

PALEOLIMNOLOGY OF THE MAYA REGION

By

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PALEOLIMNOLOGY OF THE MAYA REGION

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Archaeologically supported estimates of riparian Maya populations were combined with paleolimnological information to quantify the impact of prolonged, prehistoric Maya settlement on the watersheds and lakes of the karsted lowlands in Peten, Guatemala. The pollen record indicates that regional, human-induced deforestation began prior to the Middle Preclassic period (1000 B.C.). Forest recovery commenced with depopulation at the end of the Postclassic period (1600 A.D.).

Vegetation removal caused profound changes in sediment and nutrient loading of the Peten lakes, and the impact was sustained for nearly 3 millennia. Pre-Maya organic sedimentation was replaced by rapidly accumulating inorganic deposits, but was restored some 400 years ago when forest regrowth began. Maya exploitation in the catchments accelerated the rate of total phosphorus delivery to the lakes. In the absence of soil-anchoring vegetation, phosphorus reached the lake shores as colluvium, i.e. as redeposited soil. As was shown in 1979 at Lakes Yaxha and Sacnab, phosphorus loading was Maya-density-dependent ($0.5 \text{ kg P} \cdot \text{capita}^{-1} \cdot \text{yr}^{-1}$). Settlement

and core chemistry data from 3 other basins are consistent with the quantitative conceptual model based on this constant.

Computed microfossil accumulation rates, though confounded by diagenesis, indicate that productivity in the Peten lakes was not enhanced by the anthropogenic phosphorus. Severe siltation may have inhibited lacustrine production; moreover, most of the Maya-period phosphorus load was probably delivered to the lakes in biologically unavailable form.

Shallow-water and deep-water cores from 2 lakes demonstrate the differential distribution ("focusing") of sediment and imply that single cores in conical basins are inadequate to describe accurately the accumulation of chemical and fossil constituents.

Soil and sediment chemistry data (46 soil profiles, 40.5 m of analyzed Holocene lake sediments cored from 4 basins) indicate that Peten soils lost perhaps a third of their phosphorus stock as Maya-generated colluvium. Agricultural yields may therefore have declined due to soil nutrient depletion. Concomitant lacustrine siltation could have reduced the availability of aquatic protein. Together, nutrient sequestering and siltation may have functioned as a servomechanism, restricting Maya population growth and contributing to the 9th century Classic population collapse.

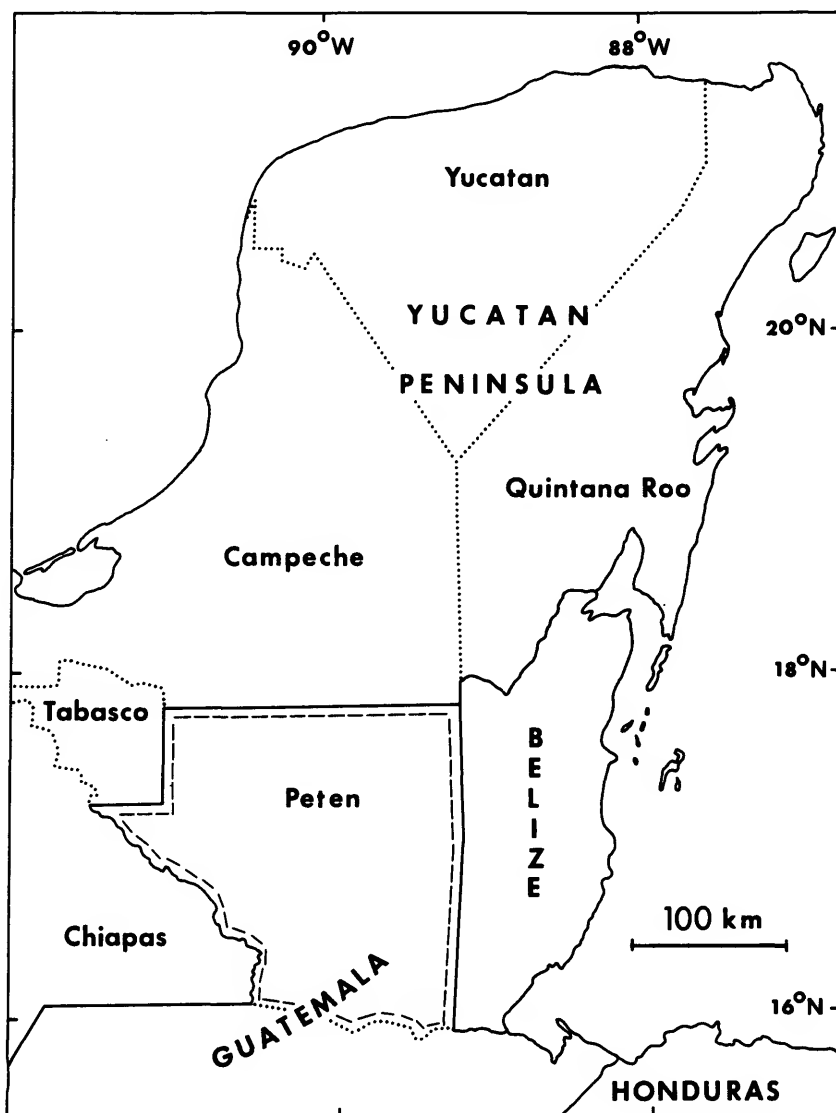
INTRODUCTION

Prehistoric Maya and Contemporary Human Population Densities of Peten, Guatemala

Guatemala's northern Peten region encompasses 35,854 km² and constitutes a large portion of the core area in which southern lowland Maya civilization arose and developed (Fig. 1). Tropical, lowland, dry forest (Holdridge 1947) covers most of the Peten (Lundell 1937), as well as portions of Belize, Mexico's Yucatan peninsula, Tabasco, and Chiapas. It was in this environmental context that lowland Maya culture originated and persisted for several millennia before collapsing mysteriously in the 9th Century A.D. (Culbert 1973).

Perhaps as a testimony to the inhospitable nature of the tropical forest, the Peten remains largely depopulated today. Cowgill and Hutchinson (1963a) reported a Peten population of 20,362 in 1957, although very recent development has raised the figure nearly 10-fold (Castellanos 1980). The sparse nature of contemporary human settlement is placed in perspective by comparison with assessments of Late Classic (550-850 A.D.) Maya population levels. Delimiting Tikal's areal extent to just under 163 km², Haviland's (1969, 1972) Late Classic estimates for this site alone fall between 40,000 and 49,000. Thompson (1966) indicates that proposed figures for pre-Columbian population levels are highly variable. They range from a low of just over a million for the

Fig. 1. Regional map. The Maya Lowlands include areas of Belize, Guatemala's Peten region, and portions of Mexico's Yucatan Peninsula, Tabasco, and Chiapas.



entire Maya region to 13,000,000 for the Yucatan peninsula alone. Admitting that his own whole-area estimate of 3,000,000 might be a bit low, Thompson (1966) was prepared to revise his figure upward, but conceded that the data base was so small as to make all assessments of Late Classic levels mere "guesstimates." In a more recent study, Adams et al. (1981) accept the notion that some 14,000,000 inhabitants occupied the Maya lowlands by A.D. 800.

Accurate appraisals of modern Peten population levels are also difficult to obtain, partly due to the seasonal immigration into the area associated with industries such as the harvest of "chicle" (Simmons et al. 1959, Cowgill and Hutchinson 1963a). From the turn of the century until the late 1960's, "chicle" was Peten's most important commodity, and the flourishing business attracted large numbers of men from Mexico, highland Guatemala, and other Central American countries (Schwartz 1974). The last two decades have witnessed a profound change in the region, as new settlers, pressured by land shortages in the highlands to the south, have streamed into Peten in response to the promise of abundant agricultural terrain. Formed in 1956, the governmental agency, Empresa Nacional de Fomento y Desarrollo Economico del Peten (FYDEP) began a land distribution program in the mid-1960's, finally granting titles to the assigned parcels in 1974. Under the auspices of FYDEP, road building and maintenance were priority projects, and by 1970 the overland route from Flores to Guatemala City was completed, making the Peten interior more accessible than ever before. In addition, communication systems were established, air service was improved, and as a consequence of the subsequent human

influx, the region is beginning to lose its distinctive cultural identity.

The attraction of available land has converted highlanders into "Peteneros" at an alarming rate. Schwartz (1977) reported an increase from 25,910 Peten inhabitants in 1964 to about 100,000 only 13 years later. Castellanos (1980) indicates that the rapid immigration that continued through the late 1970's left the Peten with some 200,000 people by the close of the decade. While government efforts to relocate land-hungry highlanders appear laudable, the program is not without its drawbacks. Native "Peteneros," while enjoying the new prosperity, feel their patrimonies are threatened (Schwartz 1977) and concern exists that there will be insufficient employment opportunities to accommodate the newcomers.

Another issue that must be addressed is how the immigrants are faring with subsistence farming practices in the Peten lowlands. They are unaccustomed to the high temperatures of the region and unfamiliar with the soils, vegetation, and shifting agricultural techniques that characterize the area. Whether the recent settlers will be able to cope in the new environment remains to be seen, but the Peten will continue to undergo drastic social and environmental change in the future as a result of increasing population density.

While the modern "experiment" in the use of the tropical, lowland forest is in its incipient stage, and it would clearly be premature to pass judgment on its success now, it can be said that the prolonged persistence of prehistoric Maya culture in the same context constituted a success that is without parallel. Bronson (1978) has likened the

Maya to three Asian civilizations that developed in apparently similar settings, but this hardly detracts from the achievements of the Maya, and the latter are, with the possible exception of the Olmec, the only New World high civilization to arise and flourish within a tropical, lowland forest ecosystem.

Maya Cultural Development in the Tropical Forest Ecosystem

While some anthropologists are perplexed by the apparent incompatibility of high civilization and the tropical forest setting, adherents of "environmental determinism" have gone so far as to deny that lowland Maya culture could have developed in situ. Meggers (1954) argued strenuously that Classic Maya culture (250-850 A.D.), with its monumental architecture, art, hieroglyphics, concept of zero, corbeled arches, calendrical system, and stela cult, could not have arisen autochthonously. Believing that the degree of cultural complexity achieved is dependent upon the agricultural potential of a region, Meggers classified the Peten as an area of limited agricultural potential (Type 2), and thus believed the area was not conducive to the florescence so evident in the archaeological record. The logical conclusion, based on the assumptions of this agriculturally deterministic law, was that Classic Maya culture was imported into the lowlands fully formed and was destined to decline following its arrival. This simple theory accounted for both the mysterious origin and inexplicable downfall of the civilization.

In the years following Meggers' (1954) paper, a number of refutations were published, perhaps laying to rest the broad claims of environmental determinists, but keeping alive the controversy surrounding the enigma of the prehistoric high civilization in the tropical forest environment. Coe (1957) took exception to Meggers' claims for a number of reasons. He contested her view that there is a lack of Preclassic-Classic transition in the lowland record and felt there was no archaeological basis for the argument that Classic culture was imported from the highlands. Additionally, he pointed out that several lowland Maya achievements, such as the corbeled arch, the Long Count, and the stela cult, seem to have no non-lowland origin. Coe's disagreement with Meggers extended to the perception of the Classic Maya collapse. While Meggers referred to a "gradual decline," initiated following the arrival of Classic culture in the lowlands, Coe pointed out that the evidence indicated a rather widespread, rapid termination following some 600 years of incremental growth.

In the year following Coe's reply to Meggers, Altschuler (1958) presented Formative phase ceramic evidence that supported the claim for autochthonous origin of lowland Classic Maya civilization. His conviction was that political problems generated the 9th century collapse. Specifically, he proposed that the ruling class attempted a political structuring that was doomed to failure because it lacked the developed techniques of exploitation.

Ferdon (1959) disagreed with Meggers' assessment of the Peten's agricultural potential, and using his criteria of temperature, soils,

precipitation, and land form, reclassified the lowlands as a favorable (Type 3 = improvable) site for agriculture. This analysis did not constitute a refutation of deterministic law as applied to the Maya by Meggers. It simply freed the civilization from having to conform to the expectations dictated by a Type 2 (limited potential) environment. However, Ferdon did take issue with environmental determinism and presented data supporting his contention that there is no correlation between natural agricultural potential and cultural development. Having disproved the role of determinism in the eventual Classic collapse, he proposed the notion that grass invasion of cleared plots and the subsequent inability to plow the tracts contributed to the downfall of the civilization.

The Origins of Maya Civilization

Recent archaeological excavations in the Orange Walk district of Belize have established that occupation of that area commenced as early as the third millennium B.C. At the site of Cuello, fragments of partially burned wood associated with ceramic material assigned to the Early Formative Swasey complex (Hammond et al. 1979) have produced several radiocarbon dates indicating an age of between 4000 and 5000 calendar years (Hammond et al. 1976, Hammond et al. 1977, Hammond 1980, 1982). These data confirm the claim that lowland Classic Maya cultural ontogeny had its roots in the lowlands.

Within the Peten region per se, the earliest ceramic material discovered to date comes from the sites of Seibal and Altar de

Sacrificios (Adams and Culbert 1977). Assigned respectively to the Real and Xe complexes, the material is dated to the Middle Preclassic (1000-250 B.C.). Middle Preclassic settlement is known at Tikal and has also been documented in the Yaxha-Sacnab watersheds of eastern Peten (Rice 1976). Following an extensive settlement survey and test-pitting program during the 1979-80 field season, occupation of this age is now recorded in four more central Peten drainages (Rice and Rice 1980a).

While the numerous discoveries of Preclassic settlement in the lowlands contradict the argument that Classic culture was brought to the region intrusively, debate continues as to what factors were the driving forces contributing to the formation of lowland Classic Maya civilization (Adams 1977). Although influences from beyond the lowlands are considered, several intrinsic processes are invoked to explain the cultural growth and change that produced the social ranking and stratification that ultimately characterized the Classic period. Willey (1977) provides a multi-causal model for Classic Maya development based on a synthesis of processual interpretations proposed by others. In formulating his "overarching model," he incorporates these models and processes that are broadly assigned to three major categories: (1) ecology-subsistence-demography, (2) warfare, (3) trade. He notes that none of these models advocates a monocausal explanation for the Classic Maya rise and cautions that the role of ideology should not be discounted.

Invoking environmental factors, though not as a determinist, Sheets (1979, 1981) sees the rise of Classic Maya civilization in the lowlands as reflecting a natural disaster in the highlands of El Salvador. Acknowledging that Classic Maya culture would have developed in any case, he argues that the eruption of El Salvador's Ilopango volcano in A.D. 260 might have accelerated the process by forcing increased political and agricultural organization to cope with the influx of immigrants who descended to the lowlands when highland agricultural land was rendered useless by the deposition of a thick ash blanket. Additionally, he points out that Tikal's Early Classic (250-550 A.D.) florescence may have been stimulated by the diversion of trade routes with Mexico that previously had passed along the Pacific coast. With the coastal road destroyed, Tikal became the major eastern site on the trade route that extended into the basin of Mexico.

Maya Agricultural Practices

During the last two decades, Maya archaeology has become preoccupied with questions about pre-Hispanic agricultural practices. Until that time, the prevailing dogma was that Maya subsistence was dependent on maize-based, swidden (slash-and-burn, shifting) agriculture. How this belief became entrenched in the literature remains unclear, but it was not necessarily supported by the archaeological record. Though corn is depicted in Maya art, the contemporary reliance on the "milpa" and the ubiquity of cornfields in the Guatemalan lowlands at the time of colonial contact and today must

certainly have contributed to the acceptance of the doctrine. While this agricultural technique may be appropriate for the sparsely populated modern Peten, there is doubt as to whether it was a feasible alternative during Classic Maya times. Because slash-and-burn requires land to be fallowed for long periods, much larger areas than the plots actually under cultivation are required. In the swidden cycle, forest is felled during the dry season (January-May), and prior to the onset of the rains, the dried vegetation is burned, delivering nutrients to the soil. Following the burn, seeds are sown in holes bored with a dibble stick, and growth commences after the first showers of the rainy season with no additional working of the soil required.

Confronted with differing assessments of Peten's agricultural potential (Meggers vs. Ferdon), Cowgill (1962) sought to resolve the disparity and interviewed 40 farmers in the region of Lake Peten-Itza in an effort to ascertain actual corn production. Summarizing the data from the interviews, she noted that first year plot yields were $1425 \text{ lb} \cdot \text{acre}^{-1}$, second year plots averaged $1010 \text{ lb} \cdot \text{acre}^{-1}$, and the five farmers who tried three years of successive planting averaged $417 \text{ lb} \cdot \text{acre}^{-1}$, with the decline likely due to nutrient depletion. Stable swidden of this nature would demand a four-year fallow following a single crop and six to eight years' rest on a plot worked two years in succession. Cowgill concluded that swidden farming could support about $38\text{--}77 \text{ people} \cdot \text{km}^{-2}$, and tentatively noted that Classic period population densities may have exceeded the restrictions imposed by stable swidden strategy.

Recent surveys of ancient Maya settlement in the Peten make it easier to evaluate the feasibility of slash-and-burn to have supported prehistoric populations. Rice (1978) used demographic data gleaned from the archaeological record together with agricultural output information to formulate a model that demonstrates the insufficiency of maize-based agriculture to have met the subsistence needs of populations in the Yaxha-Sacnab subbasins. At this locality, where slow, steady exponential population growth occurred from the Middle Preclassic (1000-250 B.C.) until the Late Classic (550-850 A.D.) (Rice 1978, Deevey et al. 1979), dependence on maize-based swidden agriculture would have resulted in food shortages by Late Preclassic (250 B.C.-250 A.D.) times, necessitating shorter fallow periods or the farming of less preferred sites solely in order to meet subsistence needs. The incorporation into the subsistence strategy of root crops, as originally hypothesized by Bronson (1966) or breadnut, "ramor" (Brosimum alicastrum) (Puleston 1976, 1982), is shown by the model to have greatly enhanced the probability of supporting large Classic populations.

With the demise of the myth that Maya subsistence was totally reliant on maize-based swidden came suggestions for other food sources and food-producing systems. Lange (1971) proposed that marine resources might have been an important constituent in the Maya diet. An inventory of Peten's potential floral and faunal trace items (Voorhies 1982) contains a varied assortment of food types, but the list of comestibles is by no means complete, as perishable goods,

incapable of being transported long distances, were excluded from this tabulation. According to Wilkin (1971), Maya food procurement was likely dependent on an array of systems that included gardening, arboriculture, gathering and intensive practices such as terracing, irrigation, and drainage.

There is now abundant archaeological evidence that the lowland Maya did employ intensive agricultural techniques. In Campeche, Mexico, ridged fields are known in the Rio Candelaria region (Siemens and Puleston 1972), and Matheny (1976) reports that extensive measures for water control were taken at Ezna. In the Rio Bec region of the southern Yucatan peninsula, terraces and raised fields are reported by Turner (1974), and Turner and Harrison (1981) have discovered raised fields at Pulltrouser Swamp, Belize, that may have been constructed as early as Late Preclassic (250 B.C.-250 A.D.) times, thereby indicating the great antiquity of the intensive agricultural systems.

The widespread presence of relict canals associated with intensive cultivation has been documented using radar imagery (Adams 1980, Adams et al. 1981). The canals, located near swamps, lakes, ponds, and rivers, were apparently constructed for drainage purposes and have been verified on the ground in areas of Mexico and Belize. Archaeological ground truth within the Peten is less secure, but should the grid patterns from the radar mapping prove to be drainage canals, it will indicate the tremendous scale on which intensive agriculture was practiced in the Maya lowlands.

The Classic Maya Collapse

The recent revelation that Classic Maya subsistence was at least in part dependent on intensive agricultural practices helps explain how the populations of the densely settled region were supported. Unless it can be claimed that these subsistence strategies caused environmental detriment, their discovery contributes little to the search for a cause of the Classic Maya collapse. What makes the Maya downfall such a perplexing event in New World Prehistory is that the disintegration of the framework that characterized the socially stratified Classic culture was accompanied by an extreme demographic change involving the relatively rapid depopulation of ceremonial centers as well as the countryside. With a shift in archaeological focus, beginning around 1950, from an exclusive preoccupation with ceremonial architecture to an interest in settlement surveys, the magnitude of the population decline was more fully appreciated (Willey 1982). Willey (1956) expressed the need for more settlement work, but the lack of evidence for Postclassic (1000-1600 A.D.) occupation of housemounds excavated during his Belize valley surveys led him to the conclusion that commoners disappeared with the demise of elite society. Stated simply,

If collapse occurred--and, indeed, something did occur--Maya priest and peasant collapsed and vanished together. Willey (1956: 781)

Adams (1973) has summarized the "collapse" problem and provides a concise recapitulation of the hypotheses that have been proposed to

account for the Maya downfall. Adams details the archaeological evidence for the disappearance of the elite class, and his summary view of the collapse encompasses not only the cessation of elite activity, but the attendant population decline, both of which occurred throughout the southern Maya lowlands within a period of 50-100 years.

Noting that there has been a recent tendency to reject single-factor reasons for the collapse in favor of multiple-factor models, Adams nevertheless classifies the explanations into broad categories. Ecological models invoke various environmental disasters, such as soil exhaustion, water loss and erosion, and savanna grass competition. Under this heading, Sabloff (1973) might add insect infestation and climatic change. Catastrophic events such as earthquakes (Mackie 1961) and hurricanes are proposed, but serious earthquakes are not characteristic of the lowlands, and events stemming from disasters such as these are hard to document using the archaeological record. Meggers' (1954) "environmental determinism" is considered an evolutionary model, but is now discredited because it is known that lowland culture arose autochthonously, and the agricultural potential of the region has been reevaluated. A demographic model for the population decline was set forth by Cowgill and Hutchinson (1963a), but receives little attention today. Studying the Indian populations around Lake Peten-Itza, they discovered that by the fifteenth year of life, the sex ratio in the population was 1.8♂:1.0♀. This they attributed to the poor care given female children between one and four years of age, by which time the skewed ratio is established. Neglect

and consequent high mortality of female children (1-5 years) is documented for many non-industrial countries (Cowgill and Hutchinson 1963b), but is likely compensated for by slightly higher male death rates in the ensuing years. It is pointed out that the extreme case discovered in the Indian populations of the Peten could have disastrous consequences. An explanation for Classic Maya depopulation was sought using this scenario, with the realization that it would have to be applied in a long-term situation.

The destruction of the social structure as a consequence of internal revolution has been posited as a factor influencing the collapse, but while it may account for the disintegration of the social hierarchy, this alone would not necessarily have led to depopulation. Invasion from outside the area has also been proposed, and in view of the post-collapse Toltec takeover in the northern Yucatan, such a scenario is not out of the question. There is some archaeological basis for the claim that intrusive elements were present at Seibal and Altar de Sacrificios prior to the decline.

Finally, disease has been repeatedly implicated as a causal factor in the collapse, though debate surrounds claims about the pre-Columbian presence in the New World of illnesses like malaria, yellow fever, and syphilis. Recent paleopathology work with skeletal material from Altar de Sacrificios has revealed the occurrence of health problems in the Maya population that occupied the site. Evidence for physical injury in the bone sample is minimal, but vitamin C deficiency and anemia, either diet-related or parasite-induced, are amply documented (Saul

1973). Additionally, the presence of bone lesions indicative of syphilis or yaws is noted.

It is clear that the various explanations for the collapse are not mutually exclusive, and several of the proposed causal factors may have worked in concert to produce the resultant downfall. Unfortunately, some of the proposed hypotheses are difficult to reject using the archaeological record alone, but a systematic program of testing the different single-factor theories may one day lead to a synthetic model that reasonably explains the Classic Maya disappearance. Such an approach will doubtless be dependent on evidence provided by ecologists, ethno-historians, soil scientists, and others outside the realm of archaeology per se.

The Historical Ecology of the Maya

Measuring Maya Environmental Impact Paleolimnologically

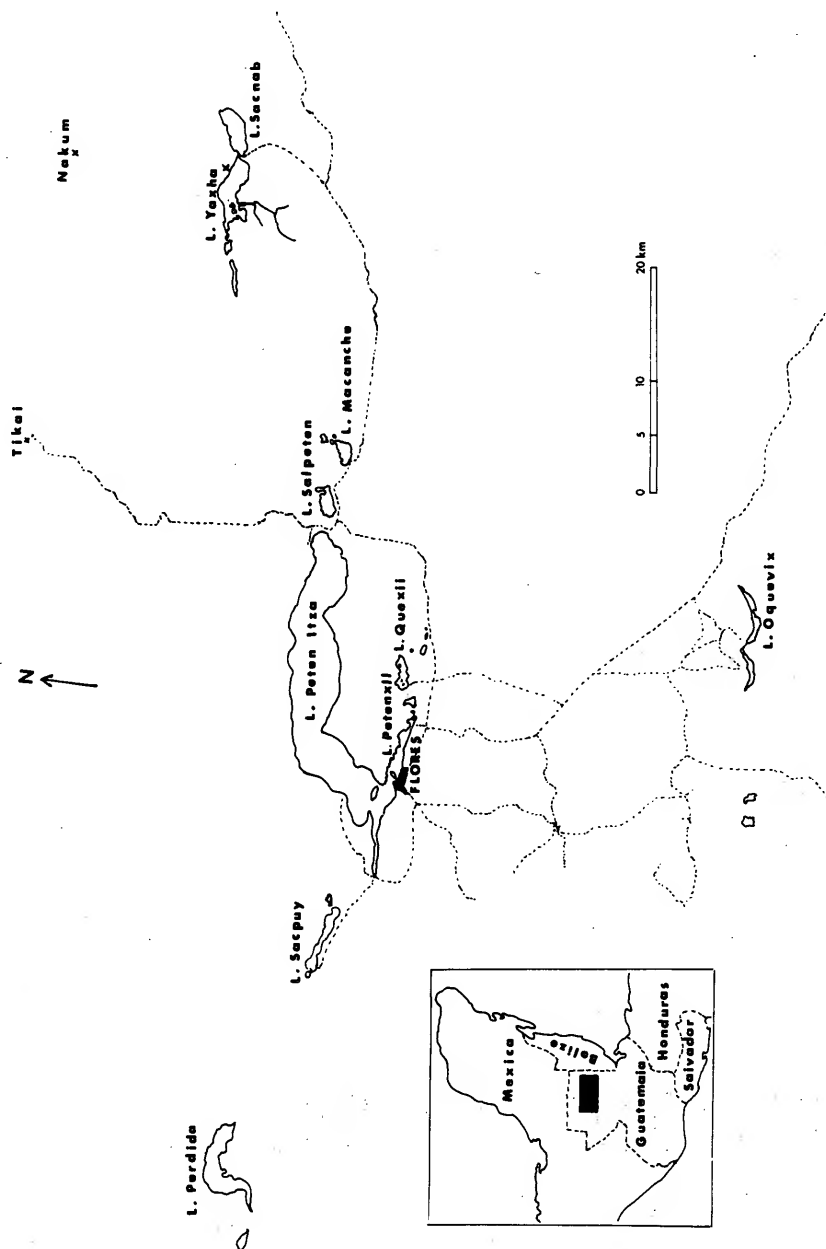
This study does not directly address the question of the mysterious Maya collapse, though the data collected do in fact suggest that ecological factors played a role in the event. Instead, the design of the experiment was chosen with the objective of shedding light on the impact that long-term Maya agro-engineering practices had on the watersheds and lakes of the Peten. In a sense, the question has been approached conversely in the anthropological literature, as social scientists have sought to determine the influence the natural environment had on settlement patterns, food-producing systems,

socio-political organization, etc. Cognizant of the fact that the interaction between humans and the ecosystem constitutes a feedback loop, this study takes a decidedly "ecocentric" viewpoint, exploring the effects of prolonged, dense human occupation on terrestrial and aquatic systems of the tropical lowlands. The Peten lake district (Fig. 2) provides a unique opportunity to examine human-environment interaction, for, in fact, the "experiment," exploitation of the lowland tropical forests and lakes, has already been conducted by a civilization now long gone. The results of that experiment need only be elucidated, and with this in mind, the "Historical Ecology of the Maya" project was conceived in 1971. Employing a multidisciplinary approach, the program involved the use of archaeological and paleolimnological techniques to examine changes in the aquatic and terrestrial systems that resulted from extended human interference.

Lake-Watershed Interactions

Proper study of lacustrine systems in general and the paleolimnological record in particular demands a view of lake basins as integral parts of a larger landscape. Though often considered as distinct entities, aquatic and terrestrial ecosystems are inextricably linked by meteorologic, geologic, and biologic processes that transfer nutrients and energy from one system to the other (Likens and Bormann 1974a). Lakes can be considered "downhill" with respect to their terrestrial surroundings and the meteorologic, geologic, and biologic

Figure 2. The Peten Lake District.



vectors that join the systems ultimately carry nutrients from upland sites of accumulation to the waters below. The kinds of nutrients and their rates of supply have a profound effect on the lake, exerting a controlling force on the physical, chemical and biological processes that occur in the aquatic realm. Mature, intact, terrestrial ecosystems tend to maintain tight nutrient cycles, with loss to the lacustrine sector minimized by the presence of the soil-anchoring, standing vegetation. When the biological component of the land system is disturbed, through forest clearance, nutrient cycles are disrupted, accelerating the delivery of dissolved and particulate matter to the lake.

Inadvertent enrichment of lake waters can occur as a result of forest clearance, but often, lacustrine pollution occurs as if by design. The "downhill" nature of lakes makes them convenient disposal systems for unwanted, accumulated wastes like domestic sewage and industrial by-products. These practices are not without their consequences and our contemporary cultural eutrophication problems stem from the casual manner in which many lakes have been used as recipients of sewage and agricultural run-off rich in plant nutrients (Edmondson 1968, 1970, 1972; Vallentyne 1974). The realization that the source area for some of these unwanted nutrient inputs lies some distance from the water's edge demands that investigators look beyond the lake itself in the study of lacustrine processes. Furthermore, awareness of acid rain problems (Likens and Bormann 1974b) demonstrates the need for consideration of the regional airshed in assessing lake dynamics.

Bormann and Likens (1967) suggested that small watersheds make ideal sites for examining nutrient cycle problems and proposed that the entire watershed be considered the basic unit for ecosystem-level lake study. Modern studies at Hubbard Brook, New Hampshire, have accumulated biogeochemical output data from undisturbed, natural ecosystems (drainage basins) (Likens et al. 1977), and these baseline values can be compared to nutrient losses from clear-cut forests (Bormann et al. 1968). Contemporary investigations of this type measure altered nutrient outputs as they occur. That is, data on the rate of nutrient transfer between the terrestrial-aquatic interface can be collected immediately following a "treatment" like deforestation. In attempting to assess the effect of past events on lakes, it is necessary to rely on the paleolimnological record.

The Paleolimnological Perspective

Paleolimnological study can document past changes in a lake and its drainage, because shifting conditions in the watershed had an impact on the lake; and a record of the alterations, though perhaps somewhat distorted, is preserved within the sediments on the lake bottom. Frey (1974) has said,

The task of the paleolimnologist is to "read" the history of the lake-watershed-atmosphere systems from the record "written" in the sediments.
(1974:95)

In dealing with the origin and developmental history of basins, paleolimnology can address questions about the ontogeny of lakes that

were free from human disturbance. Climatic change can be inferred from the palynological record and theoretical questions about ecosystem development can be approached using sedimented microfossil assemblages (Deevey 1969). With the greater awareness that human activity can radically alter watershed nutrient cycles, paleolimnological techniques are being used increasingly as a tool to assess the magnitude of human-induced changes. Sometimes historic data on demographics and waste dumping are known for a lake-watershed system, but the limnological record is restricted to the postdisturbance period. In Lake Washington, east of Seattle, the sediments yielded information concerning baseline lacustrine conditions, prior to the eutrophication that resulted from excessive sewage input to the lake (Edmondson 1974).

The paleolimnological record, in conjunction with early historical records or archaeological data, has been used to establish the impact of human activity on a number of basins, sedimentary changes having been correlated with density of occupation or shifts in land use (Cowgill and Hutchinson 1964). Like the vast majority of contemporary limnological investigations, most paleolimnological projects have been undertaken in the temperate area lakes of now-industrialized countries (Mikulski 1978, Pennington 1978, Vuorinen 1978, Warwick 1980). There is a paucity of literature concerning tropical paleolimnology, especially with regard to the impact of human disturbance on tropical ecosystems. Though regrettable, there are several factors that likely account for the restricted development of tropical paleolimnology. First, well-established limnological research centers are generally

confined to temperate regions, often in close proximity to lake districts. Therefore, mounting drilling campaigns in tropical areas can be quite costly, necessitating a large initial outlay for travel. Once in the tropics, one may encounter additional difficulties. Poor road conditions or a complete lack thereof can render potential coring sites inaccessible. Also, such projects often require the permission of foreign government officials, and even when permits are forthcoming, the local political or scientific community may lack the infrastructure to be of assistance. Political instability is a hazard to be considered and makes many potentially exciting study sites "off-limits." Finally, little is known of the regional limnology in most tropical areas, making interpretation of the paleolimnological record somewhat less secure.

Despite the many drawbacks and logistical difficulties associated with paleolimnological work in the tropics, there are significant arguments that convincingly speak to the need for more study in these regions. As the human populations in tropical countries continue to increase, deforestation and resource exploitation will accompany the demographic change. What impact the forest felling and farming practices will have on freshwater sources is not known. Limnological monitoring of newly settled drainages must begin, and sediment studies can be used to gather baseline information from basins with a long history of occupation. With continued demographic growth in the tropics, management schemes for freshwater resources will have to be instituted and cannot be formulated using the temperate data base.

Despite the differences between temperate and tropical systems, paleolimnological techniques should be applicable in both settings for documenting human intrusion in watersheds. Nutrient cycles in undisturbed, tropical watersheds are very tight and maintained by the standing vegetation. Any disruption in the drainage basin should have a noticeable, if not profound, effect on the lake and consequently the sediments (Oldfield 1977).

Several characteristics of the Peten lakes recommend them as study sites. First, the basins are closed, and because the lakes lack outlets, the sediments are the ultimate sink for much of the dissolved and particulate matter washing into the lake as well as biogenic material formed autochthonously. Secondly, a long history of Maya settlement in the Peten watersheds should be expected because of the scarcity of surface water in the lowlands. Initial settlement in the region might be supposed to have clustered around readily available sources of water. That access to water was a problem for the Maya is evident in the archaeological record at some sites in the interior. The long dry season necessitated the construction of reservoirs at Tikal, and evidently some "chultuns," hollowed-out, underground caverns, were employed for water storage (Matheny 1982). To the north, in the drier Yucatan, the situation was even more critical, and it has been pointed out that the Maya of that region developed a civilization, in a sense based on groundwater, with population centers located near water supplies in the form of natural "cenotes," caves, and "aguadas," or man-made wells (Back 1981).

One scenario for the initial Maya invasion of the Peten interior envisions the pioneers entering on the river systems and later expanding into the drier regions of the central core area (Puleston and Puleston 1971). It has been suggested that the lack of available water and necessity to cope with the problem may have been the driving force that led to substantial social organization. The oldest Peten sites of Seibal and Altar de Sacrificios are situated on rivers, and it is conceivable that the earliest emigrants from these communities, or other, as yet undiscovered river villages, traded the benefits of riverine settlement for the advantages of riparian occupation on the lake shores. Both localities would have been favorable settlement areas, providing water as well as sources of aquatic protein.

The Contemporary Peten Environment

Geology

With the exception of the mountainous Lacanoo area in the northwest and the extension of the Belizean Maya Mountains in the extreme southeast, the Peten is characterized by low-lying karsted terrain varying in elevation from about 100 to 300 m above sea level. As is typical of limestone regions, the countryside is irregularly pocked with caverns and sinkholes. The haystack hill topography developed on limestones of Cretaceous and Tertiary age (West 1964).

The Peten lake district (Fig. 2), with its center at 17°N, 89°40'W, lies within the Santa Amelia Formation, a deposit of early

Eocene age (Vinson 1962). North of the lake region, the Santa Amelia is overlain by the slightly younger limestones of the Buena Vista Formation, the basal portion of which contains a 200-m thick zone of gypsum. Both formations are locally interbedded with dolomite and gypsum. During middle Tertiary times, compressional folding and concomitant emergence resulted in a mid-Eocene to Oligocene depositional hiatus, though locally there are deposits in the Peten of Oligocene to Pliocene age. By late Pliocene, uplift, folding, and faulting put an end to Tertiary sedimentation in the region.

The lake chain at 17°N (Fig. 2) is aligned along a series of east-west trending en echelon faults, the basins occupying depressions below steep north shore scarps (Tamayo and West 1964). The principal lakes in the fault zone chain extend some 80 km from westernmost Sacpuy eastward to the twin basins of Yaxha and Sacnab, only 30 km from the Belize border. Farther to the west, but outside the main graben, lies the relatively large and limnologically unexplored Lake Perdigá. In addition to the localized standing bodies of water are seasonally inundated depressions interspersed between the limestone hills, features that are not uncommon over a large portion of the Peten landscape. These "bajos" or "akalches" are characterized by thick clay soils that give rise to swamp-thicket vegetation. It has been suggested that the "bajos" were once shallow lakes, providing water, lacustrine resources and a mode of transportation for the Maya who inhabited the shores. The silting-in of these shallow basins has been invoked as a contributing factor for the Classic collapse (Cooke 1931,

Harrison 1977). A 5-m pit dug in the Bajo de Santa Fe, near Tikal, revealed that indeed the clays that lined the floor of the depression resulted from the solution of upland limestone, but there was no evidence for lacustrine deposition having occurred during Holocene times (Cowgill and Hutchinson 1973).

The calcareous bedrock of the Peten provided the resource base for Maya architectural endeavors, as building stone was easily quarried. In addition, limestone was burned and mixed with calcareous sand ("sascab") to make construction mortar or plaster. The Maya also exploited the localized flint and chert beads, using the siliceous rock for making points and cutting tools (West 1964).

Climate and Rainfall

Lying at low altitude, within the tropic, the Peten is characterized by year-round high temperatures, the mean annual value in excess of 25°C (Vivo Escoto 1964). Mean monthly temperatures for the region range between 22°C and 28°C, but as expected in tropical areas, daily fluctuations in temperature often exceed the limits of the monthly extremes.

Within the Peten, precipitation is highly variable from station to station and varies on an annual basis at any given site. Rainfall records indicate annual precipitation values ranging from ca 900 to ca 2500 mm. A regional, yearly mean of 1601 mm is reported based on 54 station-years of data collected at 10 sites (Deevey 1978). Within the tropics, as a rule, the distribution of rainfall throughout the year is

highly seasonal (Richards 1979), and Peten is no exception. There is a long dry season from January to May with a secondary period of reduced rainfall, "canicula," interrupting the wet season in July or August. The most pronounced aridity occurs from January to March during which time the rainfall amounts to less than 10% of the total annual income (Deevey 1978).

