Journal of Paleolimnology **15:** 133–145, 1996.

Late Holocene climate change and human disturbance on Andros Island, Bahamas *

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Received 10 November 1994; accepted 10 June 1995

Key words: Bahamas, Holocene, fire history, climate change, human disturbance, charcoal stratigraphy, pollen analysis

Abstract

A 2 m sediment core from Church's Blue Hole on Andros Island, Bahamas provides the first paleoecological record from the Bahama Archipelago. The timing of events in the lower portion of the core is uncertain due to inconsistencies in the radiocarbon chronology, but there is evidence that a late Holocene dry period altered the limnology of Church's Blue Hole and supported only dry shrubland around the site. The dry period on Andros may correlate with a widespread dry period in the Caribbean from 3200 to 1500 yr BP. After the dry period ended, a more mesic climate supported tropical hardwood thicket around Church's Blue Hole. At *c.* 740 radiocarbon yr BP there is a sudden rise in charcoal concentration and a rapid transition to pinewoods vegetation, while at *c.* 430 radiocarbon yr BP charcoal concentration drops, but is higher again near the top of the core. Although climatic shifts could have caused these changes in vegetation and charcoal concentration, the changes post-date human colonization of the Bahamas and may reflect human arrival, followed by the removal of humans *c.* 1530 AD and the recolonization of Andros Island *c.* 200 years later.

Introduction

Evidence of pre-Columbian human disturbance is well documented in the mainland neotropics (Deevey *et al.*, 1979; Watts & Bradbury, 1982; Leyden, 1987; Bush *et al.*, 1989, 1992; O'Hara *et al.* 1993; Bush & Colinvaux, 1994), and it is becoming increasingly apparent that human impacts can mask or mimic the effects of climate changes. Accurate reconstructions of past climate and vegetation require an understanding of all the factors that affect the paleo-record, and human impacts cannot be ignored. Separating some types of human disturbance, such as altered fire regimes, from the effects of climate change is difficult in areas where human presence predates the Pleistocene-Holocene transition. The islands of the Caribbean, however, were occupied during the mid-to-late Holocene (Rouse, 1989) when climate was more stable and colonization dates can be determined more precisely. Paleoecological study of these islands has begun only recently, but some evidence of human disturbance has already been found (Binford *et al.*, 1987; Brenner & Binford, 1988; Hodell *et al.*, 1991; Burney *et al.*, 1994). This study reports the first paleoecological record from the Bahamas. Its purpose is to determine whether the aboriginal inhabitants of the Bahama Archipelago had a detectable impact on the vegetation of Andros Island, Bahamas.

Description of study site

Andros Island, Bahamas is located 100 km ESE of the southern tip of Florida (Fig. 1). It is the largest of the Bahama Islands, measuring 160 km long by 64 km wide and covering 5957 square km (Keegan, 1992). It is divided by several shallow bights into 2 primary islands, North Andros and South Andros, with several

* This is the 12th in a series of papers published in this special AMQUA issue. These papers were presented at the 1994 meeting of the American Quaternary Association held 19–22 June, 1994, at the University of Minnesota, Minneapolis, Minnesota, USA. Dr Linda C. K. Shane served as guest editor for these papers.

