	26	48.00	80	50.09		
0950	26	48.00	80	49.66		
0955	26	48.03	80	49.25		
1000	26	47.97	80	48.86		
1005:30	26	47.99	80	48.43		
1010	26	48.05	80	48.06		
1015	26	47.86	80	47.65		
1020	26	47.99	80	47.26		
1025	26	48.03	80	46.85		
1030	26	48.00	80	46.43		
1035	26	48.15	80	46.06		
1040	26	48.14	80	45.67		
1045	26	47.97	80	45.24		
1048	26	47.98	80	44.98	EOL 8	CONTINUOUS WITH 9
1050	26	48.07	80	44.95	SOL 9	
1055	26	48.36	80	45.06	MISSED 1055	
1100	26	48.78	80	45.04		
1105	26	49.17	80	45.08		
1110	26	49.58	80	44.98		
1115	26	49.89	80	44.90		
1120	26	50.30	80	44.98		
1125	26	50.67	80	45.01		
1130	26	51.07	80	45.00		

Table A.1

LATITUDE AND LONGITUDE AS DISPLAYED BY MICROLOGIC 7500 LORAN-C

(continued)

Time	Longitude		Longitude		Comment
1135	26	51.48	80	45.04	
1140	26	51.89	80	44.97	
1145	26	52.29	80	44.98	
1150	26	52.64	80	44.98	
1155	26	53.15	80	45.00	BEGIN SIDE-SCAN/EPC
1200	26	53.47	80	45.00	
1205	26	53.87	80	44.98	
1210	26	54.28	80	45.00	
1215	26	54.69	80	44.99	
1220	26	55.10	80	45.02	
1225	26	55.42	80	45.01	
1230	26	55.87	80	45.00	
1235:30	26	56.30	80	45.00	
1240	26	56.64	80	45.02	
1245	26	57.03	80	45.00	
1250	26	57.36	80	44.98	
1255	26	57.74	80	44.97	
1300	26	58.15	80	44.99	
1306	26	58.60	80	45.00	
1310	26	58.94	80	44.99	
1315	26	59.35	80	45.04	CHANNEL
1320	26	59.70	80	45.00	
1325	27	00.05	80	44.94	CHANNEL
1326:30	27	00.19	80	45.01	EOL 9 EOD OCT 18, 88 END OF FIELD DEPLOYMENT

Table A.2: SUMMARY OF TRACK LINES

Line No.	Length (km)	Start and End Positions								Times
		Start				End				
1	5.6	27	10.99	80	47.80	27	10.48	80	44.42	1731-1818
2	12.0	27	07.86	80	49.89	27	08.15	80	42.54	0913-1042
3	15.7	27	04.56	80	40.34	27	04.41	80	49.75	1108-1300
4	31.5	26	59.94	80	56.83	27	00.00	80	37.56	1337-1716
5	14.8	27	00.03	80	45.05	27	08.11	80	44.99	1754-1954
6	37.0	26	54.90	80	57.93	26	55.05	80	36.72	1036-1530
7	25.0	26	51.02	80	38.24	26	51.00	80	53.00	1602-1846
8	13.0	26	47.98	80	52.87	26	47.98	80	44.98	0914-1043
9	22.2	26	48.07	80	44.95	27	00.19	80	45.01	1045-1326

The sub-bottom profiling system functioned at all times except for the standard, occasional few minutes to change paper and stylus belts. Due to a combination of equipment failure, shallow water, and rough conditions, the side-scan sonar was operated for only 67 km, approximately 37 percent of the total.

A.2 Side-scan Sonography

The side-scan sonar study of the bottom of Lake Okeechobee used both the Model SMS-960 (54 km) and the Model 290 (13 km). The side-scan systems were operated concurrently with the sub-bottom profiling system on Lines 2, 3, 4 (partial), and 9 (partial). The water depths throughout lake either are so shallow as to prohibit deployment of the tow fish or are so near the instrument's service limits as to engender less than optimum quality records. Although the SMS-960 failed near the end of Line 4, wave conditions on the following day would have precluded its use on Lines 6 and 7. The side-scan was operated again, this time using the Model 290, on the last half of Line 9; the system being deployed as the waves decreased.

The side-scan sonographs depicted a generally smooth bottom with few major perturbations. There are many "point reflectors" (pepper-flake-like depictions) perhaps indicative of very local variations in surface texture or hardness or of small (centimeters), hard high spots. If the point reflectors are the result of topography, the relief is not sufficient to cast an acoustic shadow. They could also indicate the presence of gassy sediment, as elaborated in the text. There are a very few, isolated items protruding enough above the bottom to cast an acoustic shadow. These might be fragments of rock or anthropogenic debris. The dredged and spoil areas on Line 2 are shown very clearly on the sonographs in Fig. A.2.

A.3 Sub-bottom Profiles

The sub-bottom and bottom-tracking (200 kHz) systems functioned excellently throughout the exercise. Initial empirical experimentation demonstrated that 7 kHz provided the sharpest record; the other available frequencies being 3.5 and 5 kHz. The superior performance probably being a function of the short wave-length, approximately 21 cm. The system was operated with a trigger rate and a recorder sweep of 31.25 milliseconds, the most rapid available to the system, yielding a full scale record of 23 meters assuming an acoustic velocity of 1,500 m s^{-1}. In practice, the data seldom exceeded 12.5 milliseconds two-way travel time (approximately 10 m). In optimum, smooth water conditions it should be possible to resolve individual, fairly widely separated layers on the order of 10 to 20 cm thick. Graphic resolution diminished with sea state. Lines 6 and 7 were run in short period, 0.6 m, white-capped seas; hence, the ability to resolve thin layers on these lines was significantly reduced.

In addition to the thickness of the mud layer, the sub-bottom profiles reveal the presence of at least two small basins in the sub-bottom underlying the general area of the mud deposit (Figs. A.3 and A.4) and the great variation in the hardness of the mud-deposit's surface. In some areas strong reflectors occur within the mud deposits perhaps indicative of a large quantity of shell on or very near the sediment surface, of partial lithification of that surface, e.g. Fig. A.5, or of gas. Signatures in Fig. A.6 are indicative of a relatively hard bottom.