Soils

The soils of the Peten catchments represent a large potential source for lacustrine nutrients. Under conditions of deforestation, enhanced delivery of dissolved and particulate matter to the lakes is expected, and the tremendous erosive potential of intense tropical rains is a major contributing factor in the transfer of nutrients from the land to water. The extreme seasonality and heavy downpours characteristic of the tropics make rainfall at those latitudes more erosive than equivalent annual precipitation in temperate areas where the rains are distributed more evenly throughout the year (Stevens 1964).

Roughly 0.4% of the Peten landscape is covered by the major lakes, and the balance of the region is overlain by soils assigned to 26 series by Simmons et al. (1959). They relegated the department soils to two major groups: savanna soils that cover some 9.8% of Peten and forest soils that blanket 89.8% of the region. These major categories were further divided, savanna soils characterized as deep well-drained,

deep poorly or deficiently-drained, and shallow deficiently-drained. Within these subdivisions, the soils were assigned to a particular series based on a number of characteristics, including parent material, relief, color, texture and consistency, and profile thickness. With the exception of some localized soils that overlie clay-rich schists and some alluvial deposits, Peten soils are derived from the underlying limestones.

Zonal soils develop under the primary influences of regional climate and vegetation, their distribution being highly correlated with patterns reflected in the climatic regime and plant associations. Within the central portion of the Peten, soil genesis is influenced tremendously by the calcareous bedrock as well as drainage factors, to the extent that zonal soil development is precluded. In the lake district, the local geology and hydrology have generated primarily intrazonal soils assigned to the Rendzina and Hydromorphic great soil groups (Stevens 1964). Azonal Lithosols, black calcareous soils resembling Rendzina are abundant, and Stevens (1964) speculates that these youthful soils are now regenerating following a long period of erosion and depletion induced by Maya farming practices.

Though 26 soil series are described for the Peten, only three surround the lakes examined in this study. The Yaxa series covers some 15.57% of the Peten and consists of shallow well-drained forest soils that often cap flat expanses as well as hilly slopes. These black calcareous Lithosols are highly fertile, and cultivation of these soils is only restricted by their high erosivity and presence on steep

slopes. Yaxa soils surround Lake Macanche and nearly encompass Lake Salpeten, the southwest shore of which is contacted by soils of the Macanche series. Macanche series soils blanket 5.11% of the department landscape and are shallow soils with deficient drainage. Confined to primarily level topography, these Rendzinas are highly fertile and not particularly subject to erosion. Poor drainage and the adhesive nature of the soils are the only drawbacks for agriculture. Indeed, the black calcareous Lithosols and Rendzinas were certainly exploited by the Maya and numerous Classic Maya ceremonial centers are found in association with soil series of these groups (Stevens 1964).

According to Simmons et al. (1959), the western edge of Lake Quexil is contacted by Yaxa soils, but the balance of the drainage is occupied by soils of the Exkixil series. A deep poorly drained savanna soil, the Exkixil series is restricted to only 0.23% of the Peten and is found in flat areas. These soils can be assigned to the Hydromorphic great soils group and are typified by high clay and silt content and poor fertility. They are not easily eroded and today support grasses and open oak woodland.

It is noteworthy that the soils map developed by Simmons et al. (1959) is rather crude with respect to accurately delimiting the areas covered by the various soil types. Within the Peten, great variation in topography and perhaps bedrock geology can be encountered over short distances. This in turn leads to great heterogeneity and patchiness of soil types within limited areas. The incongruity of mapped soil zones (Simmons et al. 1959, and personal observations) is most clearly

demonstrated at Lake Quexil. While the map shows the Quexil watershed to be dominated by Exkixil series soils, the true drainage is primarily covered by forest soils, probably of the Yaxa series.

Vegetation

Though commonly referred to as "tropical rain forest," the vegetation of Peten grows in a region that is too dry for the development of true rain forest. Employing the climatic data criteria established by Holdridge (1947), the Peten falls within the tropical, lowland, dry forest life zone. Lundell (1937) applied the term "quasi-rain-forest" and though the vegetation is principally evergreen, some species lose their leaves periodically, the degree of deciduousness dependent on the annual distribution and amount of rainfall.

Simple description of the Peten vegetation is impossible due to the variability of vegetation types that reflect topographic and edaphic differences. Wagner (1964) reports that some 75% of the upland forest is covered by the "zapotal" association, named for the prevalence of "chico zapote" (Manilkara) in the middle tier of the forest. Characterizing this dominant association, he notes that the major floristic components in the top story are Calophyllum, Swietenia, Rheedia, Lucuma, Sideroxylon, as well as several species of Ficus. Below the uppermost tier lies a middle story of Manilkara, Vitex, Ficus, Cecropia, Bursera, Spondias, Aspidosperma, Brosimum, Pseudolmedia, and members of the Leguminosae and Lauraceae. Averaging

10 m, the lower story is typified by Trichilia, Sideroxylon, Sapium, Sebastiania, Misanteca, Parmentiera, Myriocarpa, Lucuma, Louteridium, Laetia, Deherainia, Annona, Sabal, Pimenta, Protium, Ocotea, Zanthoxylon, and species of Pithecolobium, Talisia, Cordia, and Croton. The underwood plants are Piper, Psychotria, Ruellia, Justicia, and various palms. Lianas are common, as are orchids, bromeliads, and ferns.

Wagner's (1964) enumeration of the genera that typify the Peten forest provides an impression of the floristic composition of at least one major association. The forest can also be described based on its physiognomy. During a 1974, week-long reconnaissance and vegetation sampling trip near Lake Yaxha, Ewel and Myers (1974) identified four vegetation types, the physiognomy of which reflected the underlying topography. Three of the four distinct vegetation classes were sampled, including (1) the forests of steep slopes and ridges, located on well-drained soils and possessing an irregular canopy, the rounded crowns of the tallest individuals often separated by large openings; (2) Gentle slope forests occupying deeper soils, with standing water in localized depressions, and typified by a smooth canopy with only occasional emergents; and (3) Seasonally dry "bajo" vegetation of short stature (< 20 m), with a smooth canopy and a high incidence of windfall. The unexamined wet "bajo" vegetation appears on aerial photos and evidently consists of stunted vegetation with closely packed trees. As part of their sampling procedure, Ewel and Myers established six 0.1 ha plots, two in each of the three investigated vegetation

types. Identifying all trees with a stem diameter of more than 10 cm at breast height, the investigators tallied 57 taxa. Strangely, many of the upland site species were shared by the "bajo" localities, though trees on the latter sites were much smaller.

In a similar study, I established five 10 m x 100 m plots in three vegetation types in the central Peten. One plot was placed in high forest near Lake Macanche. The remaining 0.1 ha units were located in forested areas of the primarily savanna region lying south and southwest of Lake Peten-Itza and in the area close to the archaeological sites of Chakantun and Fango (Rice and Rice 1979). At each of these sites, a sampling transect was designated in a substantial, forested area bordered by savanna and a second plot was established in a "sukche," an island of forest surrounded by savanna. All trees with a diameter of more than 5 cm at breast height were recorded, revealing a diverse flora of 77 taxa on the five transects.

While high forest of great complexity is a most striking feature of the Peten landscape, nearly 10% of the region is covered by savanna. The most expansive grasslands lie to the south of Lake Peten-Itza and in many areas interdigitate with stands of forest. While the savanna is relatively devoid of woody growth in some places, other localities like the area south of Lake Quexil support numerous oaks (Quercus). At other sites, "nanze," Byrsonima is the predominant tree and is distributed rather evenly over the grassland.

It has been suggested by Lundell (1937) that the savannas are in fact vegetational artifacts of human disturbance, created by Maya land

clearance and repeated burning. Reinvansion of the deforested areas by trees may be prevented by human-induced edaphic changes, but fire frequency is certainly a factor maintaining the grassland (Vaughan 1979). Palynological investigations of the sediments from savanna Lakes Oquevix and Ija as well as studies of grassland soils will be necessary to resolve questions about the genesis and maintenance of this unique vegetation.

Lundell (1937) believed that the high forest of modern Peten was absent during the Maya florescence, the land having been cleared for agricultural purposes. This contention is now amply supported by palynological evidence from a number of Peten lake sediment cores (Tsukada 1966, Vaughan 1979, Deevey et al. 1980c). Lundell (1937) also felt that the modern standing vegetation represents a climatic climax forest, there having been sufficient time for its development following the Maya decline. This view is somewhat contradicted by his belief that the prevalence of many useful tree species on Maya ruins constitutes evidence for the claim that the ancient Maya practiced arboriculture. Fruit-bearing trees, such as Brosimum, Talisia, and Manilkara, are common on sites as are other economically useful species, such as incense producers like Protium. While it has been suggested that these trees were selectively spared during Maya forest clearance or cultivated to some extent, Puleston (1978, 1982) argues strenuously that at least one species, "ramon" (Brosimum alicastrum) was actively planted and that its starch-rich seeds comprised a major portion of the Maya diet. Another possibility that may account for the presence of economically useful trees on previously occupied sites is

that the topographic and agronomic factors that may have been attractive to Maya settlers, like upland, level, well-drained fertile areas (Rice and Rice 1980b), may simply coincide with the ecological requirements of the tree species. Additionally, it is possible that the Maya modified the edaphic conditions, inadvertently creating optimal chemical or drainage microenvironments for the growth of the trees, thereby permitting them to flourish after the Classic collapse (Lambert and Arnason 1982).

Regional Limnology

The principal basins of the Peten lake district were formed when water filled the troughs of the east-west graben that lies at 17°N. Most of the lakes are small ($< 5 \text{ km}^2$) with the exception of the two largest, Peten-Itza (99.6 km^2) and Yaxha (7.4 km^2). Today, Lake Peten-Itza supports a substantial human population on its shores, the major riparian settlement occupying areas in contact with the southern arm of the lake. The bulk of the lakeside residents inhabit three towns, including the mainland "pueblos," San Benito, and Santa Elena, as well as Peten's political hub, Flores, formerly an island community but now connected to the southern shore by a causeway. San Andres and San Jose are the principal towns on the north shore of the lake and overlook the deep, main basin. Lakes Macanche and Sacpuy also support small, but rapidly growing "aldeas," while the remainder of the lakes are largely undisturbed, though isolated houses and farming activity in the watersheds have been noted.

While relatively small in surface area, the lakes are rather deep, many in excess of 30 m. The maximum depth is often associated with sinks or trenches that are responsible for the conical morphometry of some basins (Deevey et al. 1980a). Typically, the basins possess deep trenches in proximity to the north shore, where steep scarps descend to the lake edge. Southern shores are generally flatter, and water depth increases gradually with distance from land.

Despite the fact that exchange with groundwater in the lakes was shown to be one-way downward and slow, based on studies at Yaxha and Sacnab (Deevey et al. 1980a), the lakes are prone to rapid fluctuations in level that are probably not solely dependent on direct precipitation and drainage income. A rise of about 3 m was detected in all the lakes between 1979 and 1980 and was likely associated with groundwater intrusion. The notion that changes in the regional water table did occur is supported by the formation of a new lake in the savannas, a basin that local residents claim filled when groundwater broke through the country rock. The lakes continued to rise above the 1980 level (P. Rice, pers. comm.), but this is not the first time they have advanced. Older residents of the Peten report that Lake Peten-Itza rises every 40 years, maintaining a high stand for five years before retreating (Anonymous 1980a). The last high water was recorded in 1938, when the level was several meters above the 1980 mark, and much of Flores was inundated. Other lakes in the district have also experienced high stands in the past. Supporting evidence comes from the presence of aquatic snail shells in soils (old lake muds?) well above modern lake

surfaces. H.K. Brooks (pers. comm.) reports snail shells some 13 m above the 1973 Yaxha surface. Fred Thompson (pers. comm.) identified three species of aquatic gastropods, Pyrgophorus exiguus, Cochliopina infundibulum, and Aroapyrgus cf. petenensis, found in Salpeten south shore soil samples collected from pits dug several meters higher than the 1980 peak water mark.

Limnological reconnaissance of the Peten lakes was first undertaken by Brezonik and Fox in the summer of 1969. They reported the clinograde oxygen profiles and thermal stratification that characterize the basins (Brezonik and Fox 1974). Surface waters in the Peten often exceed 30°C, and while thermal stratification does seem to be persistent, hypolimnetic water temperatures sometimes differ from epilimnetic values by only 3-4°C. Encountering anoxic hypolimnia in most Peten lakes as well as benthic fauna indicative of oxygen stress, Brezonik and Fox (1974) concluded that thermal stratification of the lakes was stable. Additionally, they found evidence of meromixis in Lake Quexil and two small, but deep sinkhole basins, Paxcaman and Juleque. The maintenance of the thermocline was attributed to three factors: the lakes are well protected from strong winds by the forested limestone bluffs that surround them; the basins are typically small, but very deep, with contours that inhibit mixing; and finally, they note that the density difference per degree change in temperature is much greater in warm waters than in cold waters.

Over the past decade, the Peten lakes have been sampled extensively and intensively, supplementing and contradicting some of

the original findings. Lake Quexil has been studied during several field seasons, and neither chemical data nor conductivity readings point to modern meromixis, though an episode of early Holocene meromixis was detected in the sediment record (Deevey et al., in press). If contemporary meromixis is to be documented in Peten waters, it will probably be encountered in the small deep sinks like Juleque and Paxcaman or in sulfate-rich Monifata I (Deevey et al. 1980a). Numerous oxygen profiles from several of the basins show complete oxygen depletion in hypolimnetic waters to be rare and indicate that Peten lakes are perhaps polymictic, their frequent circulation associated with nocturnal cooling. However, predawn data from Lakes Quexil and Macanche taken in May 1977 demonstrate the persistence of the thermal gradient through the night, surface temperatures exceeding bottom values in the two basins by 5.9°C and 4.0°C respectively. Repeated night sampling, between May and July 1980 of a deep sink (43 m) located near the northern shore and within Peten-Itza's southern basin, failed to reveal a breakdown of the thermal gradient. Oligomixis, or irregular and uncommon turnover, may better define the mixing regime of the Peten lakes, the frequency nevertheless sufficient to prevent prolonged hypolimnetic anoxia. If episodes of mixis are to be detected, the most probable period for their occurrence is between August and December when cooler air temperatures, strong winds, and heavy rains might induce turnover. Unfortunately, these are the months for which limnological data are scanty.

Calcium and bicarbonate are the major cation and anion of Peten waters, but exceptions are found in magnesium and sulfate-rich lakes that may overlie dolomite or gypsum beds. That geological variation occurs over short distances is quite evident when nearby lake waters are compared chemically. Lakes Macanche and Salpeten are only 2 km apart but differ appreciably. Macanche is a magnesium sulfate lake and contains about twice as many magnesium as calcium ions, while the sulfate:bicarbonate ionic ratio is 1.3:1. Salpeten is a calcium sulfate lake in which magnesium ions are half as prevalent as calcium ions, and there are nearly 60 sulfate ions for each bicarbonate ion. The aptly named Salpeten, also seen in the literature as Peten-suc and Sucpeten, is highly saline, and the water contains $4.76 \text{ g}\cdot\text{l}^{-1}$ total dissolved solids. Peten waters are alkaline, their pH ranging from neutrality to 8.6, with surface waters generally producing daytime readings around 8.0.

Nutrient concentrations of Peten lakes are surprisingly low for basins in limestone terrain. In a survey of eight lakes, Brezonik and Fox (1974) reported total phosphorus concentrations from $<10\text{--}33 \text{ ug P}\cdot\text{l}^{-1}$, relegating these water bodies to the oligo-mesotrophic ($5\text{--}10 \text{ ug P}\cdot\text{l}^{-1}$) or meso-eutrophic ($10\text{--}30 \text{ ug P}\cdot\text{l}^{-1}$) categories, as defined by Wetzel's (1975) modification of Vollenweider's (1968) phosphorus-dependent trophic classification scheme. In another series of total phosphorus determinations, nine examined lakes displayed a range from 18 to $54 \text{ ug P}\cdot\text{l}^{-1}$, the low value being from savanna Lake Oguevix (Deevey et al. 1980a). The generally higher phosphorus levels

discovered in the latter study are perhaps attributable to more complete digestions or higher sestonic content in the samples, but demand placement of the lakes in the meso-eutrophic (10-30 ug P·l⁻¹) or eutrophic (30-100 ug P·l⁻¹) categories. Assignment to the trophic classes is tentative as a large fraction (40-80%) of the seston, measured in fresh sediment from traps or cores, is inorganic (Deevey et al. 1977, Deevey et al. 1980b). Much of this resuspended silt may contain mineralogic phosphorus that is biologically unavailable. In any case, high N:P ratios (>25) in Peten waters and surficial sediments suggest that productivity is phosphorus limited.

Secchi disc transparency, an indirect measure of productivity, measures turbidity in Peten lakes, as organic color is low (Brezonik and Fox 1974). However, measured transparencies may not be a very good indication of algal standing crops if much suspended material is inorganic seston. Secchi disc readings range from 1 to 5 m, the clearest water generally found in the sulfate-rich lakes. Lake Quexil, dominated by calcium and bicarbonate ions, displays low transparency, less than 2 m at times, and because seston of the lake shows relatively high loss on ignition (50-60%), the rapid disappearance of the disc with depth may indicate a substantial algal biomass. It is noteworthy that Lake Quexil (also seen in the literature and on maps as Eckixil, Ekichil, or Exiquil) derives its name from the Maya word Ekexiil (another variant) that means "agua oscura con hierbas," or water darkened by weeds (Anonymous 1980b).

Direct measurement of productivity was accomplished by light-dark bottle experiments, conducted by H.H. Vaughan at twin Lakes Yaxha and Sacnab in 1973 and 1974. Five sets of experiments at Yaxha and three at Sacnab yielded nearly identical mean values, $251.6 \pm 121.6 \text{ mg C}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ (Yaxha) and $251.7 \pm 110.6 \text{ mg C}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ (Sacnab). A single experiment was undertaken at Lake Quexil in mid-March 1978 and gave a gross production figure of $198 \text{ mg C}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ (Deevey et al. 1980a). The values obtained suggest that the lakes are at the low end of the mesotrophic ($250\text{--}1000 \text{ mg C}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) or upper end of the oligotrophic ($50\text{--}300 \text{ mg C}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) scale (Wetzel 1975), but this assignment is tentative as production undoubtedly fluctuates throughout the year, and the data set is small. Nevertheless, the range of production values encountered in the twin lakes, $157.6\text{--}449.3 \text{ mg C}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ (Yaxha) and $135.3\text{--}354.5 \text{ mg C}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ (Sacnab) is indicative of oligotrophy or mesotrophy using temperate standards.

The Peten lakes that are free from human impact generally support a small algal biomass, at times apparently dominated by the cyanophyte, Lyngbya (Brezonik and Fox 1974). Peten waters are noticeably deficient in diatoms, though Melosira ambigua and M. granulata are common in Lakes Yaxha and Sacnab. Members of the Bacillariophyceae are rare in the lake sediments, probably due to dissolution at high pH. While Yezdani's checklist of Peten phytoplankton (Leevey et al. 1980a) is long, the implied diversity is misleading, as several dominants probably constitute a large fraction of the standing crop year-round. The chlorophyte Botryococcus braunii and the blue-green Microcystis

aeruginosa are nearly ubiquitous and are encountered in large numbers. B. braunii constantly dominates net tows and its conspicuous absence from centrifuged water samples collected by Brezonik and Fox probably resulted from resuspension following centrifugation. As a dominant, B. braunii is indicative of oligotrophic conditions in temperate regions, but its value as an indicator species in the Peten lakes is questionable, as it is found under a variety of conditions in tropical and subtropical basins (Hutchinson 1967).

The open water zooplankton is numerically dominated by copepods, the four most abundant species being Diaptomus oisalis, Mesocyclops inversus, M. edax, and Tropocyclops prasinus mexicanus. Another important member of the zooplankton is the endemic, pelagic ostracod, Cypria petenensis that distinguishes itself by being rare or absent in sulfate waters. Juveniles are present in the water column at all times, while adults are migratory, leaving the benthic habitat and entering the pelagic environment only at night, a strategy that likely helps them avoid predation by fish. Eubosmina tubicen (Deevey and Deevey 1971) is the only common planktonic cladoceran, with representatives of the Sididae, Daphniidae, Macrothricidae, and Chydoridae notably rarer in open water net tows.

Thirty-two species of entomostracans are reported from plankton tows in 10 Peten lakes, the most diverse fauna (23 spp.) found in the largest lake, Peten-Itza (Deevey et al. 1980b). The lakes average 11.4 species each, the least diverse fauna encountered in sulfate-rich lakes Salpeten (4 spp.) and Monifata I (5 spp.). While the planktonic

component of the entomostracan fauna is notably undiverse, systematic sampling of a littoral zone study site in Lake Peten-Itza has expanded the list of entomostracan taxa, with 31 species of chydoriids (29 identified, 2 unknown) alone, having been enumerated (M.W. Binford, pers. comm.). Only six chydorid species were taken in the Lake Petenxil plankton (Deevey et al. 1980b), but some four times as many species were identified from remains in the Petenxil sediments (Goulden 1966). Chydorid remains are integrated into the sedimentary matrix over space and time so that more taxa are frequently encountered in mud samples than can be collected in a systematic lake sampling program (Frey 1960).

Twenty-two species of fish have been identified from collections made in five lakes (R.M. Bailey, pers. comm.), and three of these, the clupeid Dorosoma petenense, the characin Astyanax fasciatus, and an atherinid Melaniris sp., may be responsible for the low diversity and small body size that characterize the Peten zooplankton. Other potential consumers are the second characin Hyphessobrycon compressus, as well as several poeciliids and juvenile cichliids. Some members of the latter family attain significant size (1-2 kg), and some Cichlasoma species and the "blanco," Petenia splendida, are exploited by modern "Peteneros," as they undoubtedly were during Maya times.

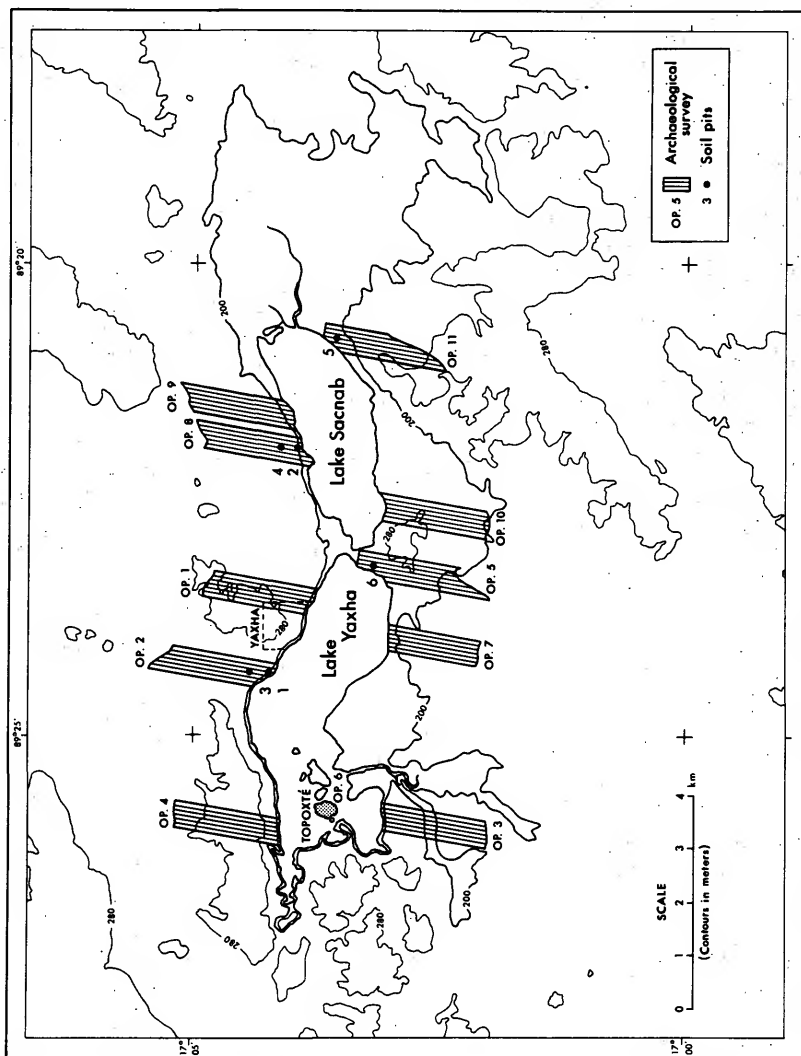
Maya Settlement in the Yaxha and Sacnab Catchments

Maya Demography

Twin Lakes Yaxha and Sacnab were originally selected as study sites because early archaeological reports indicated differential degrees of Maya settlement in the two watersheds (Bullard 1960). It was surmised that the dissimilar levels of environmental impact would be reflected in the paleolimnological record. Yaxha supported an urban center on its north shore, and the island site of Topoxte, lying within Lake Yaxha, was densely inhabited during Postclassic times (1000-1600 A.D.). Urbanization never developed in the Sacnab watershed, and the drainage remained devoid of habitation following the Classic collapse.

In order to assess changing ancient Maya riparian population densities, Don S. and Prudence M. Rice established transects radiating from the lake shores that were searched for housemounds. The transects, 2 km long and 0.5 km wide, were located on the lake edges at randomly selected points and ran in a north-south direction, perpendicular to the fault line, thereby permitting the sampling of all microtopographic zones. Six sampling units were staked out at Yaxha, and four were established at Sacnab (Fig. 3), the total area of the transects in each case equivalent to about 25% of the subbasin drainages. At Yaxha, the island of Topoxte was also designated as a sampling area. The plots were systematically searched for mounds, and a randomly selected 25% of the mounds were test-pitted so that periods of occupation could be established using the ceramic sherds extracted.

Figure 3. Twin Lakes Yaxha and Sacnab, showing the position of the archaeological sampling transects and soil pits. Op = operation.



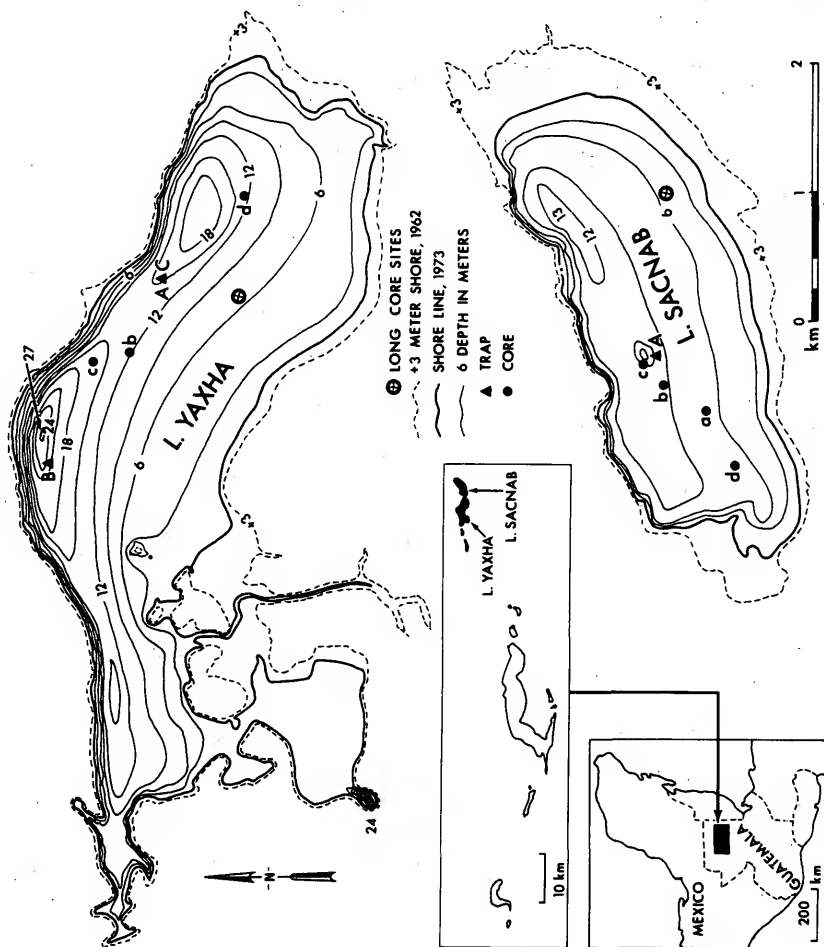
These data were then employed to calculate population densities for the ceramically defined periods using the assumptions previously applied at Tikal, that 84% of the mounds discovered were residences and that the average household consisted of 5.6 persons (Haviland 1970). By convention, the calculated densities represented levels of occupation at the end of the ceramically defined periods.

Middle Preclassic (1000-250 B.C.) population densities were slightly higher at Sacnab (34 persons·km⁻²) than at Yaxha (22 persons·km⁻²), but by the close of the Late Preclassic (250 B.C.-250 A.D.), Yaxha, having grown more quickly, had 70 persons·km⁻² to Sacnab's 51 persons·km⁻². A lag in growth at Yaxha permitted Sacnab to catch up by the end of the Early Classic (250-550 A.D.), the two subbasins hosting 101 persons·km⁻² and 102 persons·km⁻² respectively. The centripetal draw of the Yaxha urban center ultimately left that subbasin with a dense (256 persons·km⁻²) human population by the end of the Late Classic (550-850 A.D.), at which time Sacnab supported 168 persons·km⁻². Considered as a single population, the prehistoric Maya of the combined twin basins increased their numbers slowly, doubling about every four centuries, the logarithmic phase of population growth lasting about 1700 years (Deevey et al. 1979).

The Twin Basin Sediment Record

Using a Livingstone piston corer (Deevey 1965), H.K. Brooks obtained a sediment core from Lake Yaxha in 1973, and a year later H.H. Vaughan and D.S. Rice collaborated to raise a shallow-water long core from Lake Sacnab (Fig. 4). Palynological study of the 7.4-m Yaxha core revealed a stratigraphy identical to that discovered by Tsukada (1966) in the sediments of Lake Petenxil, 50 km to the west. Sediments rich in pollen of grassland and grassland arboreal species were overlain by postdisturbance mud dominated by high forest pollen indicators. Evidently, cores from both the lakes had failed to penetrate Maya-period muds, dense urban settlement at Yaxha resulting in the deposition of more than 6 m of clay-rich sediment. However, the 6.3-m Sacnab core demonstrated that the savanna pollen zone was underlain by organic-rich sediments with a high proportion of Moraceae pollen. The basal, high forest pollen section showed some indications of human disturbance and was assigned an Early Preclassic age, a time period for which archaeological evidence is lacking in Peten, but that is coeval with the Early Formative at Cuello, in Belizé. With supplementary evidence for a predisturbance high forest zone coming from Lake Quexil (Vaughan 1979, Deevey et al. 1979), Tsukada's (1966) conclusion that the Maya had transformed savanna into high forest was reevaluated. In fact, the Maya had converted high forest into grassland, the forests later recovering after the abandonment of the region.

Figure 4. Bathymetric maps of Lakes Yaxha and Sacnab, showing the locations where long cores were retrieved for paleolimnological study.



Phosphorus Loading of Lakes Yaxha and Sacnab

Efforts to assess past changes in trophic state of the lakes were attempted through an evaluation of ancient phosphorus budgets. Phosphorus has been shown to be the limiting nutrient in many aquatic systems (Schindler 1974, Vallentyne 1974) with productivity highly dependent on total phosphorus loading rates (Vollenweider 1968, Dillon and Rigler 1974, Oglesby and Schaffner 1978). Phosphorus, unlike carbon and nitrogen, lacks an atmospheric compartment in its biogeochemical cycle. Thus, nearly all phosphorus transported from the watershed to the lake is ultimately sequestered in the basin sediments. Phosphorus movement in the watershed is essentially unidirectional, removal from a lake by mechanisms such as insect emergence representing a small proportion of the phosphorus originally delivered to the lake (Vallentyne 1952).

Past rates of nutrient delivery to the basin can be calculated when phosphorus concentrations in the sediment are known and several levels in a core are accurately dated. Unfortunately, radiocarbon dates run on bulk sediments from the Peten lakes, even those pretreated for carbonate removal, proved to be unreliable due to the hard-water lake effect. Ancient carbonates, lacking the radioisotope, are solubilized, and their carbon is incorporated into autochthonous organic material, making dates appear too old (Deevey and Stuiver 1964). Ultimately, all bulk sediment radiocarbon dates were disregarded and archaeologically correlated dates were assigned to levels in the cores based on the identification of discrete pollen

assemblages (Vaughan and Deevey, 1961). The assumption used for zoning the cores was that the degree of deforestation expressed in the pollen profiles reflected changing population densities as derived from the archaeological program.

When phosphorus loading rates to the twin basins were calculated, they tracked the slow, steady exponential rise in population density that occurred between the Middle Preclassic and Late Classic. Roughly delimiting the area circumscribed by the two drainages, export of phosphorus from the watersheds, already seen to be Maya density dependent, was shown to occur at a rate of about $0.5 \text{ kg} \cdot \text{person}^{-1} \cdot \text{yr}^{-1}$. The calculated per capita rate of delivery is, perhaps coincidentally, almost equal to the physiological output of phosphorus (0.55 kg) from human bodies that are in equilibrium with respect to their intake and output of the nutrient (Vollenweider 1968). Watershed soils were the principal source of disturbance-zone phosphorus, nutrient-rich surface soils moving rapidly downhill by colluviation following Maya-induced deforestation (Brenner 1976, Deevey et al. 1979). Because bulk soil transport was the primary mechanism carrying phosphorus from the land to the lake, it was impossible to determine what proportion of the sedimented nutrient actually cycled through human bodies.

Disturbance-zone sediments of the twin lakes are highly inorganic and do not indicate that the episode of deforestation was accompanied by high lacustrine productivity. Large amounts of silica and detrital carbonate were transported with the phosphorus as soil was eroded into the lakes. The siliceous, Maya-zone sediments are dominated by

montmorillonite clay, the residue of the down-wasted country rock. High phosphorus delivery rates might be expected to correlate with high autochthonous organic production. That high rates of nutrient input were associated with inorganic mud suggested that much sedimented phosphorus was biologically unavailable and bypassed the biota before deposition on the lake bottom. Corroborating evidence for this inference came from microfossil analyses that failed to demonstrate that high primary or secondary production was associated with the enhanced phosphorus delivery (Brenner 1978). Unfortunately, enumerated microfossil remains from Peten sediments provide unreliable estimates of past productivity. Though amounts and accumulation rates of microfossils decreased with increasing phosphorus input to the twin basins, strong diagenesis (postdepositional destruction) makes the thanatocoenosis a poor estimator of the biocoenosis from which it was derived.

THE HISTORICAL ECOLOGY OF THE MAYA AT LAKES QUEXIL,
SALPETEN, AND MACANCHE

The Archaeological Record

The goal of this study is to expand the geographic scope of the "Historical Ecology of the Maya" project westward to examine three unexplored lake basins. With soil, archaeological, and paleolimnological data from the new watersheds, sedimentation processes in the Peten lakes can be evaluated better, and the phosphorus loading model developed at Yaxha and Sacnab can be tested. The new lakes considered, Quexil, Macanche, and Salpeten, differ from the twin basins in failing to display the slow, steady exponential human population growth from the Middle Preclassic until the Late Classic peak. Instead, the archaeological record shows that Maya populations in the western watersheds experienced a decline during the Terminal Preclassic (100 B.C.-250 A.D.) and Early Classic (250-550 A.D.) before rising once again in the Late Classic (550-850 A.D.) and finally collapsing about 850 A.D.

Archaeological study of the three watersheds was directed by Don S. and Prudence M. Rice during the 1979 and 1980 field seasons. To sample about 25% of the watershed area, three transects radiating from the lake edge were established in each basin, and some 25% of the

mounds surveyed were test-pitted to determine time of occupation. At Quexil (Fig. 5), a single north shore transect was laid out and two south shore sampling plots were staked. Transects were run in a north-south direction, and as at Yaxha were 0.5 km wide. In keeping with procedures used at the twin basins, the north shore transect was 2 km long, but the south shore surveys were run about 3.24 km, to the base of the karst uplift that encloses the basin. This permitted the sampling of a large savanna south of the lake. Additionally, Quexil's two islands were searched, revealing 6 structures on the western island and 20 on the eastern island.

At Salpeten, standard size (2 km x 0.5 km) transects were established with north-south orientation, two on the north shore and a single plot on the south shore (Fig. 6). A large, densely settled site on Salpeten's peninsula was also investigated. The site, called Zacpeten, is primarily of Postclassic age. At Macanche (Fig. 7), the single north shore transect and two south shore plots were oriented northwest-southeast. Mounds discovered within a walled site (Op 2), Muralla de Leon, were also surveyed, as were some structures between transects. In this basin, time period of occupation was determined by test-pitting about 25% of the mounds both on and off transects. Using the proportion of mounds showing occupation during the various periods, population levels were figured based on the density of mounds found on the delimited transects. In all three drainages, changing Maya population densities were calculated employing the assumptions used at Tikal (Haviland 1970) and at Yaxha and Sacnab, that 64% of the mounds were residences and each household consisted of 5.6 persons. Figure 6

Figure 5. Lake Quexil, showing the position of the archaeological sampling transects and soil pits. Op = operation.

LAKE QUEXIL

0 km 1

 Archaeological Transects

• Soil Pits

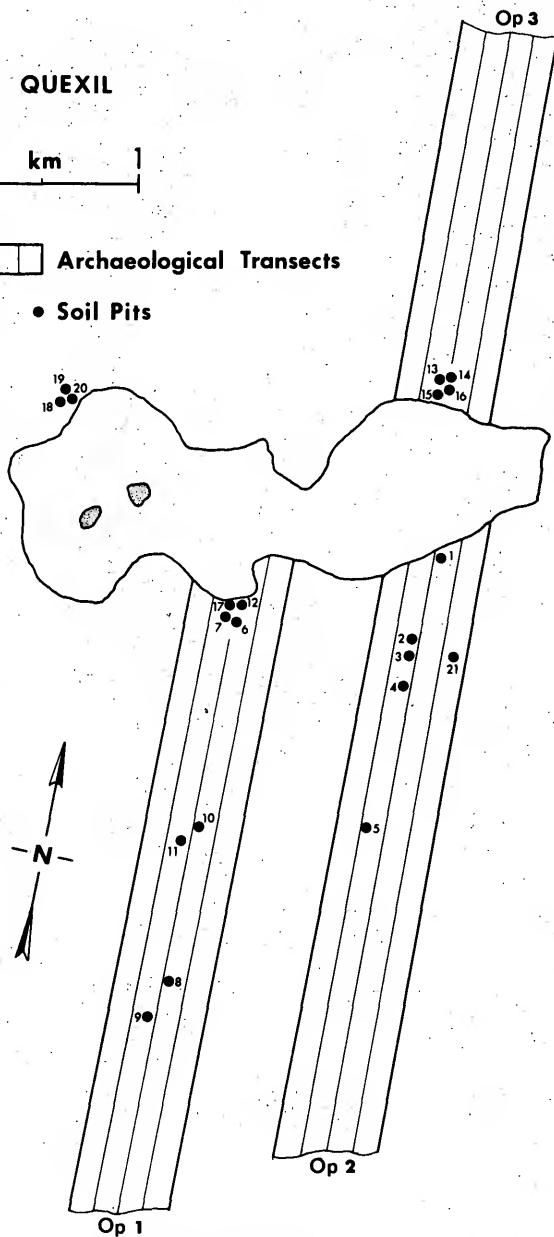


Figure 6. Lake Salpeten, showing the position of the archaeological sampling transects and soil pits. Op = operation.