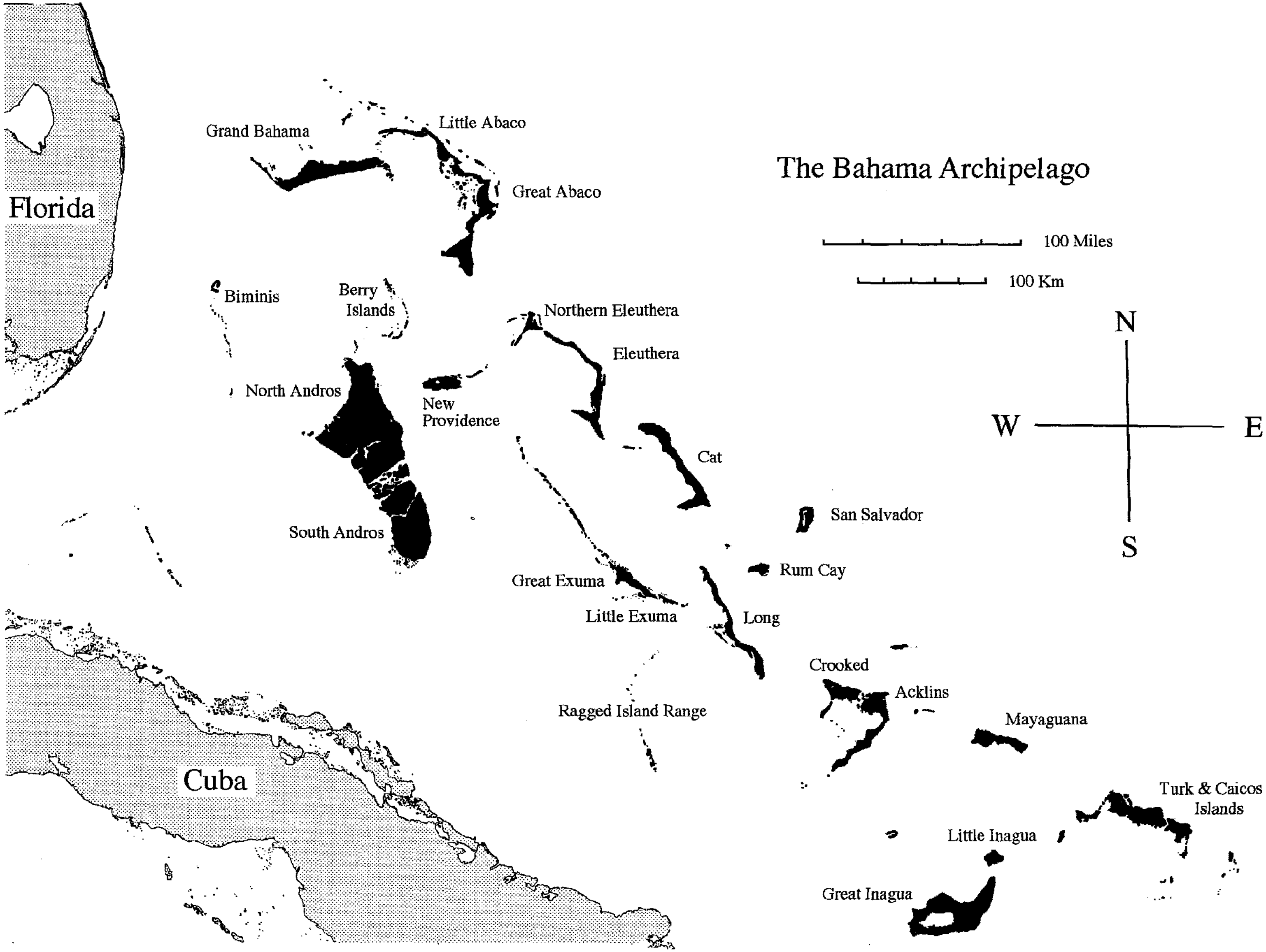

Fig. 1. Map of the Bahama Archipelago.

cays in between. This study was conducted on North Andros Island.

The relief of Andros is low with elevations ranging from 0 to 14 m. Most of the island is less than 6 m above sea level and the western half is low-lying and covered by sawgrass flats, wet scrublands and mangrove swamps (Greaves, 1978). Andros is composed entirely of limestone and the soils are thin and sparse with most of the vegetation rooting in bare, cracked rock. What little clay soil exists is derived primarily from North African Pleistocene loess (Mann, 1986), because very little substance remains after the chemical weathering of the limestone (Greaves, 1978). The soil pH averages 7–8 and can be as high as 8.5 (Greaves, 1978).

The climate is sub-tropical to tropical with mean summer temperatures of 28.3 °C and mean winter temperatures of 21.1 °C, although occasional frosts do occur (Lamb, 1973). Rainfall averages 1200 mm per year (Keegan, 1992) with most precipitation coming from convective thunderstorms that occur during the spring-summer rainy season, and rainfall is sparse in the fall-winter dry season (Lamb, 1973). Summer droughts are common and during dry periods wildfire from both human and natural sources is frequent (March, 1949; Byrne, 1980).