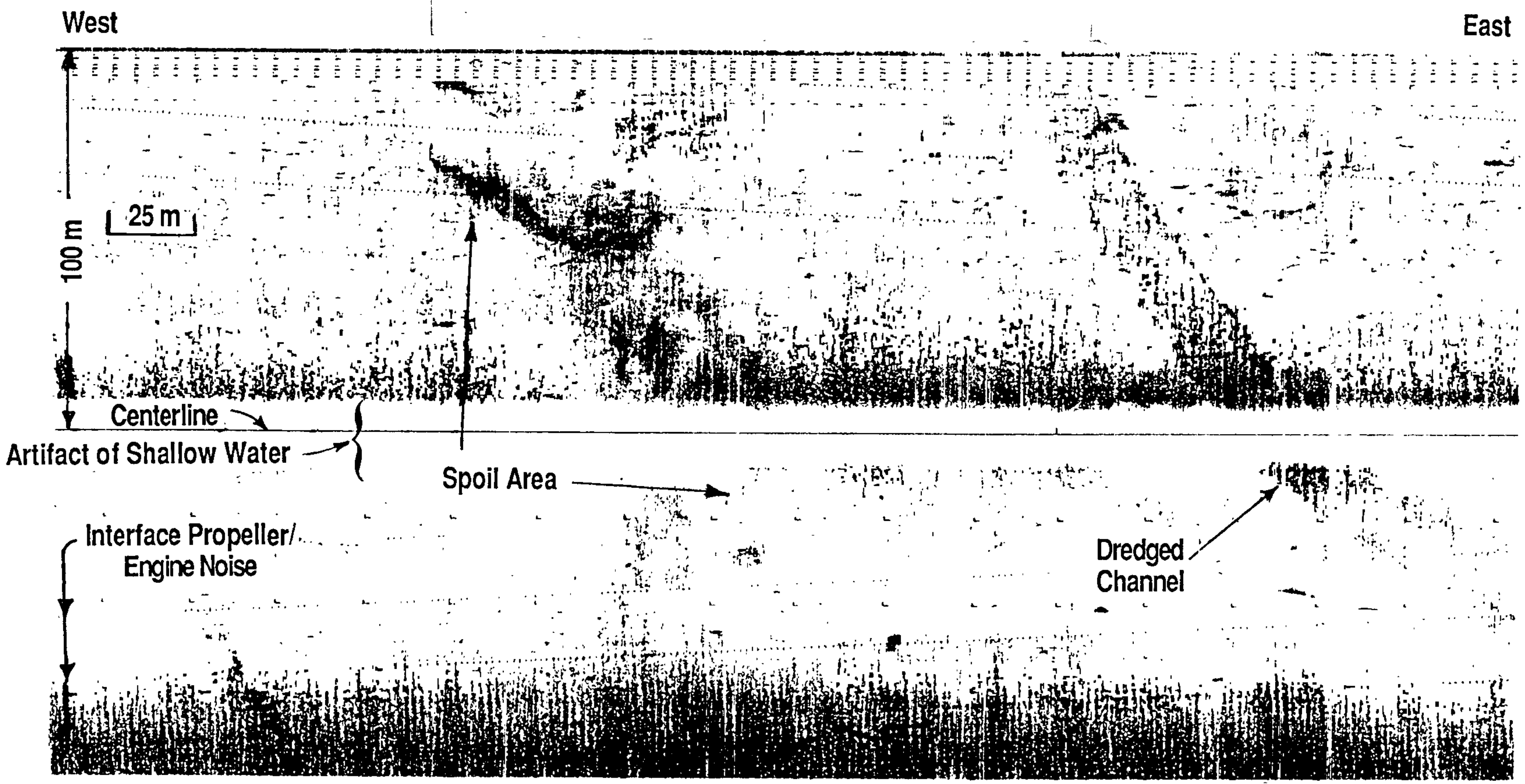

Fig. A.2. Portion of side-scan record, line 2, October 12, 1988, west-east.

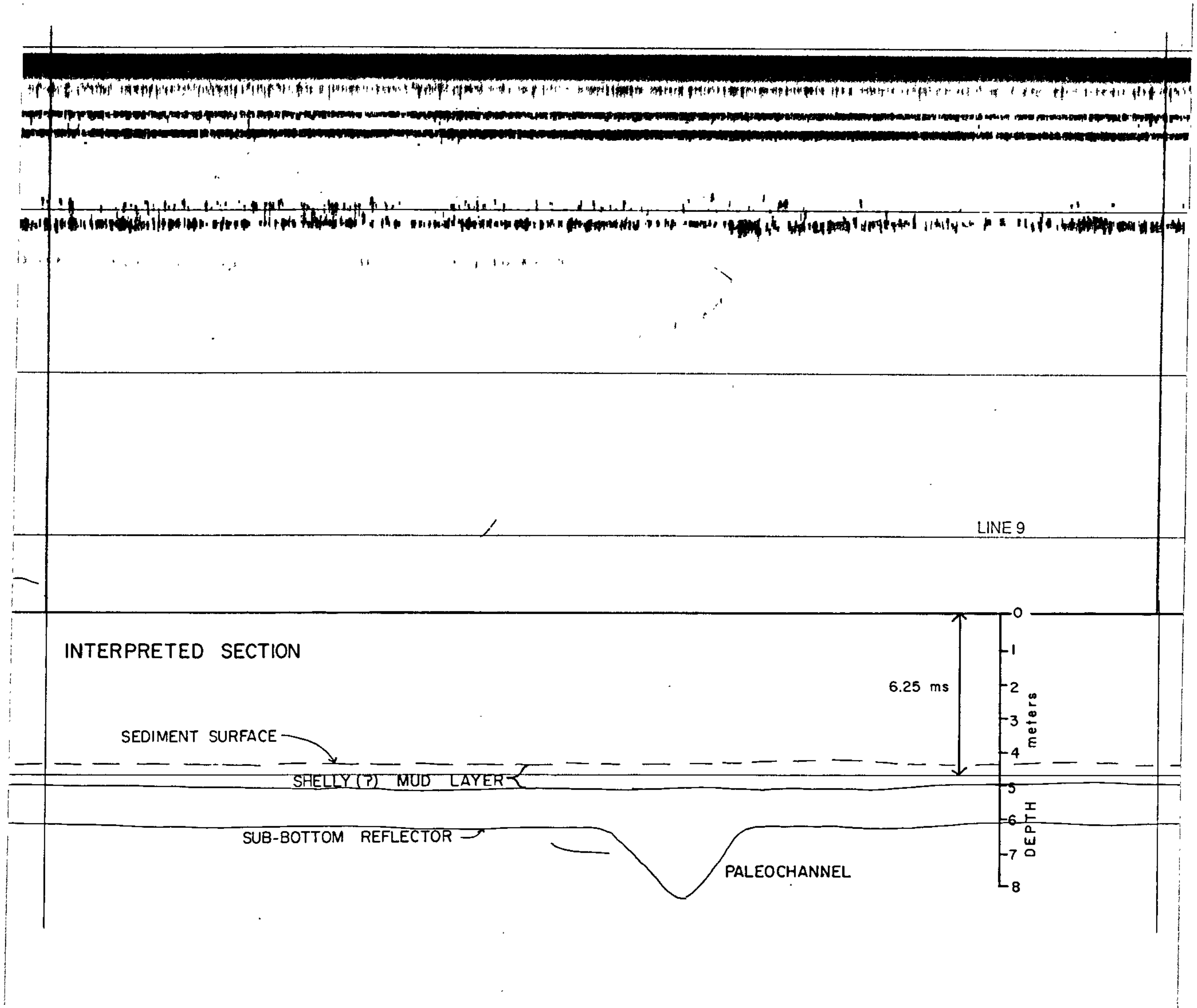

Fig. A.3. A portion of Line 9 demonstrating a shelly (?) mud layer approximately 60 cm thick over a harder substrate. The deeper sub-bottom reflector depicts a small paleochannel.

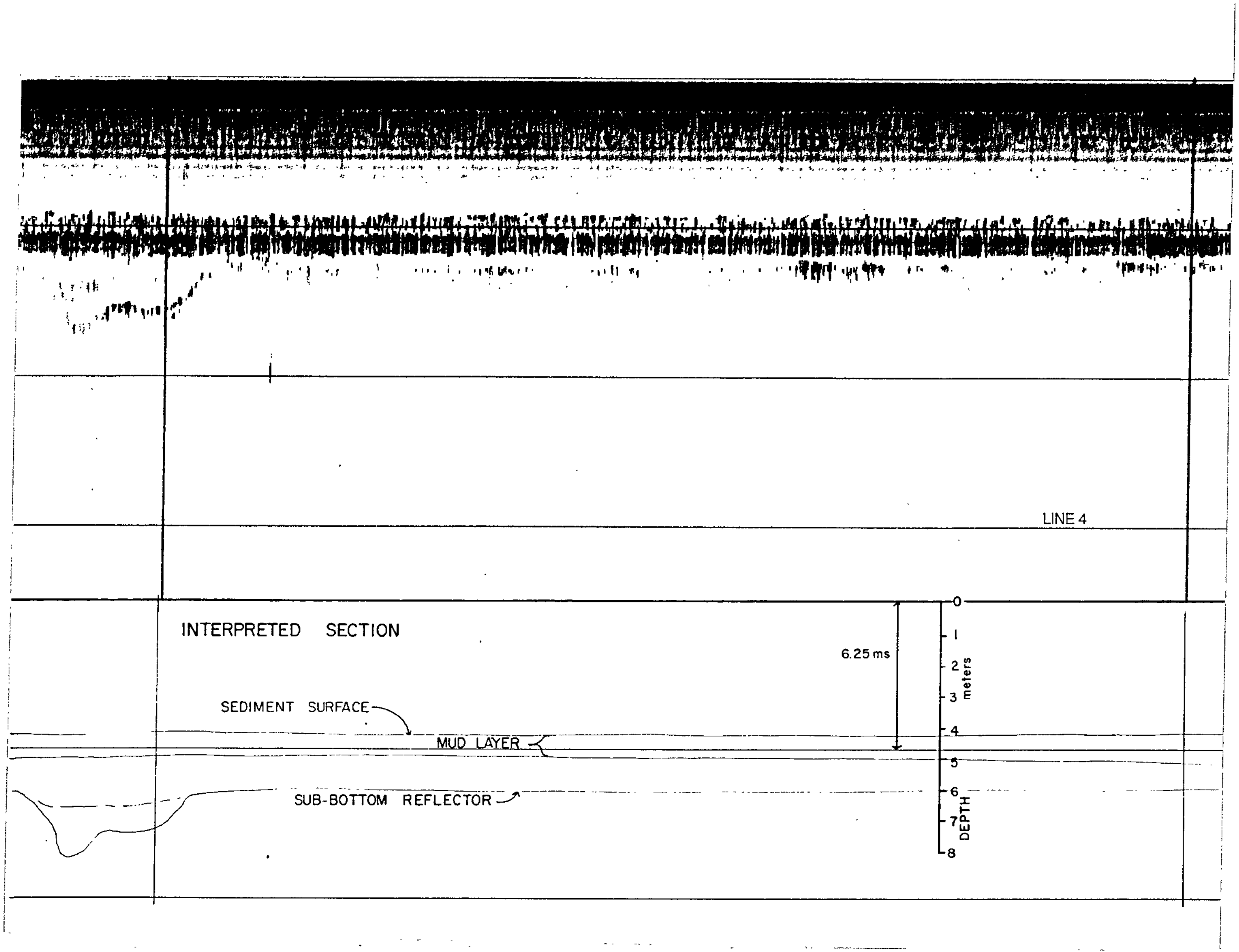

Fig. A.4. A portion of Line 4 demonstrating a relatively clean mud layer over a harder substrate. The sub-bottom reflector depicts a small paleochannel showing signs of some internal compaction.

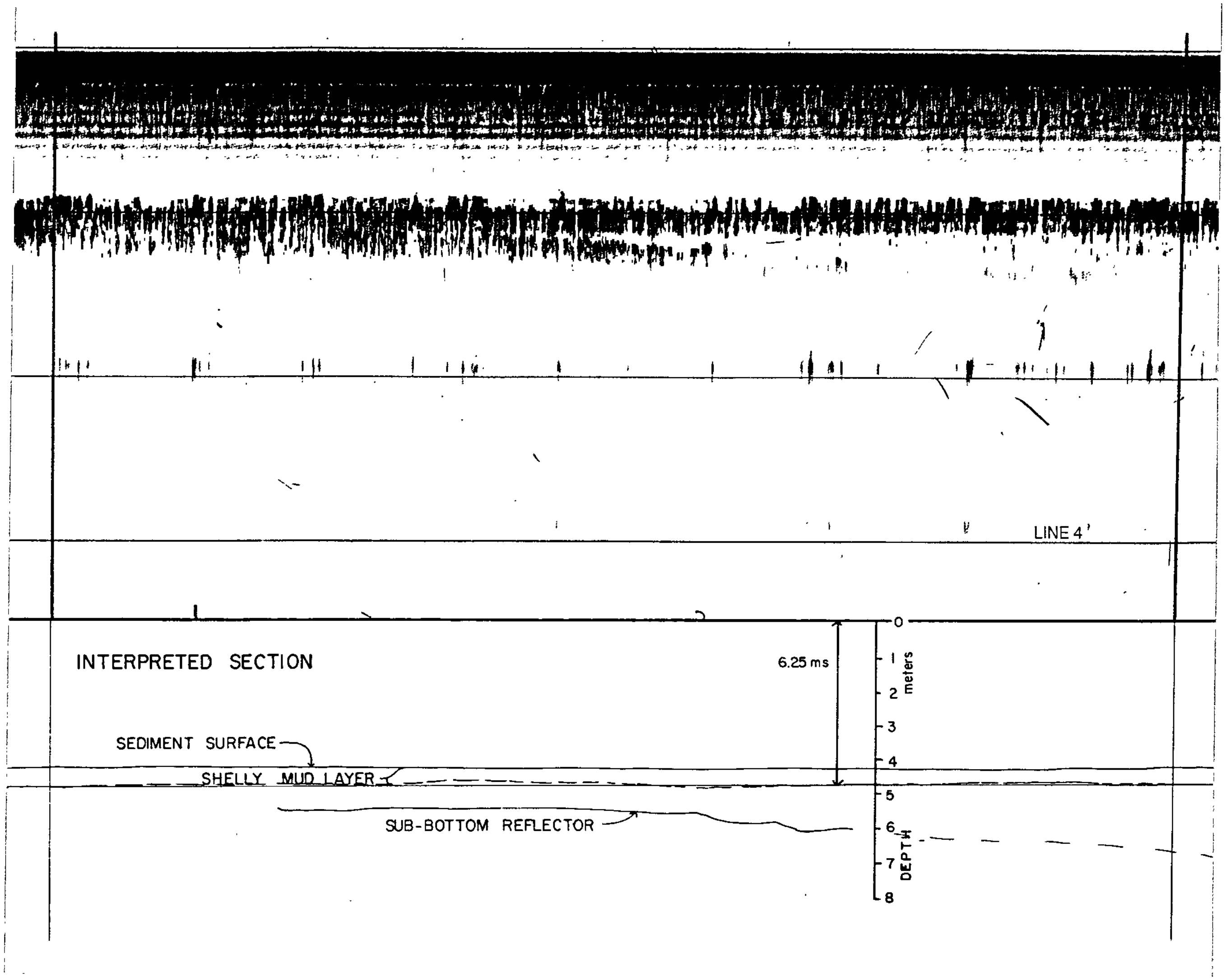

Fig. A.5. A portion of Line 4 depicting a somewhat shelly (?) mud layer overlying a harder substrate. The relatively shallow sub-bottom reflector dips toward the right.

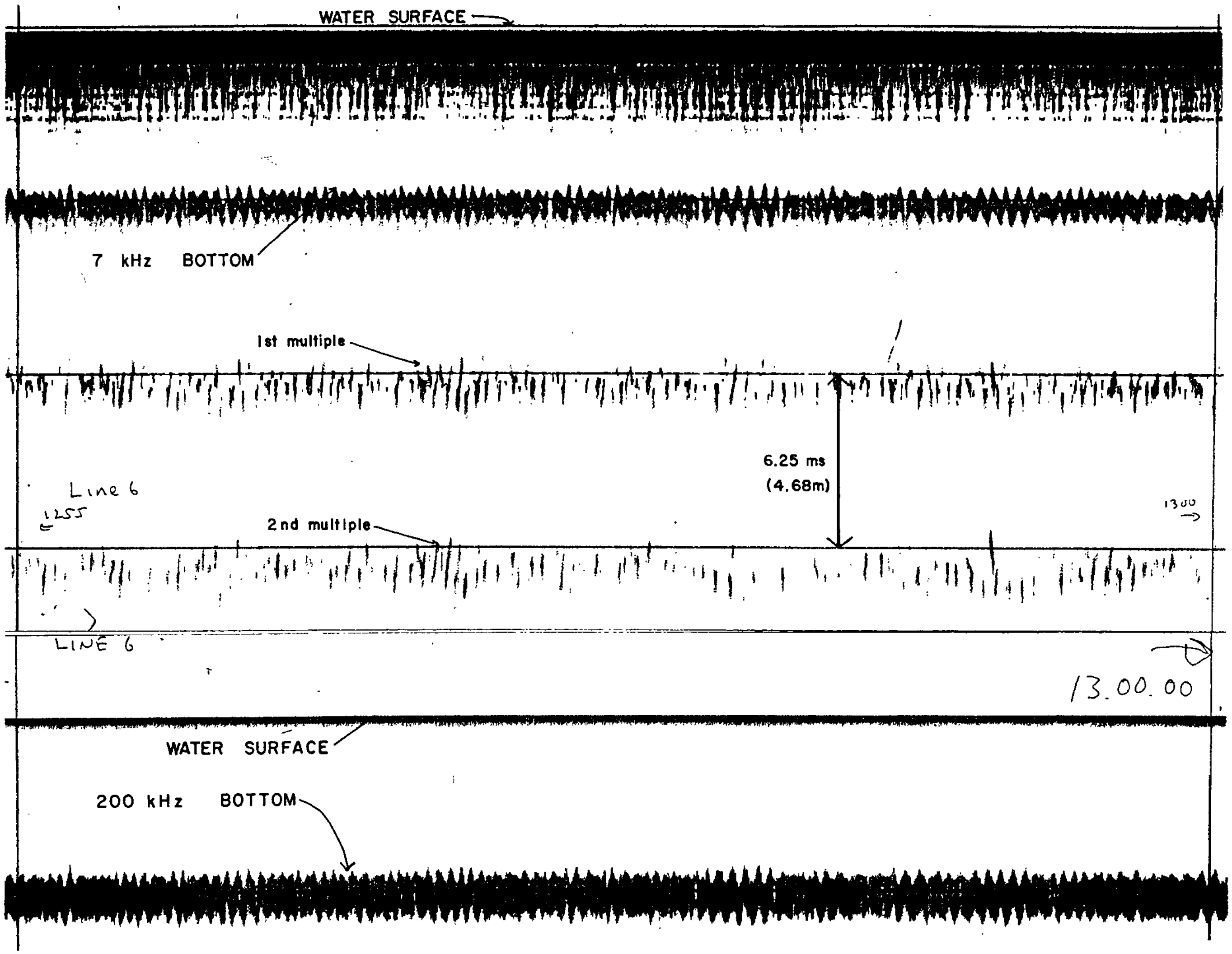

Fig. A.6. A portion of Line 6 depicting both the 7 KHz and 200 KHz bottoms. The roughness of the bottom surface is due to surface water waves approximately 0.5 m high. The strength of the multiples of the 7 KHz bottom suggests that the bottom is relatively hard.

APPENDIX B

REPORT ON CORING SURVEY

B.1 Field Operation

The coring survey was closely linked with the geophysical survey. The records obtained during the geophysical survey were interpreted with a view to choosing suitable core sampling sites within the lake to aid interpretation of the geophysics. Some 20 sites were initially chosen. A second suite of samples on the same grid as that previously occupied for a survey by UF's Soil Sience Department was also obtained (again approximately 20 sites of which a number were coincident with the geophysical survey lines).

For purposes of obtaining the undisturbed samples a large diameter, short barrelled vibracorer was designed and built. It was necessary to use a small vibracorer because of the intrinsic properties of the bed substrates of the lake. In many areas very soft and weak black clays overlie very hard or cemented calcareous, marine "beach-rock" type materials. To sample both substrates satisfactorily presented a logistic problem. Hand-held and driven corers were not adequate to the task because they would only penetrate soft mud, leading to doubt that the complete succession had been penetrated. Gravity corers were rejected because they would penetrate the mud but then fall over, leading to extreme disturbance of the upper, weak muddy material. Penetrating beach rock would also prove difficult for such devices. For these reasons the short barrelled vibracorer, which was hand-held from a boat moored over the sample site, proved ideal in sampling all substrates, while remaining in the vertical position and thus minimizing disturbance of the sample.

In addition to obtaining undisturbed samples, disturbed mud samples were also collected for erosion experiments in the annular flume at the University of Florida.

B.2 Apparatus

The sampling platform used was the university's survey vessel "Silver Bullet." The vessel is 8 m long and has a top speed of 40 km/hr, making it efficient in steaming between survey sites. Due to the fact that the vibracorer was small and hand-held, the vessel had to be moored fore and aft at each sample station to provide a stable coring platform. All position fixing was by the LORAN-C system.

The vibracorer was designed specifically to suite small vessel and shallow water operations. It comprised a standard concrete vibrator having a flexible drive (7.6 m) to the vibrator unit. The vibrator unit was bolted to an aluminum core barrel 8.9 cm o.d. and 7.6 cm i.d. The same assembly, mounted at the top of the core barrel was mated to an internal, thick, flexible, transparent core liner tube (cellulose-acetate-buterate, CAB). These contained each sample for return to the University of Florida.

At the top of the core barrel a nylon non-return valve expelled supernatant water during drilling operation and provided a component of the core retaining system. At the lower end of the barrel a steel cutting shoe provided a hardened edge to penetrate resistance bed deposits. This also acted as a core liner retainer and at the same time as a mounting for a petal-type core catcher. Finally, the vibrator assembly was equipped with a threaded collar to take the detachable aluminum pole used to guide and control coring operations by hand from the water surface.

In practice the corer was deployed when it was judged that the vessel had achieved a stable position at anchor. On reaching the lake bed slack was run off the lifting cable and the vibrator turned on. The vibrator was generally run for between 0.5 and 2.0 minutes and the vibracorer driven into the lake bed on all occasions to refusal.

On recovery the vessel heeled sharply to starboard and the resulting righting moment was used to break the corer free from the lake bed. On a number of occasions, the corer had penetrated material of a stiffness which necessitated judicious use of the vibrator to aid the withdrawal process. Several cases in which the core catcher had been turned inside out by the recovery forces indicated the importance of incorporating this device.

On recovery the cores were withdrawn in their liners, capped, cut to size and labelled. A Paar (model DMA 35) densimeter was used to make density profiles into the surface layers of the cores on board ship in circumstances where a poorly consolidated mud deposit was present. Finally, the cores were sealed and retained in the vertical position for transport to the University of Florida.

For purposes of sampling the surficial mud layers for erosion tests a simple dredge (grab) samples was used.

B.3 Itinerary

The following is the travel summary for the coring survey:

10/19/88 Travel Gainesville - Okeechobee.

10/20/88 Launch vessel at Okee-Tantie and rig vibracorer. Commerce drilling operations. Steering failure of the vessel and loss of a cutting shoe caused abandonment of operations. Three stations occupied.

10/21/88 Return to Gainesville.

10/24/88 Travel Gainesville - Okeechobee; two stations occupied.

10/25/88 Nine stations occupied.

10/26/88 Eight stations occupied; 2-1/2 hours lost refueling boat.

10/27/88 Twelve stations occupied.

10/28/88 Five stations occupied; refuel boat and return to Gainesville.

B.4 Equipment Performance

In the 4-1/2 days of survey operation 39 stations were visited resulting in 30 core samples, and 4 disturbed sediment samples for erosion experiments. The lake presents a number of significant problems for coring operations including especially the combination of extremely weak clays and very hard, cemented "beach-rock" deposits. On occasion several attempts were necessary before the vessel was moored securely. Up to 3 attempts at coring were made at several stations where substrate conditions were particularly difficult.

At 5 stations it proved impossible to anchor the vessel, or the substrate proved to be sufficiently indurated that no core sample could be obtained. Particular difficulties in this respect were encountered at the southern end of the lake.

Other than the intrinsic problems of the area, which proved at time difficult and time consuming to overcome, the only other problem encountered as when grit in the threads of the cutting shoe led to a core being jammed in the barrel of the corer on 10/26/88. Forcefully unscrewing the cutting shoe led to the thread on the barrel being partly stripped. A fresh barrel and cutter were substituted.

APPENDIX C

ILLUSTRATIVE CORE SAMPLE DESCRIPTIONS

C.1 Site: OK9 VC

Core Sample Description (Fig. C.1a)

Total 35 cm black firm mud with a sharp interface at the top made up of the following lithological units:

- ⋆ 6 cm black soft mud, no shells, no smell
- ⋆ Two layers 2 cm grey sand with fine shells and shell fragments separated by thin clay layers
- ⋆ 14 cm white and grey fine, small and large shells and shell fragments with a little sand
- ⋆ **a,b,c:** thin layers of grey color with some very fine shells
- ⋆ **d,e:** grey sandy layers with fine shells and shell fragments
- ⋆ **f:** 2 cm grey sand with fine shells and shell fragments

Bed Bulk Density and Shear Strength

Depth (cm)	Density (g cm^{-3})	Shear strength (Nm^{-2})
0 - 1	1.013	
- 2	1.023	
- 3	1.048	
- 4	1.035	
- 9	1.138	8494
- 14	1.200	7853
- 19	1.183	5681
- 24	1.175	5833
- 29	1.128	5833
- 34	1.195	5578

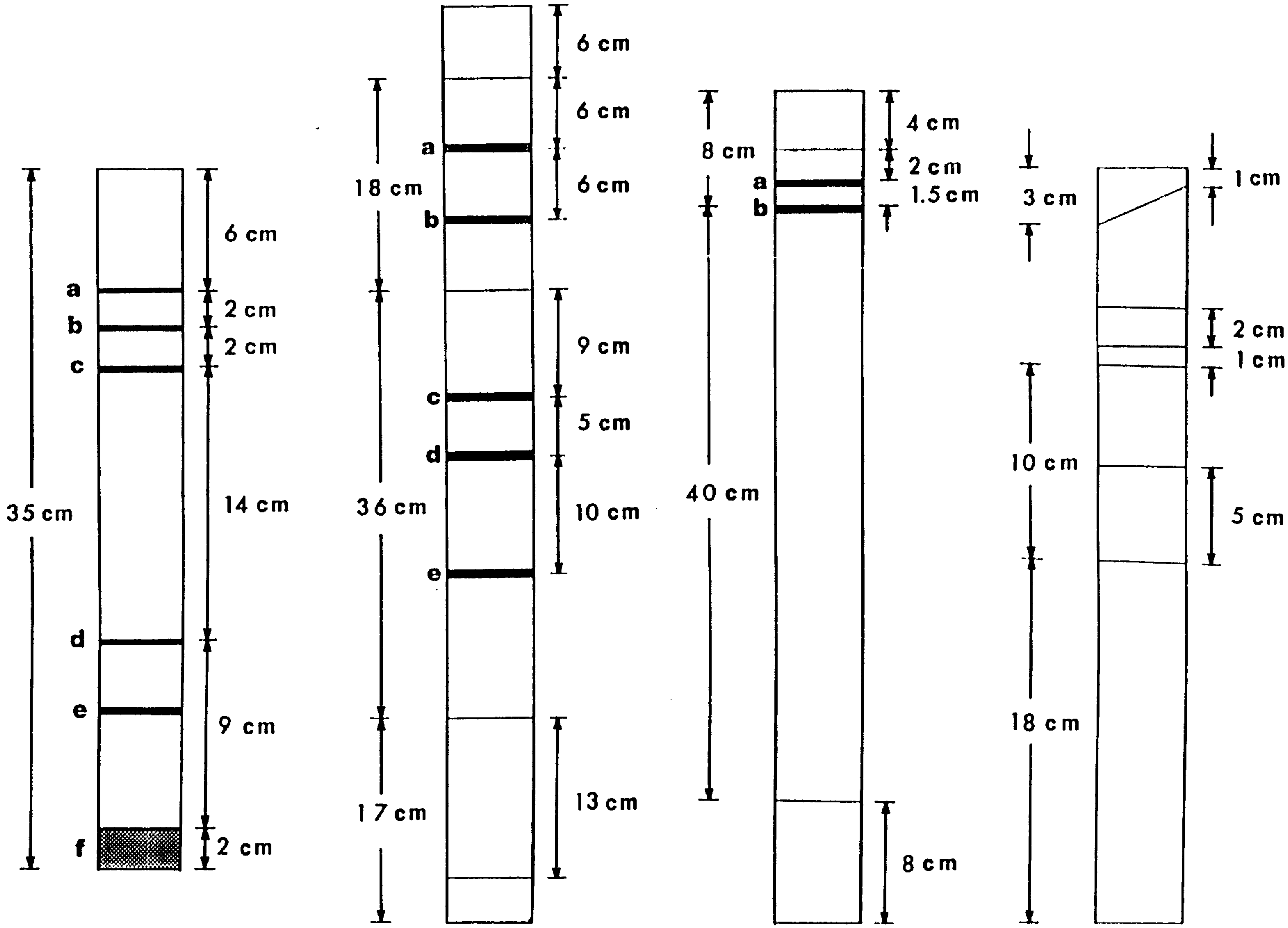

Fig. C.1. Core descriptions: a) OK9 VC, b) OK10 VC, c) OK18 VC, d) OK31 VC.

C.2 Site: OK10 VC

Core Sample Description (Fig. C.1b)

⋆ 6 cm soft black mud, no shells, no smell

⋆ Visible interface at 6 cm

⋆ 18 cm dark grey soft mud, no shells, no smell

a: thin layer (0.4 cm) of fine shells with light grey mud

b: thin light grey mud layer

⋆ 36 cm black firm mud, a few small shells, no smell

c: thin light grey mud layer with a few fine shells

d: thin light grey mud layer

e: a dark grey thin layer of mud, small shells (Augur)

⋆ 17 cm hard whitish clay with shells and shell fragments at the top, shells and large shell fragment layer (4 cm) at the base

⋆ Visible interface 4 cm above base

Bed Bulk Density and Shear Strength

Depth (cm)	Density (g cm^{-3})	Shear strength (Nm^{-2})
0 - 5	1.136	1641
- 10	1.146	1158
- 15	1.216	1303
- 20	1.235	2537
- 25	1.170	2434
- 30	1.116	2586
- 35	1.269	3034
- 40	1.287	3668
- 45	1.100	3620
- 50	1.171	3572
- 55	1.115	4537

C.3 Site: OK18 VC

Core Sample Description (Fig. C.1c)

⋆ 4 cm black peat with a small amount of sand

⋆ 2 cm light brown peat

  a,b: 0.5 cm black peat

⋆ 1.5 cm light brown peat

⋆ 48 cm mottled firm peat with visible plant roots, no shell, no smell

  40 cm mottled black and brown peat

  8 cm mottled dark grey/light brown peat and sand

C.4 Site: OK31 VC

Core Sample Description (Fig. C.1d)

⋆ 1 to 3 cm dark brown coarse sand, no shell

⋆ Fine shells and fine shell fragments with sand

⋆ 2 cm grey medium sand, no shell

⋆ 1 cm dark grey sand layer

⋆ 5 cm light grey coarse sand with fine or medium shells and small shell fragments

⋆ 5 cm brown medium sand, no shell

⋆ 18 cm sand layer, no shell, varying color from black at the top to mottled black and light grey at the base, varying sand grain size from fine at the top to coarse at the base

APPENDIX D

SEDIMENT SAMPLING IN SPRING 1988

A field visit was undertaken in March 1, 1988 to obtain sample bottom cores using a hand-held PVC piston corer designed at the Coastal Engineering Laboratory of the University of Florida, and to collect bottom sediment samples with a clamshell grab sampler for sedimentary analysis. The ten sites visited are shown in Fig. D.1.

The cores were brought to the Coastal Engineering Laboratory where they were frozen in a mixture of dry ice (frozen CO_2) and denatured alcohol, cut, and the bulk density of the cut pieces were measured. Fig. D.2 shows a frozen, cut core from site 1. The mud/water interface is fairly clearly defined by the observed color change. It should be pointed out that the freezing procedure leads to an uneven expansion of the core longitudinally. However, the procedure is fairly useful for examining the clarity of the low density region near the mud/water interface.

In Table D.1 the total thickness of mud is given for different sites. The total mud thickness was found to be generally consistent with what was obtained by Gleason and Stone (1975) based on their mud thickness contours.

The fine-grained fractions of the collected mud samples were subjected to standard hydrometer test for size determination. A modification to the method was that the sediment was not dried initially, since initial drying prevents complete dispersion of the sediment. In order therefore to determine the total dry sediment mass required for calculation purposes, the sediment was dried after the hydrometer test (Hwang, 1989).

The last four columns in Table D.1 give particle size characteristics (sizes d_{25}, d_{50} and d_{75}, and sorting coefficient, $S_o = (d_{75}/d_{25})^{1/2}$) for the fine-grained fractions at five sites. Sediment samples at these sites were first separated into coarse and fine-grained fractions by sieving through No. 200 Tyler sieve with an opening of 74 μ m. It was found that between about 75 and 90% of the material was fine-grained. This is generally consistent with the observation of Gleason and Stone (1975) who found 93% of the mud by weight to be less

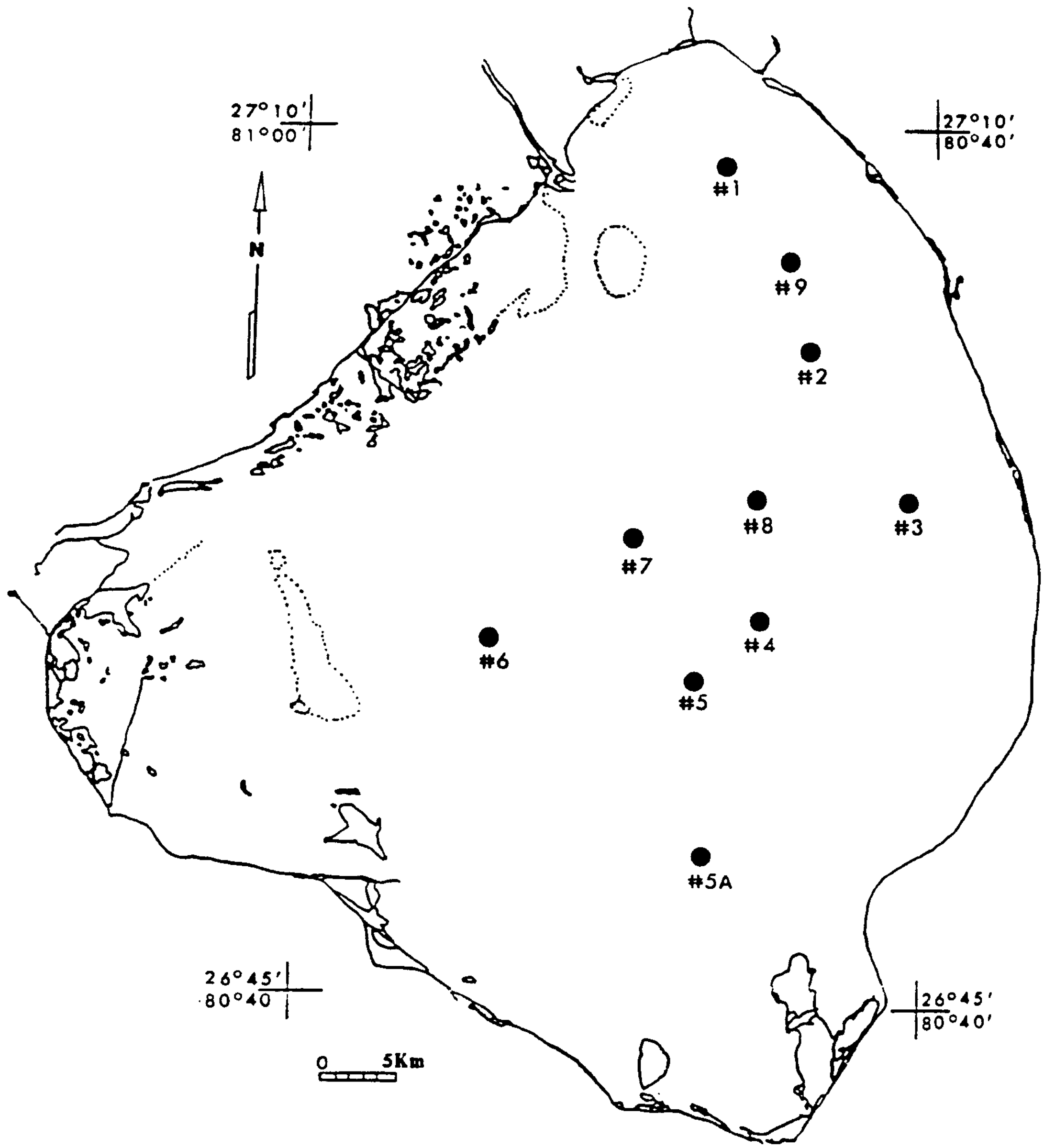

Fig. D.1. Sediment/core sampling sites in Spring, 1988.

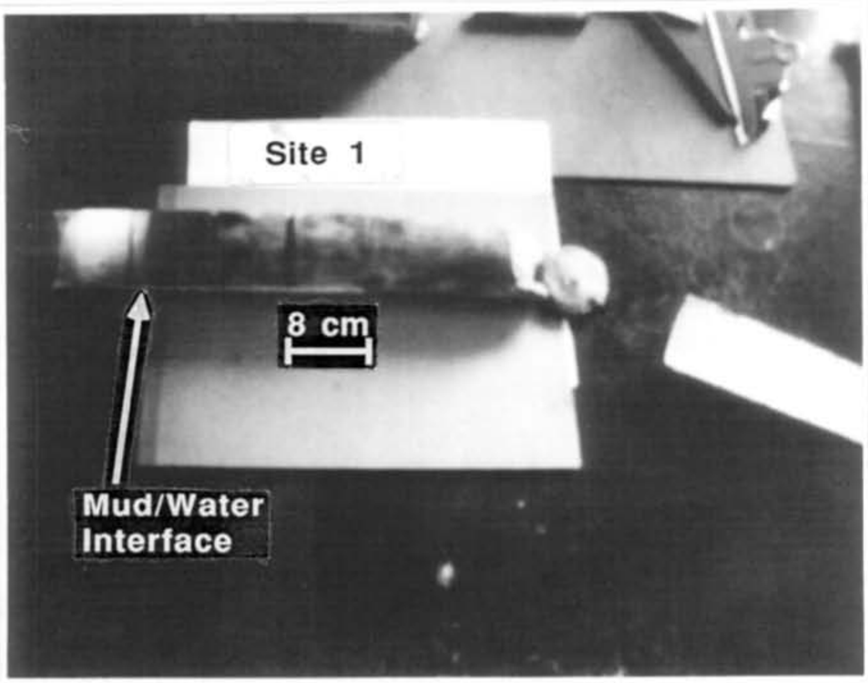

Fig. D.2. Frozen core from site 1.

than 74 μ m. They also found calcium carbonate to be present as a fine silt (2-5 μ m), and quartz grains to be slightly larger.

The last column in Table D.1 gives loss on ignition (percent by weight) of the sediment at various sites. The percent loss is fairly uniform, ranging from 36 to 41. This, in general, is indicative of the high fraction of organic matter present in the sediment.

Table D.1: Bed and Sediment Characteristics

Site No.	Total mud thickness (cm)	Fine particle characteristics				Ignition loss (%)
		d_{25} (μ m)	d_{50} (μ m)	d_{75} (μ m)	S_o	
1	30[c]	15	10	2	2.7	40
2	36	24	15	1	4.1	36
3	—[a]	13	7	0.6	4.5	43
4	—[a]	8	0.4	0.7	3.4	38
5	~ 0	—[a]	—[a]	—[a]	—[a]	—[a]
5A[b]	~ 0	10	~ 3	0.6	4.2	41
6	0	—[a]	—[a]	—[a]	—[a]	—[a]
7	66	—[a]	—[a]	—[a]	—[a]	—[a]
8	74	—[a]	—[a]	—[a]	—[a]	—[a]
9	33	—[a]	—[a]	—[a]	—[a]	—[a]

[a]Not measured.
[b]At this site the particle size analysis and ignition loss were obtained from a sample of thin mud layer above hard bottom.
[c]Including soft marl.