LAKE SALPETEN

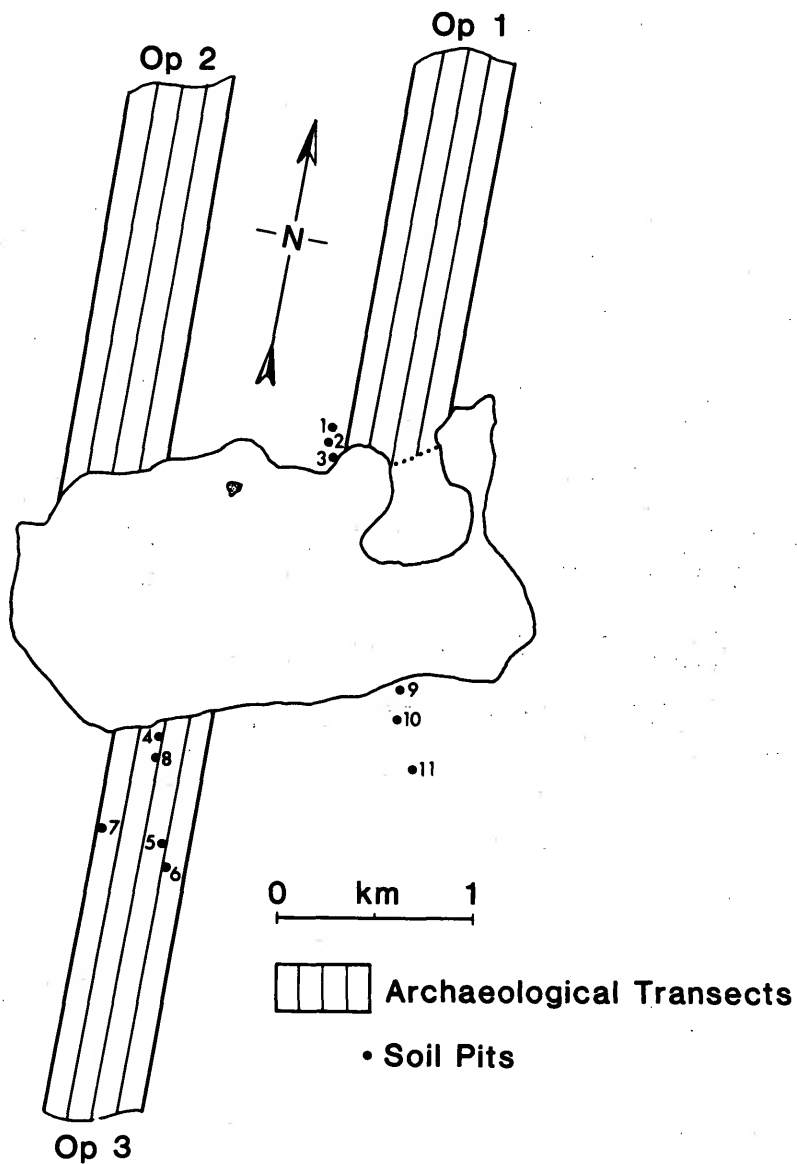


Figure 7. Lake Macanche, showing the position of the archaeological sampling transects and soil pits. Cp = operation.

LAKE MACANCHE

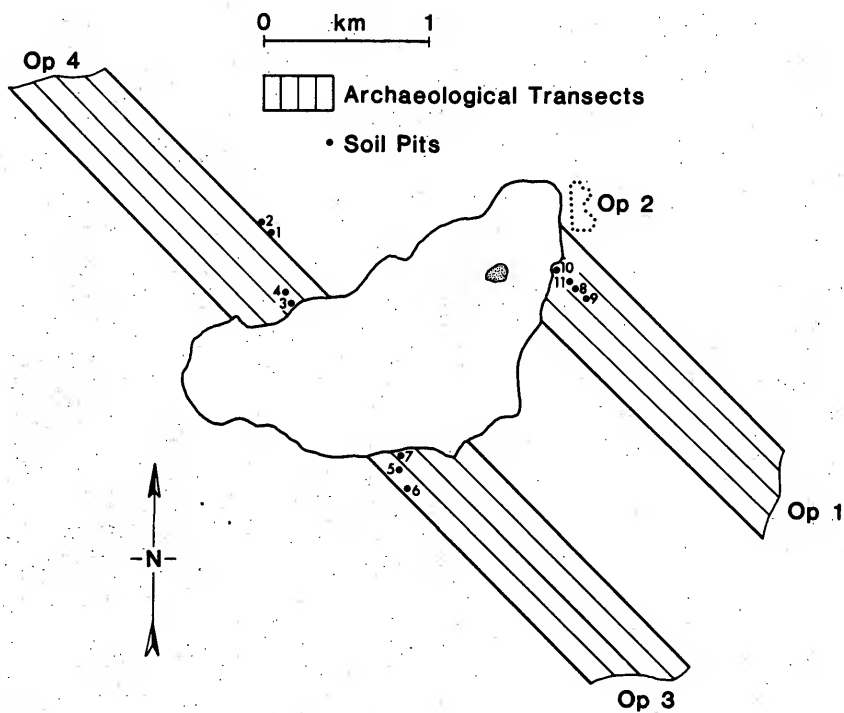
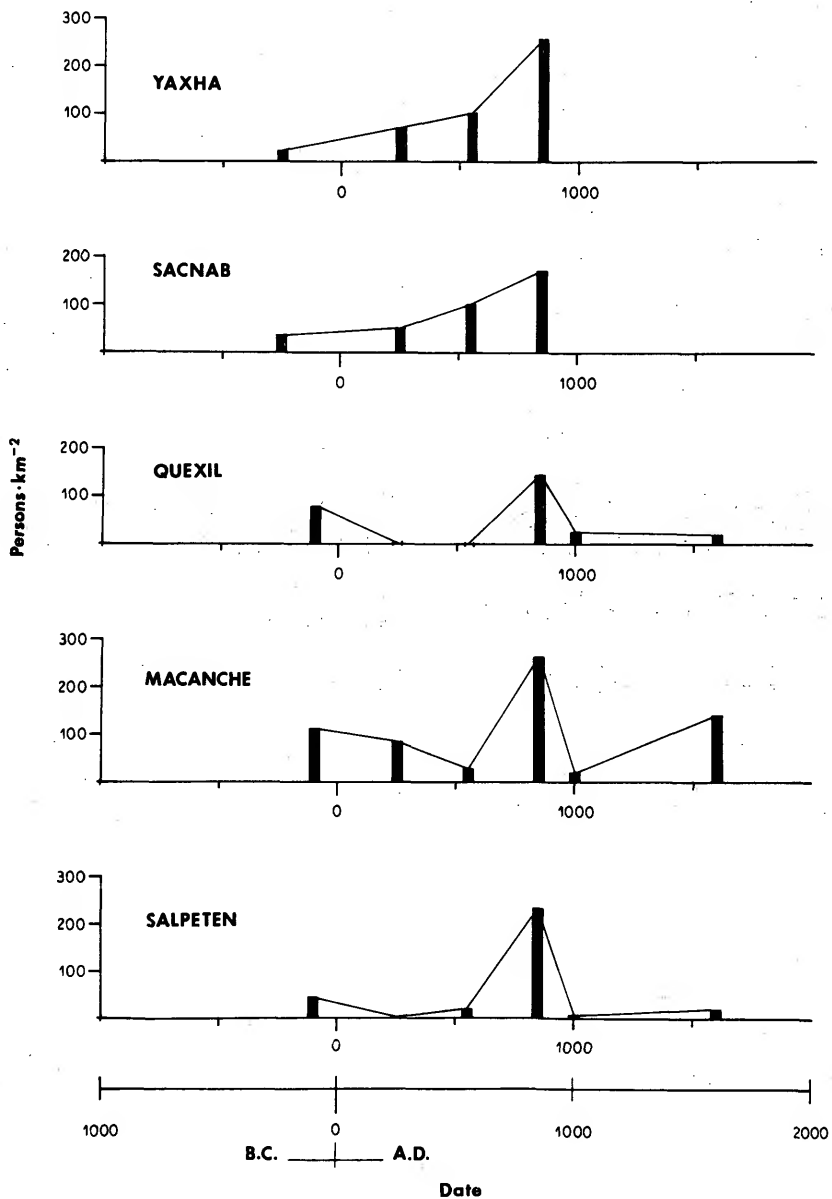


Figure 8. Crude population densities, calculated from housemound densities, in the five lake basins for which both archaeological and paleolimnological histories have been studied. Population reconstructions are based on radiocarbon dated ceramic chronologies.



shows the changing population patterns for five Peten watersheds based on mainland transect mound densities.

Soil Chemistry

Translocated soils were shown to have been the principal source of phosphorus for Lakes Yaxha and Sacnab during the period of Maya forest disturbance (Deevey et al. 1979). In extending the study to three new watersheds, soil samples were collected from several localities in each basin to assess total phosphorus and other chemical concentrations and distributions in riparian soil profiles. Because bulk movement of soils is the mechanism by which phosphorus reaches the lakes, total phosphorus was analyzed rather than the plant-available fraction.

During the 1980 field season, 21 soil pits were dug in the Quexil drainage (Fig. 5), while 11 trenches were dug in both the Macanche and Salpeten basins (Figs. 6 and 7). In each case, soil pit locations were determined subjectively in order to sample several microtopographic zones as well as areas associated with Maya construction. In most instances, samples were collected along archaeological transects so that distances from shore could be determined by reference to established, staked positions in the archaeological sampling plot.

Soil pits were dug to bedrock, sterile "sascab," or as deep as was feasible. Maximum depth from site to site was variable, but none of the sampled depths exceeded 100 cm. Samples were removed from the exposed profile wall at 10 cm intervals, each sample representing a

composite of soil collected over the full 10 cm. About 100-200 g of soil were taken at each level and stored in individual plastic bags.

In the lab, four levels from each soil pit (0-10 cm, 10-20 cm, an intermediate level between 20 cm and bottom, and bottom) were removed and air-dried, though only top and bottom samples were considered in Quexil's shallow pit #4. A subsample of each air-dried level was extracted and ground with a mortar and pestle. A portion of the powdered soil (1-6 g) was removed, weighed, and placed in a Thermolyne Type 1500 furnace for two hours at 550°C to assess organic matter content by loss on ignition. Following combustion and reweighing, a 0.3-1.5 g sample of ash was removed, weighed, and digested in 15 ml of a heated 2:1 nitric-perchloric acid mixture. When dense, white HClO_4 fumes appeared, the 250 ml beakers containing the mixture were covered with watchglasses and the oxidation process was continued for an additional hour, with distilled water added periodically to prevent total drying. After digestion, samples were filtered and the filtrate was brought to a known volume. The filtrate was delivered to the University of Florida Institute of Food and Agricultural Sciences Soils Laboratory, where cation concentrations were determined by atomic absorption and phosphorus analyses were run on a Technicon Auto Analyzer. I measured sulfur content in filtrate samples from surface and bottom profile levels using the turbidimetric procedure in Standard Methods (APHA 1971). Sulfate turbidity was read on a Coleman Model 14 Universal Spectrophotometer. Prior to running sulfate analyses on the digested, ashed soils, a series of paired ash-whole soil determinations

were made to assess sulfur loss due to ignition. Measured sulfur content, as concentration per gram whole soil was shown not to differ statistically when the two methods were compared. All soil chemical concentrations are expressed as amount per gram of air-dried whole soil.

Total phosphorus analyses run on soil profiles from Quexil, Macanche, and Salpeten reveal that in all three watersheds a strong gradient is maintained with respect to the nutrient, surface soils clearly enriched as compared to levels deeper in the profiles (Figs. 9-12). Though exceptions do occur, increasing depth in the profile is generally accompanied by decreasing phosphorus concentration. This trend is evident when the mean surface soil (0-10 cm) phosphorus concentration in a basin is compared to the mean value obtained for the basal (variable depth) levels of the pits. At Quexil, where the 21 soil pits were dug to an average of 74.3 cm, mean phosphorus concentration in surface soils was $178 \text{ ug P}\cdot\text{g}^{-1}$, or 2.48 times the average concentration ($112 \text{ ug P}\cdot\text{g}^{-1}$) calculated for the deepest strata in the pits. The average depth attained at Macanche was 73.6 cm, and an even stronger phosphorus gradient was revealed by analyses of the 11 profiles from the watershed. The mean surface soil phosphorus level ($594 \text{ ug P}\cdot\text{g}^{-1}$) exceeds the bottom concentration ($181 \text{ ug P}\cdot\text{g}^{-1}$) by 3.28 times. At Salpeten, where 11 pits bottomed-out at a mean depth of 62.7 cm, the average surficial soil nutrient concentration ($598 \text{ ug P}\cdot\text{g}^{-1}$) was 2.21 times the mean found in the basal profile levels ($271 \text{ ug P}\cdot\text{g}^{-1}$).

Figure 9. Total phosphorus concentrations at selected levels in soil pits 1-12 at Quexil.

QUEXIL

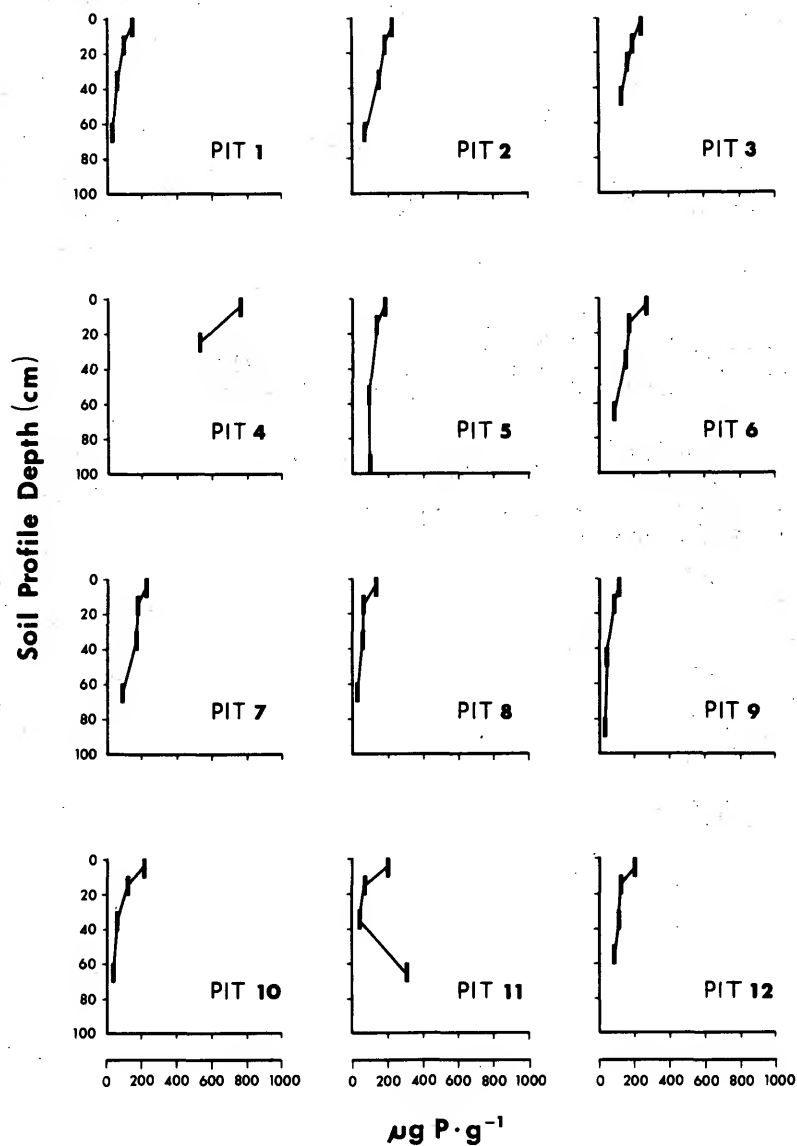


Figure 10. Total phosphorus concentrations at selected levels in soil pits 13-21 at Quexil.

QUEXIL

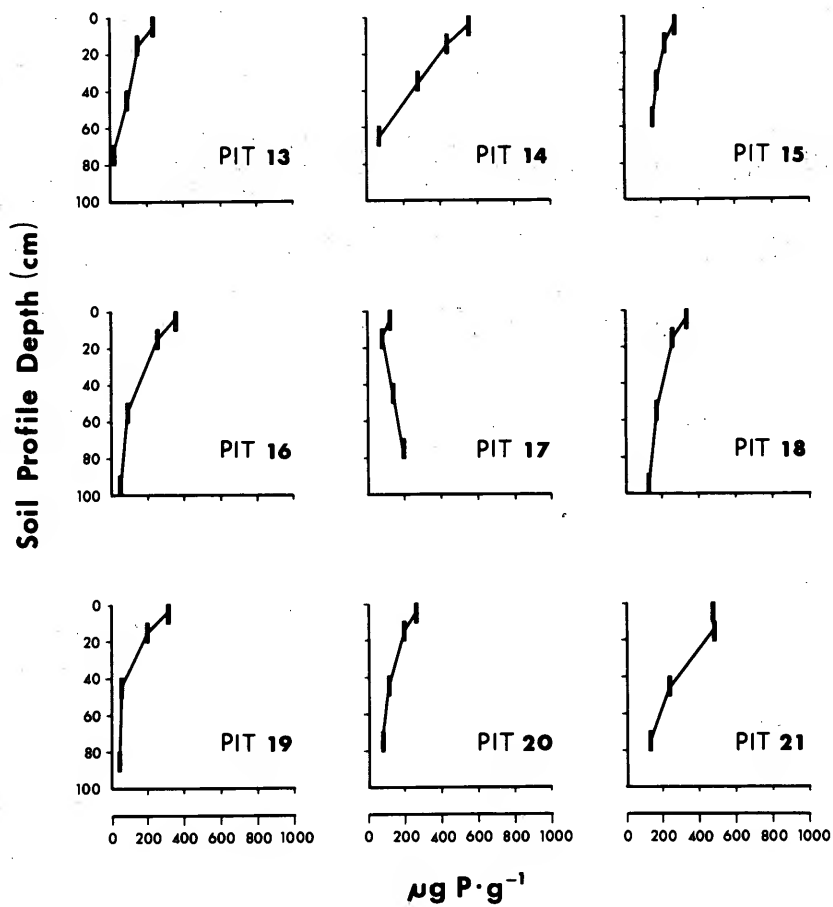


Figure 11. Total phosphorus concentrations at selected levels in 11 soil pits at Salpeten.

SALPETEN

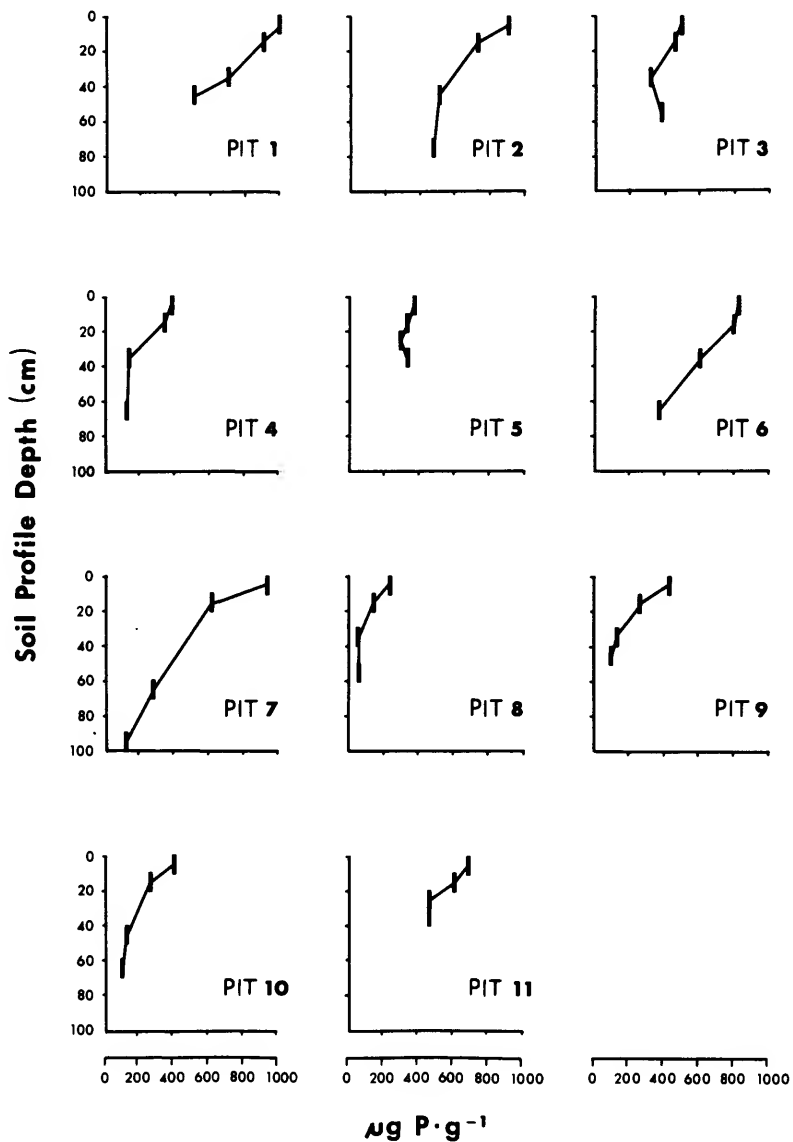
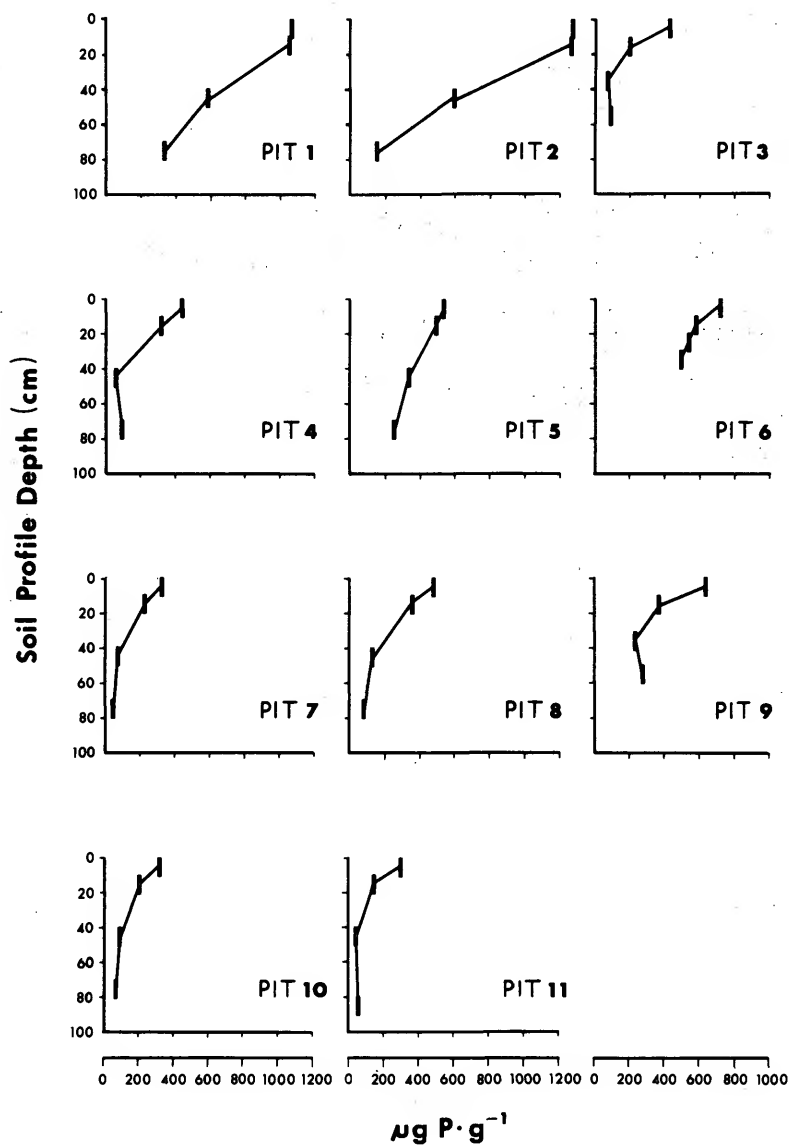


Figure 12. Total phosphorus concentrations at selected levels in 11 soil pits at Macanche.

MACANCHE



To assess how organic matter and various soil chemical concentrations change with depth in the profile, mean concentrations for all of the combined top two levels (0-10 cm and 10-20 cm) in the profiles of a basin are compared to the average concentrations calculated for the summed bottom two levels (intermediate between 20 cm and bottom, plus bottom) of the basin pits (Table 1). Quexil's shallow pit #4 was excluded from this tabulation because only two levels were analyzed, and assessments of changing sulfur concentrations with depth are reliant on surface and bottom analyses only. Additionally, whole profile mean concentrations for the various soil parameters are given, thereby permitting a rough interbasin comparison of soil characteristics.

Organic matter distribution in the soil profiles displays a trend similar to that seen for phosphorus, % loss on ignition generally decreasing with greater depth. Surface soils are also enriched in sulfur, deeper profile levels noticeably deficient with respect to the nutrient. Similar trends in organic matter and sulfur concentrations suggest that much soil sulfur is present in organic form. However, ignition of the samples at 550°C caused no apparent loss of sulfur, perhaps indicating that the bulk of sulfur is present in mineral form, or that the organic sulfur fraction is not volatilized on burning. High inorganic sulfur content would not be unexpected, particularly at Salpeten where a gypsum outcrop overlooks the northwest shore of the lake. Were this the case, sulfur distribution would be expected to track magnesium and calcium in the profiles, but it does not.

Table 1. Summarized chemical concentrations from soil pits dug in the Quexil, Macanche, and Salpeten watersheds. Concentrations in the two uppermost levels of the profile were averaged as were the two bottommost samples, thus giving a rough idea of chemical gradients in the soil profiles. Whole profile mean concentrations are also given for each chemical type. Sulfur concentrations were determined on surface and bottom levels only.

Profile Levels	Profile Depth	n	Loss on Ignition %	Ca mg·gm ⁻¹	Mg mg·gm ⁻¹	Fe mg·gm ⁻¹
QUEXIL						
Top 2 Levels	1-10 cm 10-20 cm	40	17.6	147	3.6	26.6
Bottom 2 Levels	Variable	40	10.6	212	3.3	25.8
Whole Profile	All Samples	80	14.1	180	3.4	25.3
MACANCHE						
Top 2 Levels	0-10 cm 10-20 cm	22	15.7	330	23.6	3.2
Bottom 2 Levels	Variable	22	8.9	374	24.6	2.8
Whole Profile	All Samples	44	12.3	352	24.1	3.0
SALPETEN						
Top 2 Levels	0-10 cm 10-20 cm	22	18.8	265	30.1	5.4
Bottom 2 Levels	Variable	22	9.7	304	32.3	6.0
Whole Profile	All Samples	44	14.3	284	31.2	5.7

Table 1--extended.

Al mg·gm ⁻¹	Na ug·gm ⁻¹	K ug·gm ⁻¹	P ug·gm ⁻¹	S ug·gm ⁻¹
41.6	170	848	220	130
47.2	200	673	107	50
44.4	185	761	163	90
8.6	347	609	535	690
8.0	368	453	210	440
6.3	358	531	373	565
13.1	291	1240	545	740
16.0	319	1226	296	350
14.6	305	1233	421	545

Cation distributions throughout the soil profiles are more even, without the pronounced top-to-bottom gradient seen for sulfur, phosphorus and organic matter. Potassium concentrations are slightly higher in upper soils of the profiles, while sodium content is a bit richer in the deeper levels. In all three watersheds, calcium is a bit more concentrated in deeper soils, a trend that is anticipated in limestone terrain. Magnesium displays rather uniform concentration throughout the soil profiles, and though at Quexil upper level strata contain slightly higher amounts of the cation than deep soils, the trend is reversed at Macanche and Salpeten.

Intra-basin variation in the chemical profiles is most apparent at Quexil, where forest soils, presumably of the Yaxa series, were sampled along with Exkixil, savanna soils. Low fertility, Exkixil soils are depleted in phosphorus as compared to forest soils. Surface soils from the six savanna profiles (#1, #5, #8, #9, #10, #11) have a mean concentration of $164 \text{ ug P}\cdot\text{g}^{-1}$, while the 15 forest pits display an average upper level concentration about twice as high ($324 \text{ ug P}\cdot\text{g}^{-1}$). Disregarding shallow pit #4, mean whole profile concentrations for various chemical constituents in the six savanna pits can be compared to values obtained on the 14 forest trenches. Aluminum is highly concentrated in the clay-rich savanna soils ($105.4 \text{ mg Al}\cdot\text{g}^{-1}$), whereas the forest profiles contain only $18.4 \text{ mg Al}\cdot\text{g}^{-1}$. High iron content in the savanna soils evidently is responsible for the rich red color of the earth south of Quexil, and savanna iron levels ($67.5 \text{ mg Fe}\cdot\text{g}^{-1}$) exceed forest soil levels

(7.0 mg Fe·g⁻¹) by nearly an order of magnitude. The lack of calcium in grassland soils is striking, as they possess only 2.4 mg Ca·g⁻¹. Forest soils, differing by more than two orders of magnitude, contain 256.1 mg Ca·g⁻¹. Forest soils are also richer in magnesium than savanna soils, the two series containing 4.1 mg Mg·g⁻¹ and 1.7 mg Mg·g⁻¹ respectively.

When mean, whole profile chemical concentrations are compared on an inter-drainage basis, several differences are apparent. Average iron and aluminum concentrations are higher at Quexil than at Macanche and Salpeten because of the high metal content of the grassland soils at Quexil. Likewise, calcium deficiency in the Quexil savannas is largely responsible for giving that basin an overall mean whole profile calcium value that is relatively low. Magnesium content of the Macanche and Salpeten soils exceeds that in Quexil by 7.1 and 9.2 times respectively. The difference is not accounted for solely by the low magnesium content of Quexil's savanna profiles, because even forest soils at Quexil possess considerably less magnesium than encountered in samples from Salpeten and Macanche. Dolomitization in the Macanche-Salpeten district, also reflected in the water chemistry of the two lakes, is the probable cause of high magnesium levels in the basin soils.

Though it is not certain, high sulfur concentrations determined for the Macanche and Salpeten watershed soils probably point to the presence of gypsum in the underlying bedrock of these basins. Evaporites are evidently less common at Quexil, and soil sulfur values

from the three basins generally reflect chemical levels in the lake waters (Deevey et al. 1980a).

Phosphorus is highly concentrated in the upper levels of Peten soil profiles, and under conditions of deforestation, erosional processes would be expected to carry large amounts of the nutrient to the lakes. Rapid mobilization of the available phosphorus fraction is possible, but not likely, as the homogeneous distribution in the profiles of highly soluble sodium and potassium argues against leaching.

Maya agro-engineering activities enhanced delivery rates of phosphorus to the lakes not only by accelerating downhill bulk transport of soils, but perhaps by first concentrating the nutrient in surface soils through physiological cycling, interment, and refuse disposal. Though the data are meager, three soil profiles dug in housemounds as well as several other pits located near construction contain extremely high levels of phosphorus suggesting an anthropogenic source for the nutrient in enriched surface soils. At Salpeten, south shore soil pits #6 and #7 were placed in housemounds #386 and #388, last occupied during Late Classic times. Surface soils from these pits contain 821 $\mu\text{g P}\cdot\text{g}^{-1}$ and 922 $\mu\text{g P}\cdot\text{g}^{-1}$ respectively, much more than the overall mean value for surficial soils in the basin (598 $\mu\text{g P}\cdot\text{g}^{-1}$). On the north shore of the lake, soil pit #1 was located at the crest of a steep slope, in close proximity to rubble from collapsed construction. Ceramic sherds were encountered in the excavated soil pits, and its surface soils contained 995 $\mu\text{g P}\cdot\text{g}^{-1}$. Downslope from

this site, topsoil from pit #2 yielded $895 \text{ ug P}\cdot\text{g}^{-1}$. The four Salpeten soil pits within or near Maya structures had an average surface soil nutrient concentration of $908 \text{ ug P}\cdot\text{g}^{-1}$, while top level soils of the remaining seven pits had a mean of only $420 \text{ ug P}\cdot\text{g}^{-1}$.

At Quexil, soil pit #21 was located in south shore housemound #823, a structure that was occupied during Middle and Late Preclassic times and again in the Late Classic period. Surficial soils from the pit contain $467 \text{ ug P}\cdot\text{g}^{-1}$, significantly more than the overall surface soil mean of $278 \text{ ug P}\cdot\text{g}^{-1}$ for the watershed. At Macanche, pits #1 and #2 lie on the north shore slope just below construction and their highly enriched surface soils contain $1074 \text{ ug P}\cdot\text{g}^{-1}$ and $1275 \text{ ug P}\cdot\text{g}^{-1}$ respectively, exceeding the mean surface concentration ($465 \text{ ug P}\cdot\text{g}^{-1}$) found in the remaining 9 pits.

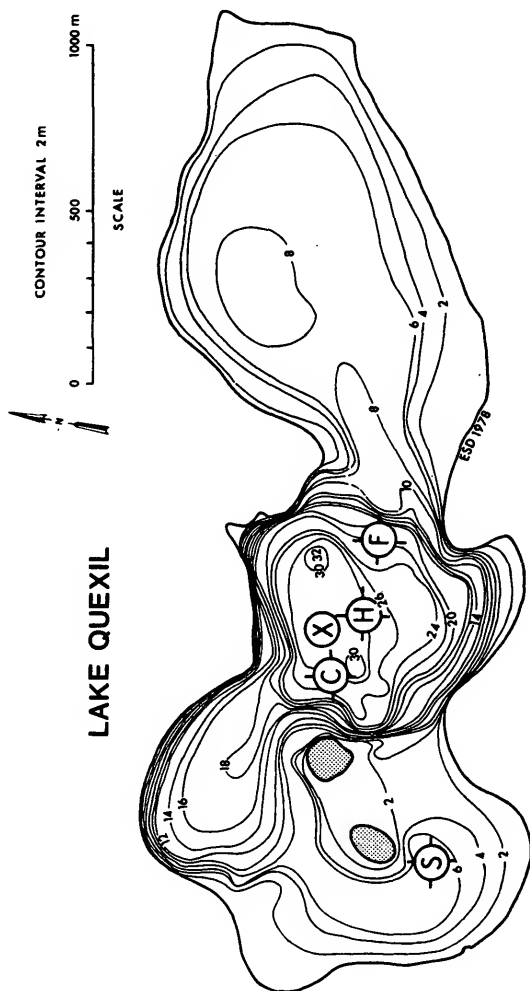
PALEOLIMNOLOGY OF LAKE QUEXIL

Comparing Shallow-Water and Deep-Water Sedimentation

The primary goal of the paleolimnological research undertaken in the three new watersheds was to assess how the proximate composition of the sediments and accumulation rates of various chemical constituents of the mud varied as a function of shifting Maya population levels. The first basin considered was Lake Quexil, lying some 8 km east of Flores and only 1 km from Lake Petenxil (Fig. 2), the basin where Maya impact on the Peten sedimentary record was first revealed (Cowgill et al. 1966).

In 1972, H.H. Vaughan and G.H. Yezouani used a Livingstone piston corer (Deevey 1965) to get a 6.5-m section in 7 m of water. The core was taken south of the lake's western island (Fig. 13). The small lake (area = 2.101 km², z_{\max} = 32 m, \bar{z} = 7.2 m; Deevey et al. 1980a) was cored again in 1978. In March of that year, M.S. Flannery, S.E. Garrett-Jones, and I raised a 9.2-m core from 26 m of water using a modified, gravity-driven, Kullenberg apparatus (Fig. 13). This core, designated Quexil B, was one of several long cores collected in the lake's deep, central basin in our effort to secure sediments of Pleistocene age.

Figure 13. Bathymetric map of Lake Quexil, showing the locations of several coring sites in the basin.



Lake	Site	Core	Year	Water depth	Depth below M.W. interface
Quexil	S	Shallow-1	1972	7 m	0-6.5 m
Quexil	C	C	1978	29.8 m	0-7.9 m
Quexil	H	H	1978	27.7 m	0-9.2 m
Quexil	F	F	1978	19.8 m	0-9.8 m
Quexil	X	80-1	1980	29.0 m	7.49-19.88 m
Quexil	X	80-2	1980	29.0 m	4.57-9.65 m

The shallow-water core was returned to Florida in the aluminum coring tubes, and the Quexil H core was transported to the Florida State Museum in the plastic tubing that lined the iron Kullenberg coring pipe. Cores were refrigerated at 4°C prior to and following extrusion. Sediment chemistry and palynology of the shallow-water section were reported elsewhere (Brenner 1978, Deevey et al. 1979, Vaughan 1979), but without accompanying data on Maya population densities in the basin. This consideration not only correlates sedimentary changes with shifting population levels, but by comparing two sediment columns, demonstrates the profound influence that core location and basin morphometry had on sediment chemistry and measured sediment accumulation rates.

Samples were removed from the extruded cores at 5-20 cm intervals, and water content was evaluated on weighed volumetric samples by drying at 110°C. A second set of samples was dried for total carbon and nitrogen analyses that were run on a Perkin-Elmer Model 240 Elemental Analyzer. A third series of volumetric samples was weighed and digested in 15 ml of 2:1 nitric-perchloric acid. After oxidation, the samples were filtered, and the filtrate was brought to a known volume. Cation analyses were run on the filtrate by atomic absorption at the University of Florida Institute of Food and Agricultural Sciences Soils Laboratory. Filtered digestate from the deep core samples was analyzed for phosphorus content on a Technicon Auto Analyzer at the Soils Laboratory. Aliquots of digestate from the shallow-water core were retained for phosphorus analyses, which were run colorimetrically on a

Coleman Model 14 Universal Spectrophotometer following blue color development by the ascorbic acid-ammonium molybdate method in Standard Methods (APHA 1971). Sulfur content in Quexil core H was measured by assessing the quantity in the filtered digestate using the turbidimetric technique in Standard Methods (APHA 1971).

When all chemical analyses were completed, chemical concentrations in dry sediment were calculated (Figs. 14 and 15), and level by level proximate composition of the sediment was figured (Figs. 16 and 17). To compute the chemical make-up of the mud at each level, the carbonate equivalents of magnesium and calcium were first calculated, thereby permitting the assessment of inorganic (carbonate) carbon content. Next, the inorganic carbon quantity was subtracted from the total carbon value to yield an organic carbon figure. Then, as at Yaxha and Sacnab (Deevey and Rice 1980), the organic carbon value was multiplied by 2.5 to produce a figure for organic matter content. Iron is reported as the oxide, Fe_2O_3 , and SiO_2 , likely an alumino-silicate, is the residue following subtraction of organic matter, CaCO_3 , MgCO_3 , and Fe_2O_3 .