Andros has no rivers or streams, but a number of tidal creeks extend far into the island. Fresh and brackish water marshes and shallow lakes are common, but the primary water source for the current human population is wells dug into the freshwater aquifers. Other aquatic systems common on Andros, the so-called 'blue holes', are large water-filled limestone sinkholes 30–100 meters deep and 30–300 meters in diameter. The deeper ones are strongly stratified with 15–25 meters of freshwater overlying anoxic salt water.

Andros Island is particularly suited to paleoecology for two reasons. First, it has an abundance of shallow ponds, lakes and sinkholes that act as pollen deposition sites. Second, the flora is not large, with only one or a few species representing each genus or family (Correll & Correll, 1982). This allows great precision in pollen identification so past plant communities can be reconstructed in unusual detail.

Vegetation

The vegetation on the eastern half of Andros consists of a mosaic of extensive pinewoods interspersed with patches of tropical hardwood thicket. Bahamian pine (*Pinus caribaea* var. *bahamensis* (Griseb.) Barrett et Golfari., Pinaceae) makes up the canopy of the pinewoods. The understory shrub layer consists of tropical hardwoods, such as poisonwood (*Metopium toxiferum* (L.) Krug & Urban, Anacardiaceae), cassada wood (*Bumelia salicifolia* (L.) Sw., Sapotaceae), tetrazigia (*Tetrazigia bicolor* (Mill.) Cogn., Melastomataceae), five-finger (*Tabebuia bahamensis* (Northrop) Britt., Bignoniaceae) and quicksilver (*Thouinia discolor* Griseb., Sapindaceae) (Kjellmark, 1995). Most of the hardwoods have the potential to become canopy trees, but they are kept in a low, root-sprouting form by frequent surface fires (Kjellmark, 1995).

The hardwood thickets vary in size from a few trees to several hectares and have canopies dominated by species that grow as shrubs in the pinewoods, especially *M. toxiferum* and pigeon berry (*Coccoloba diversifolia* Jacq., Polygonaceae), along with *B. salicifolia*, and butter bough (*Exothea paniculata* (Juss.) Radlk., Sapindaceae) (Smith, 1991). The origin and permanence of the hardwood thickets is uncertain, as they occur on the same topography and soils as the surrounding pinewoods, but they rarely burn (pers. obs.). The limestone substrate beneath them may differ from that in the pinewoods or they may be remnants of a once more extensive type of vegetation.

Human history

The human history of the Bahamas began much more recently than that of the rest of the Americas. The earliest known archaeological site is located on San Salvador in the central Bahamas and radiocarbon dates to *c.* 1100–1200 yr BP (Berman & Gnivecki, 1994). Later sites occur throughout the Bahamas (Sears & Sullivan, 1978; Berman & Gnivecki, 1994) and most of the islands appear to have been settled by 800 yr BP or later (Keegan, 1992). Remains and artifacts from aboriginal humans have been found on Andros Island, but none has been dated (Goggin, 1939; Keegan, 1992).

The aboriginal inhabitants of the Bahama Islands were Lucayan Arawaks who migrated from the Greater Antilles (Sears & Sullivan, 1978; Berman & Gnivecki, 1994). Their point of origin is unknown, but Cuba (Berman & Gnivecki, 1994), Hispaniola (Keegan, 1992), or both (Sears & Sullivan, 1978) have been proposed. Almost all Lucayan settlements that have been found are coastal, reflecting a heavy reliance on marine resources (Keegan, 1992), but the Lucayans also cultivated root crops, beans and squashes by slash-and-burn methods (Sears & Sullivan, 1978; Keegan, 1992).

Less than thirty years after Columbus landed in the Bahamas, Spanish slave raiders had completely depopulated the islands (Watts, 1987; Keegan, 1992). Although the Spanish did not colonize the Bahamas, the French and British made several attempts to do so, but French, Spanish, and British conflicts over the Caribbean Islands resulted in most of the Bahamas remaining virtually uninhabited for 200 years (Byrne, 1980; Watts, 1987). The first successful colony was established on New Providence by the British in 1666 (Byrne, 1980), but the poor, thin soil and rock on most of the islands made agriculture difficult so further colonization was slow (Dodge, 1983; Riley, 1983). It was not until 1783 when British Loyalists were granted land in the Bahamas that settlement began in earnest (Byrne, 1980), but by 1791, the combined population of the Abacos and Andros was only 220 (Riley, 1983).

The current population of 10 000 people on Andros is scattered along the east coast of the island in small villages and towns. Before the 1950's, when logging of the pinewoods began, there were no roads or settlements in the interior of the island. A network of logging roads was built on the north portion of Andros and an airport and several small communities are now located in the interior.

Methods

In January of 1993, a 209 cm core was obtained from a site known as Church's Blue Hole (24 ° 45′ N, 77 ° 53′ W) approximately 5 km from the east coast of Andros Island. This blue hole is 200 m across and 33 m deep. The water is strongly stratified, with 18 meters of fresh water overlying 15 meters of anoxic salt water. The rim of the blue hole is 6 m above the water surface and a broad, level area of cracked and honeycombed limestone covered with pinewoods vegetation surrounds the site. The core was taken from the center of the blue hole using a modified Kullenberg piston coring device with a 3 m length of 1–1/2 inch Schedule 40 PVC pipe. After it was raised to the surface, the ends were sealed with corks and duct tape and it was transported to Duke University for analysis.

The core was opened by cutting the PVC pipe lengthwise with a power saw then splitting the sediment in half with a knife. One-half cm^3 sediment samples were taken every 5 cm starting at the top. A *Lycopodium* tablet was added to each sample and they were processed using the extraction methods in Faegri & Iversen (1989). Pollen was counted at 10 cm intervals except where the pollen spectra were undergoing rapid change, in which case pollen from 5 cm intervals was counted. Four-hundred grains per level were counted. However, when pine pollen made up more than 50% of the pollen spectrum, the count was continued until at least 200 non-pine pollen grains were found. Charcoal pieces were counted in the pollen slides after the pollen count was complete and the *Lycopodium* spike was used to convert the charcoal counts to concentrations of charcoal per cm^3 of sediment. Only completely opaque black particles with sharp, jagged edges were counted as charcoal in order to distinguish charcoal from pyrite particles. Sediment composition was determined by extracting 3 cm^3 samples every 10 cm down the core. These samples were dried and weighed, then run through thermogravimetric analysis (TGA) (Wiedemann *et al.*, 1988) to determine their cellulose, lignin, and charcoal content. The sample from 140 cm was lost after dry weight was measured and only one sample could be extracted for TGA analysis from the lower third of the core because the sediment was composed primarily of small mollusk shells.

Seven AMS radiocarbon dates were obtained on the Church's Blue Hole core from Beta Analytic Laboratories. Bulk sediment from the core could not be used because it is primarily composed of algae which have incorporated fossil carbon containing bicarbonate from the limestone. Only well-washed terrestrial litter fragments extracted from the center of the core were used for the carbon dates.

Results

Core description and radiocarbon dates

Figure 2 shows the lithology, Table 1 shows the seven radiocarbon dates, and Fig. 4 shows the two depth-age models for the Church's Blue Hole core. The core is 209 cm long. The sediment in its base unit, from 209 to 148 cm, is composed primarily of shells of small bivalves and gastropods mixed with algal gyttja. The gastropods have been tentatively identified as *Batillaria minima* Gmelin (Potamididae) and *Cerithidae costa* da Costa (Potamididae), both brackish or saltwater species of shallow mud flats. The bivalves have been tentatively identified as *Cumingia antillarum* Orbigny (Semelidae), a species of shallow saltwater marshes and lagoons, and *Corbula* sp. (Corbulidae). The lower

Table 1. ^{14}C age estimates for Church's Blue Hole core samples

Depth in core (cm)	Lab number	Facility number	C13/C12	Uncalib. ^{14}C age (^{14}C yr BP)*	Calibrated age range (Cal yr BP ± 1 SD)**
27–34	Beta-75760	CAMS-15692	−25.7	430 ± 80	569–479 and 409–369
50–60	Beta-64006	CAMS-7871	No Data	740 ± 60	735–699
85–89	Beta-80676	CAMS-14916	−28.0	3290 ± 60	3624–3494
98–109	Beta-80166	CAMS-18661	−29.3	3250 ± 40	3525–3445
139	Beta-75761	CAMS-15693	−30.3	4630 ± 90	5504–5329
145–155	Beta-66135	CAMS-9037	−29.0	1530 ± 60	1563–1390
186–209	Beta-80167	CAMS-18662	−26.5	2980 ± 40	3260–3125

* All results corrected for ^{13}C.
** Calendar yr BP at 68% probability (Stuiver & Reimer, 1993).

portion of the bottom unit from 209 to 180 cm is composed almost entirely of well-preserved shells. The spaces between the shells are filled with brown algal gyttja (Munsell wet color 5Y, 3/2). Terrestrial leaf litter from the sediments between 209 and 186 cm has an average radiocarbon age of 2980 ± 40 yr BP. The middle portion of the lower unit from 180 to 164 cm is composed of roughly equal parts brown gyttja (5Y, 3/2) and shells. The upper portion of the unit from 164 to 148 cm begins with 2 cm of shells mixed with very little gyttja; above this the condition of the shells deteriorates up the core and they are mixed with pale gray calcareous mud in increasing amounts. The mud from 164 to 153 cm is darker in color (2.5Y 7/2, 6/2) than that from 153 to 145 cm (10YR 8/1). From 148 to 145 cm there is a unit composed entirely of calcareous mud (10YR 8/1). Terrestrial leaf litter from the sediments between 146 cm and 156 cm dates to 1530 ± 60 radiocarbon yr BP.

From 145 to 144 cm there is a transition to a unit which extends from 144 to 87 cm and is composed of algal gyttja and carbonate mud. Most of this unit has fine horizontal laminae <1 mm thick, but in some sections, laminae are less obvious. The lower half of this unit, from 144 to 114 cm, is gray-brown in color (5Y 3/2). A small piece of wood from the 139 cm level dates to 4630 ± 90 radiocarbon yr BP. The upper half of this unit, from 114 to 89 cm is paler gray-brown (2.5Y 3/2). Terrestrial leaf litter from 98 to 109 cm dates to 3250 ± 40 radiocarbon yr BP and terrestrial leaf litter and a bark fragment from 85 to 89 cm dates to 3290 ± 60 radiocarbon yr BP. From 89 to 87 cm there is a 2 cm transition to a unit, which extends from 87 to 0 cm. It is composed of dark brown algal gyttja (5Y 3/1, 2/1) and is similar in texture to the adjacent unit below. Terrestrial leaf litter and pine needles from the sediment between 50 and 60 cm in this unit dates to 740 ± 60 radiocarbon yr BP and terrestrial leaf litter and a bark fragment from between 27 and 34 cm dates to 430 ± 80 radiocarbon yr BP.

The dry sediment density is highest at 145 cm where the sediment is composed of calcareous mud (Fig. 2). Above this point, density is relatively uniform with gradually lower values up the core. Percent carbonate is also highest at 145 cm, then is lower, but variable up the core. Percent cellulose and lignin are lowest at 145 then variable in the rest of the core. Percent ash is low at all levels with the exception of 180 cm where it is 9.8% of the sediment.

The pollen diagram

The pollen diagram from Church's Blue Hole indicates that three distinct plant communities have grown around the site (Fig. 3). The pollen assemblage represented in Zone III from 205 to 145 cm is composed of pollen from shrub species that currently grow in open, rocky, and generally dry sites (Correll & Correll, 1982). This pollen assemblage begins a transition to a different one in the upper portion of Zone III from 165 to 145 cm, and is finally displaced at the 145 cm level. The pollen spectra in Zone II, from 145 to 55 cm, contain an assemblage of pollen from species characteristic of the patches of hardwood thicket that grow interspersed in the widespread modern pinewood community. Pine pollen shows an initial increase between 90 and 60 cm then, at the beginning of Zone I, the hardwood community is rapidly

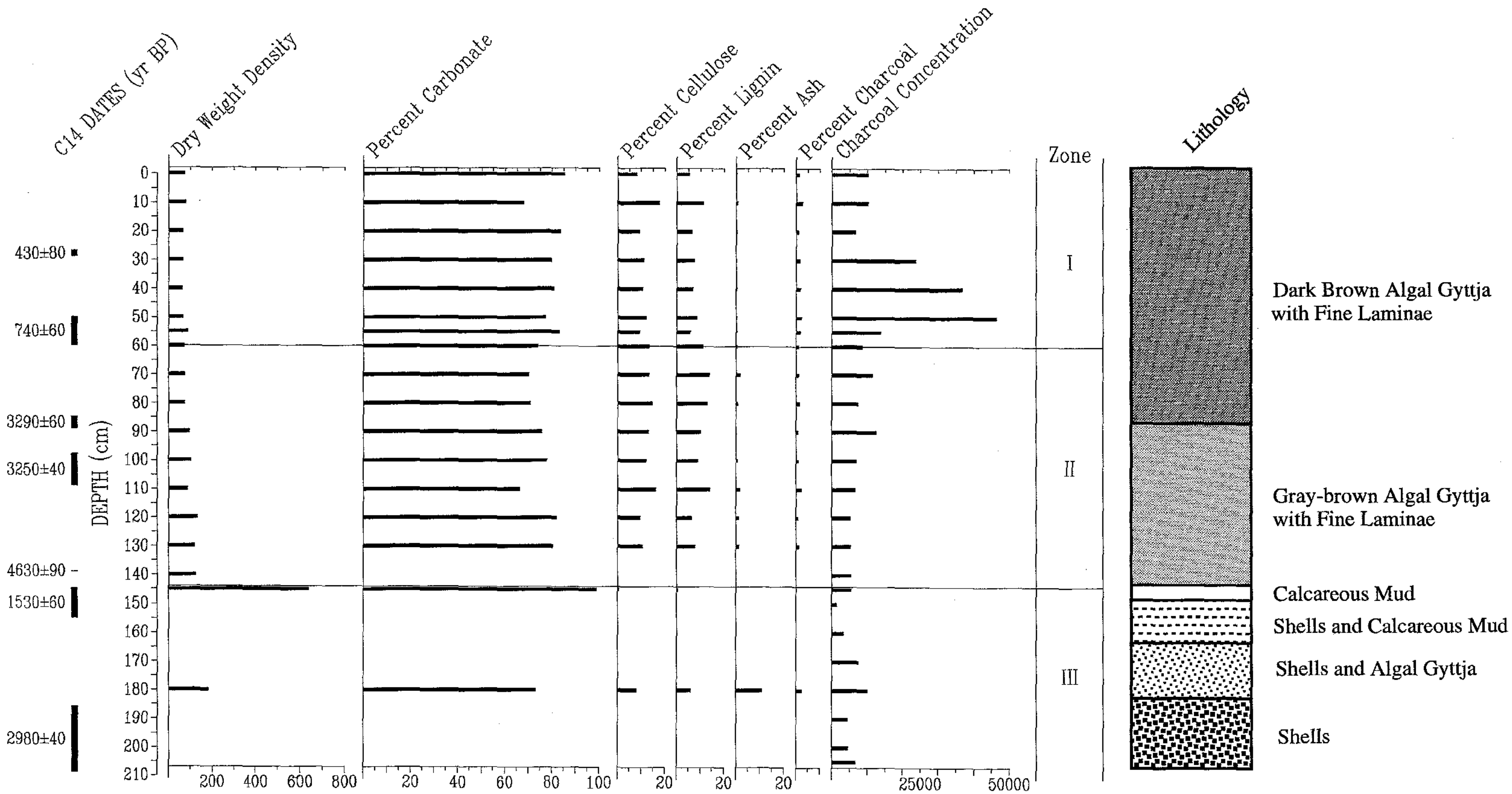

Fig. 2. TGA loss on ignition, charcoal concentration, and lithology from Church's Blue Hole sediment core. TGA data is presented as percent dry weight. Charcoal concentration data is presented as fragments cm^{-3} *of sediment.*

displaced by pinewoods as indicated by the dramatic increase in pine pollen and the appearance or increased abundance of pollen and spores from species characteristic of the modern pinewoods community. