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PALEOLIMNOLOGY OF THE MAYA LOWLANDS

Long–term perspectives on interactions among climate, environment, and humans

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Abstract

Since the late 1950s, scientists have used sediment cores from lakes on the Yucatan Peninsula to explore the complex interactions among climate, environment, and ancient Maya culture. Early paleolimnological studies generally assumed that late Holocene climate was invariable. Consequently, paleolimnologically inferred environmental changes that occurred during the past 3,000 years or so—for example, forest decline and soil erosion—were attributed wholly to anthropogenic activities such as land clearance for agriculture and construction. Recent high-resolution, proxy-based paleoclimate records from continental and insular sites around the Caribbean Sea contradict the assumption of late Holocene climate stability. Instead, these core data suggest that regional drying began about 3,000 years ago and that the past three millennia were characterized by variable moisture availability. Paleoclimate inferences from Lakes Chichancanab and Punta Laguna, northern Yucatan Peninsula, indicate that drought events over the past 2,600 years were cyclical. These dry events, thought to have been driven by solar forcing, appear to have occurred approximately every two centuries (about 208 years). The driest period of the late Holocene occurred between A.D. 800 and 1000, coincident with the Classic Maya Collapse. We review the history of paleolimnological studies in the Maya Lowlands, discuss the difficulty of differentiating climatic signals from anthropogenic signals in late Holocene lake sediment profiles, and assess current understanding of past climate changes in the region based on regional lacustrine sediment studies.

Contemporary issues such as overexploitation of marine fisheries, increasing acidity of precipitation, heavy-metal pollution, soil erosion and degradation, and lake eutrophication have created a heightened awareness of human effects on the environment. Both natural and social scientists have long been fascinated by the complex interactions between humans and the ecosystems they inhabit. Archaeologists have provided a historical perspective on this issue by elucidating case studies of human effects on ancient environments (Redman 1999). Clearly, the effects of people on their surroundings are only one way of viewing "human-environment" relationships. Advocates of "environmental determinism" viewed the interaction "in reverse," positing that the environment limits human cultural development. This point of view has gone in and out of favor, often for political reasons, but it is undeniable that environmental variables influence society in many ways. We simply maintain that people and their surrounding environment mutually affect one another.

During the past few decades awareness has been growing that humans have the capacity to alter global climate. As greenhouse gases increase, greater attention has been directed toward understanding the effects of future global warming on society. It is widely recognized that climate phenomena such as El Niño events can have dramatic effects on agricultural harvests and national economies (see, e.g., Caviedes 2001). Concerns about future climate changes acknowledge that climate–human relations involve mutual interaction. It goes without saying that climate affects the physical and biological environment in many ways. The soils, flora, and fauna of a geographic region uninhabited by humans largely reflect climatic and geologic factors. We view climate, environment, and human culture as being intimately linked (Figure 1).

Many studies of Maya prehistory have tried to make sense of climate–human–environment interactions in a low-elevation, tropical context. Archaeologists have provided insights into environmental conditions that prevailed when the ancient Maya civilization flourished. For instance, botanical and zoological remains from archaeological excavations have yielded information on plants and animals exploited by the Maya and revealed details about pre-Columbian subsistence economy (Miksicek 1983; Pohl 1985). Soil studies have been informative concerning ancient Maya agricultural strategies (Beach 1998a, 1998b; Bloom et al. 1983; Olson 1981). In some cases, excavations shed light on regional climate changes during the past few millennia (Dahlin 1983; Folan et al. 1983). Agronomic studies on the Yucatan Peninsula fueled debates about how Late Classic Maya populations were sustained, and a number of edited volumes were dedicated to pre-Columbian agricultural subsistence strategies (see, e.g., Fedick 1996; Flannery 1982; Harrison and Turner 1978).

Paleolimnological investigations have supplemented archaeological studies to help provide an environmental context in which

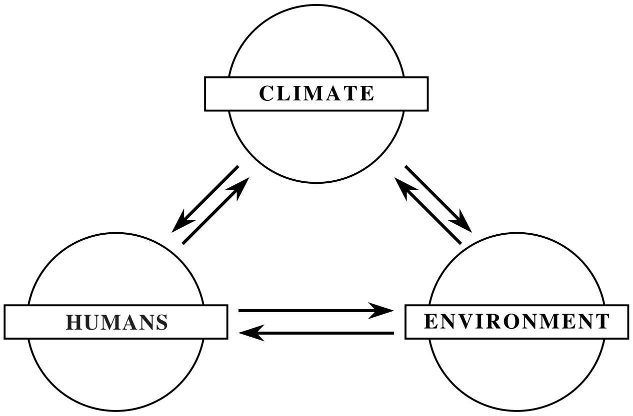

Figure 1. Conceptual graphic model illustrating the complex interactions among climate, environment, and human culture. Arrows between each compartment indicate two-way interactions. Paleolimnological studies on the Yucatan Peninsula have explored these interactions, including human effects on regional vegetation and soils and the influence of climate change on societal development.

Maya culture arose, flourished, and collapsed. Lake-sediment cores can be used to develop continuous, long-term, high-resolution records of environmental change. These lacustrine deposits can be employed to infer regional historical ecology because they accumulate in an ordered manner, deposit rapidly on lake bottoms (about 1 mm yr^{-1}), and contain physical, chemical, and biological information about past conditions within lakes and in their surrounding watersheds (Figure 2).

Continuous cores from appropriate lakes can provide a suite of information concerning paleoenvironmental conditions. For example, stratigraphic study of pollen grains in a sediment sequence can reveal details about past changes in terrestrial plant communities. These changes may reflect climatic or human effects on the regional vegetation. Diatoms are algae that leave identifiable siliceous remains in the sediments and can be used to infer past lake trophic status, lakewater salinity, and pH. Sediment geochemistry is employed to infer historical nutrient input into aquatic ecosystems, past dissolved-salt concentrations in lakewater, and patterns of soil erosion from surrounding drainage basins. Stable isotope analysis of aquatic shell material buried in lake deposits can often provide insights into past climate conditions. When long lake-sediment sequences are dated reliably using radiocarbon, the timing of past environmental changes can be estimated.

Contemporary processes that contribute to the formation and deposition of materials in modern sediments must be understood to infer past environmental conditions. Paleolimnology is thus a uniformitarian science—that is, the present is the key to the past. Sediment characteristics can be measured and used as proxies (substitute variables) for inferring prehistoric environmental conditions. Strong paleoenvironmental "reconstructions" require use of multiple lines of sedimentary evidence. They also demand that these multi-proxy studies yield coherent inferences (Binford et al. 1983; Frey 1969; Pennington 1981). In many respects, the approaches used in paleolimnology and archaeology have much in common. Whereas archaeological excavations yield artifacts that enable inferences about past cultural development, paleolimnology utilizes physical, chemical, and biological information buried in lake sediments to gain insights into paleoenvironmental conditions. In both disciplines, the fragmentary records are interpreted with a measure of uncertainty.

In this paper, we review paleolimnological investigations that were undertaken in the Maya Lowlands, summarize the major findings of these studies, and focus on the current state of knowledge concerning interactions among climate, environment, and ancient Maya culture that are based on analyses of lake-sediment cores. One of our objectives is to bring to the attention of archaeologists the many paleolimnological studies that have been done in the region. We suspect that some of this work has escaped the notice of the archaeological community because the results were published in specialized earth-science journals. We also point out that the focus of paleolimnological work in the Maya region has shifted several times in the past few decades. For instance, sediment records were sometimes employed to assess human effects on the environment, whereas at other times cores were used to explore how climate changes may have influenced Classic Maya agriculture. That paradigm shift reflects, at least in part, the prevailing issues in modern environmental science at the time the studies were undertaken. Finally, we present recent advances in understanding regional paleoclimate, discuss some limitations of the paleolimnological approach (see Brenner et al. 2002), and elaborate on several questions that must be addressed by future research.

EARLY PALEOLIMNOLOGICAL STUDIES IN THE MAYA LOWLANDS

Ursula M. Cowgill, G. Evelyn Hutchinson, A. A. Racek, Clyde E. Goulden, Ruth Patrick, and Matsuo Tsukada (Cowgill et al. 1966) published their pioneering paleolimnological work on two sediment cores collected in 1959 from Laguna de Petenxil (N16°55, W 89°50″), a small, shallow lake (area = 0.55 km^2, maximum depth = 4.0 m) in Peten, Guatemala (Figure 3). The cores were short (2.2 m and 2.5 m), and the longest sequence had a basal age of 3,990 ± 160 C-14 years B.P. The profiles were studied for sediment chemistry, minerals, pollen, diatoms and other algae, plant macrofossils, sponge spicules, and animal microfossils, primarily small crustacean remains of the group Cladocera. Although "hard-water-lake error" (Deevey and Stuiver 1964) compromised the accuracy of the core chronology, the record nevertheless provided the first glimpse into the region's historical ecology. The pollen stratigraphy in particular proved interesting and reflected substantial past vegetation changes in the area.

The Petenxil core was divided into three pollen zones and possessed maize (*Zea*) grains throughout. The oldest zone (G1) had high percentages of herbaceous pollen grains, especially grasses, suggesting that the ancient landscape was more open and less forested than today. The middle zone, designated G2, was thought to reflect the greatest amount of human agricultural activity. It displayed high relative abundance of *Ambrosia*-type pollen, a weed often associated with agricultural activity, as well as increased presence of Gramineae (grasses) and a corresponding low presence of Moraceae (high-forest) pollen. The topmost pollen zone (G3) had a high representation of forest taxa and displayed lower percentages of grains, indicative of agricultural disturbance. The authors concluded that humans had turned a grassland into a high forest, rather than the reverse, as occurred in other portions of the world. They also concluded that: (1) agriculture had been practiced in the area for more than 4,000 years; (2) there had been no significant climate change in the region during the past four mil-

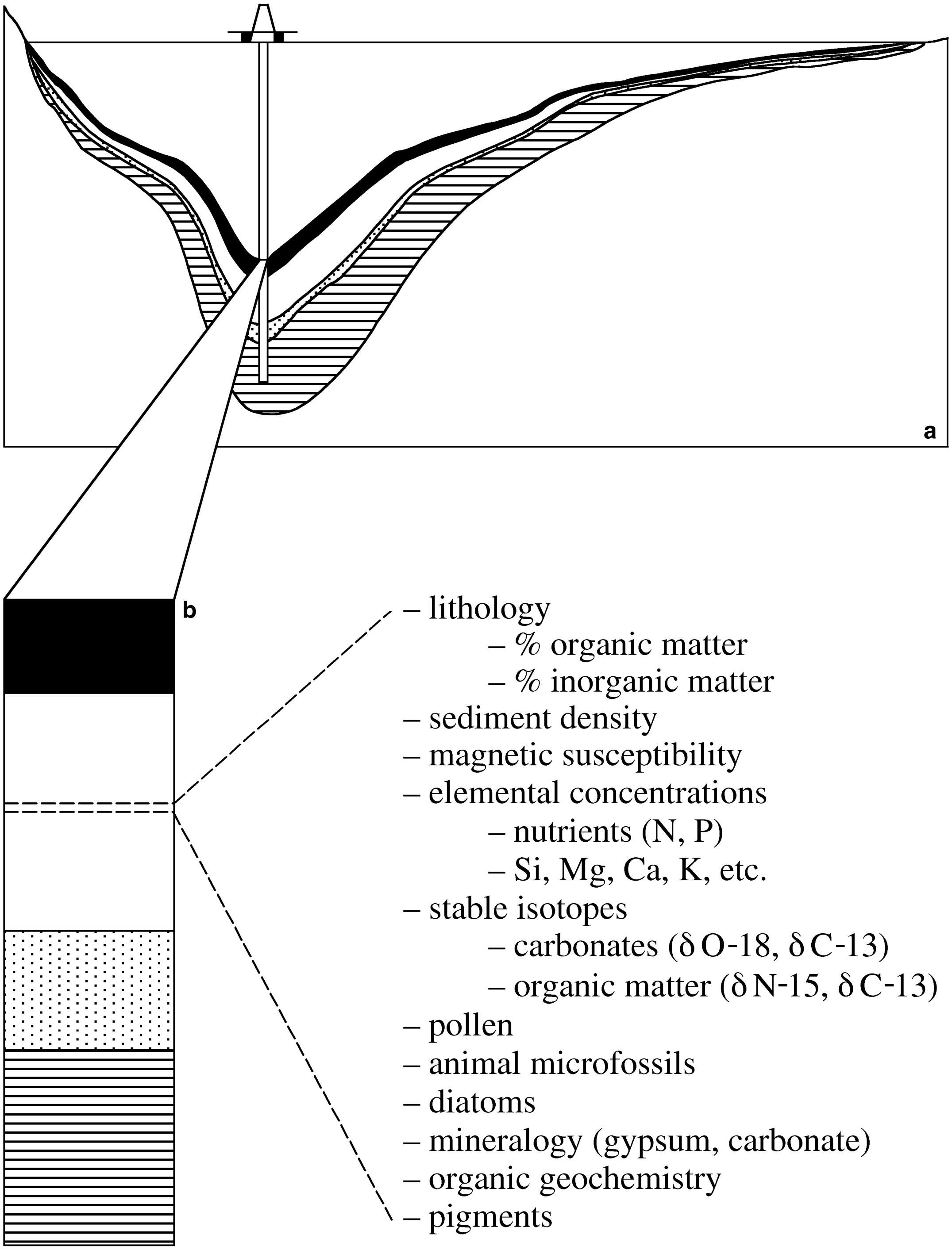

Figure 2. (a) Cross-section of a lake showing the water column, underlying sediment deposits, and a coring platform on the water surface. Mid-lake sediments accumulate in an ordered fashion at a fairly high rate (about 1 mm yr^{-1}). Sediment cores contain an archive of environmental changes that occurred within the lake and its surrounding watershed. (b) Enlarged view of a sediment core from the lake, illustrating the well-preserved stratigraphy. Cores can be analyzed for proxy environmental variables, including lithology (organic/inorganic content), density, magnetic susceptibility, element concentrations, stable isotopes, pollen, animal microfossils, diatoms, mineralogy, organic geochemistry, and pigments.

lennia, (3) there was no evidence for "disastrous" levels of anthropogenic soil erosion in the area; and (4) there was nothing to suggest that population densities ever reached levels sufficient to have caused serious environmental disturbance.