Dating the cores was once again dependent on changes in the relative pollen diagrams. An exception was provided by numerous wood fragments that were encountered at 623-624 cm in the shallow-water core. Age determination on these allochthonous plant remains is free from the confounding effects of hard-water-lake error, and a dated sample (DAL 198) gave a ^{14}C age of 8410 ± 180 years (Ogden and Hart 1977). Corrected to about 9400 sidereal years (Deevey et al. 1979),

Figure 14. The chemical stratigraphy of the Quexil shallow-water core.

QUEXIL
Shallow-Water Core

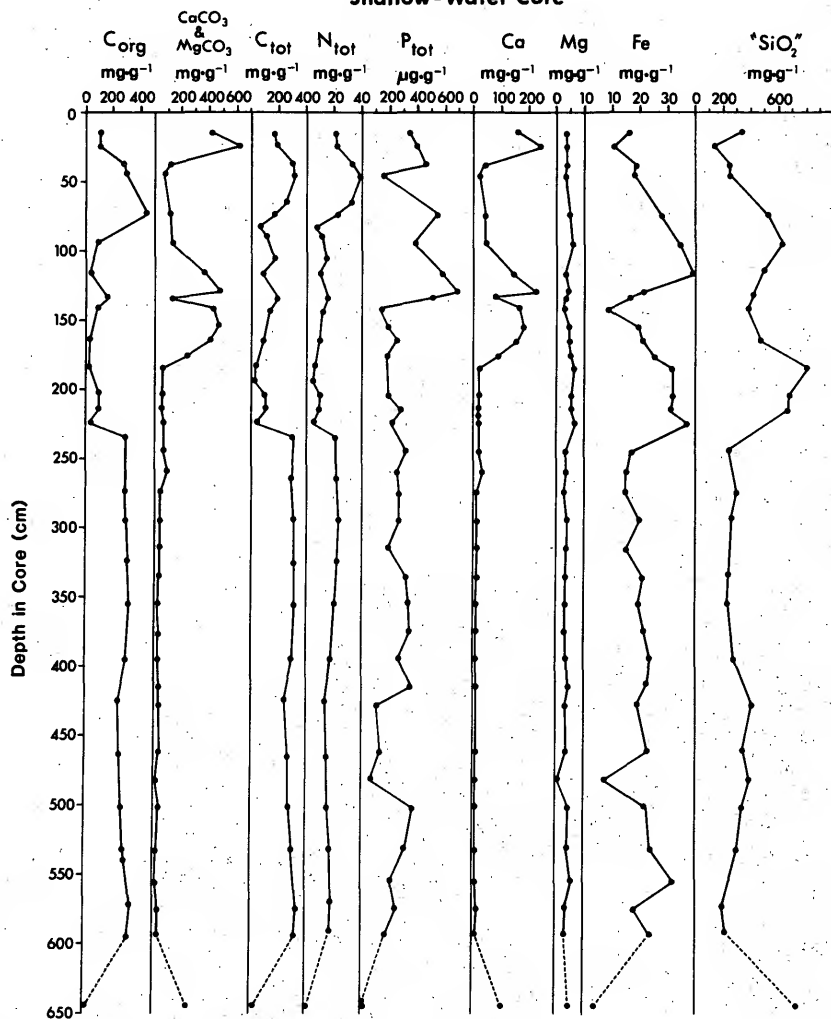


Figure 15. The chemical stratigraphy of Quexil core H.

QUEXIL Core H

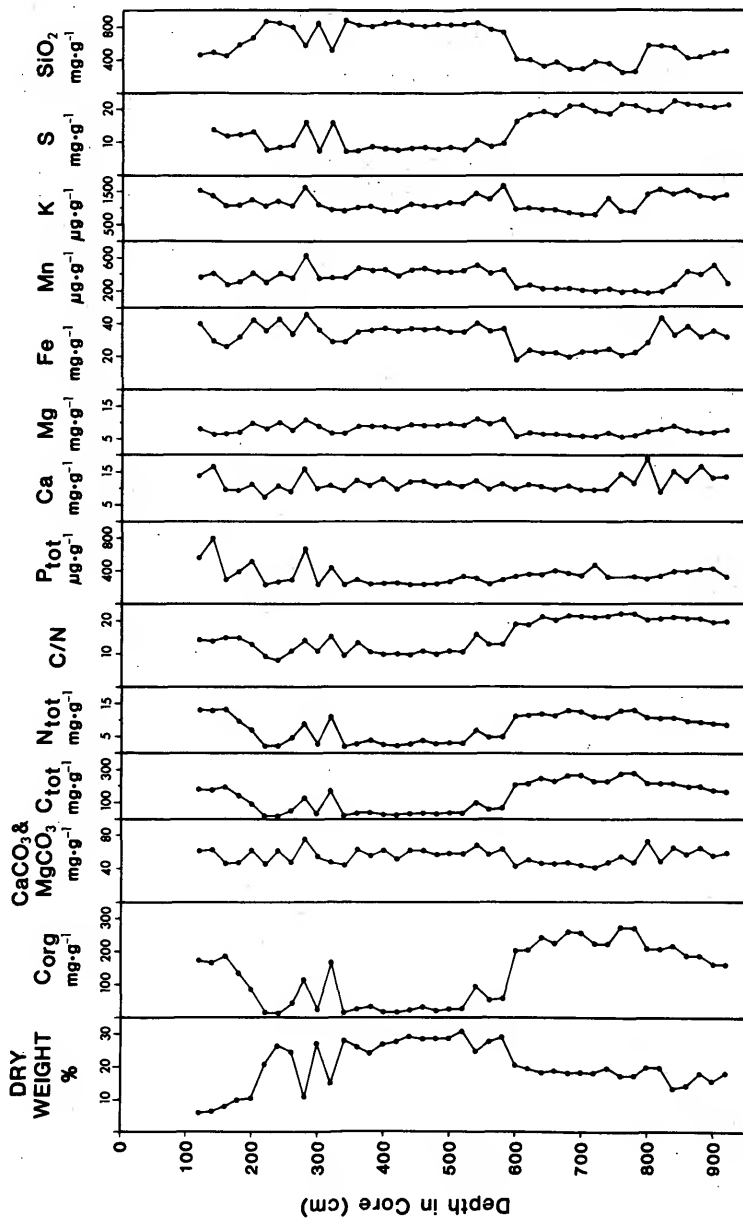


Figure 16. Proximate chemical composition, relative pollen abundance, and chemical accumulation rates at the Quexil shallow-water core site, as computed over archaeologically dated sediment zones. Core zones were determined palynologically.

QUEXIL Shallow-Water Core

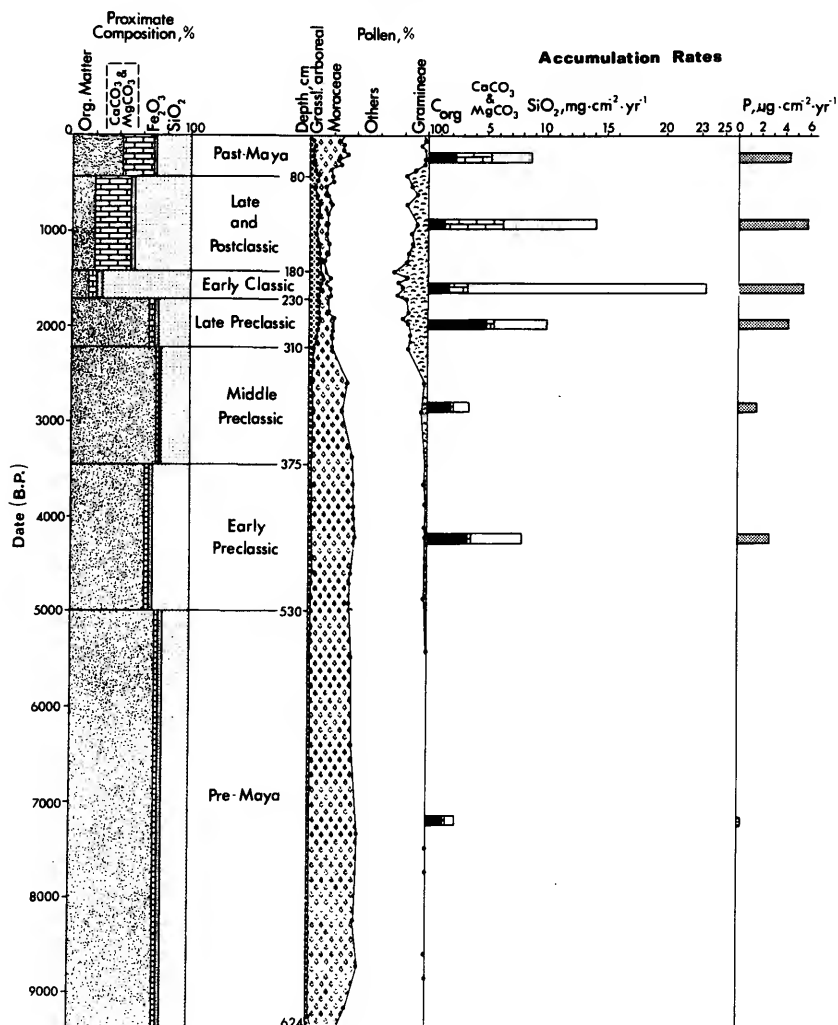
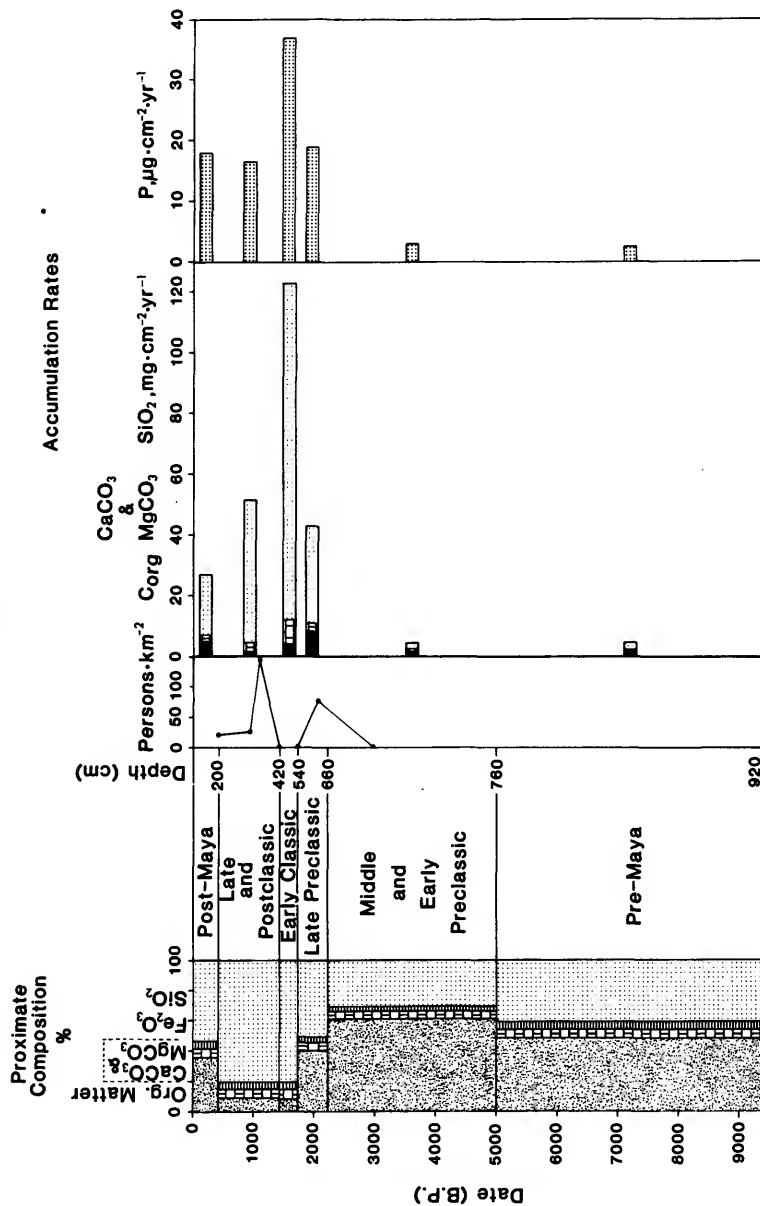


Figure 17. Proximate chemical composition and chemical accumulation rates at the Quexil core H site, as computed over archaeologically dated sediment zones. Maya population densities are levels at the termination of ceramically-defined periods. Core zones were determined palynologically.

QUEXIL Core H



the age of basal sediments from the core confirms that it is a nearly complete Holocene section. Zonation of the shallow-water core was achieved by comparison of Vaughan's (1979) relative pollen diagrams to palynological profiles from Yaxha and Sacnab (Deevey et al. 1979).

S.E. Garrett-Jones examined pollen from Quexil core H and used percentage diagrams from Yaxha and Sacnab, as well as the Quexil shallow-water section, to set zones and attach archaeologically correlated dates to levels in the core (Deevey et al. 1980c). Thus, the changing pollen spectrum, assumed to reflect changing population density in the basin, was used to date the core. Dates were assigned to levels in the Quexil cores using ages applied to archaeologically defined periods at Yaxha and Sacnab. Proximate composition of the sediment within zones was figured after zone limits were established using the pollen spectra. Based on the dates assigned to the various horizons in the cores, chemical accumulation rates for the various archaeological periods were calculated (Figs. 16-17).

The presence of a basal, high forest pollen zone in the Quexil H section that is of the same age as the bottom sediments in the shallow-water core indicates that a near-complete Holocene profile was also obtained in deep water. The Early Preclassic and Middle Preclassic zones, distinguished palynologically in the shallow-water section, could not be separated in Quexil core H and were considered as a single zone. Unfortunately, wide interval (40 cm) sampling of the Quexil H core for pollen analysis resulted in some uncertainty in establishing zone limits. Where changes in the pollen spectrum were encountered, a

horizon was designated midway between the studied levels. Lack of accuracy in defining the true levels, and hence dates, where changes occur can result in errant calculated chemical accumulation rates. This problem is most serious in dealing with zones of little thickness.

Proximate Chemical Composition of the Lake Quexil Sediments

The sediments of the Quexil shallow- and deep-water cores are not strikingly dissimilar in chemical composition though some differences do emerge. The shallow-water section contains a higher proportion of organic matter (average of zone means = 48.1% organic matter), while Quexil H is richer in silica (average of zone means = 56.5% SiO_2). Comparison of organic matter content in the two cores was achieved by assessing the zone-to-zone ratio of organic matter concentration in the shallow- and deep-water sections. For this computation, the organic matter value of the combined Early and Middle Preclassic zone was compared to both of the palynologically distinct Early and Middle Preclassic zones identified in the shallow core. When organic matter content (%) in the shallow-core zones was divided by the amount in the equivalent deep-core zones, the range of ratios extended from an Early Preclassic low of 0.97 to a Late and Postclassic high of 2.0. The mean ratio for the seven compared zones is 1.44, indicating that the Quexil shallow-water core sediments average nearly half again as much organic matter as deep-water sediments of the same age. Silica content in the two sections was compared in a similar manner, though in this case, the

zonal SiO_2 concentration of Quexil H was divided by the shallow-section SiO_2 value. The mean zonal ratio was 1.47, indicating the higher silica content in the deep-water core.

Carbonates, as CaCO_3 and MgCO_3 , comprise a rather constant 5-6% of the sediment throughout all zones of Quexil H. In the shallow-water section, the content varies from 3 to 6% by zone until the Late and Postclassic, when carbonates made up 30% of the sediment. Following abandonment of the catchment by the Maya, carbonate content of the shallow-water sediments decreased slightly, but still constituted 26% of the sediment by weight. Though ostracods are plentiful in the Late and Postclassic zone of the core, their high concentrations probably result from favorable preservation conditions, and there is little in the microfossil record to support the claim that carbonates deposited in the last 1400 years are biogenic (Brenner 1978). More likely, the carbonates are of allochthonous origin and resulted from human disturbance near the coring site. Export of detrital carbonates from Quexil's two islands during Late and Postclassic times may explain the carbonate-rich horizon from 160 to 80 cm in the shallow-water core. The islands were evidently populated during those periods, all seven test-pitted island structures indicating Postclassic period habitation. After the close of the Postclassic, the islands were abandoned, and carbonate content in the sediments dropped. High mean carbonate concentration in the post-Maya section (0-80 cm) of the core is attributable to two samples taken above 25 cm in the core. High concentrations here may have resulted from wash-in when the western access road to the lake was constructed.

Tracking the percent composition of the sediments in the two cores from the basal zones upward, both sections show a precipitous drop in organic matter content during the Early Classic and Late and Postclassic periods, followed by an increase in the post-Maya zone. While both cores show reduced organic matter content in zones dating from 250 to 1600 A.D., shallow-water sediments are about twice as rich in organic matter as deep-core sediments in the time-equivalent sections (Table 2). Both cores display SiO_2 maxima in the Early Classic as well as in the Late and Postclassic, though silica content in the zones is higher for Quexil core H.

As at Yaxha and Sacnab, human disturbance in the Quexil basin resulted in inorganic domination of the sediments, but the Early Classic organic matter minimum in both cores is anomalous as the watershed experienced a population hiatus during this period. While the mainland remained devoid of Maya inhabitants from about 100 B.C. to 550 A.D., two mounds on Quexil's eastern island were occupied during the Early Classic. This minimal disturbance can hardly account for the inorganic nature of Early Classic sediments, especially at the deep-core site. Depopulation of the drainage may not have resulted in reforestation, and even if human activity in the watershed ceased completely, a rapid return to a predisturbance equilibrium might not be expected. Support for the latter contention is provided by comparison of the pre-Maya and post-Maya zones. In neither Quexil core has the mean organic matter content in the post-Maya section returned to the predisturbance level. In the shallow-water core, this could be due in

Table 2. Percent composition of Lake Quexil shallow-water and deep-water core sediments.

Zone	Organic Matter		CaCO ₃ + MgCO ₃		SiO ₂		Fe ₂ O ₃	
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep
Post-Maya	42	36	26	5	30	54	2	5
Late and Postclassic	18	9	30	5	48	81	4	5
Early Classic	14	8	6	6	75	81	5	5
Late Preclassic	66	40	5	5	27	51	2	4
Middle Preclassic	69		3		25		3	
Early Preclassic	59	61	3	5	36	31	2	5
Pre-Maya	69	48	3	6	24	41	4	5

part to dilution by large amounts of detrital carbonate. The mean organic matter percentage for the uppermost zone of the Quexil H core might have been higher if the top meter of the section had been analyzed. That portion of the core was not assessed because the stratigraphy of the flocculent surface mud was ruined by the coring procedure. However, perfect recovery to predisturbance conditions is not expected following the Maya downfall, as the lake waters were more effectively sealed from groundwater intrusion by a thick anthropogenic clay aquiclude. Nevertheless, the extreme inorganic nature of Early Classic sediments is anomalous and hints at improper core zonation.

While human disturbance is generally associated with a shift to higher silica content in the sediments at both coring sites, deep-water sediments contain higher quantities of SiO_2 , even under pre-Maya and post-Maya conditions. Several factors are likely responsible for this phenomenon. As allochthonous material is washed out of the watershed and into the lake, large organic particles are deposited near shore, while silt- and clay-size inorganics remain in the water column or are resuspended and focused into deep-water locations. Furthermore, the shallow-water coring site was afforded some protection by Quexil's two islands and probably received little of the silt load that came off the steep north shore scarp. If water levels were lower in the past, it is conceivable that the shallow-water site could have been cut off completely from direct contact with the deep basin to the east. The coring station would have been at the southern end of a shallow north-south channel, bordered on the east by a single, flat land mass comprised of the two joined islands.

Chemical Accumulation Rates in Lake Quexil Sediments

Increasing riparian population density in the Quexil watershed was shown to be generally associated with a shift to inorganic domination of the lacustrine sediment matrix. Changing Maya population levels are now compared with shifting chemical delivery rates to the lake. Modified chemical loading rates that resulted from human activity may well have altered biological processes in the aquatic realm. Additionally, nutrient export from the watershed as well as erosional consequences of human disturbance could have had an adverse effect on Maya agriculture within the drainage.

Phosphorus accumulation rates are considered first, as phosphorus may have been the limiting nutrient for both lake trophic state and agricultural productivity. Phosphorus accumulation rates are compared to Maya population levels as expressed by mainland population densities (Fig. 17).

Comparison of changing population densities and phosphorus accumulation rates is complicated by the fact that designated time-specific ceramic assemblages, based on identified sherds from the Quexil catchment, are not time-equivalent to ceramic periods established at Yaxha and Sacnab. Ages attached to the twin Lasin ceramic sequence were correlated through palynological sequences from the paired lakes to pollen zones at Quexil; thus the time zonation for occupation at Quexil is different from the time zonation applied to levels in the core. Middle and Late Preclassic ceramics from the western drainage were not distinguished in P.M. Rice's preliminary

analysis of the material, but the sequence was refined to some degree in that Terminal Preclassic and Terminal Classic artifacts were identified. Despite these difficulties, some general correlations between Maya population levels and chemical accumulation rates are apparent. Human intrusion in the watershed is associated with increasing phosphorus delivery rates at both coring sites (Table 3), though the maxima occur at different times. At the shallow-water site, the rate of phosphorus accumulation reached a peak ($5.9 \text{ ug P}\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}$) during the combined Late and Postclassic, a figure that is some 8.9 times the predisturbance baseline value. In deep water, the Early Classic period was the time of maximum phosphorus deposition, and the rate at which the nutrient accumulated in basin sediments ($36.7 \text{ ug P}\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}$) was 14.4 times the pre-Maya rate.

Relatively high Early Classic phosphorus accumulation rates measured for both cores are anomalous as the Quexil basin experienced a population decline during that period. However, return to a predisturbance equilibrium with respect to phosphorus loading would not necessarily be expected, and high modern (post-Maya) delivery rates support this contention. Despite the evident reforestation of the watershed over the past 400 years, post-Maya phosphorus accumulation rates at the shallow-water site ($4.4 \text{ ug P}\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}$) and deep-water station ($18.0 \text{ ug P}\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}$) are 6.7 and 7.1 times their respective baseline values. In fact, return to a predisturbance equilibrium level may now be complete and is perhaps reflected by low modern productivity measurements. Considered as a complete unit,

Table 3. Chemical accumulation rates in the Lake Quexil sediments at the shallow-water and deep-water sites as amount per square centimeter per year.

Zone	C _{org} (mg)		CaCO ₃ + MgCO ₃ (mg)		SiO ₂ (mg)		P _{tot} (ug)	
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep
Post-Maya	2.2	4.6	3.1	1.8	4	20	4.4	16.0
Late and Postclassic	1.3	1.6	5.0	2.9	8	47	5.9	16.6
Early Classic	1.7	4.0	1.6	7.8	20	111	5.8	36.7
Late Preclassic	4.6	7.8	0.7	3.0	4	32	4.2	16.9
Middle Preclassic	1.8	1.6	0.2	0.4	2	2	1.7	2.9
Early Preclassic	3.3		0.3		4		2.7	
Pre-Maya	1.3	1.4	0.2	0.4	1	3	0.7	2.6

however, the post-Maya section does not suggest complete recovery, and it is likely that a lag period exists between the time human disturbance ceases and phosphorus delivery rates return to predisturbance levels. High nutrient input to the lake is maintained during the post-impact phase as anthropogenically phosphorus-enriched surface soils, carried downhill to the lake edge during the episode of deforestation, continue to move into the lake following vegetation recovery. High phosphorus concentrations in soils associated with Maya construction support the claim that complete recovery has not occurred.

A zone-to-zone comparison of phosphorus accumulation rates at the two core sites shows that the nutrient is deposited at a higher rate in deep water. In the upper four zones of the two cores, phosphorus accumulates in deep water at rates 2.8-6.4 times the age-equivalent rates measured for the shallow site. Calculated zonal phosphorus loading rates derived from the shallow-water core are all less than $7 \text{ ug P} \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$, the permissible value for a lake of 5 m mean depth (Vollenweider 1968). Since Late Preclassic times, phosphorus delivery rates to Lake Quexil, based on analysis of the deep-water section, have exceeded permissible levels ($10 \text{ ug P} \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$), even for a lake of 10 m mean depth, and the Early Classic accumulation rate ($36.7 \text{ ug P} \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$) is dangerously high. However, it is unlikely that eutrophication resulted from the enhanced nutrient delivery, as concentrations and accumulation rates of autochthonously produced microfossils are low in the Early Classic zone of the shallow-water core (Brenner 1978). As at Yaxha and Sacnab, much of the sedimented, disturbance-zone phosphorus in Lake Quexil was probably

unavailable to plants and reached the lake bottom in mineral form (apatite?), having never cycled through the aquatic biota.

Other chemical components of the Quexil sediment also responded to human disturbance with higher accumulation rates. Organic carbon deposition was maximal at both coring sites during the Late Preclassic period. Within this zone, organic carbon accumulation at the shallow and deep station occurred at rates 3.8 and 5.6 times the respective baseline rates. Carbonate accumulation on the lake bottom also increased with disturbance. At the shallow site, the maximum accumulation rate ($5.0 \text{ mg CaCO}_3 + \text{MgCO}_3 \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$) was attained during the Late and Postclassic period and was 25 times the pre-Maya rate. Carbonate deposition in deep water peaked in the Early Classic when $7.8 \text{ mg CaCO}_3 + \text{MgCO}_3 \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$ were accumulating, exceeding the baseline value by some 19.5 times. The Early Classic was also the period of maximal silica deposition at the two sites. In shallow water, the baseline SiO_2 accumulation rate was increased 20-fold, while in deep water, the rate of accumulation jumped some 37 times over the pre-Maya value. In both cores, organic material as well as carbonate and silicate deposition increased following disturbance. However, the magnitude of change was greater for the carbonates and silicates, thus accounting for the highly inorganic nature of the Maya zone sediments.

While human disturbance in the Quexil watershed led to higher chemical delivery rates at both coring sites, accumulation rates at the deep station generally exceeded those measured on the shallow-water core. This has already been shown for phosphorus, but can be

demonstrated for the other chemical types when equivalent-zone accumulation rates are compared. To elucidate this intra-basin difference, calculated chemical accumulation rates from the three principal, comparable Maya periods (Late Preclassic, Early Classic, Late and Postclassic) in the two cores were contrasted. Deep-water deposition of silica during these periods ranged from 5.6 to 8.0 times the shallow-water rates, and a similar comparison of organic carbon accumulation rates shows deep-water inputs to have been 1.2-2.4 times the shallow-site rates. Carbonates display a similar relationship in the Late Preclassic and Early Classic when deep-water deposition exceeded shallow-water accumulation by 4.3 and 4.9 times respectively, but the trend was reversed in the Late and Postclassic, when carbonates accumulated more rapidly in shallow water than at the deep-core location. Silica accumulation rates in deep water exceed shallow-water accumulation rates by a greater margin than that seen for organic carbon, and this is expressed in the relatively higher inorganic nature of the deep-core sediments.

Higher calculated chemical accumulation rates for the deep-water site were not unexpected, as greater bulk sedimentation there was obvious from the differential overall lengths of the age-equivalent cores (9.2 m vs. 6.5 m). Focusing attention on the comparable, palynologically correlated disturbance zones, twice as much sediment accumulated in deep water (660-200 cm = 460 cm) as in shallow water (310-80 cm = 230 cm) from the inception of the Late Preclassic through the Late and Postclassic period. While the volume of sediment amassed in deep water during this interval was double that accumulated in

shallow water, calculated chemical accumulation rates from the two sites often differ by more than a factor of two. This is explained by the higher percent dry weight and higher wet weight per cm^3 in the three zones of the deep core. Over the length of the three disturbance zones, the mean percent dry weight was calculated for the two cores. From 660-200 cm in Quexil H, dry weight constitutes 24.3% of the wet sediment. In the shallow-water core, dry weight makes up only 14.8% of the sediment over the time equivalent zones. Comparing the same zones with respect to wet sediment density, Quexil H mud averages $1.11 \text{ g}\cdot\text{cm}^{-3}$ wet sediment, while the more organic deposits in shallow water display a mean of $1.02 \text{ g}\cdot\text{cm}^{-3}$ wet sediment. Mean percent dry weight was multiplied by mean wet weight per cm^3 to estimate the average dry weight content of each cm^3 wet sediment in the three disturbance zones of the cores. With $270 \text{ mg dry sediment}\cdot\text{cm}^{-3}$ wet sediment, the Quexil H core contains nearly twice as much dry weight per unit volume wet sediment as the shallow-water section ($151 \text{ mg dry sediment}\cdot\text{cm}^{-3}$ wet sediment).

Higher dry weight per cm^3 wet sediment in deep-water sediments is likely a function of several factors. Greater sediment mass deposited in deep water results in more compaction of the mud at that site. Also, the inorganic nature of the deep deposit suggests that siliceous sediment of primarily clay- and silt- size grains (Binford, in press) is tightly packed when the overlying sediment accumulation becomes substantial, thereby removing much interstitial water. Relatively large, hydrophilic organic particles deposited at the

shallow-water site never become compacted to the degree achieved at the deep station and retain much water.

It has been noted elsewhere (Brenner, in press) that phosphorus and iron concentrations in surficial (0-10 cm) soils of the Quexil watershed do not differ statistically from levels encountered in the shallow- and deep-core sediments. While this may be coincidental, or simply an artifact of diagenetic processes, it at least suggests that the lake mud is composed largely of redeposited soils. If this is the case, and translocated soils are the primary source of sedimented phosphorus, carbonates, silica, and organic matter, then within-core zone-to-zone shifts in accumulation rates for any chemical pair should be positively correlated, assuming there is little change in the postdepositional content of the sediment for any chemical type.

Assessing the Quexil H core first, zone-to-zone phosphorus and silica accumulation rates are highly correlated ($r = 0.94$, $P < 0.005$), as are phosphorus and carbonate ($r = 0.96$, $P < 0.005$) and carbonate and silica inputs ($r = 0.99$, $P < 0.005$). In the shallow-water core, zone-to-zone chemical accumulation rates were correlated as follows: phosphorus and silica ($r = 0.72$, $P < 0.05$), phosphorus and carbonates ($r = 0.75$, $P < 0.05$). Carbonate and silica accumulations were not significantly correlated at the 95% confidence level ($r = 0.29$). This is no doubt in large part due to the unusually high carbonate accumulations registered for the two most recent zones in the core. In contrast to these highly interrelated delivery rates, both cores fail to show a significant correlation between zone-to-zone phosphorus and

organic carbon accumulation ($r = 0.07$, $r = 0.47$, $P > 0.05$). Perhaps zone-to-zone shifts in deposition rates for these two sedimentary constituents were actually different, as organic matter was progressively flushed from, and thus depleted in the catchment. It is likely that differential, between-zone postdepositional loss of organic carbon also accounts for the lack of correlation. That zone-to-zone phosphorus accumulation rates are significantly correlated with carbonate and silica rates at both core sites suggests that a common mechanism is responsible for delivery of these chemical types to the lake, whereas organic carbon is sedimented by a different mechanism. As at Yaxha and Sacnab, colluviation or alluviation of watershed soils probably accounted for the major portion of lacustrine sedimentation, especially during the episode of forest removal.

Maya deforestation in the Quexil watershed resulted in accelerated delivery rates of carbonates, silicates, organic matter, and phosphorus to the lake. Export of inorganic matter from the catchment was probably enhanced to a greater degree than organic matter removal, and this, along with strong diagenesis, produced disturbance-zone muds of low organic content. The episode of vegetation removal and consequent sediment loading of Quexil lasted about three millennia, and modern high phosphorus inputs measured in both cores demonstrate that the impact was sustained following abandonment of the watershed.

Calculated chemical accumulation rates for the shallow- and deep-water sections elucidate the profound effect that core location and basin morphometry had on sedimentation processes. While the shallow-

core site was protected from the erosional load coming off the steep north shore slope, the deep station was the recipient of much resuspended material. The conical bathymetry of Lake Quexil (Deevey et al. 1980a) is conducive to the focusing of sediments into the deepest areas of the lake (Lehman 1975, Davis and Ford, 1982, Deevey et al. 1977). The differential accumulation of phosphorus from site to site on the basin floor makes it somewhat difficult to use the Quexil data to refine the per capita phosphorus loading model developed at Yaxha and Sacnab. Perhaps even more problematical is the inability of the zone-to-zone phosphorus loading values computed from analysis of the two cores to track short-term Maya population fluctuations derived from the archaeological record. Several factors account for this difficulty. The cores, reliant for zonation on correlation with the discrete palynological sections distinguished at Yaxha and Sacnab, have archaeologically correlated dates that are different from the age designations applied to ceramic assemblages from the Quexil catchment. The single Late and Postclassic sediment zone encompasses three distinguishable ceramic periods (Late Classic, Terminal Classic, Postclassic) during which time the population changed drastically as a consequence of the Classic collapse. The Late Preclassic sediment zone straddles the Middle and Late Preclassic, and Terminal Preclassic archaeological periods, again two time periods of very different levels of Maya settlement. Middle and Late Preclassic ceramics have been distinguished by P.M. Rice (Rice and Rice 1981) in a reevaluation of the Quexil sherds, but this does not resolve the association of a

"no-occupation" Terminal Preclassic period with a "high-phosphorus-input," Late Preclassic sediment zone. Time designations for the archaeological record differ from ages assigned to levels in the sediment cores, but even where time congruency is perfect (Early Classic and post-Maya), high phosphorus loadings appear anomalous as they are associated with periods of basin depopulation. Long lag periods necessary to approach a predisturbance equilibrium may explain this phenomenon. On the other hand, it is conceivable that during Early Classic times, the land in the Quexil drainage was constantly exploited despite the fact that the watershed remained uninhabited. Finally, accurate age assignment to the pollen zones of the sediment cores, perhaps achieved at Yaxha and Sacnab, may not be possible at Quexil. At the twin basins, zones were set based on the assumption that the degree of deforestation reflected in the pollen spectrum was a function of the changing riparian Maya population density, known from the dateable archaeological record. At Quexil, zones were delimited by comparison with the Yaxha-Sacnab sections without archaeological data from the catchment. An assumption of slow, steady population growth in the basin did not seem unreasonable, and the Terminal Preclassic-Early Classic hiatus could not be anticipated. If indeed the watershed had been reforested during this period, sedimentation rates would have dropped, confining accumulation during the 650-year period to a thin horizon. Widely spaced (40 cm) palynological sampling of the Quexil B core can be invoked to explain the failure to identify the reforestation zone, but Vaughan's (1979) close-interval sampling of the

shallow-water section does not show a horizon of vegetation recovery either.

The inability to discern a Terminal Preclassic-Early Classic reforestation horizon in the Quexil cores is puzzling and can be interpreted in two ways. Either vegetation recovery in the basin did not occur, or if it did, evidence for forest regrowth was overwhelmed by the regional pollen rain that registered continued deforestation. If the sediments of Lake Quexil truly record the greater regional pollen rain, then zones identified at the twin basins 50 km to the east should be contemporary with the Quexil pollen zones. However, it may be that the pollen spectra of the Yaxha and Sacnab cores reflect regional vegetation changes, while Quexil's profiles constitute a mix of regional and local shifts, and the pollen-equivalent zones in cores from the widely separated lakes would thus not be expected to be contemporaneous. In addition to the differential settlement histories of the basins, the comparison of Quexil's pollen profiles to the twin basin diagrams is complicated by the presence of the large savanna area south of Quexil. If the savannas are natural and of sufficient antiquity, they certainly contributed pollen to the Quexil sediments that can be misconstrued as evidence for human-induced deforestation. While palynological dating of the Quexil sediments probably was inaccurate, the zonation of the shallow- and deep-water cores nevertheless made possible a reliable assessment of differential sedimentation at the two sites within the lake.

Having perceived the problems associated with palynological zonation of the Quexil cores, other sedimentary parameters were examined as potential dating tools. An attempt was made to use magnetic susceptibility to establish intra- and inter-basin core correlations (Oldfield et al. 1978, Thompson et al. 1980), but this failed as the Bison meter was not sensitive enough to record the low level of sedimented, magnetic particles. Magnetic susceptibility measurements on Quexil sediments are now being pursued by colleagues in England using more sensitive instrumentation. This will likely be of little help in establishing an inter-basin correlation, even when other lakes are studied, as this would demand that regional events such as ashfalls were recorded as horizons in the sediments of all the core lakes. Magnetic susceptibility measurements taken over the length of the lake sediment cores may record changing erosion rates (J.A. Dearing, pers. comm.) that were probably not contemporaneous from basin to basin, as surmised from the varying demographic histories.

Nevertheless, the magnetic susceptibility profile, as a basin-specific indicator of human disturbance, may some day be used in conjunction with the archaeological record to assign dates to levels in the cores.

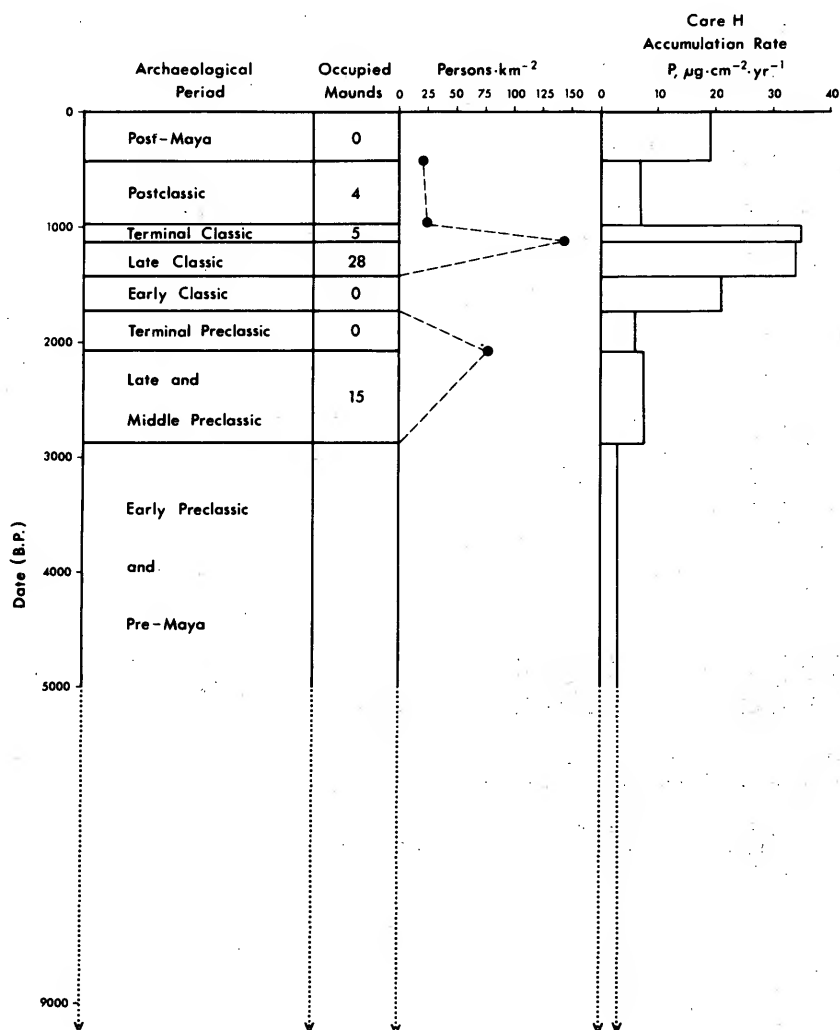
An alternative to pollen zonation at Quexil was also sought in granulometric analysis of the basin sediments. Warwick (1980), working with sediments from the Bay of Quinte, Lake Ontario, demonstrated that human disturbance resulted in an increased delivery of fine particles to the center of the lake. Binford's (in press) particle size analysis of the Quexil H mud showed that mean particle size dropped

significantly following deforestation. Within the deep-water core, fluctuations with respect to mean particle size, as well as the computed skewness and kurtosis of the measured, sampled particles were used together with the paleodemographic data to rezone and date the core (Binford, in press).

Phosphorus accumulation rates were recalculated using the granulometric zonation of the Quexil H core (Fig. 18). This improves somewhat on the pollen zonation with respect to the ability of phosphorus loading rates to track short-term population fluctuations. Baseline rates more than tripled when the catchment was settled in the Middle and Late Preclassic and fell back to nearly predisturbance levels when the watershed was depopulated in the Terminal Preclassic. The Early Classic loading rate of $21.3 \text{ ug P} \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$ still appears anomalously high considering that the basin remained uninhabited during that period. Dangerously high phosphorus loading was computed for the Late Classic, a time of dense Maya settlement, but the high nutrient input continued into the Terminal Classic, when population density was greatly reduced. Sustained high phosphorus deposition rates during the relatively brief (150 years) Terminal Classic may be explained by the lag period necessary to attain a new equilibrium. As the watershed remained nearly devoid of human habitation into the Postclassic, phosphorus loading declined, but surprisingly rose again with the total abandonment of the catchment. This fine zoning of Quexil H still results in a high Early Classic phosphorus accumulation rate, and it is particularly difficult to

Figure 18. Population densities in the Quexil watershed and total phosphorus accumulation rates at the Quexil core H site, by archaeological period. Core zones were delimited granulometrically.

QUEXIL



explain considering that there is some evidence for reduced erosion in the Terminal Preclassic period. Additionally, high modern input rates are not easy to explain in that phosphorus export to the lake was low during the preceding, Postclassic period. Analysis of the stratigraphically mixed, flocculent sediments above 120 cm might have reduced the calculated post-Maya phosphorus accumulation rate. However, even if the upper section contained no phosphorus at all, the modern deposition rate would be reduced, but still in excess of the Postclassic accumulation rate. Thus, data from Quexil, based on palynological and granulometric fine zoning of the deep-water core cannot be used to refine the per capita phosphorus loading model developed for twin Lakes Yaxha and Sacnab.

Paleoproductivity in Lake Quexil

The Significance of Microfossils

Analysis of sedimented microfossil remains can contribute to reconstructions of past lacustrine environments, especially when organisms are identified to the species level and their modern ecological requirements are known. Caution must be exercised when interpreting the microfossil record, as the death assemblage examined and enumerated may have been modified significantly as compared to the original biocoenosis from which it was derived (Covich 1970). A variety of plant and animal remains are encountered in lake sediments, but the degree of preservation for the various types is highly variable. Physical and chemical properties of the water column and

sediment matrix can affect microfossil preservation, as can the composition of the sedimented organism. The most common remains found in lake muds are typically resistant structures composed of alkaline earth carbonates, silica, chitin, cellulose, or pollinin (Frey 1976).

Many of the most useful algal types for trophic state characterization are not fossilized. Nitrogen-fixing cyanophytes, indicators of lake eutrophy, are notably absent from the fossil record (Brugam 1978), but their former presence can be documented if myxoxanthin, myxoxanthophyll, or oscillaxanthin can be detected by sediment pigment analysis (Wetzel 1975).

The five principal invertebrate groups that leave body parts or resting eggs in lake sediments and are used for environmental reconstructions are the Cladocera, midges, molluscs, ostracods, and rotifers (Crisman 1978a). Additional groups, such as rhizopods, neorhabdocoeles, sponges, and several other insect groups besides midges, leave identifiable remains at the lake bottom and may eventually prove to be useful indicators of past lacustrine conditions (Frey 1976). Stratigraphic shifts in numbers or species composition for the various taxonomic groups can, in conjunction with other evaluated sedimentary parameters, provide information concerning past conditions with respect to productivity, water chemistry, lake level, and oxygen content of the water. As with all paleolimnological studies, accurate interpretation of the sedimentary record is dependent on the analysis of an array of physical, chemical, and biological aspects of the profile. With several kinds of data from the profile,

hypotheses about past conditions can be constructed and tested. Inferences about past lake conditions that fail to explain all data sets can then be rejected (Pennington 1981).

The Microfossils of the Quexil Cores

Microfossil concentrations in the Quexil shallow-water core (Fig. 19) were reported, and accumulation rates were compared on a zone-to-zone basis to total phosphorus deposition rates (Brenner 1978). Phosphorus accumulation was positively correlated with microfossil accumulation from the earliest, pre-Maya section of the core through the Late Preclassic (Fig. 20). The trend ceased in the Early Classic when phosphorus deposition was high, but calculated microfossil delivery to the sediments was low. The inverse relationship between microfossil accumulations and phosphorus delivery was sustained into the Late and Postclassic, though ostracods were sedimented at a rapid rate in the carbonate-rich zone of the core. Following depopulation of the basin, microfossil accumulations were once again high in the organic, post-Maya section of the core, while phosphorus input dropped to 75% of the Late and Postclassic rate.

As phosphorus was thought to be the limiting nutrient for lacustrine productivity, explanations were sought to resolve the enigmatic inverse relationship between high phosphorus deposition and low microfossil accumulation, a situation that prevailed for more than a millennium. As the combined carbonate and silicate delivery rate was

Figure 19. Microfossil concentrations in the Quexil shallow-water core.

QUEXIL
Shallow-Water Core

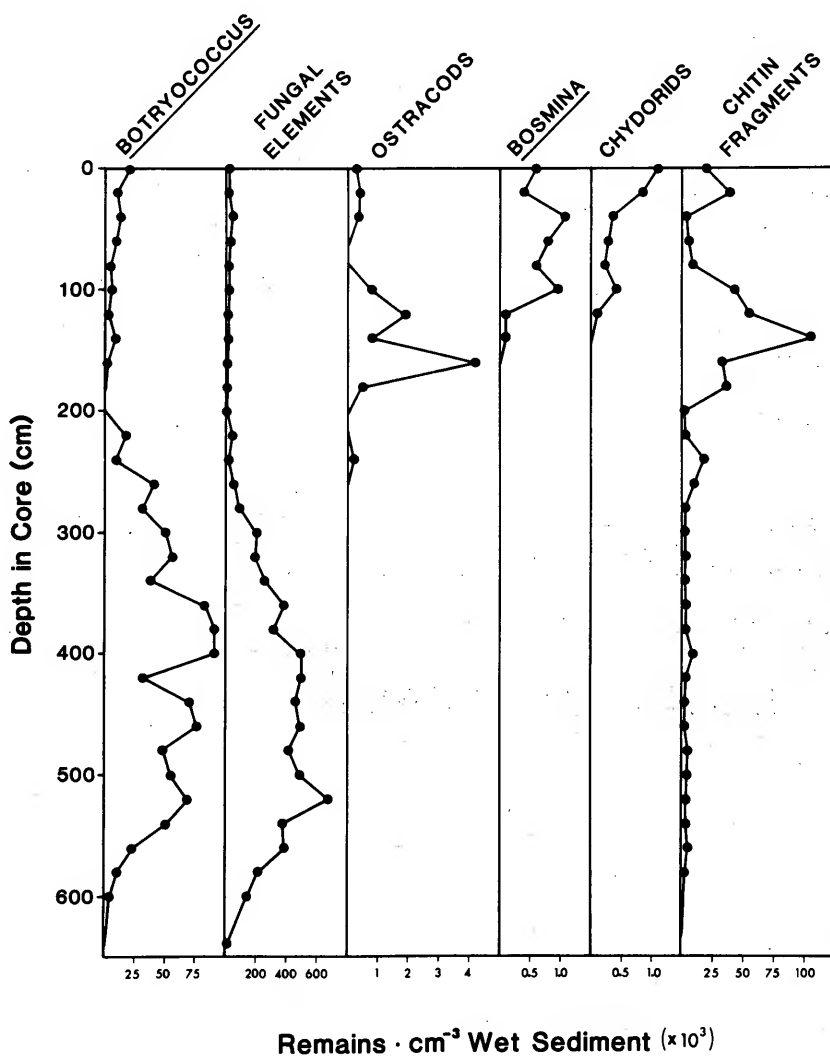
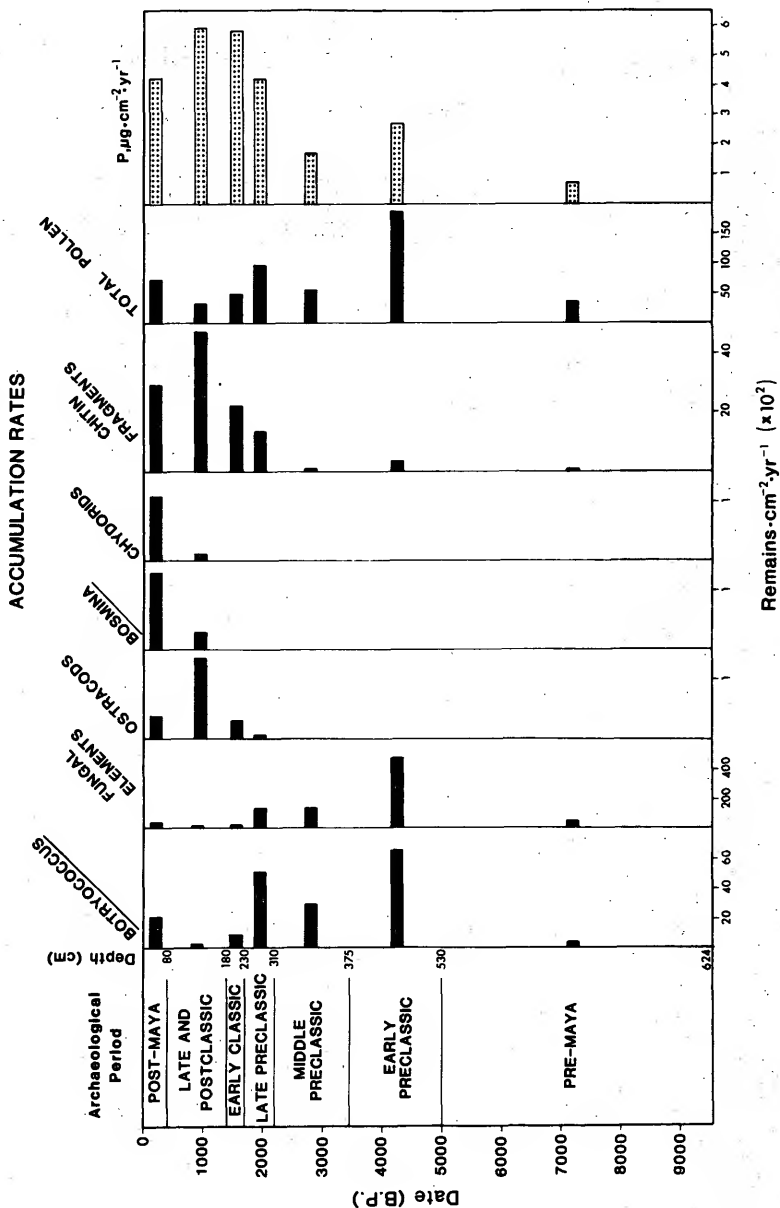


Figure 20. Microfossil and phosphorus accumulation rates at the Quexil shallow-core site, as computed for the various archaeological periods. Core zones were delimited palynologically.

QUEXIL Shallow-Water Core



maximal in the Early Classic and still high through the Late and Postclassic, siltation may have been severe enough to limit light penetration in the water column and thereby reduce productivity. The inorganic sediments of the two disturbance zones probably constitute a microenvironment that is not favorable for microfossil preservation. Low calculated microfossil accumulation rates for the Early Classic and Late and Postclassic zones may be inaccurate estimates of original deposition rates, and perhaps simply reflect severe diagenesis in the clay- and carbonate-rich sediments. Total pollen accumulation in the inorganic sections of the core was also low, and though this may have been a function of increased deforestation, postdepositional destruction of pollen grains can be invoked. The claim is supported by the very poor pollen preservation encountered in the clay-rich sediments of Lake Yaxha (Vaughan, pers. comm.).

Estimated gross sedimentation rates used to calculate zonal microfossil accumulation rates can affect zone-to-zone changes in the delivery rates computed for the remains. The Early Classic sedimentation rate ($0.17 \text{ cm} \cdot \text{yr}^{-1}$) was slightly higher than the Late Preclassic rate ($0.16 \text{ cm} \cdot \text{yr}^{-1}$). Nevertheless, Late Preclassic microfossil accumulations were much higher, indicating the higher numbers of remains per cm^3 encountered in mud from that zone. While gross sedimentation rates influence computed microfossil accumulations from zone-to-zone, they do not explain the inability of microfossil accumulations to track computed phosphorus inputs as the chemical and fossil rates are calculated employing the same zonal gross sedimentation rates.

Apparent zone-to-zone positive correlation between changing phosphorus accumulation and microfossil accumulation from the pre-Maya section of the core until the Late Preclassic may be simply a function of changing estimated gross sedimentation rates. More likely, however, is the possibility that increasing phosphorus delivery to Lake Quexil, associated with initial clearing and burning of the climax forest, did enhance productivity. The plant-available forms of the nutrient, delivered following initial land clearance, were utilized by macrophytes and aquatic microflora and ultimately sedimented on the lake bottom. After the major portion of the phosphorus originally tied up in the vegetation and litter of the basin finally reached the lake, subsequent phosphorus delivery was associated with bulk transport of watershed soils deficient in plant-available phosphorus. Even if soluble phosphorus delivery to the lake continued into the Early Classic, it is possible that the nutrient was rapidly scavenged and coprecipitated with the carbonates that were also being supplied at a great rate (Wetzel 1970, Otsuki and Wetzel 1972, Manny et al. 1978).

Despite the realization that postdepositional destruction of microfossils might affect inferences about past levels of productivity in Lake Quexil, counts were made on the Quexil H section to supplement information that had emerged from analysis of the shallow core. Accumulation rates calculated for the shallow-water section may be biased indicators of lake-wide productivity as a consequence of the unique position of the coring site. This would certainly be the case if lake levels were lower in the past and the locality had been

isolated from the rest of the basin. Accumulation rates based on counts from Quexil H might be expected to provide better estimates of changing basin-wide production. Comparison of zone-to-zone microfossil accumulation rates in the two cores can provide additional evidence for the resuspension and focusing of remains into the deep areas of the lake, a phenomenon already documented by sediment trap studies at Lakes Yaxha and Sacnab (Deevey et al. 1977). Zone-to-zone chemical and microfossil accumulation rates can be compared to test the hypothesis that productivity was phosphorus-limited. The question can be addressed on a finer scale if level-by-level concentrations of phosphorus and microfossils are examined. The instantaneous, bulk sedimentation rate is the same for any given level, whether chemical or microfossil accumulation rates are being calculated. Thus, assessment of level-by-level changes in the concentration of microfossils and phosphorus essentially evaluates the correlation between accumulation rates for the two parameters. If the microfossil accumulation were dependent on and linearly related to phosphorus accumulation (supply), the ratio of microfossil concentration to phosphorus concentration from level to level should remain about the same over the length of the core.

Samples for microfossil analysis were removed from the Quexil cores at 20 cm intervals. In the shallow-water section, sampling began at the mud-water interface, and volumetric plugs of sediment were taken over the length of the core, except at 620 cm, where the core had been previously sampled for radiocarbon dating. Sampling of Quexil H began

at 120 cm, and samples were collected every 20 cm down to 900 cm, the only exception being a gap at 860 cm where a large section was removed for ^{14}C analysis. The volume of sediment removed from each level of the shallow-water section was 0.452 cm^3 , while 0.318 cm^3 of sediment was taken from Quexil H.

Volumetric sediment samples were transferred to 15 ml Nalgene centrifuge tubes and 8 ml of 10% KOH was added. The tubes were placed in a hot water bath for 15-20 minutes, and the sediment was simultaneously disaggregated with a glass rod. Following the heating procedure, the samples were centrifuged and the supernatant was drawn off with a pipet. Distilled water was added to the tubes and the sediment was stirred with a glass rod. Again the samples were spun down and the overlying liquid was drawn off the top. After three such rinses, the mud was transferred to polystyrene tubes and centrifuged. Liquid was once again drawn off and water was added until a volumetric level marked on the tube wall was reached. Samples from Quexil H were brought to 0.95 cm^3 while the tubes containing hydrophilic organic samples from the shallow-water core were filled to 1.9 cm^3 .

When samples were brought to a known volume, magnetic stirring bars were placed in the tubes and the samples were mixed using a Cole-Parmer Mark I magnetic stirrer. While the samples were being homogenized, microscope slides were cleaned and placed on a hotplate. Two drops of glycerine jelly, lightly stained with safranin were applied to the slides at two positions. A subsample of 18.63 μl was removed from the stirred sediment slurry with a micropipet and added to

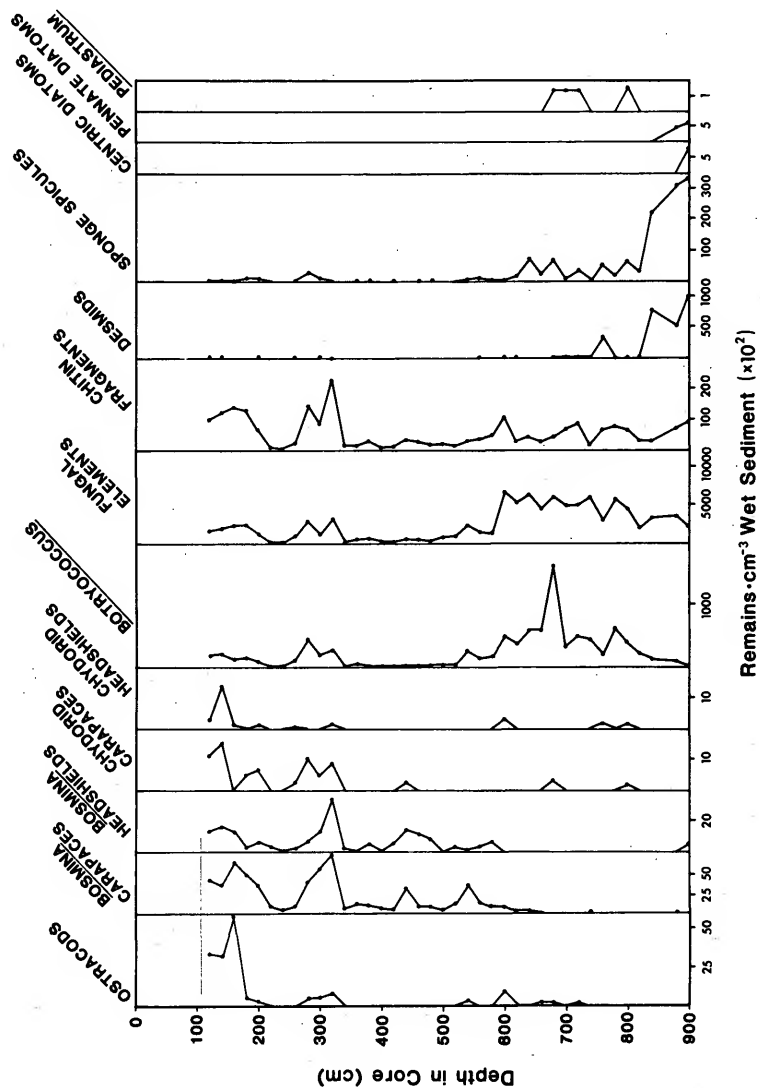
each of the glycerine jelly drops on the slide. The subsamples were mixed into the glycerine jelly with a fine needle, and following evaporation of water from the mixture, cover slips were applied, thus making good permanent slides.

Enumeration of microfossil remains was accomplished by scanning slides at 200X magnification. As each slide contained two samples prepared from a given core level, left and right samples on the slide were both examined and microfossil concentrations were figured from the average of the duplicate counts. At levels where microfossils were not plentiful, the entire area below the cover slip was studied, but where remains were abundant, fractions of the slide were examined. In the latter case, transects were scrutinized over the entire slide to account for possible non-random distribution of remains below the cover glass. Microfossil concentrations for levels in the cores were figured as remains $\cdot\text{cm}^{-3}$ wet sediment (Figs. 19 and 21). Within the delimited pollen zones, average concentration in the sediment for each microfossil type was computed and multiplied by the zonal sediment accumulation rate to calculate the zonal microfossil accumulation rate as remains $\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}$ (Figs. 20 and 22).

There is a degree of subjectivity involved in the enumeration of microfossils and criteria must be established with respect to tallying the remains, so that consistency is maintained over the length of a core and between cores. A brief discussion of what actually was counted in the two Quexil cores is appropriate. Cladocera carapaces are here reported as total carapaces (whole animals), and the

Figure 21. Microfossil concentrations in Quexil core H.

QUEXIL
Core H



concentrations are based on the enumeration of all complete half carapaces. Bosminid remains are presumably from the common modern plankter, Eubosmina tubicen, while chydorid parts are likely from several species, at least one of which is Alona affinis. Cladocera headshields, not reported for the Quexil shallow-water core, were counted in Quexil B and represent intact remains.

Ostracod remains in the Quexil sediments are reported as complete valve pairs, though single valves were tabulated. Additionally, ostracod mandibles were counted in the Quexil sediments and were generally associated with a mass of tangled appendages. The intact mandible-appendage complex or mandible pair was assumed to be equivalent to a valve pair for reporting purposes.

Botryococcus, originally considered a member of the Xanthophyceae, but now assigned to the Chlorophyceae (Hutchinson 1967), possesses cells that grow within or protruding from a gelatinous matrix (Thompson 1959). Each cell clump was enumerated as an entity. Desmids, representing several species of Staurostrum were tallied each time a semi-cell or radiating arm was encountered. Pediastrum cf. duplex was counted when at least half of the colony was present.

Reported sponge spicules represent all complete remains as well as fragments encountered. Most sponge spicules were intact and of the acerate type. No attempt was made to separate hyphal strands and fungal spores when counting, and reported values in the "fungal elements" category are for total combined individual spores and hyphal fragments. Centric and pennate diatoms were enumerated as individual

cells. Some broken pennate remains were seen, and in such cases they were counted if at least half the cell was present. Finally, the "chitin fragments" category represents incomplete bosminid, chydorid, and ostracod pieces, as well as some rarer insect remains.

Quexil H microfossils are now considered using the core zonation based on the palynological record. While dates assigned to levels in the core may be erroneous, dependence of microfossil accumulation rates on phosphorus delivery can be tested, as both parameters are subject to the same error. Pollen zonation also permits inter-core comparison of microfossil concentrations and accumulations at the shallow and deep stations.

Changing microfossil concentrations (Fig. 21) in the sediment are discussed starting with the basal, early Holocene levels and working upward in the core. Botryococcus, likely an important primary producer in modern Lake Quexil, increases steadily in abundance per cm^3 from the bottommost sample through 780 cm. Thereafter, concentrations in the sediment fluctuate a bit, reaching a peak level ($1.64 \times 10^5 \cdot \text{cm}^{-3}$) at 680 cm. While Botryococcus increases its concentration in the sediment, desmid abundance declines. Desmids are nearly absent by 800 cm, but show a resurgence at 760 cm, a level at which Botryococcus concentration drops, suggesting perhaps that these algal types were replacing each other in the early Holocene as the principal primary producers in the phytoplankton. Diatoms were encountered in low concentrations and only in the bottom two core levels. Pediastrum was identified at only four levels in the core and displays low

concentrations in those samples. Like Botryococcus, Pediastrum concentrations in the sediment are generally inversely related to desmid abundance, but the Chlorococcales drop out above 680 cm. Inferences about changing trophic state during the early Holocene history of the lake are tentative due to the lack of knowledge concerning the ecological requirements of these algal types in tropical situations. If the presence of Pediastrum cf. duplex reflects more eutrophic conditions in the lake, as it does for instance in Minnesota lakes (Crisman 1978b), the parallel rise in Botryococcus might suggest that it too is indicative of higher productivity. This is contradicted by the importance of Botryococcus in modern Lake Quexil where measured productivity is low. However, the contemporary assessment of trophic state was based on only a single light-dark bottle experiment.

Though some species of Staurastrum are characteristically found in eutrophic systems, the majority of species are encountered in the plankton of oligotrophic lakes (Hutchinson 1967), and the desmid decline moving upward through the bottom 2 meters of the core perhaps reflects increasing nutrient supply and lacustrine productivity. That conditions changed is evident not only in the shifting phytoplankton species composition of the mud, but in the gross stratigraphy of the sediments. Laminations indicative of meromixis show up below 800 cm in the core and persist until about the 590-cm level when the deposits become increasingly inorganic. The onset of meromixis might argue against increasing productivity, as nutrients trapped below the chemocline would not have been recirculated into the photic zone.

Above 680 cm, Botryococcus is the only primary producer leaving a significant number of remains in the sediment. Thereafter, concentrations decline fairly steadily until 480 cm, interrupted only by small peaks at 600 cm and 540 cm. At 480 cm, the plankton nearly disappears in the inorganic sediments of the Early Classic zone. Fungal element concentrations fluctuate over the bottom 3 m of the core but display a general increasing trend until midway through the Late Preclassic zone when concentrations drop precipitously between 600 cm and 580 cm. Concentrations increase slightly at 560 cm and rise again at 540 cm in a similar manner to Botryococcus, and then decline steadily to 480 cm, paralleling the phytoplankton.

Sponge spicules, like diatoms, are found in great abundance in the bottom two levels of the core. However, a relatively high concentration is seen at 740 cm, following the disappearance of diatoms from the record. Above this level, spicule concentrations are low, fluctuating until 600 cm, when numbers in the sediment fall to a value two orders of magnitude lower than the 900-cm peak concentration. Rather than reflecting high production rates, high concentrations of siliceous remains in the basal levels of the core might be indicative of low pH and optimal preservation conditions in the organic mud. Falling levels of siliceous remains are perhaps explained if the desmid decline does indicate increasing lake trophic state. Greater utilization of dissolved CO_2 would have raised the pH in the water column, thereby contributing to the dissolution of siliceous remains prior to their deposition on the lake bottom. With a transition to

more inorganic sediments at 590 cm, low concentrations of sponge spicules were maintained for nearly 3 m above this level, with only a slight rise in abundance seen at 560 cm.

The pattern of declining concentration associated with increasing inorganic content of the sediment is seen for several microfossil types. While chitin fragment concentrations fluctuate considerably from 900 cm up to 600 cm, their mean abundance per cm^3 in the organic, bottom 3 m of the core is more than twice as great as the mean calculated for the succeeding, overlying 2.6 m. Likewise, Botryococcus, fungal elements and sponge spicules display low concentrations in the more than two and a half meters of highly inorganic sediment from 590 cm in the core up to 325 cm depth. About midway into the palynologically defined Late and Postclassic zone, Botryococcus, fungal elements and chitin fragments show a peak at 320 cm associated with higher organic content of the sediments. All three microfossil types show a slight decline at 300 cm, a resurgence at 280 cm, and thereafter a drop in concentration to very low levels by 240 cm. The bimodal peaks (320 cm and 280 cm) occur during the granulometrically defined Terminal Classic period. With the return of more organic sediments, desmids reappear with a small peak at 300 cm. Sponge spicules too were more numerous in the organic sediments, displaying higher concentrations at 300 cm and 280 cm. Sponge spicules and desmids were absent from samples collected at 240 cm and 220 cm.

With the Maya abandonment of the drainage and a return to organic sedimentation at about 210 cm, Botryococcus, desmid, fungal element,

chitin fragment, and sponge spicule concentrations are all seen to rise between 220 cm and 200 cm in the core. Sponge spicule and desmid concentrations remain low and fluctuate in the postdisturbance section of the core while Botryococcus, fungal elements, and chitin fragments display concentrations more indicative of recovery to predisturbance conditions. Comparison of microfossil concentrations as expressed by remains $\cdot\text{cm}^{-3}$ wet sediment, between pre-Maya and post-Maya levels is confounded by more compaction and greater dry weight per unit volume down core. Correction for differential water content can be achieved by expressing microfossil concentrations as numbers per gm dry weight. Presented in this manner, abundances are seen to have nearly returned to predisturbance levels. The mean concentration of Botryococcus in the upper (120-200 cm) section of the core is 219×10^3 remains $\cdot\text{gm}^{-1}$ dry sediment, approaching the value computed for the basal organic portions (600-900 cm) of the core (242×10^3 remains $\cdot\text{gm}^{-1}$ dry sediment).

Ostracods are found in small numbers and at only a few levels in the bottom 3 m of the core, but display a bit of a peak at 600 cm, in the uppermost organic mud lying just below the thick clay-rich zone. Following the transition to inorganic sediments, ostracods show a small rise at 540 cm only to drop out until 320 cm, where their concentrations rise coincident with the increase seen for many other microfossil types. Encountered at 320-280 cm, ostracod remains disappeared once again at 260 cm only to increase in abundance when more organic sedimentation commenced following the Maya abandonment of the watershed.

Bosminids, unlike the microfossil types already discussed, are rare below the transition zone from organic to inorganic sediment at 590 cm, though many tallied fragments from the basal 3 m appeared to be bosminid mucrones. Intact carapaces and headshields of what is likely Eubosmina tubicen increase in concentration during the Late Preclassic. It is perhaps noteworthy that bosminids became an important component of the zooplankton community in Lake Quexil at about the same time that Bosmina rose in importance in Lake Valencia, Venezuela (Bradbury et al. 1981). About 10^3 carapaces are found in each cm^3 of wet sediment throughout the inorganic zone of the core, though higher concentrations were detected at 540 cm and 440 cm. Abundance per cm^3 is maximal at 320 cm and stays rather high until 260 cm, rising once again in the post-Maya segment of the core. Bosminid headshields generally follow the trend seen for carapaces and might have tracked the carapace concentrations more closely if the headshield abundances were not reliant on small sample sizes.

The graphs for chydorid remains are based on a small number of enumerated carapaces and headshields. The presence of remains throughout the bottom 6 m of the core is spotty, but as for nearly all other microfossil types, concentrations are high from 320 cm to 260 cm in the core, dropping in the inorganic levels above 260 cm, and showing a general increase again in the post-Maya sediments. Chydorid carapaces and headshields reached peak abundance in the sediment at 140 cm.

Focusing on bosminid carapace and headshield concentrations throughout the Quexil H core, it is clear that posterior portions of

the animals accumulated at a greater rate than anterior exuviae. There are 20 levels in the core in which both carapaces and headshields were found. At each of these levels the whole carapace concentration was divided by the headshield concentration, and the mean ratio calculated for all 20 levels was 4.9 carapaces per headshield. This gives a minimal estimate of the differential degree to which the body parts were subject to accumulation in deep water, as nine sampled levels contained carapaces, but no headshields, while only the bottom-most (900 cm) sample displayed the reverse situation. For the six levels containing both anterior and posterior portions of chydorids, the mean ratio was three carapaces per headshield. Five levels had carapaces but no headshields, while only three levels possessed headshields only.

Several processes might account for the higher relative concentrations in the mud of posterior cladoceran remains as compared to anterior portions. Exuviae are evidently transported long distances before final deposition on the lake bottom, and presumably the chydorid remains found in the deep-water sediments originated in distant, littoral areas. In a conical basin like Quexil, there is differential deposition of sediment over the basin bottom, with sediments preferentially laid down in deep trenches. This occurs because there is a greater amount of water and hence more suspended material above deep spots, and because particles that settle in shallow areas are resuspended and carried into deep water. When remains are focused into deep water, a winnowing process may be responsible for the preferential deposition of carapaces. This is contrary to the sorting of eroded

particles that reach the lake as alluvium or colluvium, that ultimately results in smaller particles being deposited at the lake center. If anterior and posterior portions of Eubosmina obey Stokes' Law, as Vallentyne and Swabey (1955) suggest Bosmina longirostris parts do, intact shells should be less prone to resuspension than smaller fragments and headshields. But such an assumption ignores the consideration of the hydrodynamics of the differentially shaped anterior and posterior body parts.

Carapaces may simply preserve better than headshields, and even if deposited in similar numbers at the deep-water coring site, fragility of the anterior sections may have relegated them to the chitin fragments category. While Vallentyne and Swabey (1955) argue that shells are more easily broken into unrecognizable fragments than headshields, antennules are easily lost resulting in a low proportion of complete anterior to posterior remains.

Bosminid remains outnumber chydorid remains in the Quexil H core. In eight levels between 120 cm and 320 cm, the mean ratio of carapaces was 6.3 bosminids per chydorid, and three levels contained only bosminid remains. This probably reflects the great distance of the deep-water coring site from the littoral habitat preferred by chydorids and perhaps the overall high ratio of planktonic to littoral habitat in the lake.

Interpretation of the chitin fragment category is difficult as all pieces were enumerated, regardless of size. While the bottom 3 m contain twice as many fragments per cm^3 as the succeeding 2.6 m, this

does not necessarily imply that half as many whole animals are represented in each cm^3 of the overlying inorganic mud. No effort was made to assess how many fragments constitute an individual. The decline in chitin fragments associated with the appearance of whole bosminid parts at 600 cm is somewhat anomalous as postdepositional destruction (break-up) of remains might be expected to be more severe in the clay-rich sediments above 590 cm. If a large proportion of the fragments were bosminid pieces, whole carapace and fragment concentrations should probably rise together in the inorganic section of the core. That chitin fragment concentrations decline may be explained by the dilution effect of a high inorganic sedimentation rate. The concurrent rise in bosminid density probably implies that their production rates were increasing.

While many of the fragments from the deepest section of the core appeared to be mucrones of bosminids, it is conceivable that they are not. They may be parts of cladocerans whose shells are poorly preserved. After mechanical breakage, these fragments may have been protected from further chemical destruction by deposition in deep water under anoxic conditions maintained by persistent meromixis. This would support the contention that bosminids may have only become common in the Quexil plankton about 2000 years ago.

Microfossil Accumulation Rates and Phosphorus Loading

Phosphorus and microfossil accumulations are now evaluated on a zone-to-zone basis to explore the dependency of microfossil production

rates on the nutrient supply (Fig. 22). Even if Gates employed for calculations are wrong, the error affects each parameter equally and similar zone-to-zone changes for two variables might at least suggest that delivery rates to the sediment are correlated. Botryococcus was the most common alga found in the Quexil H core, and as remains were encountered over the length of the section, changing accumulation rates that might be indicative of shifting primary productivity were compared to phosphorus accumulation rates.

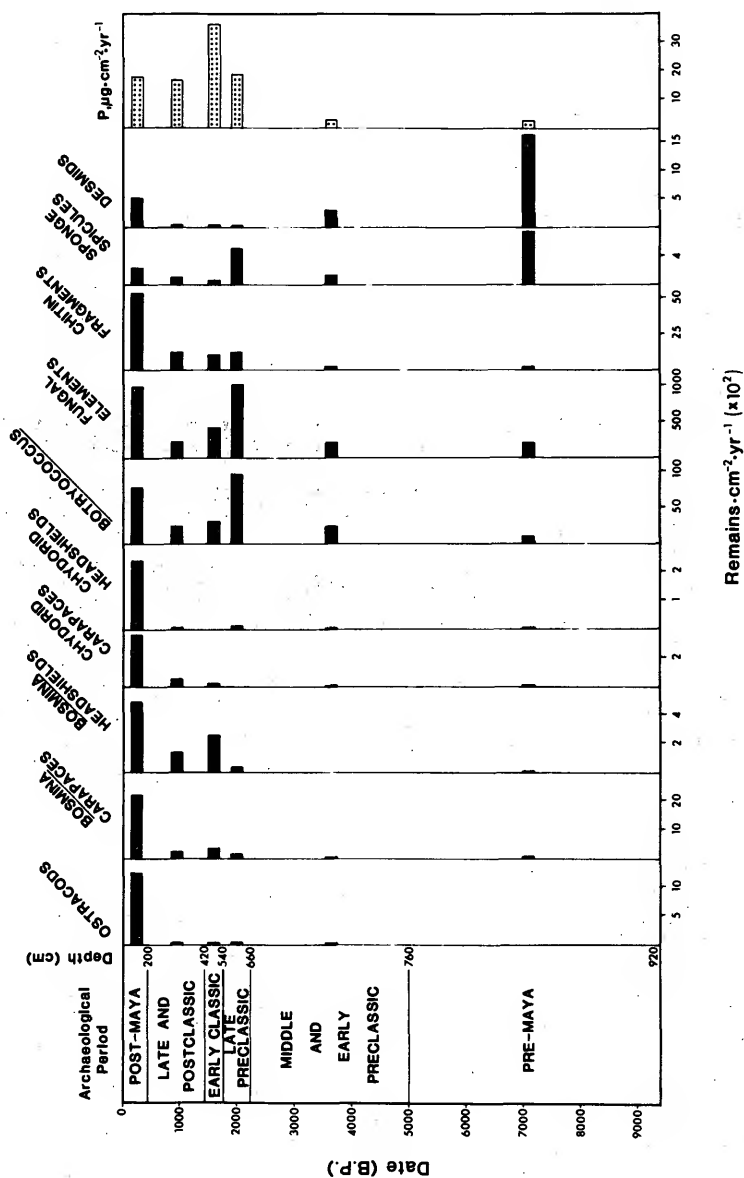
Phosphorus delivery increased from pre-Maya times through the Late Preclassic, and the rise was tracked fairly well by Botryococcus accumulations in the sediment. Between the Late Preclassic and Early Classic, phosphorus accumulation rate nearly doubled, but Botryococcus input to the sediments fell to about one-third the Late Preclassic level. When Late and Postclassic phosphorus input dropped to 45% of the maximal Early Classic rate, Botryococcus accumulation declined also, but only to 77% of the Early Classic level. Late and Postclassic phosphorus loading was nearly equivalent to delivery rates computed for the Late Preclassic, but Botryococcus accumulation had dropped to about one-fourth the Late Preclassic rate. With the Maya depopulation of the catchment, phosphorus accumulation changed little, but Botryococcus production rose more than three-fold.

Zonal changes in fungal element accumulations look similar to shifts in Botryococcus, with fungal remains tracking the phosphorus inputs until the Late Preclassic, only to have their accumulation rates drop substantially in the succeeding Early Classic and Late and

Figure 22. Microfossil and phosphorus accumulation rates at the Quexil core H site, as computed for the various archaeological periods. Core zones were delimited palynologically.

QUEXIL Core H

ACCUMULATION RATES



Postclassic zones. The return to more organic post-Maya sedimentation saw an increase in fungal element accumulation, the rate approaching that calculated for the maximal Late Preclassic. Maximal sponge spicule accumulation occurred during pre-Maya times and was associated with very low phosphorus accumulation. In the succeeding Middle and Early Preclassic section of the core, spicule deposition dropped substantially, though phosphorus accumulation increased slightly. As for Botryococcus and fungal elements, the Late Preclassic was a period of high spicule accumulation. Spicules were supplied to the sediments at slow rates from about 250 to 1600 A.D., but show a resurgence associated with the Maya depopulation of the basin. Zone-to-zone changes in desmid accumulations look much the same as sponge spicule deposition rates, with the exception that desmids fail to display a high Late Preclassic value.

Chitin fragments accumulated at very low rates until the Late Preclassic. The relatively high level of deposition achieved in the Late Preclassic was sustained over the next 13 centuries and then displayed a four-fold increase in the post-Maya sediments. The Late Preclassic was a period of high accumulation rate for animals, and except for chydorid carapaces, accumulation rates for all entomostracan remains were greater in the Late Preclassic than in the preceding underlying zone. Ostracods, like many other fossil types showed reduced delivery to the sediments in the succeeding Early Classic and Late and Postclassic zones, but post-Maya inputs were an order of magnitude greater than those calculated for any preceding period.

Bosminid parts were accumulating at their highest rates in the post-Maya section of the core, and are distinguished from other microfossil types in exhibiting a relatively high Early Classic deposition rate. Intact half carapaces of chydorids were absent in the Late Preclassic sediments, while headshields dropped out in the Early Classic. Anterior and posterior portions of these littoral cladocerans were delivered to the sediment at maximal rates in the post-Maya period.

High, computed post-Maya microfossil accumulations are undoubtedly in excess of the true postdisturbance values. Additionally, post-Maya inputs are exaggerated with respect to accumulation rates calculated for the earlier time periods. In the post-Maya section, microfossil concentration was assessed in the 120-200 cm levels only. Had the top meter been analyzed, the loosely packed, water-rich upper levels would likely have contained fewer remains per cm^3 wet sediment. Thus, the mean number of remains per cm^3 , that was multiplied by the gross sedimentation rate to compute microfossil accumulation rate, was too large. While this error makes comparison of post-Maya accumulation rates with previous period rates somewhat dubious, computed phosphorus accumulation in the post-disturbance section of the core is presumably affected similarly, and zone-to-zone correlation of nutrient and microfossil delivery throughout the core is valid.

If zone-to-zone changes in accumulation rates for total phosphorus and microfossils are inversely related, deposition rates for microfossils are likely independent of the supply rate for the nutrient. Even if total phosphorus and microfossil accumulation rates

increase and decrease together on a zone-to-zone basis, correlation is demonstrated only if the magnitude of change from one zone to the next is similar for both variables. Botryococcus, fungal elements and chitin fragments generally track phosphorus accumulations from the pre-Maya period through the Late Preclassic zone. But the Early Classic accumulation rates for these microfossil types are relatively low despite the dangerously high phosphorus loading rate. Only the Cladocera demonstrate a positive response to enhanced Early Classic phosphorus input. Modern microfossil accumulation rates are all at least twice as high and some many times higher than Late and Postclassic rates, while phosphorus delivery increased only 8% over the value for the preceding period.

The association of high phosphorus delivery with low microfossil inputs to the sediment during the Early Classic is somewhat anomalous if productivity is assumed to have been phosphorus-limited. It is possible that other factors may have restricted photosynthesis during this period. If siltation were sufficiently severe, high phosphorus loading rates may have had little effect on primary productivity. Production may have declined as a consequence of reduced plant-available phosphorus delivery. While the total phosphorus accumulation was maximal in the Early Classic, a small proportion of the delivered element may have been usable for phytoplankton growth. Finally, the Early Classic sediments are highly inorganic (92% inorganic content), and probably constitute a poor preservation medium for sedimented microfossil remains. If diagenesis of deposited microfossils were

particularly severe in the inorganic section of the core, calculated accumulation rates for the remains are poor estimators of the original organismal production rates.

The transition from the Late and Postclassic to the post-Maya period saw a great increase in microfossil accumulation and only a small change in phosphorus loading, suggesting that there was a change in the delivery rate of available phosphorus and/or better preservation conditions. The increasingly rapid deposition rate of organic matter as compared to inorganic matter, resulted in a higher organic proportion in the proximate composition of the sediment, thereby creating better conditions for microfossil preservation. Increasing calculated microfossil accumulations would thus seem to result from a positive feedback system. As more fossils are deposited on the lake bottom, the organic content of the sediment matrix increases, resulting in better preservation of remains and high counts.

Zone-to-zone changes in the average accumulation rates for phosphorus and microfossils may provide some insight into the reliance of microflora and microfauna production on the nutrient supply. However, because average concentrations and mean sedimentation rates are employed in the calculation of the zonal accumulation rates, the true relationship between the parameters can be obscured. A level-by-level comparison of the two variables can evaluate better the reliance of microfossil production rates on the rate of phosphorus supply.

The dependency of microfossil accumulation rates on the total phosphorus input can be tested by calculating the ratio of microfossil

numbers to phosphorus concentration at every level over the length of the Quexil H core. Both variables must be expressed in the same units, as amount per gram dry weight or as amount per cm^3 wet sediment. Instantaneous gross sedimentation rates are the same at a given level whether microfossils or chemistries are being considered. Thus, dilution of one variable by clays, for instance, dilutes the second variable equally. Therefore, the ratio between the accumulation rates for any two variables at a given level is the same as the ratio between their concentrations.

If the accumulation rate of a microfossil type is dependent on and linearly related to the total phosphorus supply in a positive manner, the ratio of microfossil numbers to phosphorus concentration should remain relatively constant over the length of the section. Large variations in the computed ratios suggest that microfossil accumulation rates are independent of or inversely related to the rate of total phosphorus supply.

Botryococcus is the most prevalent primary producer whose remains are abundant in the Quexil H sediments. Botryococcus concentrations, expressed as numbers per cm^3 wet sediment, were divided by the corresponding total phosphorus concentrations, expressed as $\mu\text{g P}$ per cm^3 wet sediment. The calculation was run on 38 levels in the core, and the resultant ratios display a wide range, varying from 6.4 to 1060. The mean ratio is 318, and the standard deviation for the computed values is 294. High variability in the ratios, ranging over more than two orders of magnitude implies that Botryococcus

accumulation in the sediments is not reliant on the total phosphorus supply.

Lack of Botryococcus dependence on the total phosphorus supply was suspected at the outset when concentrations for the two parameters were assessed over the length of the core. Total phosphorus and Botryococcus concentrations fluctuate to different degrees throughout the section, suggesting that inputs to the sediment of the two variables are independent or at least not linearly related in a positive way. Phosphorus concentration averages $70.9 \text{ ug P} \cdot \text{cm}^{-3}$ wet sediment over the length of the core, with a standard deviation of 19.0. Botryococcus concentrations in the core range over two orders of magnitude, displaying a mean value of $24.1 \times 10^3 \text{ remains} \cdot \text{cm}^{-3}$ wet sediment and a standard deviation of 29.8×10^3 .

When the level-by-level Botryococcus-total phosphorus ratios were computed for the Quexil H core, a trend became evident. Higher ratios were encountered in the more organic sediments. Means and standard deviations of the ratios were computed for three major zones in the core, distinguished simply by their different organic matter content. Fourteen samples collected from the organic horizons between 600 cm and 900 cm yielded a mean ratio of 516 ± 294 . Post-Maya organic sediments above 210 cm gave a similar value of 481 ± 201 . In the predominantly inorganic mud between 220 cm and 580 cm, 19 samples produced a mean ratio of only 129 ± 173 . When the ratios in the more organic levels between 280 cm and 320 cm were deleted, the remaining 16 levels had a mean of only 72 ± 95 . Lower numbers of algae relative to phosphorus in

the inorganic disturbance-zone sediments might suggest diagenetic loss of cells in this region of the core. Alternatively, available phosphorus in the clay-rich zones may constitute a smaller proportion of the total phosphorus supply.

The data suggest that Quexil's trophic state, as inferred from Botryococcus concentrations, was not dependent on the total phosphorus supply. Such a conclusion must be qualified. Botryococcus is an important component of the modern phytoplankton, but may have been replaced in the lake during the past, by other, poorly preserved algae. Even the claim that Botryococcus production was not phosphorus limited is stated tentatively. While some other nutrient may have limited the chlorophyte production rate, it is possible that total phosphorus levels measured in the sediment provide little insight into the amount of plant-available phosphorus delivered to the lake. If the proportion of available nutrient as a fraction of the total remained the same through time, conclusions about the phosphorus limitation of Botryococcus might be valid. However, there is little reason to believe that plant-available phosphorus constituted a constant proportion of the total phosphorus reaching the lake, especially following forest clearance and subsequent, prolonged soil erosion. Even if Botryococcus production rates were dependent on the total phosphorus rate of supply, postdepositional destruction of sedimented remains may have obscured the relationship.

Carbon-Nitrogen Ratios in Quexil Core H

Carbon and nitrogen values may reveal information about past levels of lacustrine productivity when their ratio is considered over the length of the core. In the organic-rich segment of the core below 590 cm, C:N ratios are high (18-22) and are adjusted downward only minimally by subtraction of inorganic carbon, which makes up a small fraction of the total carbon pool in this section of the core (Fig. 15). Low productivity, slow sedimentation rates, and consequent prolonged diagenesis of surface muds may have allowed for relatively greater removal of nitrogen, thereby producing the high C:N ratio. A similar explanation has been proposed to account for high C:N ratios in surface sediments of Florida's oligotrophic lakes (Flannery et al. 1982). Thin laminations throughout the basal 3 m of the Quexil H core support the claim that sedimentation was slow during the early Holocene. While the presence of undisturbed laminae implies hypolimnetic oxygen depletion and less rigorous chemically oxidizing conditions, loss of nitrogen from the organic matter may have occurred rapidly when the material was suspended in the warm waters of the photic zone.

Appreciable inputs of allochthonous material with a high C:N ratio (Hutchinson 1957) might be responsible for the measured elemental relationship. This contention is supported by the abundance of terrestrial leaf, twig, and seed remains in the basal part of the core.

With the commencement of inorganic sedimentation came a drop in the C:N ratio. If only the organic carbon fraction had been

considered, ratios would be even lower, as inorganic carbon constitutes a significant amount of total carbon in the clay-rich zones. Several processes may have reduced the C:N ratios throughout the inorganic, disturbance sediments. Following deforestation of the catchment and depletion of the terrestrial organic matter reservoir, autochthonous organic carbon deposition may have increased relative to allochthonous organic carbon input to the sediments. Additionally, rapid sedimentation rate during the period of inorganic deposition may have precluded diagenetic nitrogen loss. As the episode of inorganic sedimentation was associated with high levels of human population density, export of human effluent rich in nitrogen may have reduced the C:N ratio. However, the Terminal Preclassic-Early Classic population hiatus does not show up unless it is the C:N peak at 540 cm. Finally, the rise in abundance of ostracod remains may in part be responsible for the downward shift in C:N ratio. Chitin is a polymer of N-acetylglucosamine (Barnes and Barnes 1978), and higher ostracod concentrations relative to algal remains would tend to depress the C:N ratio in the inorganic portion of the core, assuming that the stability of nitrogen containing compounds in the animal remains is greater than that occurring in plants. With the return of organic sedimentation in the post-Maya period, C:N ratio rose to an average value of 13.8. Though perhaps indicating some terrestrial contribution, the ratio is not much greater than the 12:1 ratio expected from the decomposition of lake plankton (Wetzel 1975).

Comparing Microfossil Accumulation Rates at the Two Quexil Coring Sites

Microfossil accumulation rates at the shallow and deep-water coring sites are now compared on a zonal basis revealing differences in sedimentation at the two stations. Accumulation of bosminid and chydorid carapaces proceeded at similar rates in shallow water. During the Late and Postclassic, bosminids accumulated only 2.39 times faster than chydorids, and in the modern sediments bosminids and chydorids accumulated in a ratio of 1.19:1. In deep water, the Late and Postclassic bosminid:chydorid ratio was 9.6:1 and dropped to only 6.11:1 in the post-Maya sediments. The lower bosminid:chydorid ratio in shallow water sediments reflects the proximity of the coring site to littoral habitat preferred by chydorids. Conversely, the deep coring station is surrounded by planktonic habitat, while littoral zones are a distance away.

Deep water accumulation rates for each fossil type were divided by the corresponding shallow-water zonal accumulation rates to assess the magnitude of differential deposition at the two localities (Table 4). Despite the position of the Quexil H coring site with respect to the littoral areas, resuspension and focusing of chydorid remains into deep water resulted in higher chydorid accumulations there than in shallow water. Late and Postclassic and post-Maya deep-water chydorid accumulation proceeded at rates 4.10 and 3.35 times faster than shallow-water accumulation. At the same time, differential deposition of bosminid carapaces was more pronounced, and deep-water accumulation

Table 4. A comparison of microfossil accumulation rates in Quexil shallow- and deep-water localities. Quexil H zonal microfossil accumulation rates were divided by corresponding Quexil shallow-core accumulation rates. H indicates the fossil was found only in deep-water sediments of the specified zone. A dash indicates the fossil was absent from the zone of both cores.

Archaeological Period	Ostracods	<u>Bosmina</u>	Chydorids	<u>Botryococcus</u>	Fungal Elements	Chitin Fragments
Post-Maya	32.5	17.12	3.35	3.70	21.72	1.84
Late and Postclassic	0.25	16.44	4.10	6.65	22.12	0.26
Early Classic	0.67	H	H	3.08	27.33	0.47
Late Preclassic	4.95	H	-	1.83	7.36	0.96
Middle Preclassic and Early Preclassic	H	H	H	0.49	0.60	0.91
Pre-Maya	-	H	H	2.34	2.71	60.98

rates were 16.44 and 17.12 times the corresponding shallow-core rates in the two recent zones. Valid comparison of post-Maya accumulation rates in the two cores is doubtful, as calculated modern accumulation rates for Quexil H are excessively high because water-rich, and presumably microfossil-poor, sediments in the top meter of the core were not analyzed.

Botryococcus accumulated more quickly in deep water, except during the combined Early and Middle Preclassic period when gross sedimentation at the shallow site was greater than that measured for the deep site. Higher sedimentation rate in shallow water occurred during the time when laminations were forming in deep-water sediments, implying meromictic lake conditions. Productivity in the deep central basin may have been restricted if nutrient regeneration from deep waters was impeded by the chemocline. Productivity may not have declined in the shallow areas to the south and west of the Quexil islands. It is conceivable that this morphometrically distinct region of the lake was not affected by the meromixis detected in the central basin. Resuspension and focusing of remains from shallow to deep water may have been prevented by the presence of a chemically induced density gradient, and fossils would have been preferentially deposited at the monimolimnion boundary.

Fungal elements accumulated at much higher rates in deep water, particularly during Early Classic and Late and Postclassic times. Again, comparison of post-Maya accumulation rates is invalid as modern deep-water accumulations are excessively high. Two processes probably

contributed to greater fungal element accumulation in deep water. The small particles are easily resuspended from the sediment surface and redeposited at the deep site. While focusing of fungal remains may account for some of the differential deposition, order of magnitude differences at the two sites require further explanation. Silicates, delivered as particles of primarily clay and silt size, are also preferentially deposited in deep water. During early Classic and Late and Postclassic times, silicates were deposited in deep water at rates 5.6 and 5.9 times faster than shallow water rates. The biological remains show an even greater tendency for deposition in deep water and fragmentation of hyphal strands in the deep-water inorganic sediments probably contributed to the very high counts.

Ostracod remains only became common in the Quexil sediments during Late Preclassic times. Individuals, as measured by mandibles, were deposited in deep water 4.95 times faster than whole organisms were sedimented in shallow water, as determined by valve enumeration. But the ratio of deep-water to shallow-water accumulation rates dropped below unity in the Early Classic (0.67) and fell even lower (0.25) in the subsequent Late and Postclassic period, indicating higher shallow-water accumulation rates for about 13 centuries. It is possible that the low oxygen content of deep, benthic waters may have restricted ostracods to shallower areas. Additionally, highly inorganic deep-water sediments may have provided a poor habitat for benthic species of seed shrimp. Thus, deep-water production rates of ostracods may have been reduced with the onset of inorganic sedimentation.

Even if ostracod production in deep-water areas declined, focusing of remains into deep trenches might tend to raise computed deep-water accumulation rates. It is likely that many remains deposited in deep water were lost through mechanical break-up and dissolution. The extreme rarity of valves in deep water suggests that carbonates there are readily solubilized, probably under conditions of high CO_2 concentration and low pH. Ostracod shells are only present in deep-water sediments of high organic matter content. Under such conditions, physical destruction is less likely, and the presence of organic matter may reflect less aerobic and anaerobic loss of carbon and hence less CO_2 . Chitin fragments were preferentially accumulating in shallow water during the Early Classic and Late and Postclassic. Large numbers of ostracod shell fragments were encountered in the shallow-water sediments, while deep-water remains assigned to the fragment category were dominated by pieces of cladocerans.

High carbonate content of the shallow-water Late and Postclassic sediments might be invoked to account for the excellent preservation of ostracods in that zone, especially if the presence of detrital carbonates buffers conditions at the sediment surface. As the shallow-water site shows high carbonate content into the post-Maya period, much higher ostracod accumulation in deep water is unexplained. As for other remains, modern deep-water ostracod accumulations are too high, because the flocculent sediments above 120 cm were not analyzed. Even if ostracod remains were absent in the top meter of the core, the computed deep-water accumulation rate would exceed the shallow-water

accumulation rate by more than an order of magnitude. Relatively greater deep-water ostracod accumulation is associated with the return to organic sedimentation and probably resulted from the improvement of the deep-water benthic habitat, resuspension and focusing of remains, and enhanced preservation at the deep site.

TESTING THE PHOSPHORUS LOADING MODEL DEVELOPED AT YAXHA-SACNAB

Coring in Lakes Salpeten, Macanche, and Quexil, 1980

Coring operations at Lakes Salpeten, Macanche, and Quexil were undertaken during the spring of 1980. Long cores from deep water were sought in order to clarify the picture of regional Maya disturbance in the Peten and to obtain sediments of pre-Holocene age that could verify the existence of arid Pleistocene climates in the Central American lowlands. Proxy data documenting such Pleistocene conditions were unknown between Florida (Watts 1975, Watts and Stuiver 1980) and northern South America (Wijmstra and van der Hammen 1966, Bragbury et al. 1981). Deep trenches of the Central Peten lakes were suspected of being probable repositories of Pleistocene-age sediments, as the depressions may have held water even during periods of lower sea levels and water tables. The belief that Pleistocene lake deposits could be retrieved from the Guatemalan lowland basins prompted the 1977 and 1978 Kullenberg coring attempts in Lakes Macanche and Quexil. In 1977, a 5.4-m core (Mac D) was obtained in deep water at Lake Macanche, but the section desiccated and shrank to 4.2 m prior to extrusion. Bottoming in organic-rich mud, the core just managed to penetrate the thick clay lens deposited as a consequence of Maya-induced erosion. Further attempts to obtain even older material from Macanche were thwarted when

the core lift motor was stolen, bringing the 1977 field season to a premature close.

The following year, three, long, deep-water sections were raised from the central basin of Lake Quexil (Fig. 13), but all the cores evidently bottomed in early Holocene deposits. Even when loaded with 220 kg of lead drive weight, the gravity corer was slowed considerably on passage through the thick anthropogenic clay aquiclude and could not penetrate beyond the early Holocene organic deposits below.

The Kullenberg corer proved to be incapable of raising Pleistocene sediments and consequently, a professional drilling company was contracted to obtain sections in 1980. Daho Pozos of Guatemala City conducted coring operations in Lakes Quexil, Salpeten, and Macanche between 22 April and 22 May 1980. The drilling equipment was bolted to a 6.1 m x 9.1 m raft, and samples were taken with a 45.7 cm split-spoon sampler, bearing a 5.08 cm cutting edge or nose cone. The split spoon was lined with plastic pipe and as samples were brought on deck, the tubes were labeled, stoppered, and wrapped in heavy plastic to prevent drying of the sediments. Nose cone samples were packaged separately in Whirl-pak bags. Iron casing pipe was used to guarantee that successive core sections came from the same hole, and the casing was washed out prior to each stepwise lowering. Core samples were stored in wood boxes and returned to the Florida State Museum in September 1980 where they were refrigerated at 4°C before and after extrusion.

At Salpeten (area = 2.626 km², z_{\max} = 32 m, \bar{z} = 7.6 m; Deevey et al. 1980a), a deep-water core (Sal 80-1) was obtained in 26.1 m of water (Fig. 23) and penetrated to 15.1 m below the mud-water

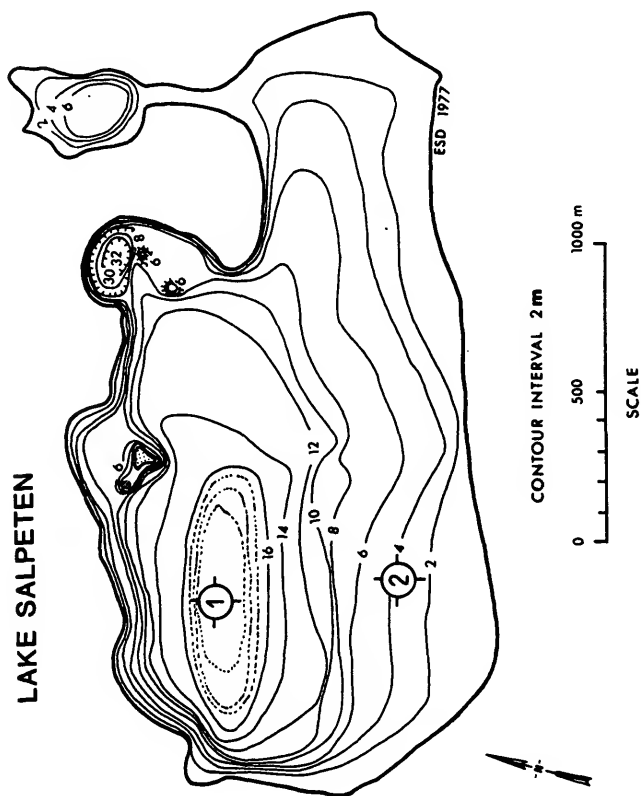
interface. Flocculent, organic surface sediments were not retained in the split-spoon sampler, and the uppermost, clay-rich mud retrieved was thought to lie about 1.6 m below the sediment surface. However, a 1.67-m mud-water interface core taken several meters from the Sal 80-1 site contained a higher water and organic matter content at 1.6 m than the topmost sediments of the Sal 80-1 core. This indicates a probable small gap in the section, but the exact size of the missing section remains undetermined. This difficulty is unresolved as a result of the inability to measure accurately the depth of the loosely packed surface mud.

Continuing the work at Salpeten, a shallow-water section, designated Sal 80-2, was taken in 6.4 m of water (Fig. 23) to compare deep- and shallow-water sedimentation in the saline lake. The top 2 m of the core were obtained with a Livingstone piston-corer (Deevey 1965) and subsequent sections were collected with the split-spoon sampler, thus raising a complete 5.39 m profile.

The Sal 80-1 core was sampled at 52 levels over its total length and Sal 80-2 was sampled at 28 levels. At each sampling point in the cores, two 1 cm³ volumetric plugs of sediment were removed and weighed to determine wet weight per unit volume. These samples were next dried at 110°C to evaluate percent dry weight, and then burned at 550°C in a Thermolyne Type 1500 furnace to assess organic matter content by loss on ignition. A second set of samples was dried at 110°C and ground to a fine powder with a mortar and pestle. Weighed aliquots of the pulverized sediment were used for total carbon analyses

Figure 23. Bathymetric Map of Lake Salpeten showing the location of the shallow-water and deep-water coring sites.

LAKE SALPETEN



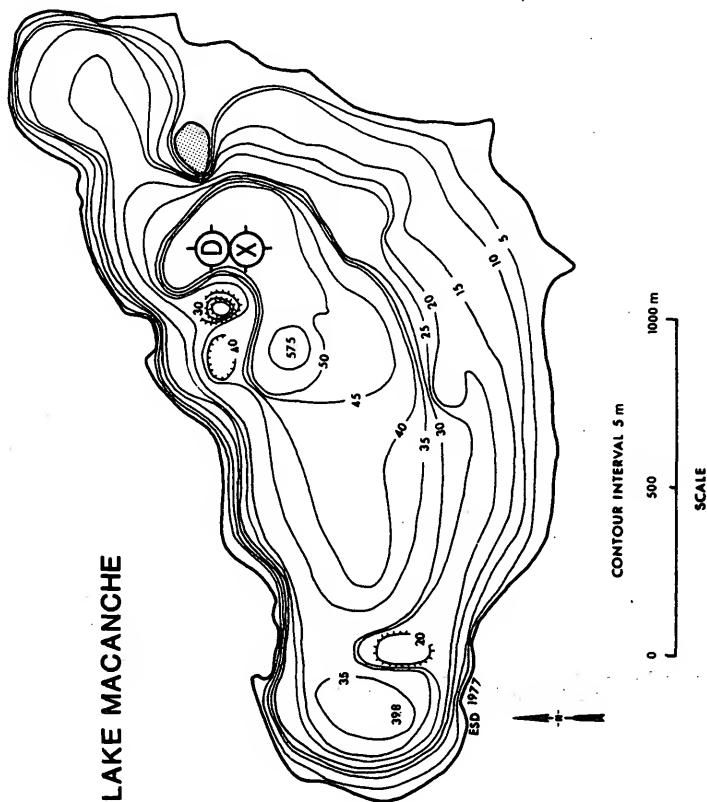
<u>Lake</u>	<u>Site</u>	<u>Core</u>	<u>Year</u>	<u>Water depth</u>	<u>Depth below M.W. Interface</u>
Salpeten	1	80-1	1980	26.1 m	1.29-15.1 m
Salpeten	2	80-2	1980	6.4 m	0-5.39 m

that were run in a LECO induction furnace. Another portion of the ground sediment was weighed and digested in 15 ml of a 2:1 nitric-perchloric acid mixture. The digested samples were filtered and the filtrate was brought to a volume of 50 ml. Sulfur determinations were run on the digestate turbidimetrically according to Standard Methods (APHA 1961). Cation analyses were done by atomic absorption and total phosphorus was run on a Technicon Autoanalyzer at the University of Florida Institute of Food and Agricultural Sciences Soils Laboratory. Chemical concentrations in the mud were then figured as amounts per gram of dry sediment (Figs. 25 and 26).

At Lake Macanche (area = 2.166 km^2 , $z_{\text{max}} = 57.5 \text{ m}$, $\bar{z} = 25.1 \text{ m}$; Deevey et al. 1980a), more than 10 m of sediment was retrieved in 55.8 m of water. Coring began about 0.61 m below the mud surface and terminated 10.77 m below the mud-water interface. The sediment profile, designated Mac 80-1, was obtained in deep water southwest of the island in the basin and south of the 1977, Mac D coring site (Fig. 24). Sampling and processing of the 39 samples taken over the length of the core were similar to the treatment of Salpeten samples, with minor exceptions. Cation determinations on digestate were run by atomic absorption at the University of Florida Department of Environmental Engineering and total phosphorus analyses were run manually on a Coleman Model 14 Spectrophotometer, after blue color development by the ascorbic acid-ammonium molybdate technique. As at Salpeten, chemical concentrations were figured as amounts per gram of dry sediment (Fig. 27).

Figure 24. Bathymetric Map of Lake Macanche showing the locations of the deep-water core sites.

LAKE MACANCHE



Lake	Site	Core	Year	Water depth	Depth below M.W. interface
Macanche	D	D	1977	54.5 m	0-4.22 m
Macanche	X	80-1	1980	55.8 m	0.81-10.77 m

Figure 25. The chemical stratigraphy of the Salpeten 80-1 deep-water core. Dry weight and organic matter values for a mud-water interface core are also shown. There is a small gap of unretrieved sediment between the base of the mud-water interface core and the top of Sal 80-1.

SALPETEN **Core 80-1**

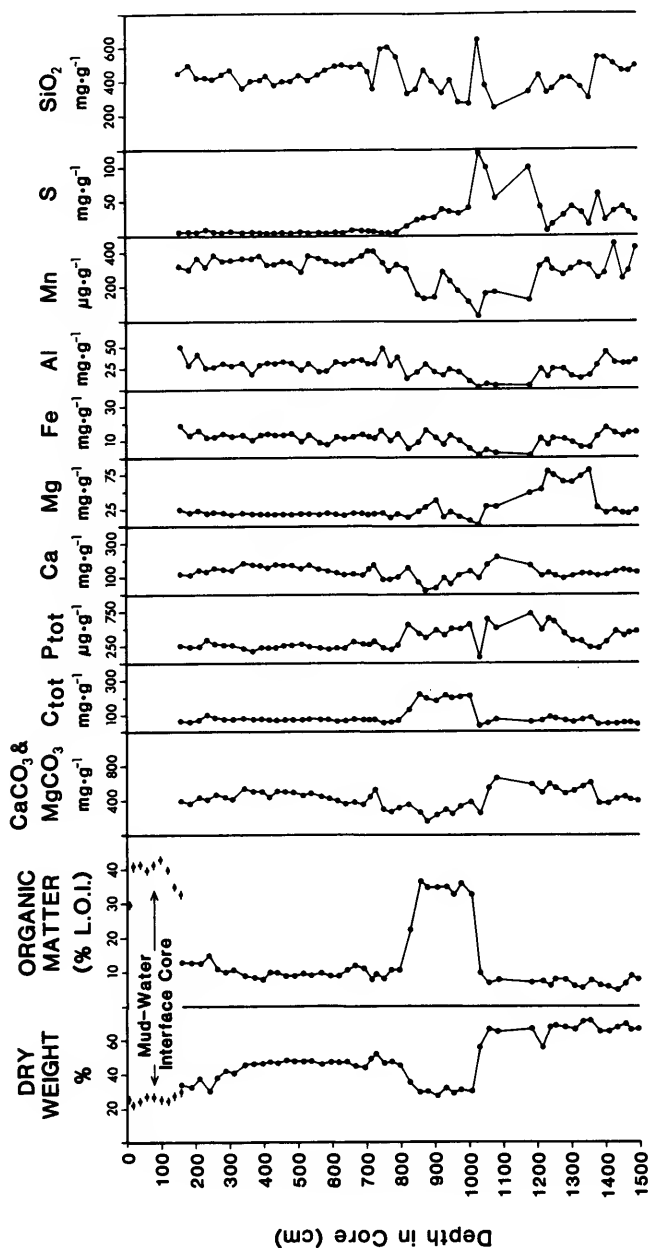


Figure 26. The chemical stratigraphy of the Salpeten 80-2, shallow-water core.

SALPETEN
Core 80-2

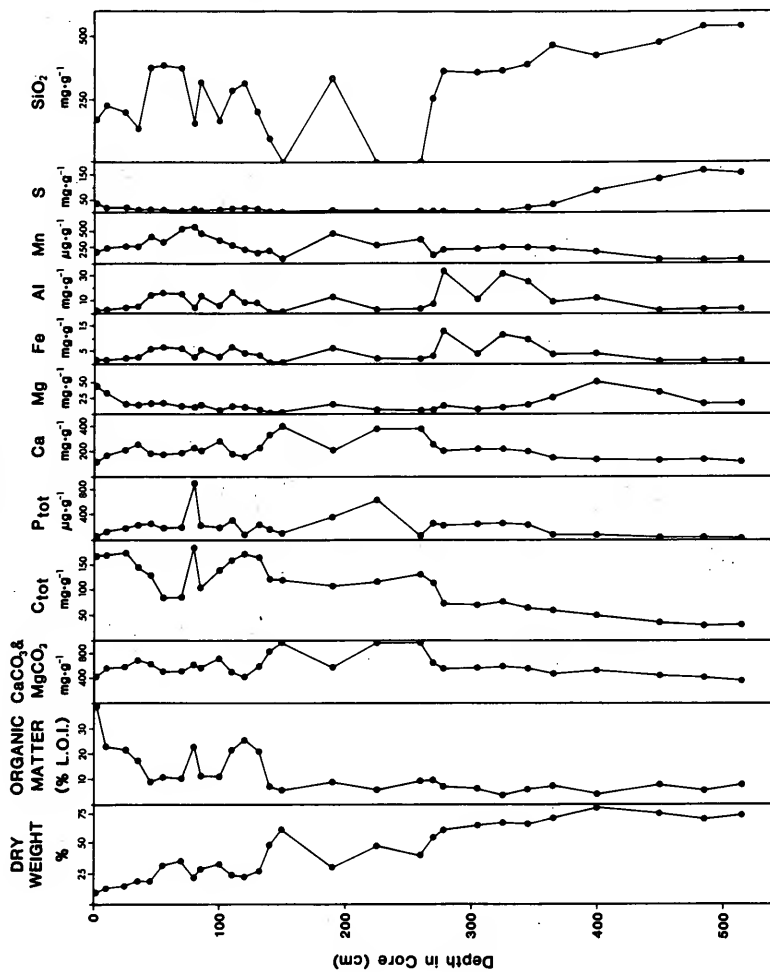
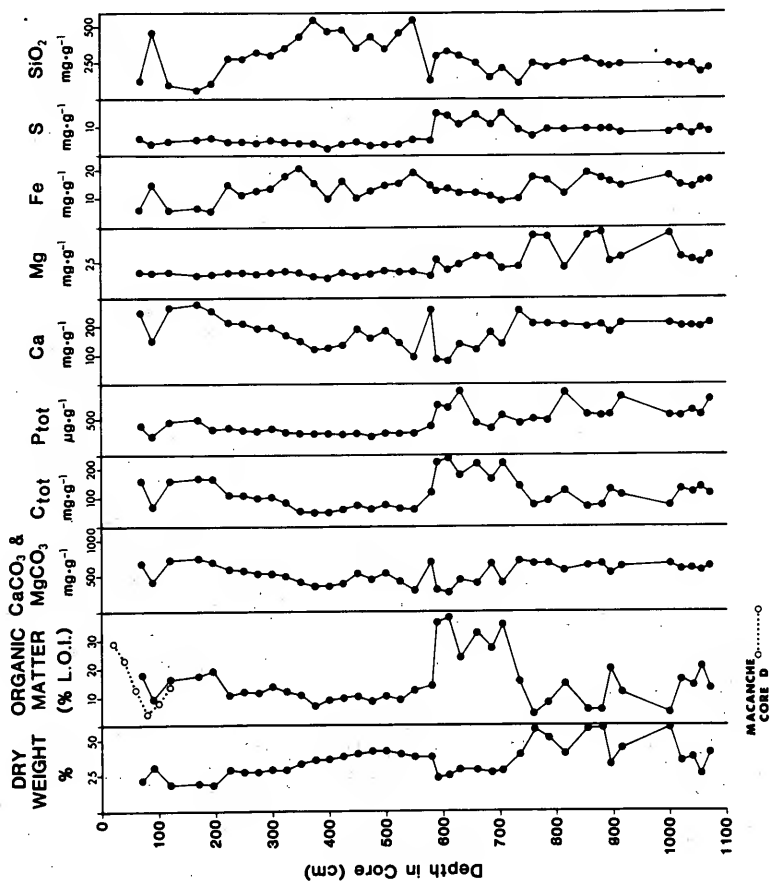


Figure 27. The chemical stratigraphy of the Macanche 80-1 core.

MACANCHE

Core 80-1



Lake Quexil yielded two deep-water (29 m) profiles of differing length. Core Que 80-2 comes from 4.57-9.65 m below the mud surface and the unextruded uppermost sediment from the profile contains a high clay content. This inorganic deposit is anthropogenic and is assigned a Maya-period age by gross stratigraphic correlation with Quexil core H. At about 5 m depth, there is a transition to more organic sediments and this condition prevails until about 8.9 m depth in the profile where the deposits are again dominated by inorganics that mark the Pleistocene-Holocene boundary. Core Que 80-1 began in organic sediment 7.49 m under the mud surface and drilling ended 12.19 m below this depth. Basal sediments from the section were taken from 19.68 m below the mud-water interface, extending the Quexil H core sediment record by more than 10 m. Core Que 80-1 has been analyzed mineralogically and the bottom 10 m are rich in calcite and gypsum, presumably deposited when lake levels were low during late Pleistocene times (Deevey et al., in press).

Lying above and in contact with the inorganic Pleistocene deposits of Que 80-1 are humified organic sediments, at some levels rich in leaf and wood fragments. Small bits of wood were removed from a 7 cm portion of the core (8.94-9.01 m) and pooled as a sample for radiocarbon dating. The sample (SI-5257) was run by Robert Stuckenrath at the Smithsonian Institution Radiation Biology Laboratory and produced a radiocarbon age of $10,750 \pm 460$ B.P. Though the error on the determined age is large, the terrestrial wood date is free from the confounding problem of the hard-water-lake effect. Gross stratigraphic

correlation of Que 80-1 with the 1978 Quexil H section confirms the claim that a near-complete Holocene profile was obtained by the Kullenberg corer. The 1980 Quexil cores await further chemical and palynological examination.

Sediment Chemistry of the Macanche and Salpeten Cores

Proximate composition of the Macanche and Salpeten sediments was figured on a level-by-level basis. Carbonate content was assessed by calculating the carbonate equivalents of magnesium and calcium and summing the two chemical types. Iron was assumed to be present as Fe_2O_3 and organic matter content was obtained directly by the loss on ignition procedure. Silicates, presumably present as aluminosilicates, were assumed to be the residue following subtraction of organic matter, CaCO_3 , MgCO_3 , and Fe_2O_3 (Figs. 25-27).

In computing the proximate composition of the Salpeten sediments, some error was introduced by assuming all calcium and magnesium to be bound with carbonate. In the sulfur-rich inorganic sections of the cores, much of the calcium and magnesium is doubtless bound with sulfate. Thus, because silicates are figured by difference and carbonate has a lower molecular weight than sulfate, SiO_2 values are probably overestimated in the sulfurous levels of the cores. The computation of proximate composition assumes that organic matter, CaCO_3 , MgCO_3 , Fe_2O_3 , and SiO_2 comprise 100% of the sediment. Most of the aluminum reported for the Salpeten cores represents a

fraction of the SiO_2 value, and is presumed to have been extracted, in part, from clays. Other chemical constituents of the mud probably amount to less than 1% of the sediment dry weight. Sulfur is the exception, and in the basal, sulfur-rich levels, proximate make-up of the sediment is grossly miscalculated, as sulfur comprises more than 5% of the sediment by weight in several levels of both cores.

Palynological zonation of core Quexil H proved ineffective for refining the phosphorus loading model developed at Lakes Yaxha and Sacnab. Cores obtained at Lakes Macanche and Salpeten during the 1980 field season have not yet been studied palynologically, but as these watersheds also experienced a Maya population hiatus in the Early Classic (Fig. 8), anticipated phosphorus loading figures based on palynological fine-zoning may be poor estimates of the true loading values. With sediment chemistry completed on shallow- and deep-water cores from several lakes, an alternative, crude test of the phosphorus loading model was formulated. Rather than testing the response of phosphorus inputs to incremental Maya population changes in a single basin (intensively), the total phosphorus load attributable to Maya disturbance can be assessed and compared to integrated Maya population curves in several basins (extensively).

Lacking pollen data from the Salpeten and Macanche cores, alternative parameters were employed for zonation of the profiles from these lakes and for rezoning the Sacnab core, Quexil H, and the Quexil shallow-water section. At Sacnab and Quexil, Maya agro-engineering activities were shown to have caused a shift in the proximate

composition of the sediment to an overwhelming domination by the inorganic components, and abandonment of the catchments resulted in a resumption of more organic deposition. While the palynological record may represent a mix of regional and local vegetation changes, shifts in the chemical composition of the sediments indicate changing erosional processes within the drainage. Thus, the major inorganic-organic transition horizons are considered to be reliable basin-specific markers that identify the inception and termination of Maya occupation in the watersheds. In Quexil and Salpeten, where the corer penetrated beyond the organic, pre-Maya sediments, the calcite and gypsum-rich underlying deposit distinguishes a dated, climatically-induced change in sediment composition that marks the Pleistocene-Holocene boundary (Deevey et al., in press). With dates attached to three levels in the cores (Pleistocene-Holocene transition, initial Maya disturbance, Maya disappearance), and complete chemical profiles, pre-Maya, baseline chemical accumulation rates can be computed as can disturbance period chemical delivery rates.

Using this type of dating procedure, several questions can be addressed. Export of inorganic matter from terrestrial areas is accelerated by human disturbance, and the magnitude of change over baseline rates can be evaluated. Delivery of phosphorus to the lakes presumably increased as a consequence of vegetation removal, and the degree of change attributable to human perturbations can be measured. Annual per capita phosphorus export to Lakes Yaxha and Sacnal was estimated at about 0.5 kg (Deevey et al. 1979). Together with

archaeologically derived demographic histories from the watersheds, the chemical stratigraphy can be used to test this proposed figure.

Finally, within- and between-lake comparisons of phosphorus accumulation rates permit an assessment of the influence that core location and lake morphometry have on estimating the lake-wide phosphorus accumulation rate.

Assessing the Maya Annual Per Capita Phosphorus Output Zoning the Cores Chemically

To test the phosphorus loading model developed at Yaxha and Sacnab, the procedure employed at the twin basins was essentially reversed. In the easternmost twin lakes, the effective riparian area was delimited and phosphorus outputs from the Maya populations during any given archaeological period were calculated, assuming export from the watershed to have equalled the phosphorus input values derived from the study of the sediment cores. On these assumptions, export was at a rate of $0.5 \text{ kg} \cdot \text{capita}^{-1} \cdot \text{yr}^{-1}$. The new back-calculation procedure assumes export at this per capita rate and abandons the fine-zoning technique used at the twin lakes. The entire disturbance-zone sequence is considered as a single unit.

The rate at which phosphorus accumulated on the lake bottom as a consequence of disturbance was computed by calculating the disturbance-zone phosphorus accumulation rate and subtracting the pre-Maya baseline rate. This rate was multiplied times the span of

Maya time and the lake area, to compute the total amount of phosphorus deposited on the basin floor as a result of human disturbance. It was assumed that the disturbance phosphorus load reached the lake at a rate of $0.5 \text{ kg} \cdot \text{capita}^{-1} \cdot \text{yr}^{-1}$, and the number of person-years necessary to generate the disturbance phosphorus load was computed. Next, the population density graph for a watershed was integrated, to provide a figure that represents the number of person-years lived per km^2 over the span of Maya time. The number of person-years necessary to generate the disturbance phosphorus load was then divided by the number of person-years $\cdot \text{km}^{-2}$ lived throughout Maya time. This procedure provides a value representing the area that must have been occupied throughout Maya time to account for the disturbance phosphorus input. If the estimated annual per capita phosphorus export figure (0.5 kg) is reasonable, the calculated effective riparian area should approximate the true source area for eroded soils, the region enclosed by nearest high ground.

Zones in the cores were delimited based on changes in the organic matter concentration of the sediment. Thus, changes in loss on ignition or calculated organic carbon figures were employed to distinguish horizons. The bottommost, Pleistocene-Holocene transition was assigned a date of about 10,000 B.P., or 8000 B.C., for calculating pre-Maya accumulation rates. As wood from the basal portion of the Quexil shallow-water core gave an age of 8410 ± 180 radiocarbon years (Ogden and Hart 1977) and the climatically-induced sediment transition was dated at $10,750 \pm 460$ radiocarbon years in core Que 80-1

(Stuckenrath, pers. comm), the assigned age for the inception of the Holocene is not unreasonable. The age is consistent with the 10,500 B.P. estimates for the early Holocene lake level rise of Lake Valencia, Venezuela (Bradbury et al. 1981, Binford 1982), and with ^{14}C dates for the inception of "Early Holocene moist periods" in tropical Africa (Butzer et al. 1972) and southern Australia (Bowler et al. 1976).

The age of the Pleistocene-Holocene transition is perhaps slightly underestimated. This has the effect of reducing by a small amount the number of years allowed for pre-Maya sedimentation, and thus causes a minor overestimation of pre-Maya chemical accumulation rates. Computed predisturbance chemical accumulation rates are based on a pre-Maya time span of 7000 years, so if post-Pleistocene organic sedimentation truly began as early as 11,000 B.P., the calculated predisturbance chemical accumulation rates would be too high by a factor of only 14%. As predisturbance chemical accumulation rates are generally small relative to delivery rates calculated for the Maya disturbance zone, the chemical accumulation rate due solely to human impact (Maya zone rate-baseline rate) is changed little by adjustment of the Pleistocene-Holocene transition age.

Initial Maya intrusion in the Peten watersheds is detected in the cores by a reduction in sediment organic content (Figs. 14, 15, 25, 26, 27), and the horizon was assigned an age of 1000 B.C. The oldest ceramic sherds encountered at Lakes Yaxha and Sacnab were relegated to the Ah Pam complex, while Amanece ceramics are the oldest artifacts encountered in the western watersheds (Rice and Rice 1981). As both

the ceramic complexes are of Middle Preclassic age (1000 B.C.-250 B.C.), the inception of Maya settlement in the drainages was dated at 1000 B.C. Earlier studies at Sacnab and Quexil (Deevey et al. 1979) pushed the Middle Preclassic boundary to 1500 B.C. to accommodate possible pioneer settlement in the catchments, but this test of the model hews to the archaeological record and uses the oldest, generally accepted Middle Preclassic age.

It is certainly possible that initial settlement in the basins postdated 1000 B.C. Nevertheless, assigning the earliest disturbance-zone sediments the maximum archaeologically supported age of 1000 B.C. allows the longest period of time for the accumulation of Maya-zone sediments. This results in the lowest possible calculated Maya-period chemical accumulation rates, and computed increases over baseline rates can be considered minimal. Further reduction of the Maya-period chemical accumulation rates could be accomplished by using an even older date for the organic-inorganic transition. However, lacking archaeological evidence for earlier human activity in the drainages, the 1000 B.C. date provides the most conservative estimate of human impact consistent with other data.

Maya abandonment of the Peten watersheds caused the resumption of organic sedimentation and this horizon was assigned a date of 1600 A.D., some 75 years after colonial contact and nearly a century before the Spanish conquest of the Itza Indians in the Central Peten (Stuart and Stuart 1977). Thus, Maya occupation of the Peten watersheds is registered as a 2600-year inorganic interruption in the Holocene,

lacustrine, organic sediment record. Post-Maya, deep-water sediment accumulations in the Peten lakes range from a minimum of roughly 80 cm (Macanche) to 210 cm (Quexil), and it is thought to be unlikely that the onset of organic sedimentation postdates 1600 A.D. An argument might be made for dating the resumption of organic sedimentation at about 850-900 A.D., concurrent with the Classic Maya collapse.

However, reforestation apparently commenced following the end of the Postclassic phase of occupation (Vaughan and Deevey 1981), and in the Quexil shallow-water core, Quexil H, and Macanche core D, forest recovery and organic sedimentation begin at nearly identical levels in the sections. Use of the more recent date (1600 A.D.) allows more time for Maya-period sedimentation. The tendency is to bias on the low side all chemical accumulation rates in the disturbance zone. Increases over predisturbance rates, which constitute a measure of human impact, are thus considered to be minimum values.

Six sediment sections from four lakes were used to reevaluate the phosphorus loading model developed at Yaxha and Sacnab: Quexil H, the Quexil shallow-water section, Sal 80-1, Sal 80-2, Mac 80-1, and the Sacnab profile. Some of the sediment sections do not span the entire Holocene, and a brief discussion of the problems associated with each is appropriate. The Quexil cores bottomed-out above the Pleistocene boundary, thus pre-Maya, baseline phosphorus accumulation rates are underestimated slightly if the basal age of the cores is truly under 10,000 years old. It has been argued elsewhere that the bottommost levels of the Quexil sections are likely about 9400 calendar years old

(Deevey et al. 1979; Brenner, in press), implying that calculated predisturbance phosphorus accumulation rates are off by no more than about 10%. As pre-Maya accumulation rates are small, relative to Maya period rates, the computed accumulation rate due to disturbance alone is altered minimally by the error in the baseline estimation.

At Sacnab (area = 3.897 km^2 , $z_{\text{max}} = 13 \text{ m}$, $\bar{z} = 6.5 \text{ m}$; Deevey et al. 1980a), the pre-Maya phosphorus accumulation rate is grossly underestimated if the bottom of the core is assigned an age of 8000 B.C., as the Livingstone piston-corer failed to even reach the pre-Maya pollen zone known from analysis of the Quexil cores. The consequence is an overestimation of the phosphorus accumulation rate due to Maya activity alone.

Macanche core 80-1 did not reach the Pleistocene boundary, but is thought to be a fairly complete Holocene section. A basal, bulk sediment sample (SI-5254) yielded a radiocarbon age of 9855 ± 230 , but is subject to hard-water-lake error and is too old to be corrected for possible atmospheric ^{14}C enrichment using the bristlecone pine chronology. If atmospheric levels of ^{14}C remained high as far back as the Pleistocene-Holocene transition (Stuiver 1970), the two principal phenomena contributing to dating error would tend to cancel each other. The radiocarbon age of the bottommost Mac 80-1 sediments may be roughly equal to the sidereal age. At Salpeten, both cores penetrated the Pleistocene boundary and the pre-Maya portion of the Holocene sequence is complete.

The inorganic Maya disturbance zone is complete in all the cores except Sal 80-1. As the topmost sediments of the section are inorganic, no post-Maya mud was recovered, and the latter part of the Postclassic sequence is apparently missing. Nevertheless, the incompleteness of the section is thought to have a negligible effect on the computed Maya zone sediment accumulation rate, reducing it by less than 10%. The split-spoon sampler, lowered 50.78 cm with each successive drive, was unable to retrieve post-Maya organic material because it was loosely packed and simply fell from the coring tube. Inorganic deposits, rich in clay, were held without the aid of a core-catcher, and it is unlikely that an entire drive segment of disturbance zone mud was lost. Even if 50 cm of the section did fall from the sampler, 685 cm of Maya zone mud was obtained, and the missing portion represents, at most, 7% of the disturbance zone segment.

When zonal chemical accumulation rates for the cores were computed, it was evident that both phosphorus and inorganic matter were delivered to the basins at accelerated rates as a consequence of Maya activity in the catchments (Table 5). Focusing on phosphorus, it is apparent that the measured increases in accumulation rates over baseline levels range from 16% at Macanche to more than an order of magnitude registered in shallow water at Salpeten. Baseline phosphorus accumulation rates were subtracted from Maya zone rates to compute the rate of accumulation on the lake bottom due to disturbance alone. Assuming the disturbance rate to have been uniform over the basin floor, the entire phosphorus load deposited as a consequence of human

Table 5. Total phosphorus and inorganic matter accumulation rates for six long cores. Core zones were delimited based on changes in the organic matter (LOI) or C_{org} content of the profiles.

Core	Zone	Years In Zone	Depth In Core (cm)	Inorganic Accumulation Rate $mg \cdot cm^{-2} \cdot yr^{-1}$	Phosphorus Accumulation Rate $ug \cdot cm^{-2} \cdot yr^{-1}$
Quexil Shallow- water	Maya	2600	230-80	8.9	2.9
	Pre-Maya	7000	642-230	2.4	1.6
Quexil H	Maya	2600	590-210	38.7	12.0
	Pre-Maya	7000	920-590	4.1	3.2
Salpeten 80-2	Maya	2600	105-40	7.1	2.3
	Pre-Maya	7000	135-105	0.9	0.2
Salpeten 80-1	Maya	2600	845-160	138.1	39.4
	Pre-Maya	7000	1025-845	5.7	4.1
Sacnab	Maya	2600	380-100	36.1	5.3
	Pre-Maya	7000	625-380	5.7	2.2
Macanche 80-1	Maya	2600	585-85	67.0	24.1
	Pre-Maya	7000	1070-585	29.7	20.7

activity was calculated for each lake. Testing of the model then required the integration of the archaeologically derived, Maya population density curves.

The reconstruction of prehistoric Maya population density curves for the Peten watersheds has been briefly discussed. The procedure is detailed here to point out slight between-watershed differences in the integration process used to compute person-years·km⁻² lived in each basin over Maya time, and to explain the treatment of the isolated island populations in Quexil and the peninsula inhabitants at Salpeten. P.M. Rice's preliminary analysis of ceramic sherds from test pits dug in mounds at Quexil, Salpeten, and Macanche permitted the assignment of each artifact to one of six chronostratigraphic periods. In the earlier study at Yaxha and Sacnab, ceramic material from the housemounds was relegated to one of five archaeologically defined zones (Table 6), though Postclassic occupation of the twin basin region was confined to the Yaxha island sites.

Within each basin, the percentage of mounds occupied during a given archaeological period was calculated by dividing the number of time-specific occupations, as derived from the ceramic record, by the total number of test-pitted mounds. The density of housemounds in a watershed was figured by assuming that 84% of the structures on transects were residential, while some 16% were adjunct constructions, as had been done at Tikal (Haviland 1970). The proportion of time-specific occupations was then multiplied by the total residence density to obtain the number of residences occupied per km² during

Table 6. Ceramically defined archaeological periods of the Peten watersheds. Ceramics from housemounds in the catchments were assigned to the various periods, thus dating the occupation of a structure.

Quexil, Salpeten, Macanche			Yaxha-Sacnab		
Archaeological Period	Age	Duration (Years)	Archaeological Period	Age	Duration (Years)
Postclassic	1000- 1600 A.D.	600	Postclassic	850- 1600 A.D.	750
Terminal Classic	850- 1000 A.D.	150	Late Classic	550- 850 A.D.	300
Late Classic	550- 850 A.D.	300	Early Classic	250- 550 A.D.	300
Early Classic	250- 550 A.D.	300	Late Preclassic	250 B.C.- 250 A.D.	500
Terminal Preclassic	100 B.C.- 250 A.D.	350	Middle Preclassic	1000 B.C.- 250 A.D.	750
Middle & Late Preclassic	1000- 100 B.C.	900			

each of the designated archaeological time periods. The residence density (residences \cdot km $^{-2}$) for each time span was then multiplied by the number of persons per residence (5.6) to calculate the number of persons per km 2 , which by convention is the population density for the end of a time period. While Haviland (1972) has argued that a figure of 5.0 inhabitants per structure might be more appropriate, this crude test of the model employs his earlier (1970) value to be consistent with the phosphorus loading model developed at Yaxha and Sacnab.

The mean population density for each defined archaeological period was figured as the average level between the end of the preceding period and the end of the time span being considered. The mean population density for a period was then multiplied by the number of years in the zone to obtain the number of person-years \cdot km $^{-2}$ lived during the time interval. This was done for each archaeologically-defined time period and the values were summed, essentially integrating the population density graphs and producing a figure that represents the total number of person-years \cdot km $^{-2}$ lived in a basin over Maya time (1000 B.C.-1600 A.D.). The integration procedure was modified slightly when dealing with Sacnab's population. As Sacnab supported no Postclassic settlement, and the Classic period collapse in population likely occurred over a span of 50-100 years, a mean Postclassic population level intermediate between the Classic peak value (168 persons \cdot km $^{-2}$) and zero grossly overestimates the density in the basin following the Classic period termination. Thus, for

calculating purposes, the mean population density after 850 A.D. was assumed to be $14 \text{ persons} \cdot \text{km}^{-2}$ or about 10% of the Late Classic mean ($135 \text{ persons} \cdot \text{km}^{-2}$). This allows for the persistence in the basin of some Terminal Classic habitation, or use of the catchment by some of Yaxha's Postclassic inhabitants. In any case, the integrated postcollapse population density at Sacnab accounts for only about 10% of the total integrated Maya period population density in the basin.

The rate of phosphorus accumulation on the lake floor attributable to human activity was calculated by subtracting the baseline rate from the Maya zone rate. Assuming sediment accumulation to be uniform over the basin bottom, the disturbance phosphorus accumulation rate was multiplied by the lake area and 2600 years of Maya time. This computation produced a figure equal to the entire disturbance-generated phosphorus load on the lake bottom. To calculate the number of person-years necessary to produce this phosphorus input, the load was expressed in kg and divided by the proposed per capita loading rate ($0.5 \text{ kg} \cdot \text{person} \cdot \text{year}^{-1}$). This procedure was used to compute the number of riparian person-years necessary to generate the disturbance load at Sacnab and Macanche.

At Quexil, the two islands were occupied and the phosphorus generated by the island inhabitants had to be considered prior to the determination of the "mainland" person-years required to produce the "mainland-derived" phosphorus load. The proportion of test-pitted island mounds showing occupation during the archaeologically defined time periods was multiplied by the total number of residences on the

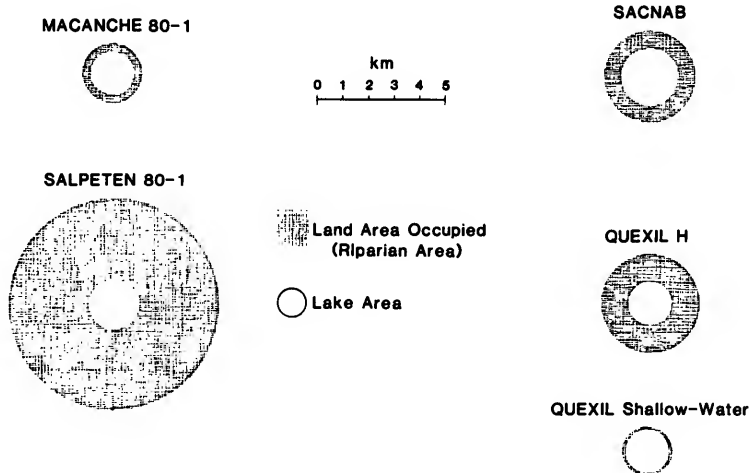
islands to obtain the total number of housemounds occupied during each ceramically identified time period. The total number of occupied residences for each period was multiplied by 5.6 persons \cdot residence $^{-1}$ to obtain the maximal island populations for the close of each archaeological time period. Mean population levels for the time periods were determined and multiplied by the number of years in each period to calculate the number of person-years lived on the islands by time period. The summation of these values provides the total integrated number of person-years lived on the islands throughout Maya time. This figure was multiplied by 0.5 kg phosphorus \cdot person-year $^{-1}$ to obtain the total disturbance phosphorus load contributed by the island inhabitants. This value was subtracted from the total Quexil disturbance phosphorus load to produce a figure equal to the total disturbance phosphorus input attributable to the "mainland" populations. This number was then divided by the per capita loading rate to obtain the number of person-years required to account for the nutrient input originating on the "mainland." For Salpeten, the peninsula site of Zacpeten, that was densely settled in the Postclassic, was treated in the same manner as the Quexil islands in order to compute the number of person-years required to account for the phosphorus brought in from the land surrounding the basin. To accomplish this, the phosphorus generated by the peninsula inhabitants was subtracted from the total disturbance phosphorus load before the number of "mainland" person-years necessary to produce the "mainland-derived" phosphorus input was calculated.

For each basin, the number of riparian person-years required to generate the phosphorus load was divided by the archaeologically derived figure for the number of person-years·km⁻² lived throughout Maya time. This produced a computed riparian area that was evidently occupied to account for the measured "mainland" disturbance phosphorus load. If the annual per capita phosphorus loading value (0.5 kg) is reasonable, the computed riparian area should match the size of the true drainage, the region from which colluvium could have been derived. A model was constructed that assumes the lakes are circular and considers the occupied riparian region to have been a concentric band surrounding the lake (Fig. 28) . This permits the calculation of the approximate distance from shore that would have been occupied (effective riparian distance) in each watershed.

The Impact of Sediment Focusing

The two Quexil cores have already been used to document the effects of sediment focusing in the conical basin. The differential, calculated effective riparian areas derived from study of the two sections again reflect the impact of sediment focusing. Evidently, single cores from conical basins can be poor estimators of the integrated, mean lake-wide sedimentation rate. The Quexil H core undoubtedly overestimates the true riparian area, as the core site received much of the Maya-induced colluvial load emanating from the steep north slopes as well as redeposited material originally

Figure 28. Sensitivity of the phosphorus output model developed at Yaxha-Sacnab to inaccurate estimates of lake-wide phosphorus accumulation resulting from sediment focusing. Deep-water cores in conical Lakes Salpeten and Quexil overestimate the riparian area while shallow-water cores underestimate the region. Cores from ellipsoid Lakes Macanche and Sacnab most closely approximate the true riparian area.



Lake Core	Lake Area (km ²)	Computed Riparian Area (km ²)	Computed Maximum Riparian Distance from Shore (km)	Potential Effect of Sediment Focusing
QUEXIL SHALLOW-WATER	2.101	0.47	0.09	HIGH
QUEXIL H	2.101	8.66	1.05	HIGH
SALPETEN 80-1	2.828	46.81	3.08	VERY HIGH
SALPETEN 80-2	2.826	--	--	VERY HIGH
MACANCHE 80-1	2.188	1.78	0.28	LOW
SACNAB	3.897	5.78	0.64	LOW

sedimented in shallow areas. The deep-water core demands the occupation of 8.88 km^2 , thus resulting in a grainage to lake ratio of 4.23:1. This requires that settlement as far from the lake shore as 1.05 km be considered truly riparian, which is unlikely as nearest high ground is encountered much closer to the lake edge in most areas.

The Quexil shallow-water core site, by virtue of its protected position southwest of the islands and its shallow water location, produced a section that underestimates lake-wide phosphorus sedimentation. Requiring the occupation of less than 0.5 km^2 to account for the disturbance phosphorus load, the core implies a drainage to lake ratio of 0.22:1, and allows riparian settlement to have extended only 90 m from the lake shore. It is likely that the phosphorus accumulation rates due to disturbance, as computed from these two cores, bracket the true, integrated mean accumulation rate that could have been employed to compute the actual phosphorus load delivered to the lake as a consequence of Maya activity.

Sediment accumulation is not uniform over the bottom of conically shaped basins as can be noted from a comparison of the two Quexil cores. This conclusion is corroborated by consideration of the two Salpeten profiles. The riparian area (46.81 km^2) calculated using Sal 80-1 as an estimator of lake-wide phosphorus accumulation is clearly excessive, requiring that Maya inhabitants living more than 3 km from the lake shore be considered riparian. If the computed occupied region is assumed to define the true catchment, the resulting drainage to lake ratio is 17.83:1, again much too high for this karsted

area where nearest high ground is often close to the lake edge.

Accumulation of phosphorus at the Sal 80-1 coring site is greater than the mean lake-wide accumulation rate by virtue of the station's proximity to the steep north shore slopes and its position in a deep trench.

At both coring sites in Salpeten, the Maya zone phosphorus accumulation rate was about 10 times greater than the baseline accumulation rate. Comparing the two stations, zonal phosphorus accumulation rates for the deep-water site are more than an order of magnitude higher than rates computed for equivalent zones in Sal 80-2 (Table 5). The computed effective riparian area as calculated using the deep-water core, overestimates the area that defines the drainage. When the shallow, Sal 80-2 core disturbance phosphorus accumulation rate is used to calculate the basin-wide disturbance phosphorus load, it is not possible to even account for the phosphorus export expected from the peninsular site of Zacpeten alone. The two profiles, taken in deep and shallow water, again demonstrate the differential distribution of sediment over the bottom of trumpet-shaped basins.

Having considered multiple sections from the conical Quexil and Salpeten basins, it was shown that deep- or shallow-water cores respectively overestimate or underestimate the integrated lake-wide mean sedimentation rate, the degree of error being a function of lake morphometry and core position. In situations where sediment deposition is more likely to have been uniform over the entire lake bottom, a single core can be used to assess basin-wide sediment accumulation more

accurately. Ellipsoid basins meet this criterion, and calculated riparian areas should approximate most closely areas from which phosphorus-enriched colluvium was derived (true, occupied riparian area), when computed using cores from pan-shaped lakes. Thus, determined occupied areas surrounding the more elliptical Sacnab and Macanche basins (Deevey et al. 1980a) should delimit the true source areas for eroded topsoil. The only caution is that the Sacnab area is probably overestimated due to the incompleteness of the core. The baseline phosphorus accumulation rate is underestimated, resulting in a computed nutrient accumulation rate due solely to human activity that is too high.

Predictions about the effect of lake morphometry on sedimentation are fulfilled by a basin-to-basin comparison of computed occupied areas and maximal distances from shore considered to be riparian. Calculations based on the Mac 80-1 core require Maya occupation of a 1.78 km² land area, or a riparian band extending 0.29 km from the lake shore. Morphometric considerations, based on hypsimetric curves developed for the Peten lakes (Deevey et al. 1980a), would predict a smaller calculated riparian area for Lake Sacnab. However, the incomplete pre-Maya sequence in the Sacnab core results in overestimation of the disturbance phosphorus accumulation rate, thereby exaggerating the computed occupied riparian region (5.78 km²) and the distance from shore contributing colluvium (0.64 km). When the Pleistocene-Holocene transition date of 8000 B.C. is abandoned in favor of the admittedly questionable ¹⁴C age of the basal Sacnab sediment

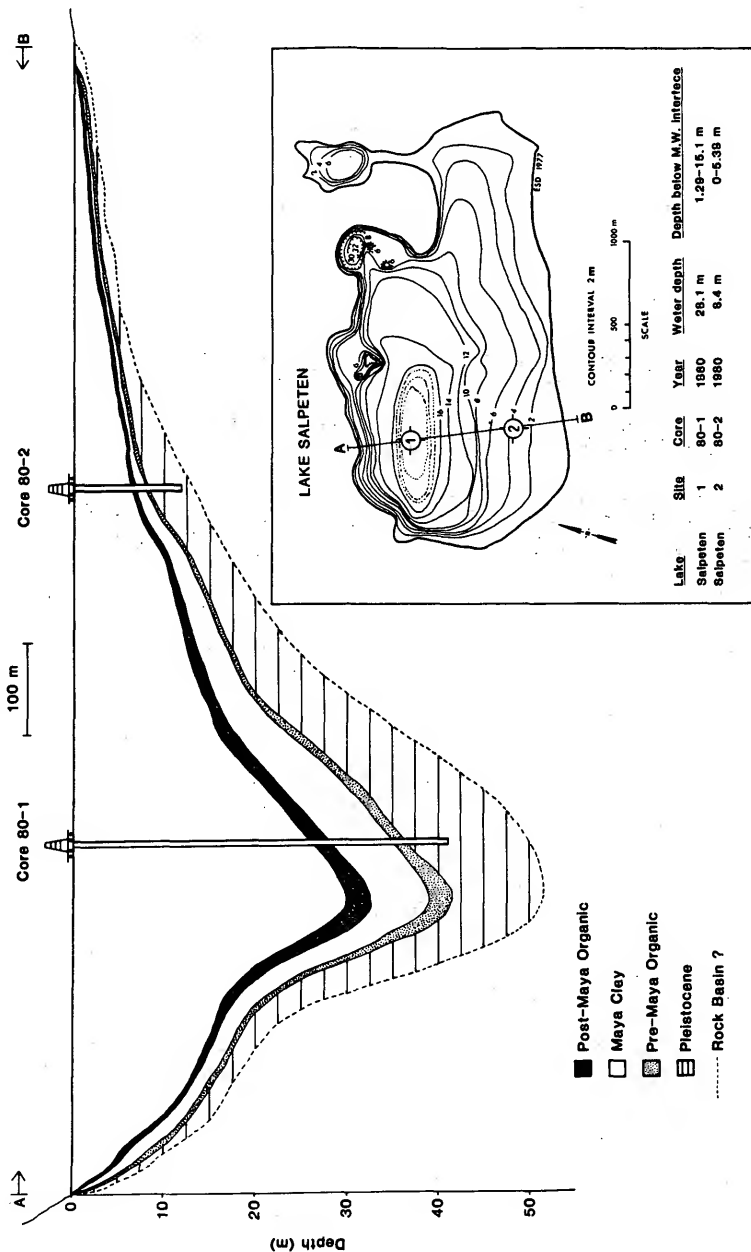
(QL-1029, 6410 ± 100 ; Deevey 1978), the calculated occupied riparian area is reduced. Using this procedure, Sacnab's effective riparian region is shown to be 1.36 km^2 or an area extending 0.18 km from the shore.

Quexil's hypsimetric curve closely approximates the curve for an idealized conical basin and focusing of sediments into deep water is not surprising. Computed sediment accumulation rates based on the study of deep-water core Quexil H are excessive and lead to the computation of an effective riparian area that is too large. As expected, the computed riparian area for Quexil exceeds values calculated for the more ellipsoid Macanche and Sacnab basins. The occupied region around Quexil is nevertheless smaller than that computed for trumpet-shaped Salpeten, based on the study of the deep-water, Sal 80-1 core. While conical like Salpeten, Lake Quexil may have been subject to less intense sediment focusing because the deep central basin of the lake, though steep-sided, possesses a large flat area enclosed by the 28 m contour.

The Salpeten deep-water core (Sal 80-1) demands the extension of the riparian area to 3.06 km from the lake shore, encompassing an area (46.81 km^2) that certainly exceeds the true region from which disturbance-zone sediments were derived. This is expected, as Salpeten was shown to be the most hyperconical of the studied Peten lakes (Deevey et al. 1980a). The deep trench where the core was taken, was only discovered in 1980, and its contours are not known well enough to warrant a revision of the hypsimetric curve for the basin. The

Figure 29. Crude stratigraphy of two borings in Lake Salpeten, illustrating the importance of sediment focusing in hyperconical basins set against fault scarps, in exaggerating thickness of the Maya clay and apparent inputs of colluvial sediment.

LAKE SALPETEN



interpretation is not altered by the presence of this depression, and the coring site, in 26.1 m of water, was located just south of the maximum trench depth. The limited, deep-water region undoubtedly receives much focused sediment (Fig. 29). While hypsometric curves may provide insight into the expected degree of modern sediment focusing in Peten basins, it is difficult to assess the past impact of the process, as deep trenches and sinks may have been obliterated by infilling during 10,000 years of deep-water Holocene sedimentation.

In order to verify that the assumed Maya annual per capita export figure of 0.5 kg P is reasonable, it is necessary to compare computed occupied riparian areas to the true drainage areas from which colluvium could have been derived. The validity of the test is weakened somewhat by the inability to delimit objectively the true drainage area. The karst terrain is deeply dissected and maps do not resolve the problem as contour intervals are often widely spaced, thereby failing to identify nearest high ground. Despite this difficulty, maps and personal observations suggest that the potential source area for colluvium probably extends to an average distance of about 0.5 km around each lake. This figure is approximated by computed riparian areas based on cores from the ellipsoid Macanche and Sacnab basins. The vagaries of sediment focusing are apparent at Quexil and Salpeten where deep-water cores overestimate lake-wide sedimentation rates, thereby resulting in excessive computed riparian areas. Nevertheless, phosphorus accumulation rates computed from dual borings in the two conical basins apparently bracket the integrated mean accumulation rate, as computed riparian areas based on the shallow-water sections underestimate the true drainage.

Crude sensitivity testing of the model was accomplished by calculating riparian areas and distances from shore considered riparian employing annual per capita phosphorus export figures of 0.05 kg and 5.0 kg, or an order of magnitude lesser and greater than the proposed value. A 5.0 kg annual per capita export figure cannot account for the sedimented nutrient derived from the Quexil islands or the peninsular site of Zacpeten, while at Macanche and Sacnab, the computed areas considered riparian extend only 30 m and 80 m, respectively, from the lake shore. Use of the 0.5 kg figure enlarges the distance considered riparian to excessive degrees, from a minimum distance of 1.47 km using the Quexil shallow-water core, to 11.86 km employing Sal 80-1.

Zoning the Cores Palynologically

The estimated per capita phosphorus output figure was originally proposed based on studies at Yaxha and Sacnab, where cores were fine-zoned using pollen. As pollen zonation was shown to be unreliable for dating sediments at Quexil, the changing chemistry of the sediment was used as a dating tool to test the phosphorus loading model in four basins. The changing proximate composition of the lake sediment is thought to be a better basin-specific indicator of disturbance. Nevertheless, it can be demonstrated that crude zonation of the cores using pollen, has little influence on the outcome of the model testing.

At both Quexil and Sacnab, the palynologically determined inception of the Middle Preclassic lies below the organic-inorganic

transition. If pollen is used to identify the Middle Preclassic boundary (1000 B.C.), the Maya disturbance zone is expanded and the pre-Maya zone is reduced. In Quexil B, the Early and Middle Preclassic zones were not distinguished palynologically, so the beginning of the Middle Preclassic was assigned to the 720 cm level, about midway into the 1-m thick zone. The resumption of organic sedimentation and palynological evidence for reforestation used to identify the Maya abandonment of the watersheds occur concurrently in the Sacnab core as well as in the Quexil shallow-water section. In Quexil B, the post-Maya zone is chemically identified at 210 cm and placed at 200 cm palynologically. Where changes in chemical composition or relative pollen percentages occurred, the midpoint was selected as the limit between zones. The slightly different chemical and pollen horizons marking the inception of the post-Maya period may simply reflect the wide spacing of samples taken for pollen analysis.

Having rezoned the cores crudely into pre-Maya and Maya zones using pollen, the phosphorus loading model was again tested by calculation of effective riparian areas (Table 7). For Sacnab, palynological zonation requires the effective drainage be expanded to 19.11 km², extending the source area for redeposited soil to 1.55 km from the shore. This apparently overestimates the true drainage area. In Quexil, rezonation of the shallow-water core increases the computed riparian area, demanding that land up to 0.49 km from the lake shore be considered part of the true drainage. The already excessive riparian area determined by chemical zonation of the Quexil B core is expanded even more by palynological identification of the Middle Preclassic boundary.

Table 7. Testing the phosphorus loading model using pollen zonation of the cores.

Core	Zone	Years In Zone	Depth In Core (cm)	Phosphorus Accumulation Rate $\text{ug} \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$	Effective Riparian Area (km^2)	Maximum Riparian Distance From Shore (km)
Quexil Shallow- water	Maya	2600	375-80	4.8	3.27	0.49
	Pre- Maya	7000	624-375	1.0		
Quexil B	Maya	2600	720-200	15.9	14.86	1.51
	Pre- Maya	7000	920-720	1.6		
Sacnab	Maya	2600	590-100	10.5	19.11	1.59
	Pre- Maya	7000	625-590	0.3		

An alternative approach to assessing the effect of rezonation was tried. Riparian areas, as calculated from the chemical zonation of the cores, were held constant, and new per capita phosphorus export values were computed based on pollen zonation. As palynological zonation expands the disturbance zones in the cores, the computed annual per capita export rates were raised above the 0.5 kg figure originally used in the riparian area calculations. For core Quexil H, the annual per capita phosphorus loading rate was raised to 0.8 kg, while the shallow-water core required that each person contribute 1.42 kg of phosphorus annually. For Sacnab, the new computed per capita loading rate was 1.65 kg of phosphorus per year. Though somewhat higher than the proposed annual per capita phosphorus export value of 0.5 kg, the figures are not inconsistent with the range of zonal per capita delivery rates measured at Yaxha and Sacnab ($0.25-1.46 \text{ kg} \cdot \text{capita}^{-1} \cdot \text{year}^{-1}$) based on seven zones. Reliance on pollen as opposed to chemistry for gross core zonation and testing of the model does not alter dramatically the computed riparian areas. Differences are compensated for by small, conceivable changes in the annual per capita phosphorus loading rate.

Calculated effective riparian areas, or regions from which colluvium was derived during Maya occupation of the Peten watersheds, in some cases approximate the true drainage areas enclosed by nearest high ground. The equivalency of the computed and true drainage is approached most closely using cores from pan-shaped lakes, while deep-water sections from conical basins overestimate the occupied

riparian region contributing slopewash, and shallow-water profiles underestimate the area. Phosphorus export from the watersheds may well have had an impact on Maya agriculture, and presumably the effect of colluviation was not confined to lake watersheds. Wherever forest clearance occurred, it no doubt precipitated soil erosion from the karsted hills and nutrients were likely sequestered in "bajos" or dry depressions.

Assessing the Impact of Soil Nutrient Loss

Rates of phosphorus delivery to the Peten lakes increased as a consequence of human disturbance, and large amounts of the nutrient were sequestered on the basin bottoms due to Maya agro-engineering practices. Up to this point, the human-mediated transfer of phosphorus from land to water has been discussed from the limnological viewpoint, that is, with respect to the rate of nutrient supply or total amount of nutrient delivered to the lakes. At Lake Quexil, as at Yaxha and Sacnab, the microfossil record was examined to determine whether lacustrine productivity changed in response to the altered rate of phosphorus income. Nothing has yet been said about the consequences of nutrient removal from the riparian region. Phosphorus delivered to the lakes as a consequence of disturbance was phosphorus removed from the drainages, and quantification of the terrestrial nutrient loss might provide a crude measure of the environmental impact sustained by the watershed soils and vegetation.

The proportion of phosphorus removed from the watersheds and transferred to the lakes as a result of 2600 years of Maya occupation was computed in an effort to quantify roughly the impact of human-induced nutrient export from the terrestrial sector. Soil concentrations were known and the effective riparian areas had been delimited. These figures, together with values for the total phosphorus load delivered to the lakes as a consequence of "mainland" disturbance, permit the calculation of the exported portion of the predisturbance soil phosphorus standing stock.

The test assumes that physical translocation of soils was the mechanism by which phosphorus entered the lakes. Furthermore, it is accepted that soil phosphorus concentrations have returned to nearly predisturbance levels during the four centuries since the Maya abandoned the catchments. While very high nutrient concentrations are encountered near Maya construction, the presence of climax forest, and a modern pollen rain with similar relative proportions to the pre-Maya pollen spectrum indirectly suggests the attainment of a new soil equilibrium that approximates the predisturbance state. The potentially disturbed regolith was considered to extend to a depth of 50 cm and the soil was assumed to have a specific gravity of 1.1 (Deevey et al. 1979). The mean, whole profile phosphorus concentration from all the pits in a basin was then used to calculate the standing stock of total phosphorus in the top 50 cm of the riparian soils. For Sacnab, the computed value is based on a small sample of three pits, and for Quexil, the mean whole profile concentration was computed

omitting shallow pit #4. The sedimented, disturbance phosphorus load emanating from the riparian area was divided by the total phosphorus stock in the riparian soils. This calculation provides an estimate of the proportion of soil phosphorus transferred to the lake as a consequence of human disturbance (Table 8).

While core location affects the computed lake-wide disturbance phosphorus accumulation, it in turn influences the calculated riparian area. Thus, though deep-water cores from conical basins may exaggerate the disturbance phosphorus load on the lake bottom, the occupied area and riparian soil phosphorus stock are also overestimated. The computed proportion of soil phosphorus exported to the lake as a consequence of Maya activity remains the same whether the Quexil shallow-water core and small riparian area are used, or Quexil h and the larger riparian area are employed.

The average annual riparian disturbance phosphorus input to each lake was figured by dividing the total "mainland" derived phosphorus load by the 2600 years of Maya time. This value was then divided by the amount of phosphorus in the riparian soil compartment, yielding the proportion of the riparian soil phosphorus stock removed annually by the Maya (Table 8).

In the four basins considered, some 20-54% of the riparian soil phosphorus stock was transferred to the lakes as a consequence of human activity. The mean proportion of transferred soil phosphorus for the four watersheds is 40.8%. This value is undoubtedly too high, as

Table 8. Soil phosphorus depletion attributable to Maya agro-engineering activities.

Core	Proportion of Soil P stock exported by Maya over 2600 years (%)	Mean annual mainland disturbance P load (kg)	Proportion of Soil P stock removed annually (%)
Quexil H	54	165.1	0.021
Salpeten 80-1	20	844.2	0.008
Macanche 80-1	52	73.6	0.020
Sacnab	37	120.4	0.014

felled trees and litter on the forest floor contributed to the sedimented phosphorus load. At Hubbard Brook, New Hampshire, the above and below ground biomass and forest floor stocks of phosphorus amount to $0.0165 \text{ kg phosphorus} \cdot \text{m}^{-2}$ (Likens et al. 1977), a value that includes some nutrient contained in surficial soils. Rodin and Bazilevich (1967) estimate that tropical rain forests contain about $0.03 \text{ kg phosphorus} \cdot \text{m}^{-2}$ in the plant biomass. Jordan (1970) reports that woody tissue and leaves of the Puerto Rican rain forest possess $0.0071 \text{ kg phosphorus} \cdot \text{m}^{-2}$. Lacking data on the phosphorus content of the Peten forest and litter, the literature values are relied upon as a crude estimate.

Using the mean of the average whole profile soil phosphorus concentrations for the four Peten basins, the top 50 cm of watershed soils are shown to contain $0.1675 \text{ kg phosphorus} \cdot \text{m}^{-2}$. It was assumed that the vegetation of Peten is comparable to the rain forest with respect to its phosphorus content ($0.03 \text{ kg} \cdot \text{m}^{-2}$). The forest floor phosphorus content measured at Hubbard Brook ($0.0078 \text{ kg} \cdot \text{m}^{-2}$), which includes some soil nutrient, was used to estimate the phosphorus content of Peten's litter. Summing the vegetation, litter, and soil values, it is surmised that the Peten forest contains about $0.2053 \text{ kg phosphorus} \cdot \text{m}^{-2}$ down to 50 cm in the soil profile. The vegetation and litter account for about 18.4% of this phosphorus pool. Thus, even when using the maximal reported value for vegetation phosphorus, and adding to it a figure for the phosphorus content of litter, the calculated proportions of soil phosphorus exported to the lakes as a

consequence of disturbance (Table 8) are adjusted downward by a small amount. Accounting for the phosphorus contained in the living and dead biomass of the forest, the mean proportion of exported soil phosphorus for the four watersheds is reduced from 40.6% to 33.3%.

While a significant proportion of the soil regolith was ultimately transported to the lakes during 2600 years of Maya occupation, the process occurred at a very slow rate. The average annual disturbance phosphorus load delivered to the lakes (Table 8) amounted to between 0.008% (Salpeten) and 0.021% (Quexil) of the soil compartment phosphorus stock. These values are shifted downward minimally by consideration of the vegetation and litter contribution to the sedimented phosphorus load. The mean annual rate at which phosphorus was exported from the basins during Maya time was evidently rather low. However, the rate of soil removal in any given year was certainly a function of Maya population density and land use. During periods of high population density, annual soil losses may have been considerably higher than the computed mean value. Maya population levels may have, in turn, responded to the increased erosion rates if soil loss reduced agricultural yields or had an indirect, negative impact on harvests of aquatic resources.

Erosion Rates for the Peten Watersheds

The proportion of soil phosphorus transported to the Peten lakes as a consequence of Maya activity is impressive and implies significant

landscape reduction. Predisturbance and Maya period erosion rates were calculated for comparison with published values from other forested and disturbed watersheds. While erosion has been quantified in a number of temperate studies, there is a paucity of literature on tropical catchments.

Erosion of the Peten soils was assessed by looking at the inorganic load deposited in the lake basins. The sedimented inorganics are believed to be of primarily allochthonous, terrestrial origin, with little deposition resulting from biological processes within the lake (eg. carbonate sedimentation). While a portion of the siliceous and carbonaceous sediments (the bulk of the inorganic fraction) may have been delivered to the lakes in soluble form, the majority of the material presumably arrived as particulates. During episodes of deforestation, nearly all the inorganic material likely reached the lake shores via soil creep. Sedimented organic material was ignored in the erosion calculations, as allochthonous organics may have been lost through diagenesis and are inseparable from autochthonous organic remains.

Erosion rates are generally calculated by measurement of dissolved, suspended and bedloads in streams or rivers draining catchments. Alternatively, erosion has been assessed directly by measurement of soil loss around dated archaeological ruins or age-old trees (Judson 1968a). These latter methods, like the paleolimnological approach, provide a long-term evaluation of the erosion rate, while stream loads vary with rainfall and must be monitored over a long period of time.

Erosion rates were figured based on data from four cores: Quexil H, Sal 80-1, Mac 80-1, and Sacnab. Initial computations ignore special consideration of the Quexil islands or the peninsular site of Zacpeten, and assume all inorganics came from the computed riparian area. For each lake, the annual predisturbance and Maya period inorganic loads were computed by multiplying the zonal inorganic accumulation rates times the lake area. The annual load of inorganics delivered to the lake was then divided by the calculated effective riparian area, the region from which colluvium was derived. (As was argued for phosphorus, while deep-water cores from conical basins exaggerate the lake-wide sediment accumulation, the riparian region from which the redeposited soil came is also overestimated). This computation yields pre-Maya and Maya period inorganic export rates. The erosion rates are expressed in metric $\text{tons} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$, and landscape reouction, presented as $\text{cm} \cdot 1000 \text{ yrs}^{-1}$ was computed assuming the soil has a specific gravity of 1.1 (Table 9).

Predisturbance rates of inorganic loss for the four watersheas are variable, but with the exception of Macanche, the catchments all display baseline rates that are comparable with rates measured elsewhere. Predisturbance export of inorganics from the Frains and Murray Lake watersheds in Michigan proceeded at rates of nine $\text{tons} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$ and 20-30 $\text{tons} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$ respectively (Davis 1976). Predisturbance erosion rates were computed based on Bonatti and Hutchinson's paleolimnological study of Lago di Monterosi, Italy. In that watershed, and throughout Italy, erosion prior to human intervention proceeded at rates of about 52-78 $\text{tons} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$.

Table 9. Erosion in Peten watersheds.

Core	Time Period	Annual Inorganic Loading to Lake by Time Period (kg)	Computed Effective Riparian Area (km ²)	Mean Annual Rate of Inorganic Export from Watershed (metric tons·km ⁻²)	Erosion Rate as Landscape Reduction (cm·1000 yrs ⁻¹)	Proportion of Soil Inorganic Stock Exported by Maya (%)
Quexil H	Maya	813087	8.88	91.6	8.33	40
	Pre-Maya	86141		9.7	0.88	
Salpeten 80-1	Maya	3626506	46.81	77.5	7.05	37
	Pre-Maya	149682		3.2	0.29	
Macanche 80-1	Maya	1451220	1.78	815.3	74.09	244
	Pre-Maya	643302		361.4	32.82	
Sacnab	Maya	1406817	5.78	243.4	22.09	112
	Pre-Maya	222129		38.4	3.49	

(Judson 1968b). Forested watersheds of the Maryland Piedmont yield less than $35 \text{ tons} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$ as a consequence of erosion (Wolman 1967), while Mississippi catchments covered in mature pine-hardwood forests lose some $2-9 \text{ tons} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$ (Ursic and Dendy 1965). In Kenya, studies of forested drainages produced erosion rates ranging from $20-30 \text{ tons} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$. Quexil, Salpeten, and Sacnab erosion rates are consistent with the literature values and are revised upward minimally if organic material is considered, as the whole soil profiles average some 14% organic matter down to 50 cm, and soils are the presumed source of the sediment.

Macanche's predisturbance inorganic export rate ($361.4 \text{ tons} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$) appears anomalously high. Unlike the other lake sediment cores that contain pre-Maya deposits of uniformly high organic matter content, Macanche's predisturbance muds possess a high proportion of inorganic matter below 705 cm. The inorganic sediments at the base of the section may indicate very early human activity in the catchment, predating the inception of the Middle Preclassic. There is, however, no archaeological evidence to support this notion.

Alternatively, it might be suggested that the inorganic-rich muds below 705 cm are of Pleistocene age. If this were the case, the pre-Maya Holocene sequence would be confined to only 120 cm of organic material between 585 cm and 705 cm in the core. Rezoning the core in this manner produces a pre-Maya bulk sediment accumulation rate of $0.017 \text{ cm} \cdot \text{yr}^{-1}$, a value that seems quite slow. The phosphorus loading model was tested using 705 cm as the Pleistocene-Holocene

boundary. The calculated riparian region (11 km²) overestimates the true source area for colluvium, permitting the extension of the effective riparian area to a distance 1.22 km from the lake shore. The overly large computed riparian area probably results from the underestimation of the baseline phosphorus accumulation rate. The predisturbance rate is no doubt too small because the Pleistocene boundary in fact lies well below 705 cm.

Placement of the Pleistocene-Holocene contact at 705 cm was also rejected using the basal radiocarbon date from the core. Lying more than 3.5 m below the proposed boundary, the bulk sediment at 1060-1072 cm has a radiocarbon age of nearly 10,000 years. In order for the 705 cm level to possess a sidereal age of 10,000 years, the basal sediments would have to be much older. There is no reason to suspect that the radiocarbon age of the bottommost portion of the core is grossly underestimated or substantially younger than the calenorical age. Ultimately it may be possible to assign a rough age to the inorganic-organic transition at 705 cm using the pollen profile from the section.

As the Macanche core is thought to be a near-complete Holocene profile, an alternative hypothesis was sought to explain the inorganic nature of the predisturbance mud below 705 cm. A dry stream bed opens into the eastern end of the lake, and the shallows east of the island may be the result of accumulated deltaic deposits. Some of the streamload, particularly small clay- and silt-size particles may have been carried as far as the deep-water coring site. The accumulation

rate of the stream-transported material was undoubtedly influenced by a number of factors. Lake level fluctuations may have changed the position of the stream discharge point relative to the coring site, and the streamload probably varied with rainfall and runoff. There is no reason to believe that the stream-carried sediment accumulation rate at the coring site was the same during pre-Maya and Maya times. Nevertheless, high predisturbance and disturbance period accumulation rates for both inorganic matter and phosphorus suggest that preferential sediment deposition at the coring locality has occurred throughout most of the Holocene. The highly organic material underlying the earliest Middle Preclassic mud may have been deposited during a period of reduced stream flow or when stream-delivered suspended material was impeded from transport to the coring site.

In testing the phosphorus loading model at Macanche, the calculated riparian area was found to extend 0.29 km from the lake shore, slightly underestimating the true source area for colluvium. Underestimation of the disturbance generated phosphorus load might have caused the discrepancy between the computed and actual riparian areas. It is possible that the pre-Maya stream-delivered phosphorus accumulation rate was higher than the stream-carried phosphorus accumulation rate during Maya times. Subtraction of the inflated baseline value from the Maya period phosphorus accumulation rate would have resulted in an anthropogenically derived accumulation rate that is underestimated by a small amount.

Erosion rates computed for the Macanche catchment using core Mac 80-1 are almost certainly overestimated, as the coring site was the

repository for much inorganic material brought in by stream flow. Nevertheless, pre-Maya erosion rates can be roughly compared to disturbance period rates in all four Peten basins.

Erosion rates for the Maya period exceed baseline rates in the Peten watersheds, though the magnitude of change differs for the four basins. At Macanche, where baseline rates were high, the disturbance period erosion rate was only 2.3 times the pre-Maya rate. At the other extreme, Salpeten's Maya period erosion rate was 24.2 times greater than the baseline value. The mean Maya period-baseline ratio for the four drainages is 10.6, indicating that disturbance resulted in erosion rates an order of magnitude greater than baseline values.

At Frains Lake, the postdisturbance watershed erosion rate was 10 times the baseline figure and in the Murray Lake drainage, human intrusion caused a five-fold increase in erosion over the predisturbance level (Davis 1976). At Lago di Monterosi, human disturbance resulted in erosion rates about an order of magnitude greater than predisturbance rates (Judson 1968b). Evidently the increase in erosion resulting from human activity is highly variable and in part dependent on land use. Ursic and Lendy (1965) indicate that erosion from cultivated agricultural catchments in Mississippi may be as much as three orders of magnitude greater than that registered for forested watersheds. Wolman (1967) argues that agriculture raises erosion rates by about an order of magnitude over the baseline condition. It is noted, however, that active construction projects on exposed land may lose more than 1000 times the material exported from forested watersheds.

Alternatively, erosion can be assessed by calculating the proportion of inorganic matter in the riparian soils that was transported to the lakes as a consequence of Maya activity. The baseline inorganic accumulation rate was subtracted from the Maya zone rate to compute the accumulation rate due to disturbance. This value was then multiplied by the area of the lake to obtain the annual lake-wide inorganic load. As some inorganic loading emanated from the Quexil islands and Salpeten's densely settled Postclassic peninsular site, an adjustment in the annual loading rate was made in an effort to compute the load derived from the "mainland," or effective riparian area. Phosphorus generated by Quexil's island inhabitants accounted for 10.7% of the total disturbance phosphorus load, and it was assumed that the islanders contributed an equivalent proportion of the total disturbance inorganic load. Thus, the average annual inorganic load derived from the "mainland," or calculated effective riparian area, is 89.3% of the total annual disturbance input. The site of Zacpeten generated 8.9% of Salpeten's disturbance phosphorus load and the annual disturbance inorganic loading figure was adjusted downward by this amount to compute the amount coming from the calculated effective riparian area.

The annual inorganic loading rates attributable to mainland disturbance were then divided by the respective calculated effective riparian areas. This computation provides values for the annual rate of inorganic export from the watersheds resulting from disturbance. The annual "mainland" derived inorganic loading rate was also

multiplied by 2600 years of Maya time to compute the entire inorganic yield attributable to riparian Maya populations.

Assuming that soils have returned to a near predisturbance equilibrium with respect to their inorganic content, the inorganic stock in the contemporary watershed soils was figured for each basin. In each basin, the mean whole profile inorganic percentage was used for calculation. Loss on ignition was not run on soils from the three Sacnab pits, so the average of the mean percent inorganic values for the other three basins was employed to evaluate the total stock in the Sacnab basin soils. As mean whole profile inorganic proportions in Salpeten, Quexil, and Macanche range from only 85.7% to 87.7%, the Sacnab estimate is likely reasonable. Assuming soils have a specific gravity of 1.1, the inorganic material contained in the top 50 cm of the regolith was computed on a km^2 basis. Then, multiplying this factor times the computed effective riparian area, the total inorganic stock in the top 50 cm of the riparian soils was figured. For each basin, the total inorganic yield delivered to the lake as a consequence of Maya disturbance was divided by the inorganic stock present in the riparian soils. This provides an estimate of the proportion of soil stock inorganics transferred to the lake during 2600 years of Maya land use (Table 9).

At Quexil, the proportion of phosphorus removed from the soils as a consequence of Maya-induced erosion (54%) exceeds slightly the inorganic fraction transported (40%). The near equivalence of the values is not surprising as zone-to-zone changes for phosphorus

accumulation rates in Quexil core H were shown to be correlated with both carbonate and silicate accumulation rates, when the core was zoned palynologically. The positive correlations suggested a common delivery mechanism for the three chemical types and bulk soil transport was proposed. Mean soil profile concentrations were used to calculate phosphorus and inorganic stocks in the riparian soils, but if phosphorus-rich, organic topsoils comprised the bulk of the eroded material, a slightly higher proportion of phosphorus as opposed to inorganic removal might be expected. Additionally, if the standing vegetation contains a significant portion of the watershed phosphorus stock, but relatively little of the inorganic material in the catchment, deforestation would contribute a relatively higher fraction of the phosphorus compartment as compared to the inorganic stock.

In the Salpeten, Macanche, and Sacnab watersheds, the computed proportion of soil inorganics transported to the lakes over Maya time exceeds the fraction of soil phosphorus moved. At Salpeten, the soil phosphorus stock was depleted by 20%, while 37% of the soil inorganic compartment was transferred to the lake. Macanche soils lost 52% of their phosphorus supply, but evidently 244% of the soil inorganic stock down to 50 cm was carried to the lake. At Sacnab, too, more than all (112%) of the inorganic material in the top 50 cm of the riparian soils was lost to the lake, while only 37% of the phosphorus stock crossed the drainage-lake interface.

The discrepancy in the computed proportions of transported phosphorus and inorganics is not surprising. The sedimented

disturbance inorganic loads in Macanche and Sacnab exceed the total inorganic stock in the top 50 cm of the riparian soils. This suggests that there may be an error in restricting the potentially erodable regolith to the uppermost 50 cm for calculating purposes. The high, measured proportions of transferred inorganics may indicate large losses of deep, inorganic-rich and phosphorus-poor "sascab." If indeed subsoil below 50 cm were transported to the lakes, the erodable inorganic stocks in the watersheds were underestimated and consequently, the proportions exported to the lakes were overestimated. Lowering the erodable boundary to 100 cm and measuring loss on ignition throughout the profiles would likely more than double the calculated inorganic stocks figured for the watersheds, as only surficial soils contain appreciable organic matter and "sascab" probably has a higher specific gravity than topsoil. Inclusion of the deep, subsoil levels in the assessment of the riparian phosphorus stock would change the computed Maya-transported phosphorus fraction by only a small amount. This would hold if phosphorus concentrations were measured over the entire profiles down to 100 cm, and the concentration curves were integrated to evaluate the total phosphorus content in the soil compartment. The phosphorus content in the subsoil from 50-100 cm would undoubtedly amount to a small fraction of the total regolith phosphorus stock, and, therefore, would add little to the amount measured in the half meter of topsoil.

It is likely that the depth to which the soil was eroded varied between watersheds and from place to place within a catchment. This

being the case, arbitrary limitation of the erodable regolith to the upper 50 cm for calculating purposes would be expected to result in differential exports of phosphorus and inorganic matter. High proportions of calculated inorganic matter transport might be expected in watersheds where urban construction or other engineering endeavors mobilized large amounts of phosphorus-depleted inorganic material from deep in the soil profile.

At Macanche, much silt was sedimented as a result of the construction of the defensive wall, Muralla de Leon, near the northeastern shore of the lake. The small site of Cerro Ortiz, overlooking the southeastern edge of the lake, may have contributed much inorganic material. At Salpeten, the peninsular site of Zacpeten very likely contributed a substantial inorganic load to the lake during Postclassic times. While the total Maya period inorganic load was adjusted downward by 8.9% to compute the "mainland" derived load, the correction is probably insufficient to allow for the massive silt output from the urbanized peninsular site. At Sacnab, construction efforts cannot be invoked to explain the large export of inorganics as the catchment never hosted urban development.

Maya activity in the Peten watersheds accelerated phosphorus and inorganic matter delivery to the lakes, and both chemical types probably reached the waters' edge in eroded soil. Nevertheless, when the erodable soil section is assumed to extend to 50 cm, it is shown that differential proportions of phosphorus and inorganics were removed from the soil compartment of each watershed. With only four

lake-watershed systems studied, and cores grossly zoned, explanations for the unequal proportions of Maya-eroded soil inorganics and phosphorus remain speculative. The problem may be resolved partially by future fine-zoning of the sediment profiles, particularly if relative changes in phosphorus and inorganic loading rates are compared with archaeologically documented shifts in social organization or land use. Massive exports of inorganics resulting from ceremonial, urban, or defensive construction could then be demonstrated not only by between-catchment comparisons, but within a watershed.

SUMMARY

Paleolimnological data from Peten lake sediment cores were used in conjunction with paleodemographic information on riparian Maya populations to elucidate the environmental impact of prolonged human settlement in the watersheds of the karsted Guatemalan lowlands. Palynological study of sediment profiles from central Peten Lakes Quexil (Vaughan 1979, Deevey et al. 1980c), Petenxil (Tsukada 1966), Macanche (Garrett-Jones, pers. comm.), and the easternmost twin Lakes Yaxha and Sacnab (Deevey et al. 1979) revealed the widespread extent of deforestation associated with Maya occupation of the region. Forest clearance may not have proceeded at identical rates in all basins. Nevertheless, in each core the mix of regional and local pollen recorded evidence of increasing forest removal continuing until Late Classic times, when Maya population densities were maximal throughout the area. Following the Classic collapse, the human-induced savanna conditions were sustained by the small, nucleated Postclassic populations.

At Sacnab and Quexil, where retrieved basal sediment levels are sufficiently old, human-influenced vegetational changes were detected in horizons predating the inception of the Middle Preclassic period (1000 B.C.). At Yaxha (Deevey et al. 1979) and Petenxil (Tsukada 1966) coring efforts failed to obtain muds antedating Middle Preclassic age,

but the episode of grassland expansion was amply documented. High forest pollen comprised a progressively smaller proportion of the pollen sum through Late and Postclassic times. In all five lakes assessed palynologically, the uppermost sediments contain a record of forest recovery that commenced at the close of the Postclassic, some 400 years B.P.

Deforestation and subsequent Maya agro-engineering practices within the Peten catchments changed sedimentation processes in the lakes. As people moved into the drainages, predisturbance organic sedimentation was supplanted by the accumulation of deposits dominated by clay-rich inorganics. The general, gross stratigraphic pattern of Holocene sedimentation in the Peten basins is known from four lakes: Macanche, Salpeten, Quexil, and Sacnab, the latter two lying some 50 km apart. Maya period anthropogenic, inorganic sediments are intercalated between Holocene organic muds of pre-Maya and post-Maya age. At Lakes Petenxil and Yaxha, borings failed to penetrate through the "Maya clay" deposit. Coring at Yaxha was impeded by the thickness (> 6 m) of the clay lens, which stopped the small piston corer. The tremendous thickness of the erosional load that blankets the Yaxha basin is attributable to the archaeologically documented dense Classic occupation of the drainage as well as substantial urban construction in the watershed. It is suspected that the anthropogenic clay aquiclude is underlain by organic lacustrine deposits in both Yaxha and Petenxil.

Land clearance caused an increase in the sediment accumulation rate as erosion carried large amounts of soil into the lakes. Organic

matter contained in the felled vegetation, litter, and uppermost soil horizon was quickly flushed from the catchments, and subsequent, rapid sediment accumulation was dominated by inorganics. The depletion of the allochthonous organic matter pool, together with decreased lacustrine productivity and severe diagenesis of any sedimented allochthonous or autochthonous remains, resulted in disturbance-zone muds with low organic content.

At Lake Quexil, a prolonged episode of predisturbance meromixis was inferred from the undisturbed laminated sediments underlying the anthropogenic clay section. Forest clearance may have disrupted the stable chemical stratification as the consequent soil erosion supplied the mixolimnion with large amounts of dissolved and particulate matter. Additionally, increased wind movement over the lake surface would have resulted following tree removal, thereby enhancing the possibility of holomixis. Alternatively, it is conceivable that turnover was inhibited following riparian disturbance, but evidence for the continued meromixis was obliterated by the high rate of colluviation that overwhelmed the short-term (annual?) organic-inorganic cycle of sedimentation responsible for producing the laminae.

The paleolimnological record has been used to determine past levels of phosphorus loading to the Peten lakes. As phosphorus is often the limiting nutrient for primary productivity in lacustrine systems, paleoproductivity can sometimes be inferred from past rates of phosphorus supply. Furthermore, phosphorus sequestered in basin

sediments represents a potential nutrient supply deflected from cycling within the terrestrial sector. Phosphorus transported to the lakes as colluvium was no longer potentially available for Maya agricultural production, and an increasing rate of accumulation in the lake sediments can be equated with decreasing riparian soil productivity.

Inputs of ^{14}C -deficient, carbonate carbon to the Peten lake sediments made reliable radiocarbon dating of the profiles impossible. At Lakes Yaxha and Sacnab, dates were assigned to levels in the cores where major changes in the pollen spectra were detected (Vaughan and Deevey 1981). The paleodemography of the basins was known, and it was assumed that the degree of forest removal detected in the pollen profiles was a reflection of changing population density in the watersheds. Maya populations in the twin basins grew at a slow, steady exponential rate from the Middle Preclassic through the Late Classic period. When phosphorus accumulation rates were computed based on palynological dating of the cores, phosphorus supply to the lakes, delivered primarily as colluvium, was shown to be Maya density-dependent (Brenner 1978). Not only did phosphorus input to the basins track population growth, but the per capita contribution was shown to be about $0.5 \text{ kg}\cdot\text{yr}^{-1}$, a value that perhaps coincidentally matches the annual physiological flow of phosphorus through human bodies (Deevey et al. 1979).

Lacustrine productivity, as inferred from microfossil enumerations, evidently rose with initial human intrusion in the watersheds, but by Early Classic and Late and Postclassic times, when phosphorus was

supplied to the lakes at very high rates, microfossil accumulations dropped precipitously. During periods of massive colluviation, the bulk of the phosphorus delivered to the lakes probably arrived at the waters in unavailable mineral form (apatite?) and bypassed the biota en route to sedimentation on the basin bottom. Productivity may have actually been inhibited by the severe siltation, and any phosphorus delivered in available form may have been rapidly scavenged and coprecipitated with carbonates or clays. It is also likely that microfossils buried in the anthropogenic clay sediments were subject to severe mechanical abrasion and diagenesis, so that the remains retrieved and enumerated represent only a small proportion of the microfossils originally deposited.

Shallow- and deep-water cores from Lake Quexil were studied to test the phosphorus loading model developed for the twin basins. Unlike the Yaxha and Sacnab catchments, Quexil experienced a Terminal Preclassic-Early Classic Maya population decline that was undetected in the pollen record. Pollen zonation of the Quexil cores was achieved by matching with the discrete assemblages from the twin basin profiles. Phosphorus loading rates derived from palynological zonation of the two sections failed to track the human population changes in the basin. This is in part due to the lag period between the time that soils are anthropogenically phosphorus-enriched following vegetation clearance, and the time they are delivered to the lake by colluviation. Additionally, ages assigned to pollen horizons in the Quexil cores are probably incorrect. Lake Quexil lies about 50 km west of the twin

lakes, and while core zones from the three basins were matched by equivalency of pollen proportions, the delimited zones are not necessarily contemporaneous.

Ages applied to the pollen zones in the Quexil cores might be inaccurate, but the horizons are useful zonation tools for testing the dependence of microfossil accumulation rates on the rate of total phosphorus supply, and for intra-basin core correlation. As at Yaxha and Sacnab, microfossil accumulation rates appear to have been independent of the supply rate of total phosphorus. Nevertheless, phosphorus limitation is not disproven, as the plant-available phosphorus delivery rate is unknown, and postdepositional loss of microfossils in the clay-rich zones of the cores makes the enumerated thanatocoenosis a poor estimator of the biocoenosis from which it was derived.

Comparison of the Quexil shallow- and deep-water sections revealed between-site sediment differences. The shallow-water core site lies in a subbasin of the lake. Located south of the islands in the lake, it was sheltered from the colluvial load coming off the steep north shore slopes. Consequently, zones of the shallow-water section contain more organic matter than equivalent zones of the deep-water profile. Direct deposit of north shore slopewash, as well as resuspension and focusing of fine, silt- and clay-size inorganics into deep water, accounts for the high silica content of the deep-water core. Comparing zonal chemical and microfossil accumulation rates at the two sites demonstrated the profound effect of sediment focusing in this conical

basin. The reconstruction of ancient phosphorus budgets for lakes with conical morphometry is thus confounded by the unequal distribution of sediments over the basin floor. Single cores from such basins can provide inaccurate estimates of mean lake-wide chemical accumulation rates.

As pollen was shown to be an unreliable tool for dating the Quexil cores, alternative methods were sought for fine-zoning the profiles. The Quexil H core was rezoned using particle size analysis, but phosphorus accumulation still failed to track population levels closely. Ultimately, fine-zoning was abandoned in favor of crude division of the profiles from four lakes (Quexil, Macanche, Salpeten, Sacnab) into pre-Maya and Maya zones. Zones were delimited by the organic matter content of the sediments, as the changing chemical stratigraphy of the profiles was thought to be a good basin-specific disturbance indicator. Maya period phosphorus and inorganic matter accumulation rates exceeded predisturbance, baseline values in all six cores from the four lakes. Gross stratigraphic correlation of a shallow- and deep-water section from Lake Salpeten again demonstrated the consequences of sediment focusing in conical basins.

The phosphorus loading model developed from the Yaxha-Sacnab study was reevaluated by crude zonation of the six long cores from four lakes (Quexil, Salpeten, Macanche, Sacnab). Multiple cores (deep-water and shallow-water) from conical basins Quexil and Salpeten verified predictions concerning the influence of lake morphometry on calculated annual per capita phosphorus inputs. Deep-water sections, containing

large amounts of resuspended and focused material, overestimated annual per capita loading rates, while shallow-water sections underestimated the true value. In ellipsoid Lakes Macanche and Sacnab, single cores proved to be more reliable estimators of the lake-wide sedimentation rate. Despite the vagaries of sediment focusing, it was shown that riparian populations in the watersheds did supply phosphorus to the lakes at a rate of about $0.5 \text{ kg} \cdot \text{capita}^{-1} \cdot \text{yr}^{-1}$.

Testing of the phosphorus loading model was complicated by several factors, some of which might be resolved by future work. Acoustic reflection profiles from the basins can provide a three dimensional picture of sediment distribution over the lake bottom (Schubert 1980). Using this technique, calculated chemical accumulation rates derived from single cores could be corrected to account for the effects of unequal lake-wide sediment deposition. Testing of the model was reliant on the accurate delimitation of the true drainages surrounding the Peten lakes. Lacking detailed topographic maps of the watersheds, it was necessary to settle for rough estimates of the drainage areas. Intensive surveys of the basins might better define the true source area for colluvium, the riparian land area enclosed by nearest high ground.

Between-basin differences in topography may influence actual per capita phosphorus inputs to the lakes. Individuals living on steep slopes certainly contribute more colluvium per year than persons occupying level terrain. For model testing purposes, it was assumed that basin-to-basin topographic differences were negligible and that

Maya populations showed no inter-basin difference with respect to topographic preference. Detailed surveys of the geographic features, in conjunction with settlement data, might explain between-lake differences in computed annual per capita phosphorus output figures.

Riparian soil phosphorus concentrations and soil erodibility can also affect the per capita delivery rate of phosphorus to the lakes. Microregional differences in the local geochemistry are reflected in basin-to-basin chemical differences. These dissimilarities are detected in lake waters, sediments, and catchment soils. Iron concentrations are notably higher in Quexil soils and sediments than in soils or muds from Salpeten and Macanche. In the dolomitized Salpeten-Macanche district, magnesium concentration is higher in soil, lake water, and sediment samples as compared to levels measured in the various compartments at Quexil. Lake Quexil would be expected to have received a somewhat lower annual per capita phosphorus supplement than the other Peten lakes because a portion of the lake shore is contacted by phosphorus-deficient Exkixil soils that are resistant to erosion.

Maya agro-engineering activities transported a large proportion of the riparian soil phosphorus stock to the Peten lakes. Correcting for the sedimented phosphorus load contributed by forest vegetation and litter, it is estimated that 2600 years of human activity depleted the soil compartment phosphorus pool in the basins by a mean value of about one-third. In computing the proportion of phosphorus lost from each basin, it was assumed that the disturbance-generated load originated in the soils, litter, and vegetation lying within the computed riparian

area. The watershed-lake system was assumed to have been closed with respect to the transfer of phosphorus into or out of the drainage. The only obvious external phosphorus source, that delivered in precipitation, was accounted for by the subtraction of the baseline phosphorus accumulation rate prior to the computation of the disturbance load.

During the 2600 years of Maya occupation in the Peten watersheds, the drainage-lake ecosystems may not have been closed in terms of phosphorus movement. Food grown outside the drainage may have been imported into the catchment for consumption. Nutrients contained within the comestibles would have been delivered to basin soils in refuse, excreta, and human burials. Ultimately, following a period of retention in the soils, the imported nutrients would have reached the lakes in colluvium. It cannot be determined whether there was a net flow of phosphorus into the catchments. While the import of food might suggest the net centripetal movement of phosphorus to riparian population centers, this may have been partially balanced by the exodus of large numbers of Late Classic inhabitants who exported phosphorus sequestered in their bodies. If indeed there were a net flow of phosphorus into the catchments, the computed fraction of phosphorus removed from basin soils by human disturbance might be overestimated. Regardless of provenience, the sedimented phosphorus load represents a huge potential nutrient supply deflected from possible agricultural production.

Maya populations of the central Peten drainages stressed the ecosystems through forest clearance and subsequent agro-engineering activities. There is an irresistible temptation to link the consequent environmental strain to the eventual Classic Maya collapse. Forest removal, erosion, and rapid nutrient sequestering are documented in the paleolimnological record. Further questions must be addressed before these processes can be invoked to account for the Classic decline. Erosion and soil nutrient loss in the context of a tropical karst environment can certainly have a negative impact on agricultural output. Modern agronomic studies in the Peten could provide a quantitative measure of the long-term yield limitations imposed by extensive and intensive agricultural strategies. It is conceivable that ancient Maya agriculturalists perceived the loss of soil as a problem, and they may have taken steps to retain soils in some localities. Potential soil conservation schemes should be postulated, and archaeological evidence for their practice might be sought, though remnants of these agricultural techniques may lie buried beneath thick beds of colluvium.

Maya food procurement may have been limited not only by terrestrial nutrient loss, but by the massive siltation of the lakes. The microfossil record suggests that lacustrine productivity declined during Early Classic and Late and Postclassic times. Aquatic resource availability may have declined too. At Yaxha and Sacnab, archaeological recoveries of snail shells, turtle remains, and net sinkers are maximal in Middle Preclassic and Postclassic contexts (Rice

1976). The data suggest that aquatic animal populations declined in the Late Preclassic, perhaps due to habitat destruction and overharvesting, recovering only after the Classic collapse.

This study comprises one aspect of the "Historical Ecology of the Maya" project. Maya occupation of the Peten watersheds was shown to have drastically modified rates of material flow in the drainage-lake ecosystems. Models designed to explain the prolonged persistence or sudden disappearance of Maya civilization in the tropical lowland setting must consider the impact of human disturbance on the environment.

The paleolimnological record has shed some light on the environmental history of the Peten. While elucidating the past, the information may prove to be valuable for predicting the consequences of future human-induced stresses on the environment. The human population of the Peten is growing rapidly, doubling every 3-7 years (Schwartz 1977, Castellanos 1980). Modern population densities for the Peten as a whole remain minuscule ($6 \text{ persons} \cdot \text{km}^{-2}$) compared to Late Classic population levels deduced for several sites. However, the contemporary doubling time for the Peten population is about two orders of magnitude shorter than the value computed for the ancient Maya population inhabiting the combined Yaxha-Sacnab drainage.

Peten's natural resources are again being exploited, and as forest removal proceeds, the terrain will be utilized for crop production, cattle grazing, and silviculture. Development schemes for the region will likely be formulated to fulfill the economic objectives of a

select few. The rapid deforestation that is anticipated may maximize profits in the immediate future, but the approach is myopic with respect to hopes for long-term resource exploitation. It has been suggested that Central American lowland forests on arable land will be completely removed by the year 2000, the rapidity of their demise being a function of the interaction between the demand for food production and the costs of clearing, drainage, and disease control (CEQ and DOS 1981). There is no reason to believe that the Peten will be exempt from this scenario.

The findings of this paleolimnological study support the recommendation that future development of the Peten proceed with as little perturbation of the natural forests as possible. Strip cutting of vegetation (Jordan 1982) and other soil retention schemes should be implemented where forest clearance is necessary. These techniques should minimize erosion and nutrient loss. Unless far-sighted management procedures are instituted, it may be possible over the next two decades to assess again the impact of widespread human-induced deforestation on Peten's tropical karst environment.

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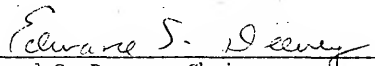
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BIOGRAPHICAL SKETCH

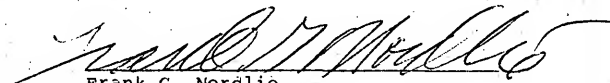
Mark Brenner was born on March 3, 1952, in New York City. He attended high school at Rockland Country Day School in Congers, New York, and graduated in 1969. His undergraduate years were spent at Grinnell College, where he received a B.A. in Biology in 1973. From 1973 to 1975 he worked for the Department of Biological Oceanography at Lamont-Doherty Geological Observatory. He was involved with mariculture research at field stations in Queens, New York, and in St. Croix, U.S. Virgin Islands. From February 1975 through June 1975 he traveled extensively in Central America. He began graduate school at the University of Florida in September 1975 and worked in tropical paleolimnology, receiving his M.S. in 1978. His M.S. and Ph.D. field work took him to Mexico, Belize, and Guatemala, where his primary interests were tropical ecology, limnology, and paleolimnology.

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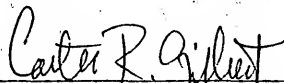
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Graduate Research Professor of
Zoology and
Graduate Research Curator, Museum

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Frank G. Nordlie
Professor of Zoology

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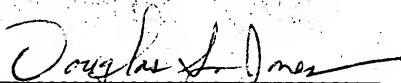
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This dissertation was submitted to the Graduate Faculty of the Department of Zoology in the College of Liberal Arts and Sciences and to the Graduate School, and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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