Aguada Santa Ana Vieja (N16°42″, W 89°45″) is located about 35 km south of Lake Petenxil (Figure 3). A small (200-m diameter), shallow (1 m) water body, it lies in Peten's savanna country but is partly surrounded by high forest. Two short cores were

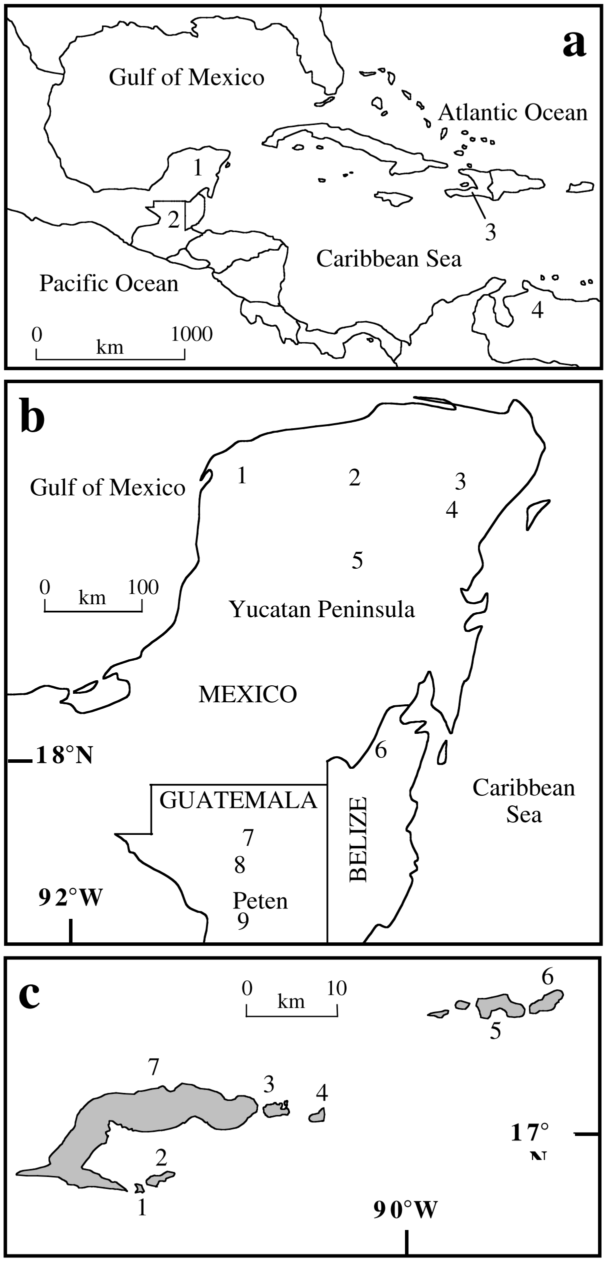

Figure 3. (a) Map of the circum-Caribbean region showing the general geographic locations of paleolimnological study sites discussed in the text: 1 = northern Yucatan Peninsula; 2 = southern Yucatan Peninsula; 3 = Lake Miragoane, Haiti; 4 = Lake Valencia, Venezuela; (b) map of the Maya Lowlands, showing the approximate geographic locations of lakes used to investigate regional paleoenvironmental conditions: 1 = San José Chulchaca; 2 = Sayaucil; 3 = Coba; 4 = Punta Laguna; 5 = Chichancanab; 6 = Laguna de Cocos; 7 = Central Peten Lakes (see c); 8 = savanna lakes Santa Ana Vieja, Chilonche, Chimaj, and Oquevix; 9 = Río de la Pasión drainage basin lakes Tamarindito and Las Pozas; (c) enlargement showing the Central Peten Lake District water bodies: 1 = Petenxil; 2 = Quexil; 3 = Salpeten; 4 = Macanche; 5 = Yaxha; 6 = Sacnab; 7 = Peten-Itza.

collected in 1959. The studied core was only 23 cm long and consisted largely of stiff, indurated clay. Uppermost deposits contained slightly more water and organic material. The undated pollen record from the pond sediments showed it always to have been surrounded by grassland, with some indication of high forest expansion near the top of the sequence (Cowgill and Hutchinson 1966). By palynological correlation with the dated Petenxil core, it was thought that the shift toward greater forest representation began late in the first millennium A.D. Some paleoenvironmental conclusions based on study of the Petenxil and Santa Ana Vieja sediment sequences were erroneous, in part because the records failed to reach older, "pre-disturbance" deposits, and because radiocarbon dates were artificially old relative to their true radiocarbon ages. Nevertheless, these early studies demonstrated that sediment cores from lakes in the Maya region lent themselves to stratigraphic investigation.

Between 1965 and 1969, cores were collected from several other waterbodies on the Yucatan Peninsula. Study sites included Lake Peten-Itza (N16°55″, W 89°50″), the largest lake in the region (about 100 km^2), and Lake Chichancanab (N19°50″, W 88°45″), a sulfate-rich basin in the north-central part of the peninsula (Figure 3). The undated, 3.7-m core from Peten-Itza was collected in the southern basin of the lake, about .5 km east of the island of Flores. Sedimented shells from five snail species were used to evaluate temporal changes in the mollusc community (Covich 1976). Stratigraphic shifts in the relative abundance of prosobranch (*Pyrgophorus*, *Tryonia*, *Cochliopina*) versus pulmonate (*Biomphalari*a, *Stenophysa*) snails were thought to have been driven by changes in nutrient availability and water-column oxygen concentration. Pulmonates have a competitive advantage in the presence of low oxygen because of their ability to use atmospheric O_2. Alan P. Covich (1976) suggested that periods of high nutrient loading and consequent low oxygen concentration resulted from past and present agricultural activities in the watershed. He also noted that other factors, such as removal of mollusc predators (e.g., turtles) by humans, may have influenced the competitive advantage of certain species, thereby altering the relative abundances of various taxa. Covich (1978) even suggested that many modern terrestrial and aquatic communities of the Maya Lowlands represent cultural artifacts, having been modified by the prolonged impact of agricultural activities. These early paleolimnological studies focused on Maya effects on aquatic fauna and terrestrial vegetation and may have reflected the emerging concerns in the 1960s and 1970s about contemporary human effects on the environment.

Cores were collected from Lake Chichancanab in 1968 and 1969 and used to infer past climate change based on shifts in the ratio of two stable isotopes of oxygen, O-18 and O-16, in sedimented snail shells (Covich and Stuiver 1974). The two oxygen isotopes have different masses and therefore undergo fractionation when they enter into physical, chemical, and biological processes in the environment. This means that the relative abundances of the two isotopes change when, for example, water is evaporated from a lake or bicarbonate ion (HCO_3^-) is incorporated into the calcium carbonate ($CaCO_3$) shells of invertebrate organisms such as snails. These isotopic ratios can be measured by mass spectrometry and employed to gain insights into paleoclimate conditions. The isotope ratio is typically expressed in what is called standard delta notation (δO-18), which represents the ratio of O-18 to O-16 in a sample of shell material relative to the oxygen isotope ratio in a Vienna Peedee Belemnite (VPDB) standard:

$$\delta\text{O-18} = \frac{(\text{O-18/O-16})\ \text{sample} - (\text{O-18/O-16})\ \text{VPDB}}{(\text{O-18/O-16})\ \text{VPDB}} \times 10^3‰$$

The value is an expression of the departure of the O-18/O-16 ratio in the sample from that of the standard, expressed on a per-mil (‰) basis.

Two principal factors govern the isotope ratio (δO-18) of sedimented freshwater shells: (1) the lakewater δO-18 at the time the organism lived; and (2) the temperature at which shell carbonate was precipitated. Holocene temperature changes in the tropics are thought to have been minimal. Assuming that tropical temperatures did not shift appreciably over the past 10,000 years or so, changes in lakewater δO-18 during that period would have been the primary determinant of δO-18 in freshwater shell carbonate. Hydrologic factors, in turn, govern the O-18/O-16 ratio of lakewater. If the δO-18 of water entering a tropical, "closed-basin" lake remained fairly constant throughout the Holocene, then past changes in the lakewater oxygen isotope ratio must have been governed by shifts in the relationship between hydrologic inputs (rainfall and runoff) and outputs (evaporation) (Fontes and Gonfiantini 1967; Gasse et al. 1990; Lister et al. 1991). During dry periods—that is, when the evaporation/precipitation ratio (E/P) is high, O-18 is concentrated in lakewater because lighter H_2O-16 is evaporated preferentially. During wetter times (low E/P), the lakewater displays relatively low δO-18. Throughout the Maya Lowlands today, lakewaters are relatively "heavy"—that is, they have more positive δO-18 signatures compared with local rainfall, runoff, and groundwater. This reflects the evaporative concentration of the heavier isotope (O-18) in lakes (Brenner et al. 2002; Covich and Stuiver 1974; Hodell et al. 1995).

Several kinds of aquatic organisms that inhabit inland waters, including gastropods (snails), pelecypods (clams), ostracods (bivalved crustaceans), and foraminifera, form shells of calcium carbonate ($CaCO_3$). Their shells preserve a record of the lakewater δO-18 and hence the E/P ratio that prevailed when the animals were alive. On death, the shells are incorporated into the lake sediments, thereby preserving a record that can be used to infer past climate change. Past shifts in available moisture (E/P) can be discerned by stratigraphic determination of δO-18 in carbonate of sedimented shell material by mass spectrometry.

Covich and Minze Stuiver (1974) recovered a 12-m sediment section from Lake Chichancanab that had a basal radiocarbon age of 28,830 ± 500 C-14 years B.P. The bottom 3 m of mud showed evidence of a sedimentation hiatus, but the uppermost 9 m reflected continuous lacustrine deposition over the past 8,000 or so years. Seventeen measurements on Holocene-age snail shells of the genus *Pyrgophorus* yielded an average sample spacing of about 500 years. Long-term shifts in Holocene moisture availability were nevertheless evident, and a "shallow–deep–shallow" or "dry–wet–dry" pattern was inferred for the past eight millennia. According to the core chronology, relatively positive δO-18 values, indicating drier conditions (high E/P), prevailed between the bottommost Holocene deposits and about 5,500 C-14 years ago. Thereafter conditions were apparently wetter, as indicated by a decrease in δO-18 values. Dry conditions appear to have returned during the past two millennia. Although only three radiocarbon ages were obtained for the Holocene section of this Chichancanab core, and sampling was done at broad intervals, the study nevertheless demonstrated the feasibility of using stable oxygen isotopes to discern past climate variability. It also revealed climate changes throughout the Holocene, including during the period of ancient Maya occupation. The results hinted that Holocene climate variability may have influenced geographic distributions of plants and animals on the Yucatan Peninsula and may have even played a role in Maya cultural development.

THE CENTRAL PETEN HISTORICAL ECOLOGY PROJECT

In the early 1970s, the Central Peten Historical Ecology Project (CPHEP) was initiated under the direction of Edward S. Deevey. The project was explicitly multidisciplinary, involving the combined efforts of archaeologists and paleolimnologists (Rice 1996). Deevey envisioned the period of ancient Maya occupation in the Guatemalan lowlands as a "grand experiment" in long-term use of a tropical karst environment (Deevey et al. 1979). Reflecting his belief that one could "coax history to conduct experiments" (Deevey 1969), Deevey argued that the environmental consequences of Maya agricultural and engineering activities were quantitatively preserved in Peten lake sediments and could be revealed by paleolimnological methods. The primary objective of the research was to assess human effects on the environment by correlating paleoenvironmental and paleodemographic data (Rice 1978).

The archaeological research design involved mapping and test-pitting residential structures on transects established in six watersheds. This permitted "reconstruction" of temporal changes in prehistoric Maya population density (Rice and Rice 1983, 1990). The watersheds chosen for study surrounded six lakes, from west to east: Petenxil, Quexil, Salpeten, Macanche, Yaxha, and Sacnab (Figure 3). Contrary to the conclusions in Cowgill et al. (1966), population estimates based on systematic house mound surveys suggested that by Late Classic times (A.D. 550–850), densities had been high, in some cases 200–300 persons/km^{-2}.

Detailed palynological and geochemical examination of long sediment cores from several of the basins also contradicted the conclusions of the early study at Petenxil (Cowgill et al. 1966). An approximately 8,000-year pollen record from a shallow-water site in Lake Quexil demonstrated that tropical forest had dominated the area at least since the early Holocene (Deevey 1978; Deevey et al. 1979; Vaughan et al. 1985; Wiseman 1985). A major decline in forest taxa began before 3000 B.P. The vegetation shift generally coincided with early agricultural activities in the region (Rice and Rice 1983, 1990; Rice et al. 1985) and with the climatic drying detected at Chichancanab by Covich and Stuiver (1974).

Since the inception of the CPHEP, other studies have looked at the regional vegetation history. A date on terrestrial wood from a core taken in Lake Yojoa, Honduras, suggests that food procurement in that area began as early as some 4,500 C-14 years B.P. (Rue 1987). Likewise, a reliably dated pollen sequence from Lake Peten-Itza shows that forest reduction predates archaeological evidence for sedentary human settlement in central Peten (Islebe et al. 1996). The pollen data also suggest that the appearance of modern forest was not a consequence of Maya agricultural activities, as had been suggested in Cowgill et al. (1966). On the contrary, it appears that the Maya converted tropical lowland forest into an agricultural, savanna-like landscape, probably during a period of regional climatic drying. The modern forest represents vegetation that "recovered," following a reduction in anthropogenic stress (i.e., slash-and-burn agriculture), some time after the Collapse in the ninth century A.D.

The Holocene pollen stratigraphy of the Maya Lowlands has been reproduced in other C-14–dated cores from Lake Quexil (Vaughan et al. 1985), and in cores from Lakes Salpeten (Leyden 1987), Sacnab (Deevey et al. 1979; Vaughan et al. 1985), Macanche (Vaughan et al. 1985), and Peten-Itza (Curtis et al. 1998; Islebe et al. 1996). Similar paleovegetation patterns are recorded in pollen diagrams from other lakes in the Maya Lowlands, including among others, Laguna de Cocos, in northern Belize (Hansen

1990), and Lake Coba, in the moist part of the northeastern Yucatan Peninsula (Leyden et al. 1998). At Laguna Tamarindito, in the Río de la Pasión area, a 235-cm core representing a near-complete record of Holocene sedimentation (Dunning, Beach, and Rue 1997; Dunning, Rue, Beach, Covich, and Traverse 1997) displayed a pollen record that differed somewhat from those of the Central Peten Lakes District. Along the Pasión drainage, deforestation began in the Preclassic (>3000 B.P.), when early settlers cleared vegetation along waterways, but population density declined sufficiently in the Early Classic period (A.D. 250–550) to enable regrowth of mature forest. Intensive land clearance resumed in the Late Classic period (A.D. 550–850), and the pollen profile contains evidence of renewed land clearance.

LATE GLACIAL CONDITIONS IN THE MAYA LOWLANDS

By the late 1970s, the scope of paleolimnological research in Peten had expanded to include exploration of environmental conditions during the late Glacial period. No lacustrine records from the region were yet available to provide insight into late Pleistocene vegetation or climate. In 1977 and 1978, a Kullenberg-type gravity-piston corer was deployed in deep water at Lakes Quexil, Salpeten, and Macanche. Near-complete Holocene sections were taken, but longer cores could not be collected partly because of a thick, nearly impenetrable layer of clay on the lake bottoms.

In 1980, a professional drilling company, Daho Pozos, was contracted to take sediment profiles from the three basins using a split-spoon corer. Lake Quexil yielded the longest sequence. In conjunction with a previously obtained Kullenberg core, a 19.6-m record was obtained, representing about 36,000 years of sediment accumulation (Brenner 1994; Leyden et al. 1993, 1994). It remains the longest lacustrine sediment record yet retrieved from a site in the Maya Lowlands. The pollen record from that sequence showed that tropical forest taxa did not exist in the region during the cold, dry late Glacial period. Leyden et al. (1993) estimate that between 24,000 and 12,000 C-14 years B.P., temperatures were about 6.5–8°C cooler than at present. Pleistocene-age deposits were dominated by inorganic matter, including carbonates, gypsum, and silicate clays. This sediment type suggested relatively dry conditions. About 10,500 years ago, lake levels rose, sediments became more organic, and tropical forest colonized the area as a consequence of the onset of warmer, wetter climate conditions (Deevey et al. 1983; Leyden 1984; Leyden et al. 1993, 1994; Brenner 1994; Huang et al. 2001). It had generally been assumed that modern Peten forests represented “age-old” tropical vegetation. The long Quexil core revealed that relatively mesic forest existed in the area for only 6,000–7,000 years before it was cleared by early farmers for slash-and-burn agriculture, perhaps coincident with the onset of regional drying. The Pleistocene–Holocene transition, however, illustrates the strong control that climate alone exerted over vegetation on the Yucatan Peninsula some 10,500 years ago, prior to significant human intrusion.

MAYA-PERIOD SOIL EROSION AND NUTRIENT DEPLETION

Sedimentological and geochemical studies of Peten lake cores elucidated the impact of protracted deforestation on regional soils during the period of Maya occupation. Holocene sediment sequences from small lakes in central Peten have similar lithologic stratigraphies (Figure 4). Early Holocene deposits contain relatively high concentrations of organic matter (30–60%), but are overlaid by a thick, inorganic layer composed mostly of montmorillonite clays. This fine-grained deposit has been referred to as “Maya clay” and is itself overlaid by more recent, organic-rich sediments. The onset of clay deposition appears to have begun about 3,000 years B.P. (Brenner 1994; Rosenmeier, Hodell, Brenner, Curtis, Martin, Anselmetti, Ariztegui, and Guilderson 2002). This deposit is believed to reflect severe soil erosion that resulted from widespread, human-mediated deforestation (Binford 1983; Binford et al. 1987; Brenner 1994; Deevey and Rice 1980; Deevey et al. 1979; Vaughan et al. 1985). It may also be partly a consequence of regional drying (Covich and Stuiver 1974; Hodell et al. 1995; Curtis, Hodell, and Brenner 1996; Curtis, Brenner, and Hodell 2001). In any event, when vegetation disappeared from steep hillsides in Peten, nutrient-rich surface soils were exposed and became vulnerable to downslope colluvial transport.

High rates of erosion from uplands in Peten probably resulted in long-term soil-nutrient depletion. Mollisols (calcimorphic rendzinas) are the common soil type on Peten hillsides. These thin (typically <1 m) mineral soils develop over friable, calcium carbonate-rich material called *sascab*. Phosphorus (P) profiles from soil pits (Figure 4) show that this essential plant nutrient is most concentrated in uppermost soil layers and declines in concentration with increasing depth (Brenner 1983a). Hence, P exported from hill slopes in colluvium ended up in landscape depressions, including *rejolladas*, *bajos*, and lakes. Accelerated sequestering of P on the bottom of lakes was a function of increasing population density and land use (Brenner 1983a, 1983b; Deevey and Rice 1980; Deevey et al. 1979). There is evidence that the ancient Maya were aware of this problem. During the Late Classic period, terracing of uplands in the Río de la Pasión drainage reduced soil erosion significantly (Dunning, Beach, and Rue 1997).

High rates of phosphorus transfer from temperate watersheds to lakes generally results in eutrophication—that is, nutrient enrichment of lake waters and consequent increases in lacustrine productivity. Massive siltation, however, accompanied P input to Peten basins. High silt loads probably adsorbed nutrients, inhibited light penetration through the water column, reduced aquatic primary production, and interfered with the filter feeding apparatus of aquatic invertebrates (Deevey 1985). Long-term transfer of soil and associated nutrients from land to water may have had a negative effect on Maya populations by reducing both terrestrial crop yields and aquatic protein production.

POST-MAYA REFORESTATION

Sometime after the Classic-period Collapse, Peten forests regrew. The factors that led to vegetation regrowth in Peten, as well as the exact timing of reforestation, require further study. Afforestation was originally thought to have been a purely anthropogenic phenomenon, coinciding with the Classic Collapse (ca. 900 A.D.). Hardwater-lake error (Deevey and Stuiver 1964), however, has made it difficult to establish the exact timing of forest recovery. Lacustrine pollen records have typically been dated by radiocarbon analysis of organic matter in bulk lake sediment, which may be contaminated with “old” carbon. In the limestone terrain of northern Guatemala, local country rock is slowly dissolved by slightly acidic rainfall. Bicarbonate ions from the ancient bedrock are delivered to lakes in runoff and groundwater. Cretaceous-age limestone in the watersheds possesses no radiocarbon and the bicarbonate of input waters is thus depleted in C-14. Dissolved bicarbonate reaching the lake can be used as a photosynthetic carbon source by algae and higher

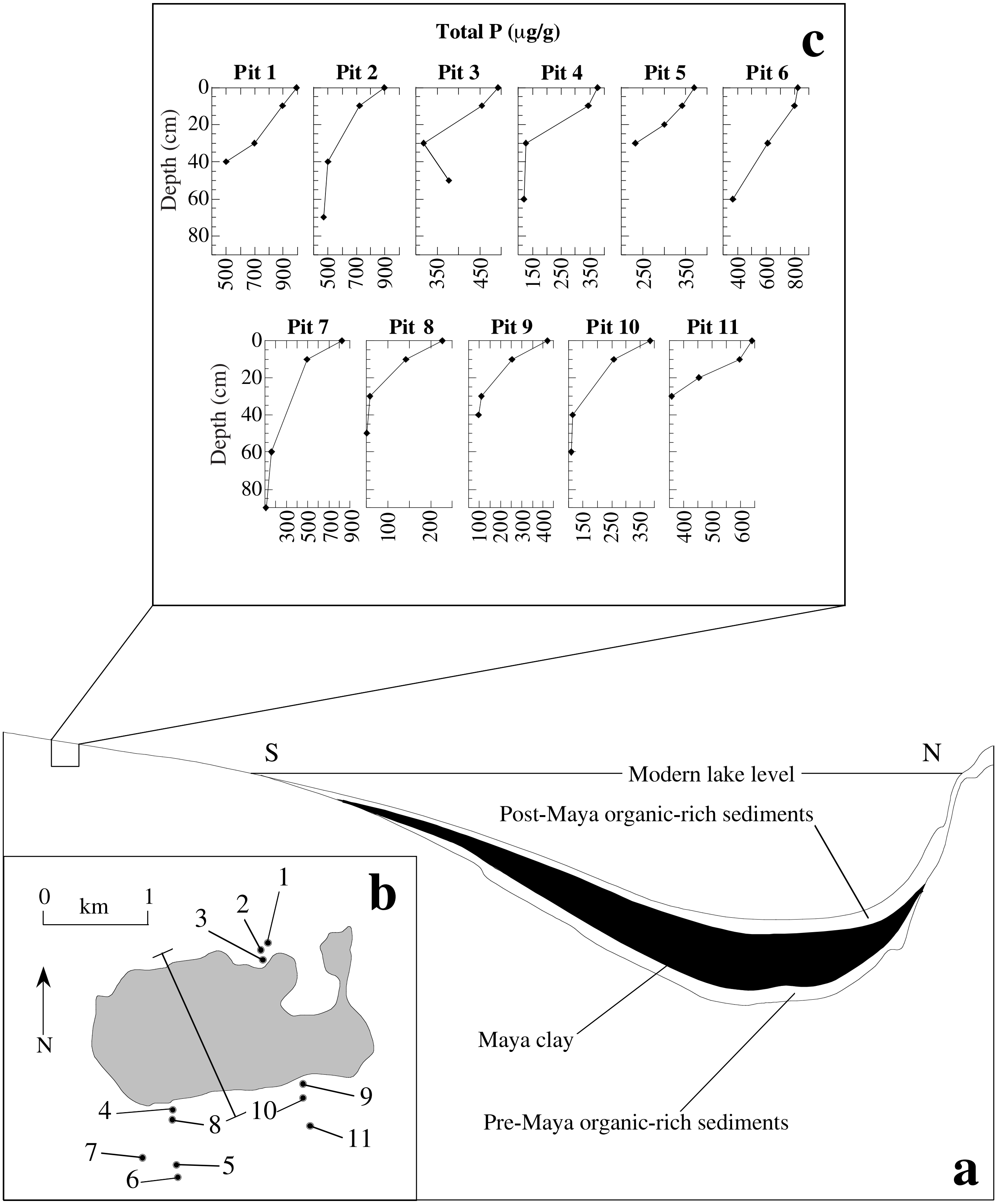

Figure 4. (a) Cross-section of the sediment lens in Lake Salpeten, Guatemala, based on a north-south seismic line (see inset b). Holocene deposits from Peten lakes typically contain three lithologic zones: (1) a pre-Maya, organic-rich sediment; (2) a thick, clay-rich deposit (known as Maya clay) that is thought to be an erosional artifact of watershed deforestation; and (3) an overlying post-Maya organic-rich layer, accumulated following the Maya Collapse and regional reforestation; (b) outline map of Lake Salpeten showing the position of the north–south seismic line on which the bathymetry and sediment cross-section are based and the approximate locations of soil pits used to evaluate stratigraphic distribution of total phosphorus in watershed soils; (c) total phosphorus profiles from 11 soil pits around Lake Salpeten (see b), illustrating that this necessary plant nutrient displays highest abundance in surface soils and is prone to loss via erosion and colluviation when watershed vegetation is cleared.

aquatic plants. These primary producers may then be exploited by aquatic herbivores, which are in turn consumed by carnivores. Because the dissolved inorganic carbon used for aquatic plant photosynthesis was not in equilibrium with the atmosphere, radiocarbon dates on lacustrine-derived organic matter can be artificially old—that is, older than their true radiocarbon age.

Three cores from Lake Quexil were used to date organic-rich bulk sediments that immediately overlie the "Maya clay." Radiocarbon ages for the lithologic contact varied from 730 to 1,500 C-14 years B.P. among the sections (Leyden et al. 1994), and the dates were rejected as unreliable. Aguada Chilonche, in the Peten savannas, yielded a pollen-analyzed sequence with a post–Collapse radiocarbon date on terrestrial wood. The pollen record suggests that reforestation began after 305 ± 55 C-14 years B.P.—that is, that forest regrowth postdated European arrival and that contemporary Peten forests are very young (Brenner et al. 1990). The Chilonche pollen record is replicated at nearby lakes Chimaj and Oquevix (Brenner et al. 1990). The wood date from Chilonche hints that reforestation was postponed until after European contact, implying that, despite the demographic decline associated with the Classic Collapse, Postclassic Maya populations were sufficiently large at some central Peten localities (Rice and Rice 1983, 1990) to clear secondary vegetation routinely. Complicating the issue, the Chilonche record contains evidence that forest expansion several centuries ago may have been partly a response to wetter climate. A core from Petapilla Swamp, near the archaeological site of Copan (Honduras), shows that reforestation occurred after 750 C-14 years B.P., suggesting that early Postclassic populations continued to occupy the area. Here, too, there is some indication that increased moisture played a role in revegetation. The swamp expanded after 750 C-14 years B.P., as indicated by rising percentages of hydrophytes (Rue 1987).

Frederick M. Wiseman (1985) used cores collected in 1975 from Lake Quexil to argue that reforestation in Peten commenced shortly after the Classic Collapse. He also pointed out that faunal remains from Postclassic archaeological contexts do not reflect an open, savanna landscape; rather, they are dominated by animal taxa from forested environments. He noted that acceptance of "post-contact reforestation" places the pollen zones with the greatest amount of maize grains and other disturbance indicators in the Postclassic period. This would suggest, erroneously, that there had been little human impact on the environment during Preclassic and Classic times. Pollen data from a core collected in Lake Peten-Itza in 1993 bolster the argument for rapid reforestation following the collapse (Islebe et al. 1996; Curtis et al. 1998). The sequence has four wood and charcoal ages spanning the period A.D. 410–1890 and shows that reforestation began immediately after the ninth century A.D.

Based on study of sediment record that spans about 4,000 years from Laguna Las Pozas, in the Río de la Pasión drainage, Kevin J. Johnston, Andrew J. Breckenridge, and Barbara C. S. Hansen (2001) suggest that early Postclassic populations colonized and deforested remote areas that had been relatively undisturbed during Classic times. Following the ninth-century Collapse, the pattern of reforestation in the Maya Lowlands may have varied in space and time. Further studies will be required to establish why, when, and how quickly the landscape changed during the past millennium.

HOLOCENE CLIMATE VARIABILITY IN THE MAYA LOWLANDS AND CIRCUM-CARIBBEAN

Pollen analysis has often been used to evaluate past climate changes. As noted by Hague H. Vaughan, Edward S. Deevey, and Sam E. Garrett-Jones (1985) and J. Platt Bradbury, Richard M. Forester, W. Anthony Bryant, and Alan P. Covich (1990), human effects on forests in the Maya Lowlands were severe and easily can be confused in the pollen record with the effects of climate change. It is therefore impossible to disentangle anthropogenic and climatic signals using pollen from Peten lake cores. Improvements in mass spectrometry since the early work of Covich and Stuiver (1974) provide an alternative approach for investigating past climate changes such as shifts in moisture availability. Close-interval δO-18 measurements on carbonate shells from lake-sediment cores have the potential to provide high-resolution records of past relations between evaporation and precipitation. Whereas pollen is generally well preserved in lake mud, not all lakes possess the carbonate microfossils or other characteristics that make them appropriate for isotopic studies. Waterbodies that are best suited for doing paleoclimate reconstructions based on δO-18 of carbonate microfossils share common qualities (Brenner et al. 2002). They typically lack overland outflows and lose water principally to evaporation. Their water level (stage) changes quickly in response to shifts in the evaporation/rainfall ratio, and these lakes gain or lose a significant proportion of their total water volume as a consequence of alterations in the hydrologic budget. Ideally, their watersheds should not have been subjected to massive human disturbances (e.g., deforestation), which can alter their hydrology. Lake waters must have relatively high concentrations of carbonate and bicarbonate to promote invertebrate shell formation. Shell remains of these organisms (ostracods, snails, clams, foraminifera) must be abundant and well preserved in the continuously accruing lake sediments. Sediment cores should also contain remains of terrestrial organic matter throughout to provide a reliable radiocarbon chronology.

In 1985, a 7.5-m core was retrieved from Lake Miragoane in southern Haiti (N 18°24″, W 73°05″). The section was collected with the objective of inferring Holocene environmental changes at an insular Caribbean site that had not been subjected to intense human effects during the pre-Columbian era. One of the few deep natural waterbodies in the Caribbean, Lake Miragoane yielded a 10,500-year or so record of climate and vegetation change (Brenner et al. 1994; Curtis and Hodell 1993; Curtis et al. 2001; Higuera-Gundy et al. 1999; Hodell et al. 1991). Several years after collection, the core was sectioned at 1-cm intervals for oxygen isotope and trace metal (Ca, Sr, Mg) analysis of ostracod shells, with the goal of providing a high-resolution record of E/P shifts. Each 1-cm sample represented, on average, about 14 years of sediment accumulation. The δO-18 and trace-metal records showed that conditions were dry in the oldest part of the section but became increasingly moist between about 10,000 and 7,000 C-14 years B.P. Moist conditions persisted until about 3,200 C-14 years B.P., when a drying trend began. The past three millennia in the Miragoane record display evidence of high-frequency changes in δO-18 values. The isotope record from Haiti was in general similar to Covich and Stuiver's (1974) findings at Lake Chichancanab on the Yucatan Peninsula, though their early study lacked the sampling resolution to distinguish the short-term fluctuations that are discernible in the Miragoane profile. Nevertheless, both records suggested that cool, dry conditions in the latest Pleistocene and earliest Holocene gave way to warmer, moister conditions, followed by general drying during the past three millennia. It is worth noting that the emergence of Maya agriculture on the Yucatan Peninsula generally coincided with late Holocene drying.

It has been postulated that orbitally forced changes in solar insolation drove long-term climate trends in Haiti (Hodell, Curtis, Jones, Higuera-Gundy, Brenner, Binford, and Dorsey 1991; Hodell, Brenner, and Curtis 2000). Changes in the Earth's precessional cycle, in conjunction with modern climatological studies in the circum-Caribbean (Hastenrath 1984), help explain the Holocene pattern of moisture availability inferred from the Miragoane core. Today, unusually wet years in the Caribbean are characterized by extreme northward migration of the Intertropical Convergence Zone (ITCZ) during the summer rainy season. The ITCZ moves far to the south during the dry, Northern Hemisphere winter. Early Holocene wet conditions were caused by a consistently enhanced annual cycle—that is, greater seasonality. Based on the Earth's precessional cycle, the greatest seasonality would have occurred around 8,000 C-14 years B.P., when the Earth, during its annual revolution, passed closest to the sun during the Northern Hemisphere summer (summer perihelion). The difference between summer and winter insolation remained high into the mid-Holocene but has been diminishing ever since. Reduced intensity of the annual cycle may account for the drying trend that commenced about 3,000 years ago.

Several studies at other circum-Caribbean sites suggest that the Miragoane findings (Hodell et al. 1991) reflect regional Holocene climate dynamics. For instance, a laminated marine core from the anoxic Cariaco Basin, north of Venezuela, contains a high-resolution proxy record of rainfall and river discharge for the past 14,000 C-14 years (Haug et al. 2001). Titanium (Ti) concentrations in the sediments reflect the amount of waterborne terrigenous material transported from the coastal environment. In the early Holocene part of the core, deposited from about 10,400 to 5,400 calendar years B.P., Ti concentrations are high, indicating abundant rainfall and runoff. Ti content begins to drop about 5,400 calendar years B.P., and there is high variability in the record during the interval 3,800 to 2,800 years ago. The last 3,000 years of the record reflect some of the driest conditions since the Younger Dryas. Long-term Holocene rainfall changes inferred from the Cariaco Basin core are thought to be a consequence of shifts in the latitudinal position of the Atlantic Intertropical Convergence Zone (Haug et al. 2001).

The Miragoane record (Hodell et al. 1991) renewed interest in pursuing paleoclimate reconstructions at sites in the Maya Lowlands. Lakes San Jose Chulchaca, Sayaucil, and Coba lie on an east–west transect across the northern Yucatan Peninsula (Figure 3). Cores from the basins were examined for geochemistry, pollen, diatoms, and stable isotopes (Brenner et al. 2000; Leyden et al. 1996; Whitmore et al. 1996). None of the cores was ideally suited for isotopic study because the sequences failed to contain carbonate microfossils throughout. Nevertheless, the fairly complete Coba record (Whitmore et al. 1996) displayed a Holocene E/P reconstruction that was similar in many respects to both the paleoclimate inferences from the Lake Miragoane core (Curtis et al. 2001; Hodell et al. 1991) and those based on the early, "skeletal" isotope record from Chichancanab (Covich and Stuiver 1974). Basal radiocarbon dates on the Coba and San Jose Chulchaca cores also indicated that the lakes initially filled about 8,000 years ago, consistent with the timing of filling at Lake Chichancanab (Covich and Stuiver 1974) and with the inundation of shallow areas in Lake Quexil (Vaughan et al. 1985). Similar to the situation at Miragoane and in Florida (Watts 1969), shallow lakes at low-elevation sites on the northern Yucatan Peninsula first filled with water in the early Holocene in response to both sea-level rise and increased rainfall.

Encouraged by the results from Lake Miragoane, a project was initiated in 1993 to investigate high-resolution Holocene climate variability at several continental locations around the Caribbean Sea (Curtis et al. 2001; Hodell et al. 2000). The principal objective was to employ stable oxygen isotopes to infer past changes in moisture availability. The hope was that climate-driven isotope changes in lakewater—and, hence, sedimented microfossils—would be immune to the vagaries of human influences that preclude climatic interpretation of late Holocene pollen records in the Maya region. Lakes were chosen for coring based on the likelihood of their containing long, continuous sediment records, replete with carbonate shell material. Lakes Chichancanab (Hodell Curtis, and Brenner et al. 1995; Hodell, Brenner, Curtis, and Guilderson 2001) and Peten-Itza (Curtis et al. 1998), on the Yucatan Peninsula (Figure 2), were selected because the two water bodies had been shown to meet these criteria (Covich 1976; Covich and Stuiver 1974). Lake Punta Laguna (N 20°38″, W 87°30″) (Curtis et al. 1996) lies about 18 km north of Coba (Figure 3) and was chosen based on the high shell content of its shallow-water sediments, which had been sampled during an earlier reconnaissance survey. Lake Valencia, Venezuela (Curtis et al. 1999), was selected to represent the southernmost site (N10°10″, W 67°52″) in the suite of sampling localities, based on previous studies in the basin (see, e.g., Binford 1982; Bradbury et al. 1981).

A 4.9-m core was collected from Lake Chichanacanab in 1993 (Hodell et al. 1995). The core bottomed on terrestrial soil (a paleosol), but its uppermost 4.2 m are composed of lake sediment. The base of the lacustrine portion of the sequence is anchored in time by three AMS radiocarbon dates on charred grass remains at 421 cm. They yielded virtually identical ages (7,460 ± 60, 7,560 ± 35, 7,600 ± 60 C-14 years B.P.). The core was sectioned at 1-cm intervals, each of which, on average, represented about 18 years of sediment deposition. Oxygen isotope profiles were developed using both aragonite snail shells (*Pyrgophorus coronatus*) and calcite ostracod shells (*Cypria ophthalmica* and *Cyprinotus* cf. *salinus*). The δO-18 profiles were supplemented by measurements of sulfur (gypsum) content in the sediments. Lake Chichancanab is currently at saturation with respect to gypsum ($CaSO_4 \cdot 2H_2O$), which precipitates on the lake bottom during drought periods when E/P is high, lake stage is low, and gypsum solubility is exceeded. The presence of a benthic foraminifer, *Ammonia beccarii*, also served as an indicator of past conditions. The organism can tolerate a wide range of temperatures (10–35°C) and salinities (7-67 g L^{-1}), but reproduces only at salt concentrations between 13 and 40 g L^{-1} (Bradshaw 1957).

In the early part of the Chichancanab record (about 7,600–7,000 C-14 years B.P.), the presence of foraminifera and high concentrations of gypsum in the sediment indicate low water level and high salinity. Inferred dry climate conditions (high E/P) are corroborated by the relatively positive δO-18 values of ostracod and gastropod shells. By 7,000 C-14 years B.P., gypsum deposition had largely ceased, having been replaced by carbonate sedimentation. *Ammonia beccarii* disappeared from the lake, and oxygen isotope values had declined by about 3‰, indicating a dramatic decline in E/P. Wetter conditions prevailed for about four millennia. About 3,000 C-14 years B.P., just as sedentary Maya agriculture was being established on the peninsula, Lake Chichancanab began to deposit gypsum again, and δO-18 values increased. This drying trend continued for nearly two millennia. The highest δO-18 values and gypsum concentrations since early Holocene filling were recorded at a depth of 65 cm, dated to 1,140 ± 35 C-14 years B.P., based on analysis of a terrestrial seed. The 2σ range on the calibrated age of the seed shows that it dates to between A.D. 780 and 990, suggesting that this Late Holocene arid phase coincided generally with the Classic Collapse. Following this extremely dry period, there was an abrupt shift to wetter conditions, as documented by a pronounced reduction in sulfate precipitation and a decline in oxygen isotope values.

Although investigation of the 1993 Chichancanab core was originally undertaken to examine long-term, high-resolution Holocene climate variability in the circum-Caribbean, it quickly became apparent that the core contained paleoenvironmental information relevant to Maya prehistory. Interpretation of the isotopic record suggested that the driest time of the past 7,000 years occurred during the last two centuries of the first millennium A.D., and that drought might have played a role in the Terminal Classic Maya cultural demise (Hodell et al. 1995). This marked a clear paradigm shift in the application of paleolimnological methods, because lacustrine sediment records were now being used to explore possible climatic effects on Maya culture (Brenner et al. 2001).

Paleoclimate interpretations from Chichancanab were corroborated by results from Punta Laguna (Figure 3). A 6.3-m section from Punta Laguna represented only about 3,500 years of sediment deposition, but the high sediment accumulation rate at the coring site meant that 1-cm sampling intervals yielded relatively high temporal resolution. Over the length of the section, the mean sedimentation rate was about .18 cm per year—that is, each cm sample represented, on average, about six years of accumulation. What the record lacked in deposits of pre-Maya age, it made up for in its high-resolution picture of conditions during and after the Maya florescence (Curtis et al. 1996). Discrete oxygen isotopic records for the Punta Laguna section were developed based on analysis of ostracod (*Cytheridella ilosvayi*) and gastropod (*Pyrgophorus coronatus*) shells. The two records display high stratigraphic δO-18 variability but are highly coherent with one another. Paleoclimatic interpretation of the isotope stratigraphies suggests that mean conditions during the Classic and early Postclassic periods (around A.D. 250–1050) were somewhat drier than the time periods before and after. Inferences suggested that the driest periods culminated around A.D. 590, 860, 990, and 1050. There is also a Postclassic dry episode that terminates around A.D. 1390. The dry period in the middle of the ninth century A.D. is thought to be contemporaneous with the Late Classic drought detected in the Chichancanab core. Similar to the situation at Chichancanab, it appears that conditions became moister—at least, for a time—following the extreme dry episode of the Late Classic period. The high-resolution Punta Laguna record strongly suggests that E/P fluctuated on a submillennial scale. Alternating wet and dry episodes may not have been detectable to an individual Maya farmer during his lifetime, but these climatic fluctuations probably influenced agricultural yields on longer time scales.

Oxygen-isotope records from Lakes Chichancanab and Punta Laguna paint a fairly coherent picture of shifts in moisture availability on the northern Yucatan Peninsula over the past 3,500 years. Attempts to extend the isotope approach to the wetter central Peten region have been equivocal. The 1993 core collected from Lake Peten-Itza contains about a 9,000-C-14-year record of continuous sediment accumulation (Curtis et al. 1998). Three discrete, high-resolution δO-18 profiles were developed based on two snail taxa (*Cochliopina* sp. and *Pyrgophorus* sp.) and ostracods, the latter a combined record using *Cytheridella ilosvayi* and *Candona* sp. The isotope record differs in some aspects from the Chichancanab sequence. Isotope values remain fairly positive between about 9,000 and 6,800 C-14 years B.P. and decrease over a longer period of time, reaching a new equilibrium relatively late in the Holocene, around 5,000 C-14 years B.P. The pollen record from the core is at odds with the climatic intepretation based on isotope values. Mesic forest dominates during the earliest Holocene when δO-18 values suggest high E/P—that is, dry conditions. This discrepancy between the two climate proxies might be explained by the fact that this very large lake lost a relatively greater proportion of its annual water budget to evaporation during the early stages of its long filling process. More likely, it reflects long-term shifts in vegetation density in the watershed that ultimately controlled drainage-basin hydrology (Rosenmeier, Hodell, Brenner, Curtis, Martin, Anselmetti, Ariztegui, and Guilderson 2002). Dense early Holocene vegetation would have intercepted much of the rainfall in the watershed, and evapo-transpiration, along with soil water storage, probably limited water runoff to the lake.

Over the past 5,000 C-14 years or so, the isotope record from Lake Peten-Itza displays little variation (<1‰) and no discernible trend. The data may be interpreted in two ways. The fairly constant δO-18 values could reflect unchanging E/P conditions during the past five millennia. Alternatively, due to the extremely large volume of the basin, isotope ratios in the lake water may not have changed appreciably, even if climate shifts did occur. Once the lake filled with water, annual evaporative losses from the lake would have represented only a tiny fraction of the total water in the basin. Even dramatic shifts in water level may not have altered the isotopic signature of the lake appreciably. Findings at Peten-Itza suggest that smaller water bodies are probably better candidates for study. They are more sensitive climate indicators because they respond by gaining or losing a larger proportion of their volume as a consequence of E/P changes.

Lake Salpeten was re-cored in 1997 (Rosenmeier, Hodell, Brenner, Curtis, and Guilderson 2002; Rosenmeier, Hodell, Brenner, Curtis, Martin, Anselmetti, Ariztegui, and Guilderson 2002) in an effort to produce a high-resolution E/P record for Peten. New profiles supplemented information from the deepwater Salpeten core collected in 1980. Similar to findings in Lake Peten-Itza, the δO-18 and pollen data yielded contradictory results. Relatively enriched O-18 values in the early Holocene, which would suggest relatively dry conditions, occurred simultaneously with pollen evidence for high, moist forest presence. Palynologically documented forest removal was associated with rather low δO-18 values between about 3,500 and 1,800 C-14 years B.P. The apparent discrepancy between proxy indicators of moisture availability is probably a consequence of the fact that watershed hydrology was dramatically altered by human-mediated deforestation. Despite pollen evidence for relatively wet conditions in the early Holocene (see, e.g., Deevey 1978; Islebe et al. 1996; Leyden 1984, 1987; Leyden et al. 1993, 1994; Vaughan et al. 1985), the well-established, dense forest probably promoted high rates of evapo-transpiration and soil moisture storage. Consequently, surface and groundwater flow to the lake would have been minimal. When humans began to clear vegetation in the drainage basin, evapo-transpiration and soil water storage both declined. Consequently, there was greater runoff of isotopically “light” water to the lake. High lake stage during the period of Maya occupation is confirmed by radiocarbon dates on aquatic snail shells found in soil profiles (i.e., exposed lake sediments) that lie between 1 and 7.5 m above the present lake surface. Ages on shell samples from three soil profiles are in stratigraphic order, and many date to the period between 1000 B.C. and A.D. 1000 (Rosenmeier, Hodell, Brenner, Curtis, and Guilderson 2002; Rosenmeier, Hodell, Brenner, Curtis, Martin, Anselmetti, Ariztegui, and Guilderson 2002).

If human-mediated deforestation altered the hydrology of the Salpeten watershed, then paleoclimatic interpretation of the δO-18 record is confounded. The Salpeten findings cast doubt on the feasibility of using stable oxygen isotopes to reconstruct past climatic conditions in the Peten region. Several geographic factors conspire to complicate the interpretation of δO-18 data from the southern Maya Lowlands. Rainfall is higher in the south, forests are dense and of greater stature, and there is significant topographic relief. Abundant high vegetation has a profound effect on local hydrology, and its removal can influence lacustrine oxygen isotopic signatures. It is unlikely that δO-18 of lakes on the northern part of the Yucatan Peninsula would have been affected as significantly by human settlement. Those water bodies lie in drier, flatter terrain and are surrounded by lower-stature forests. Furthermore, there is as yet no evidence for widespread urbanization around Chichancanab or Punta Laguna. Future efforts to explore late Holocene climate changes in the Peten will require identification of watersheds that experienced minimal human disturbance during the period of Maya occupation. This may prove difficult, because dense human populations probably exploited all areas in the southern Lowlands near potable water sources.

LATE HOLOCENE CLIMATE FORCING IN THE MAYA LOWLANDS

The Earth's precessional cycle helps explain long-term, millennial-scale changes in moisture availability around the Caribbean that are recorded in sediments from sites such as lakes Miragoane and Chichancanab, and in the Cariaco Basin, north of Venezuela. Higher-frequency climate shifts of the past 3,000 years, however, may be of greater interest to Maya scholars. Several possible forcing factors might account for these centennial changes in E/P. One potential cause may be cyclical variations in solar intensity (Hodell et al. 2001).

In May 2000, a 1.9-m core was collected in 11 m of water from Lake Chichancanab. The section represents about 2,600 years of sediment accumulation. Similar to that of the 1993 core, the profile contained gypsum bands that reflect periods of low lake level and, hence, dry climate. Abundant terrestrial organic matter (seeds, charcoal, wood) enabled AMS C-14 dating of 12 depths in the recent core, providing a high-resolution chronology for the time period covering Maya occupation. Gypsum is present throughout the record, and its abundance was estimated by continuous measurement of density (gamma-ray attenuation) along the length of the section. Power spectra of the density record showed significant peaks (95% confidence interval) at intervals of 208, 100, and 50 years (Hodell et al. 2001). The 208-year cycle dominates the density record. This time span is nearly identical to the known 206-year cycle of cosmogenic nuclide production (C-14 and Be-10). High production of these naturally occurring radionuclides is associated with periods of low solar activity. Gypsum precipitation in Lake Chichancanab is exactly out of phase with C-14 production, suggesting that droughts occurred during periods of high solar activity. Likewise, δO-18 data from the 1993 Punta Laguna core show droughts occurring at 208-year intervals, out of phase with cosmogenic nuclide production and coincident with gypsum deposition at Chichancanab. These dry events were probably regional in extent, as the approximately 200-year cycle is also recorded in mineral magnetic parameters from marine cores collected in the northeastern Caribbean, near Puerto Rico (Nyberg et al. 2001). Although droughts in Yucatan appear to occur at regular intervals, they are not all of the same magnitude. Both Chichancanab and Punta Laguna contain evidence of very strong droughts during the Terminal Classic period. Some of the other inferred dry events appear to have been associated with periods of Maya social reorganization, such as the Preclassic Abandonment, suggesting a cultural response to climate change.

Significant power in the Chichancanab and Punta Laguna records at intervals other than 208 years suggests that solar intensity is not the only factor driving dry spells on the Yucatan Peninsula. Furthermore, the mechanisms by which small changes in solar output translate into regional climatic drying in the Maya Lowlands are poorly understood. These minute differences in solar intensity require amplification via atmospheric and oceanic processes (Hodell et al. 2001). Shifts in the ultraviolet (UV) part of the light spectrum may affect ozone production and temperatures in the stratosphere. Cosmic-ray intensity may influence cloud formation and rainfall. Climate modeling suggests that changing solar output may affect global mean temperature, humidity, convection, and Hadley circulation in the tropics. Given the pronounced geographic variation in rainfall over the Yucatan Peninsula, from the extremely arid northwest (<500 mm yr^{-1}) to the more humid south-central region (2,500 mm yr^{-1}), any disruption of Hadley circulation or convective activity would be expected to alter regional rainfall.

SUMMARY AND FUTURE PROSPECTS

Paleolimnological studies of sediment cores from the Maya Lowlands have begun to shed light on environmental changes in the Yucatan Peninsula since the late Glacial epoch. A long, 36,000-year sequence from Lake Quexil provided insight into late Pleistocene climate and vegetation in the region. Prior to about 10,500 C-14 years B.P., tropical forest was absent. Instead, savanna-like vegetation prevailed under conditions that were cooler and drier than those of today. Tropical forest invaded the Peten area in the early Holocene in response to warmer, wetter conditions. Shallow lakes on the northern Yucatan Peninsula began to fill with water about 8,000 C-14 years B.P. as a consequence of increased rainfall. Filling of some depressions may also have been influenced by rising sea level that increased the level of the overlying freshwater lens. Climatic amelioration in the early Holocene may have been driven by orbital forcing. Early Holocene summer perihelion in the Northern Hemisphere tropics brought highly seasonal, moister conditions to the Yucatan Peninsula. Moist conditions enabled synthesis of tropical forest about 10,500 C-14 years B.P. that prevailed for some 7,000 years. The environmental changes that occurred on the Yucatan Peninsula during the late Glacial and early Holocene were driven by climate shifts. Human population densities were probably too small during the first half of the Holocene epoch to have had any significant impact on regional vegetation and soils.

Pollen profiles from lake sediment cores in the Maya Lowlands record the disappearance of tropical forest beginning more than 3,000 C-14 years B.P. Forest loss generally coincided with the expansion of Early and Middle Preclassic Maya populations throughout the Yucatan Peninsula. With the exception of the early work by Cowgill, Hutchinson, Racek, Goulden, Patrick, and Tsukada (1966), late Holocene forest decline, detected in pollen spectra from the area, has been interpreted as reflecting human-mediated land clearance. This point of view was expressed explicitly in the statement, "Climatic changes during and since Maya time were unimportant, and the major environmental perturbations arose from human settlement and technology" (Deevey et al. 1980). Recent paleoclimate investigations on the Yucatan Peninsula and elsewhere around the Caribbean Sea call for reconsideration of this conclusion. Paleoclimate inferences from low-elevation lake sites in the Yucatan Peninsula (Hodell, Curtis, and Brenner 1995; Hodell, Brenner, Curtis, and Guilderson 2001), Haiti (Curtis and Hodell 1993; Hodell et al. 1991), and northern Venezuela (Bradbury et al. 1981; Curtis et al. 1999), as well as from marine cores off the Venezuelan coast (Haug et al. 2001), suggest that climatic drying began about 3,000 years ago. Contemporaneous, late Holocene drying at several distant sites suggests that this climatic trend occurred on a regional scale.

Although the Maya undoubtedly played a role in late Holocene forest reduction, it is conceivable that climatic drying also influenced the pollen record. A climatic effect may be superimposed on the anthropogenic signal in the pollen record (Figure 5). This begs a question: How much of the late Holocene forest reduction in the Maya Lowlands, particularly in Peten, is a human artifact, and how much was climatically driven? A related question is: Could widespread human land clearance have affected the regional climate? In any event, one consequence of deforestation was rapid erosional loss of soils from Peten hillsides. This erosion is expressed in Peten lake-sediment stratigraphies as a thick unit of clay-rich material intercalated between highly organic sediments of pre–Maya and post–Maya age. Nutrient-rich surface soils were most prone to colluviation, and one consequence of long-term topsoil loss may have been reduced soil fertility.

The exact timing and cause of late Holocene reforestation in Peten remains uncertain. The sediment record from Lake Chilonche, in the Peten savannas, suggests that reforestation was a post–European-contact phenomenon (Brenner et al. 1990), but other records indicate that vegetation began to regrow in Peten immediately after the Classic Collapse (Wiseman 1985). Recent evidence from Laguna las Pozas in the Río de la Pasión drainage suggests that early Postclassic Maya "refugee" populations deforested the area for the first time as late as A.D. 900–1,200 (Johnston et al. 2001). To complicate matters, there is some evidence that reforestation may have been associated with wetter conditions, suggesting a climatic contribution to the reforestation process (Brenner et al. 1990; Rue 1987). Determining the onset, rate, and geographic heterogeneity of forest regrowth will require further study.

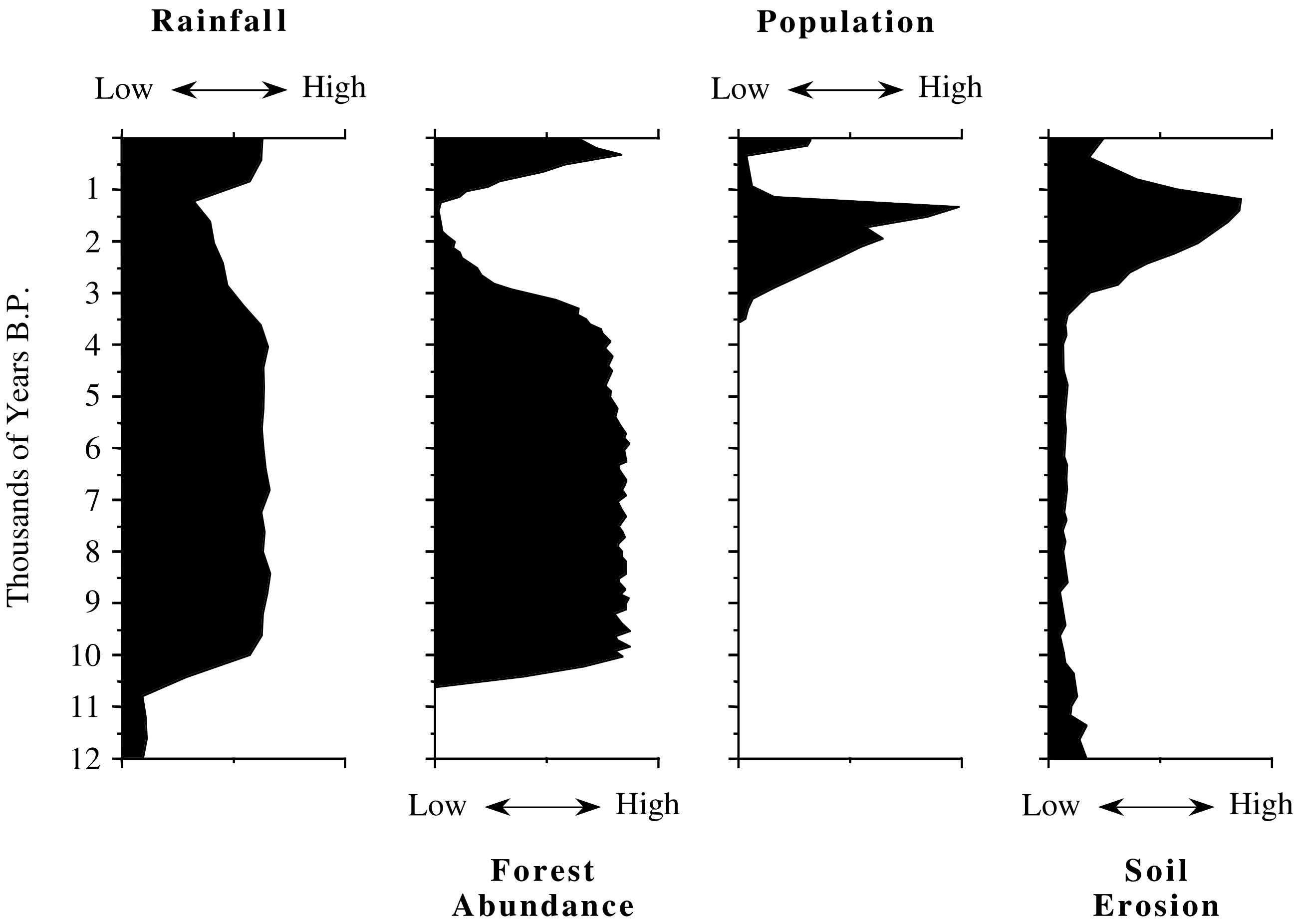

Figure 5. Generalized results of paleolimnological and archaeological investigations in the Maya Lowlands, showing relative changes in vegetation, climate, human population density, and soil erosion during the Holocene (modified from Binford et al. 1987). Growth of sedentary human populations beginning more than 3,000 years ago is associated with climate drying, making it difficult to differentiate climatic from human effects on the environment. Depopulation in the ninth century A.D. is thought to be associated with a protracted drought, inferred from sediment cores taken in the northern Yucatan Peninsula lakes Chichancanab and Punta Laguna.

To nail down the timing of reforestation, it will be necessary to do high-resolution pollen counting or isotopic analysis of n-alkanes on cores with reliable, close-interval chronologies. This will entail high-density AMS radiocarbon dating of terrestrial organic matter over the time span of interest. To evaluate the causes of reforestation, it will be necessary to explore in greater detail the climate fluctuations of the past few millennia.

High-resolution, isotope-based paleoclimate reconstructions from Lakes Chichancanab (Hodell, Curtis, and Brenner 1995; Hodell, Brenner, Curtis, and Guilderson 2001) and Punta Laguna (Curtis et al. 1996) pose further interesting challenges for paleolimnologists and archaeologists. The sediment records implicate climate change in the Classic Collapse, and although this "drought hypothesis" has been argued at length by R. B. Gill (2000), numerous questions remain. One challenge has been the accurate dating of climatic events or other environmental shifts recorded in lake cores from the Maya region and their subsequent temporal correlation with cultural changes. To some degree, the advent of AMS C-14 dating has helped overcome some problems associated with hard-water-lake error. Very small bits of terrestrial organic matter found in sediments can now be dated, and these yield more reliable results because they are not contaminated with "old" carbon. They also enable assessment of the magnitude of hard-water-lake error associated with dates on carbonate remains from the same stratigraphic levels and have been used to "correct" other carbonate-based ages (Curtis et al. 1996; Hodell et al. 1995).

Another complication with core chronology stems from the fact that the timing of late Holocene climatic events such as droughts is often determined by interpolation between two dated depths in a core. Typically, the age of an undated horizon is estimated assuming that the sedimentation rate between two dated depths was constant, or by using an age-depth model fitted to the entire core or a section of the core. The problem arises when appropriate datable material simply does not exist at the depth at which the climate change was inferred. The best solution to this difficulty is to obtain close-interval dates whenever possible.

Even when dates are obtainable from depth horizons that indicate climatic or environmental shifts—for example, the Late Classic drought event in the 1993 Chichancanab core (Hodell et al. 1995)—several sources of error can affect calibrated C-14 dates.

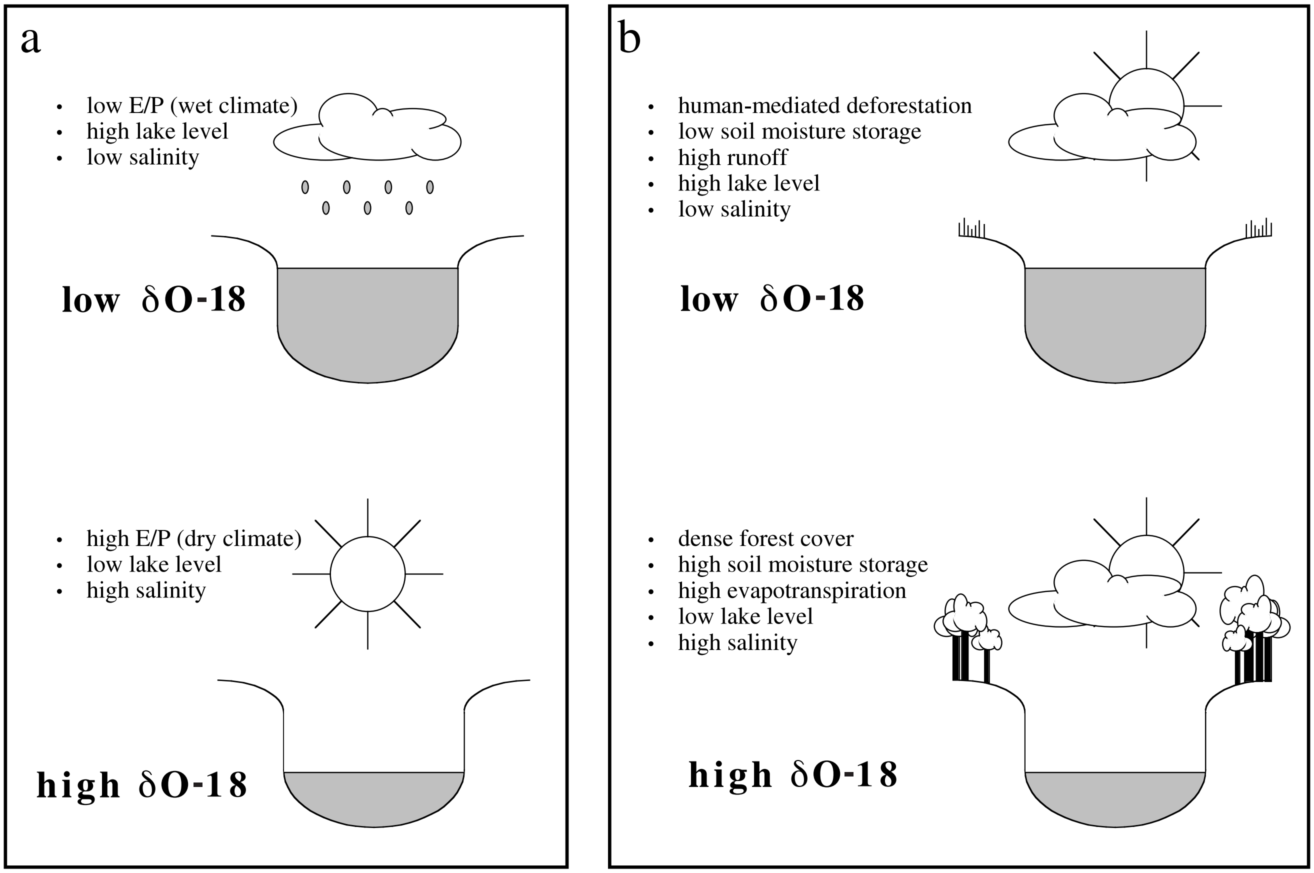

Figure 6. (a) Conceptual model of hydrologic changes in Lake Chichancanab, northern Yucatan Peninsula, showing the effects of different evaporation/precipitation ratios (E/Ps) on lake stage, lake-water salinity, and lake-water δO-18; (b) conceptual model of hydrologic changes for Lake Salpeten, Peten, Guatemala, showing how human-mediated deforestation may affect lake stage, lake-water salinity, and lake-water δO-18. In the anthropogenically deforested Lake Salpeten watershed, high lake stage is a consequence of high runoff of isotopically light rainwater and low water-storage capacity in basin soils. Similar to the situation for pollen, both climatic and human effects can influence the proxy variable (δO-18 in sedimented carbonate) that is used to infer past environmental conditions. Consequently, in some regions (e.g., Peten), interpretation of paleoclimate records based on δO-18 in sedimented shell material may be confounded by human activities.

Errors in radiocarbon dates reflect the statistical errors associated with measurement. The 95% confidence intervals on calibrated ages (2σ) often encompass large time spans, reflecting the precision of calibration programs. It is wise to keep in mind that error terms associated with dates reflect precision rather than accuracy. Even the calibrated 95% confidence interval on a radiocarbon date may not encompass the true age of the dated material. Temporal linkage of lake-sediment records and cultural processes is further complicated by the fact that archaeological artifacts also have errors associated with their ages. Some of these difficulties may be overcome by improvements in technology. For instance, the ability to isolate terrigenous organic material from bulk lake sediments may enable more reliable, close-interval dating of deposits from depths at or close to horizons where environmental changes are detected.

Further paleolimnological study will be required to evaluate the geographic extent of the inferred Late Classic dry period. Not all lakes possess sediment records that lend themselves to isotopic study using oxygen isotope ratios in carbonate microfossils. The situation is further confounded in the Central Peten Lake District by the fact that the Maya altered the watershed hydrology by deforesting drainage basins surrounding potential study lakes (Figure 6). The best candidates for study are lakes in watersheds that were not densely settled and that lie in level terrain. Perhaps the large lakes Ija and Oquevix in the Peten savannas south of Flores meet these criteria. They must, however, also contain continuous sediment records that are rich in carbonate microfossils. A remaining task is the "translation" of stratigraphic shifts in δO-18 into quantitative reductions in rainfall. It is possible that modeling efforts will enable us to estimate past shifts in long-term, mean annual rainfall, but we still may never know whether the reductions in precipitation came at critical times in the annual agricultural cycle.

With the advent of new technology, alternative approaches to inferring past climate conditions are now possible. This may broaden the list of "candidate" study lakes. For instance, using gas chromatographic (GC) methods, it is possible to isolate organic compounds of terrestrial origin from those of aquatic origin in bulk lacustrine organic matter (Huang et al. 2001; Sauer et al. 2001). This enables mass spectrometric (MS) measurement of isotope ratios (e.g., D/H and C-13/C-12) in organic materials of known provenience. These measures permit study of the isotopic composition of past rainfall, shifts in the dominance of C_3 versus C_4 vegetation on landscapes, and evaluation of the isotopic composition of paleo-lake waters. It will also help avoid the difficulty of hard-water-lake error by making it possible to AMS C-14 date organic matter that comes from definitively terrestrial sources. The ubiquity of organic matter in lake sediments will make this GC–MS approach a valuable new tool in paleoclimatology.

Archaeological evidence should exist for the occurrence of severe prehistoric droughts. For instance, Nicholas P. Dunning (1992) noted the widespread use of *chultunes* (underground cisterns) in the Puuc region and suggested that a severe drought or a series of droughts could have precipitated the abandonment of the area. Greater use of water vessels (*tinajas*) may also reflect insecurity about dry-season water resources. One might speculate that, as droughts became more severe, there was greater reliance on xeric-adapted agricultural plants. During periods of low rainfall, human populations probably expanded into seasonally inundated *bajo* areas that had dried. In any event, the inferred Late Classic-period drought can be viewed as an environmental stress to which there were probably cultural responses. These cultural responses may well be detectable in the archaeological record.

RESUMEN

Desde la década de los 1950s, algunos paleolimnólogos han utilizado núcleos de sedimentos lacustres colectados en la península de Yucatán para aumentar nuestro conocimiento de las complejas interacciones entre el paleoclima, el medioambiente, y la antigua cultura maya. Las primeras interpretaciones de estos perfiles de sedimentos asumieron que las condiciones climáticas del Holoceno tardío eran invariables. Por eso, los cambios paleoambientales inferidos para los 3,000 años pasados, como la perdida de vegetación y erosión de suelos, fueron atribuidos totalmente a las actividades humanas—por ejemplo, deforestación para la agricultura y construcción. Recientemente, varios registros paleoambientales de alta resolución, obtenidos no solo en la región maya, sino en otros sitios alrededor del mar Caribe, contradicen la idea de estabilidad climática durante el Holoceno en esta región neotropical. Al contrario, empezando hace unos 3,000 años, los registros paleolimnológicos indican una tendencia hacia condiciones mas secas y una reducción en el contraste estacional. También, los datos muestran evidencias de fluctuaciones significativas en la relación entre evaporación y precipitación. Por ejemplo, inferencias paleoclimáticas basadas en estudio de núcleos de los lagos Chichancanab y Punta Laguna, en el norte de la península de Yucatán, sugieron que durante los 2,600 años pasados, hubo una serie de sequías que ocurrieron con una periodicidad regular de aproximadamente 208 años. Estos eventos de clima seco pudieron haber sido inducido por cambios en la intensidad solar, porque coinciden con ciclos de baja producción de radionúclidos (Be-10, C-14) en la atmósfera. Según varios registros obtenidos en el norte de la Península de Yucatán, la época mas seca del Holoceno tardío ocurrió hacia el siglo nueve d.C., y coincidió con el ocaso de la civilización maya. Nosotros sugerimos que este cambio climático brusco y prolongado pudo haber afectado de manera sustancial la producción agrícola en la región, generando consecuencias graves para la sociedad alli establecida. En este trabajo discutimos los métodos paleolimnológicos que se aplican actualmente para la reconstrucción del paleoambiente en la región maya y revisamos los numerosos estudios paleoambientales realizados en la área. Además, discutimos los varios indicadores de paleoambiente que encontramos en los sedimentos y elucidamos la dificultad de distinguir entre señales climáticas y antrópicas en sedimentos depositados en la región durante los trés milenios pasados. Al fin, evaluamos el entendimiento de cambios climáticos en la región Maya desde el termino del Pleistoceno tardío.

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REFERENCES

Beach, Timothy

1998a Soil Catenas, Tropical Deforestation, and Ancient and Contemporary Soil Erosion in the Petén, Guatemala. *Physical Geography* 19:378–405.

1998b Soil Constraints on Northwest Yucatan, Mexico: Pedoarchaeology and Maya Subsistence at Chunchucmil. *Geoarchaeology* 13:759–791.

Binford, Michael W.

1982 Ecological History of Lake Valencia, Venezuela: Interpretation of Animal Microfossils and Some Chemical, Physical, and Geological Features. *Ecological Monographs* 52:307–333.

1983 Paleolimnology of the Peten Lake District, Guatemala, I. Erosion and Deposition of Inorganic Sediment as Inferred from Granulometry. *Hydrobiologia* 103:199–203.

Binford, Michael W., Edward S. Deevey, and Thomas L. Crisman

1983 Paleolimnology: An Historical Perspective on Lacustrine Ecosystems. *Annual Review of Ecology and Systematics* 14: 255–286.

Binford, Michael W., Mark Brenner, Thomas J. Whitmore, Antonia Higuera-Gundy, Edward S. Deevey, and Barbara W. Leyden

1987 Ecosystems, Paleoecology, and Human Disturbance in Subtropical and Tropical America. *Quaternary Science Reviews* 6: 115–128.

Bloom, Paul, Mary Pohl, Cynthia Buttleman, Frederick Wiseman, Alan Covich, Charles Miksicek, Joseph Ball, and Julie Stein

1983 Prehistoric Maya Wetland Agriculture and Alluvial Soils Near San Antonio Rio Hondo, Belize. *Nature* 301:417–419.

Bradbury, J. Platt, Richard M. Forester, W. Anthony Bryant, and Alan P. Covich

1990 Paleolimnology of Laguna de Cocos, Albion Island, Río Hondo, Belize. In *Ancient Maya Wetland Agriculture: Excavations on Albion Island, Northern Belize*, edited by M.D. Pohl, pp. 119–154. Westview Press, Boulder, CO.

Bradbury, J. Platt, Barbara W. Leyden, Maria Salgado-Labouriau, William M. Lewis, Jr., Carlos Schubert, Michael W. Binford, David G. Frey, Don R. Whitehead, and Franz H. Weibezahn

1981 Late Quaternary Environmental History of Lake Valencia, Venezuela. *Science* 214:1299–1305.

Bradshaw, John S.

1957 Laboratory Studies of the Rate of Growth of the Foraminifer, "*Streblus beccarii* (Linné) var. *tepida* (Cushman)." *Journal of Paleontology* 31:1138–1147.

Brenner, Mark

1983a *Paleolimnology of the Maya Region*. Ph.D. dissertation, Department of Zoology, University of Florida, Gainesville.

1983b Paleolimnology of the Peten Lake District, Guatemala, II. Mayan Population Density and Sediment and Nutrient Loading of Lake Quexil. *Hydrobiologia* 103:205–210.

1994 Lakes Salpeten and Quexil, Peten, Guatemala, Central America. In *Global Geological Record of Lake Basins*, vol. 1, edited by E. Gierlowski-Kordesch and K. Kelts, pp. 377–380. Cambridge University Press, Cambridge.

Brenner, Mark, Barbara W. Leyden, and Michael W. Binford

1990 Recent Sedimentary Histories of Shallow Lakes in the Guatemalan Savannas. *Journal of Paleolimnology* 4:239–251.

Brenner, Mark, Barbara W. Leyden, Jason H. Curtis, Roger M. Medina-Gonzalez, and Bruce H. Dahlin

2000 Un registro de 8,000 años del paleoclima del noroeste de Yucatan, Mexico. *Revista de la Universidad Autonoma de Yucatan* 15:52–65.

Brenner, Mark, David A. Hodell, Jason H. Curtis, Michael F. Rosenmeier, Flavio S. Anselmetti, and Daniel Ariztegui

2002 *Paleolimnological Approaches for Inferring Past Climate Change in the Maya Region: Recent Advances and Methodological Limitations.* Haworth Press, Binghamton, NY, in press.

Brenner, Mark, David A. Hodell, Jason H. Curtis, Michael F. Rosenmeier, Michael W. Binford, and Mark B. Abbott

2001 Abrupt Climate Change and Pre-Columbian Cultural Collapse. In *Interhemispheric Climate Linkages*, edited by V. Markraf, pp. 87–103. Academic Press, New York.

Brenner, Mark, Jason H. Curtis, Antonia Higuera-Gundy, David A. Hodell, Glenn A. Jones, Michael W. Binford, and Katherine T. Dorsey

1994 Lake Miragoane, Haiti (Caribbean). In *Global Geological Record of Lake Basins*, vol. 1, edited by E. Gierlowski-Kordesch and K. Kelts, pp. 403–405. Cambridge University Press, Cambridge.

Caviedes, Cesar N.

2001 *El Niño in History: Storming Through the Ages*. University Press of Florida, Gainesville.

Covich, Alan P.

1976 Recent Changes in Molluscan Diversity of a Large Tropical Lake (Lago de Peten, Guatemala). *Limnology and Oceanography* 21:51–59.

1978 A Reassessment of Ecological Stability in the Maya Area: Evidence from Lake Studies of Early Agricultural Impacts on Biotic Communities. In *Pre-Hispanic Maya Agriculture*, edited by P.D. Harrison and B.L. Turner II, pp. 145–155. University of New Mexico Press, Albuquerque.

Covich, Alan P., and Minze Stuiver

1974 Changes in Oxygen 18 as a Measure of Long-Term Fluctuations in Tropical Lake Levels and Molluscan Populations. *Limnology and Oceanography* 19:682–691.

Cowgill, Ursula M., and G. Evelyn Hutchinson

1966 La Aguada de Santa Ana Vieja: The History of a Pond in Guatemala. *Archiv für Hydrobiologie* 62:335–372.

Cowgill, Ursula M., G. Evelyn Hutchinson, A.A. Racek, Clyde E. Goulden, Ruth Patrick, and Matsuo Tsukada

1966 The History of Laguna de Petenxil, a Small Lake in Northern Guatemala. *Memoirs of the Connecticut Academy of Arts and Sciences* 17:1–126.

Curtis, Jason H., and David A. Hodell

1993 An Isotopic and Trace Element Study of Ostracods from Lake Miragoane, Haiti: A 10.5 kyr Record of Paleosalinity and Paleotemperature Changes in the Caribbean. In *Climate Change in Continental Isotopic Records*, edited by P.K. Swart, K.C. Lohmann, J.A. McKenzie, and S. Savin, pp. 135–152. Geophysical Monograph No. 78. American Geophysical Union, Washington, DC.

Curtis, Jason H., Mark Brenner, and David A. Hodell

1999 Climate Change in the Lake Valencia Basin, Venezuela, ~12,600 Years B.P. to Present. *Holocene* 9:609–619.

2001 Climate Change in the Circum-Caribbean (Late Pleistocene to Present) and Implications for Regional Biogeography. In *Biogeography of the West Indies: Patterns and Perspectives*, 2nd ed., edited by C.A. Woods and F.E. Sergile, pp. 35–54. CRC Press, Boca Raton, FL.

Curtis, Jason H., David A. Hodell, and Mark Brenner

1996 Climate Variability on the Yucatan Peninsula (Mexico) During the Past 3,500 Years, and Implications for Maya Cultural Evolution. *Quaternary Research* 46:37–47.

Curtis, Jason H., Mark Brenner, David A. Hodell, Richard A. Balser, Gerald A. Islebe, and Henry Hooghiemstra

1998 A Multi-Proxy Study of Holocene Environmental Change in the Maya Lowlands of Peten, Guatemala. *Journal of Paleolimnology* 19:139–159.

Dahlin, Bruce H.

1983 Climate and Prehistory on the Yucatan Peninsula. *Climate Change* 5:245–263.

Deevey, Edward S.

1969 Coaxing History to Conduct Experiments. *Bioscience* l9:40–43.

1978 Holocene Forests and Maya Disturbance Near Quexil Lake, Peten, Guatemala. *Polish Archives of Hydrobiology* 25:117–129.

1985 Stress, Strain, and Stability of Lacustrine Ecosystems. In *Lake Sediments and Environmental History*, edited by E.Y. Haworth and J.W.G. Lund, pp. 203–229. University of Minnesota Press, Minneapolis.

Deevey, Edward S., and Don S. Rice

1980 Coluviacion y retencion de nutrientes en el distrito lacustre del Peten central, Guatemala. *Biotica* 5:129–144.

Deevey, Edward S., and Minze Stuiver

1964 Distribution of Natural Isotopes of Carbon in Linsley Pond and Other New England Lakes. *Limnology and Oceanography* 9:1–11.

Deevey, Edward S., Mark Brenner, and Michael W. Binford

1983 Paleolimnology of the Peten Lake District, Guatemala, III. Late Pleistocene and Gamblian Environments of the Maya Area. *Hydrobiologia* 103:211–216.

Deevey, Edward S., Mark Brenner, Michael S. Flannery, and G. Habib Yezdani
1980 Lakes Yaxha and Sacnab, Peten, Guatemala: Limnology and Hydrology. *Archiv für Hydrobiologie Supplement* 57:419–460.

Deevey, Edward S., Don S. Rice, Prudence M. Rice, Hague H. Vaughan, Mark Brenner, and Michael S. Flannery
1979 Mayan Urbanism: Impact on a Tropical Karst Environment. *Science* 206:298–306.

Dunning, Nicholas P.
1992 *Lords of the Hills: Ancient Maya Settlement in the Puuc Region, Yucatan, Mexico*. Monographs in World Archaeology, No. 15. Prehistory Press, Madison, WI.

Dunning, Nicholas P., Timothy Beach, and David Rue
1997 The Paleoecology and Ancient Settlement of the Petexbatun Region, Guatemala. *Ancient Mesoamerica* 8:255–266.

Dunning, Nicholas P., David Rue, Timothy Beach, Alan Covich, and Alfred Traverse
1997 Human–Environment Interactions in a Tropical Watershed: The Paleoecology of Laguna Tamarindito, El Petén, Guatemala. *Journal of Field Archaeology* 25:139–151.

Fedick, Scott L. (editor)
1996 *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*. University of Utah Press, Salt Lake City.

Flannery, Kent V. (editor)
1982 *Maya Subsistence: Studies in Memory of Dennis E. Puleston*. Academic Press, New York.

Folan, William J., Ellen R. Kintz, and Laraine A. Fletcher
1983 *Coba: A Classic Maya Metropolis*. Academic Press, New York.

Fontes, Jean-C., and R. Gonfiantini
1967 Comportement isotopique au cours de l'evaporation de deux bassins sahariens. *Earth and Planetary Science Letters* 3:258–266.

Frey, David G.
1969 The Rationale of Paleolimnology. *Internationale Vereinigung für Theoretische und Angewandte Limnologie Mitteilungen* 17:7–18.

Gasse, Françoise, R. Téhet, A. Durand, E. Gilbert, and Jean-C. Fontes
1990 The Arid–Humid Transition in the Sahara and Sahel During the Last Glaciation. *Nature* 346:141–146.

Gill, Richardson B.
2000 *The Great Maya Droughts: Water, Life, and Death*. University of New Mexico Press, Albuquerque.

Hansen, Barbara C.S.
1990 Pollen Stratigraphy of Laguna de Cocos. In *Ancient Maya Wetland Agriculture: Excavations on Albion Island, Northern Belize*, edited by Mary D. Pohl, pp. 155–186. Westview Press, Boulder, CO.

Harrison, Peter D., and Billie L. Turner II (editors)
1978 *Pre-Hispanic Maya Agriculture*. University of New Mexico Press, Albuquerque.

Hastenrath, Stefan
1984 Interannual Variability and the Annual Cycle: Mechanisms of Circulation and Climate in the Tropical Atlantic Sector. *Monthly Weather Review* 112:1097–1107.

Haug, Gerald H., Konrad A. Hughen, Daniel M. Sigman, Larry C. Peterson, and Ursula Röhl
2001 Southward Migration of the Intertropical Convergence Zone Through the Holocene. *Science* 293:1304–1308.

Higuera-Gundy, Antonia, Mark Brenner, David A. Hodell, Jason H. Curtis, Barbara W. Leyden, and Michael W. Binford
1999 A 10,300 ^{14}C-Year Record of Climate and Vegetation Change From Haiti. *Quaternary Research* 52:159–170.

Hodell, David A., Mark Brenner, and Jason H. Curtis
2000 Climate Change in the Northern American Tropics since the Last Ice Age: Implications for Environment and Culture. In *Imperfect Balance: Landscape Transformations in the Precolumbian Americas*, edited by D.L. Lentz, pp. 13–38. Columbia University Press, New York.

Hodell, David A., Jason H. Curtis, and Michael Brenner
1995 Possible Role of Climate in the Collapse of Classic Maya Civilization. *Nature* 375:391–394.

Hodell, David A., Mark Brenner, Jason H. Curtis, and Thomas P. Guilderson
2001 Solar Forcing of Drought Frequency in the Maya Lowlands. *Science* 292:1367–1370.

Hodell, David A., Jason H. Curtis, Glenn A. Jones, Antonia Higuera-Gundy, Mark Brenner, Michael W. Binford, and Kathleen T. Dorsey
1991 Reconstruction of Caribbean Climate Change over the Past 10,500 Years. *Nature* 352:790–793.

Huang, Yongsong, F. Alayne Street-Perrott, Sarah E. Metcalfe, Mark Brenner, Michael Moreland, and Katherine H. Freeman
2001 Climate Change as the Dominant Control on Glacial–Interglacial Variations in C_3 and C_4 Plant Abundance. *Science* 293:1647–1651.

Islebe, Gerald A., Henry Hooghiemstra, Mark Brenner, Jason H. Curtis, and David A. Hodell
1996 A Holocene Vegetation History from Lowland Guatemala. *Holocene* 6:265–271.

Johnston, Kevin J., Andrew J. Breckenridge, and Barbara C.S. Hansen
2001 Paleoecological Evidence of an Early Postclassic Occupation in the Southwestern Maya Lowlands: Laguna Las Pozas, Guatemala. *Latin American Antiquity* 12:149–166.

Leyden, Barbara W.
1984 Guatemalan Forest Synthesis after Pleistocene Aridity. *Proceedings of the National Academy of Sciences USA* 81:4856–4859.
1987 Man and Climate in the Maya Lowlands. *Quaternary Research* 28:407–414.

Leyden, Barbara W., Mark Brenner, and Bruce H. Dahlin
1998 Cultural and Climatic History of Cobá, a Lowland Maya City in Quintana Roo, Mexico. *Quaternary Research* 49:111–122.

Leyden, Barbara W., Mark Brenner, David A. Hodell, and Jason H. Curtis
1993 Late Pleistocene Climate in the Central American Lowlands. In *Climate Change in Continental Isotopic Records*, edited by P.K. Swart, K.C. Lohmann, J.A. McKenzie, and S. Savin, pp. 165–178. Geophysical Monograph No. 78. American Geophysical Union, Washington, DC.
1994 Orbital and Internal Forcing of Climate on the Yucatan Peninsula for the Past ca. 36 ka. *Palaeogeography, Palaeoclimatology, Palaeoecology* 109:193–210.

Leyden, Barbara W., Mark Brenner, Thomas J. Whitmore, Jason H. Curtis, Dolores R. Piperno, and Bruce H. Dahlin
1996 A Record of Long- and Short-Term Climatic Variation from Northwest Yucatan: Cenote San José Chulchacá. In *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, edited by S.L. Fedick, pp. 30–50. University of Utah Press, Salt Lake City.

Lister, Guy S., Kerry Kelts, Chen Ke Zao, Jun-Qing Yu, and Frank Niessen
1991 Lake Qinghai, China: Closed-Basin Lake Levels and the Oxygen Isotope Record of Ostracoda since the Latest Pleistocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* 84:141–162.

Miksicek, Charles H.
1983 Macrofloral Remains of the Pulltrouser Area: Settlement and Fields. In *Pulltrouser Swamp: Ancient Maya Habitat, Agriculture, and Settlement*, edited by B.L. Turner II and P.D. Harrison, pp. 94–104. University of Texas Press, Austin.

Nyberg, Johan, Antoon Kuijpers, Björn A. Malmgren, and Helmar Kunzendorf
2001 Late Holocene Changes in Precipitation and Hydrography Recorded in Marine Sediments from the Northeastern Caribbean Sea. *Quaternary Research* 56:87–102.

Olson, Gerald W.
1981 Archaeology: Lessons on Future Soil Use. *Journal of Soil and Water Conservation* (September–October):261–264.

Pennington, Winifred
1981 Records of a Lake's Life in Time: The Sediments. *Hydrobiologia* 79:197–219.

Pohl, Mary D.
1985 The Privileges of Maya Elites: Prehistoric Vertebrate Fauna from Seibal. In *Prehistoric Lowland Maya Environment and Subsistence Economy*, edited by M.D. Pohl, pp. 133–145. Papers of the Peabody Museum of Archaeology and Ethnology No. 77, Harvard University, Cambridge, MA.

Redman, Charles L.
1999 *Human Impact on Ancient Environments*. University of Arizona Press, Tucson.

Rice, Don S.
1978 Population Growth and Subsistence Alternatives in a Tropical Lacustrine Environment. In *Pre-Hispanic Maya Agriculture*, edited by P.D. Harrison and B.L. Turner II, pp. 35–61. University of New Mexico Press, Albuquerque.
1996 Paleolimnological Analysis in the Central Petén, Guatemala. In *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, edited by S.L. Fedick, pp. 193–206. University of Utah Press, Salt Lake City.

Rice, Don S., and Prudence M. Rice

1983 El impacto de los Mayas en el ambiente tropical de la cuenca de los lagos Yaxha y Sacnab, El Peten, Guatemala. *American Indigena* 43:261–297.

1990 Population Size and Population Change in the Central Peten Lake Region, Guatemala. In *Precolumbian Population History in the Maya Lowlands*, edited by T.P. Culbert and D.S. Rice, pp. 123–148. University of New Mexico Press, Albuquerque.

Rice, Don S., Prudence M. Rice, and Edward S. Deevey

1985 Paradise Lost: Classic Maya Impact on a Lacustrine Environment. In *Prehistoric Lowland Maya Environment and Subsistence Economy*, edited by M.D. Pohl, pp. 91–105. Papers of the Peabody Museum of Archaeology and Ethnology No. 77. Harvard University, Cambridge, MA.

Rosenmeier, Michael F., David A. Hodell, Mark Brenner, Jason H. Curtis, and Thomas P. Guilderson

2002 A 3,500 Year Record of Environmental Change from the Southern Maya Lowlands, Peten, Guatemala. *Quaternary Research* 57:183–190.

Rosenmeier, Micheal F., David A. Hodell, Mark Brenner, Jason H. Curtis, Jonathan B. Martin, Flavio S. Anselmetti, Daniel Ariztegui, and Thomas P. Guilderson

2002 Influence of Vegetation Change on Watershed Hydrology: Implications for Paleoclimatic Interpretation of Lacustrine δO-18 Records. *Journal of Paleolimnology* 27:117–131.

Rue, David J.

1987 Early Agriculture and Early Postclassic Maya Occupation in Western Honduras. *Nature* 326:285–286.

Sauer, Peter E., Timoth I. Eglinton, John M. Hayes, Arndt Schimmelmann, and Alex L. Sessions

2001 Compound-specific D/H Ratios of Lipid Biomarkers from Sediments as a Proxy for Environmental and Climatic Conditions. *Geochimica et Cosmochimica Acta* 65:213–222.

Vaughan, Hague H., Edward S. Deevey, and Sam E. Garrett-Jones

1985 Pollen Stratigraphy of Two Cores from the Peten Lake District. In *Prehistoric Lowland Maya Environment and Subsistence Economy*, edited by M.D. Pohl, pp. 73–89. Papers of the Peabody Museum of Archaeology and Ethnology No. 77, Harvard University, Cambridge, MA.

Watts, William A.

1969 A Pollen Diagram from Mud Lake, Marion County, North-Central Florida. *Geological Society of America Bulletin* 80:631–642.

Whitmore, Thomas J., Mark Brenner, Jason H. Curtis, Bruce H. Dahlin, and Barbara W. Leyden

1996 Holocene Climatic and Human Influences on Lakes of the Yucatan Peninsula, Mexico. *Holocene* 6:273–287.

Wiseman, Frederick M.

1985 Agricultural and Vegetation Dynamics of the Maya Collapse in Central Petén, Guatemala. In *Prehistoric Lowland Maya Environment and Subsistence Economy*, edited by M.D. Pohl, pp. 63–71. Papers of the Peabody Museum of Archaeology and Ethnology No. 77, Harvard University, Cambridge, MA.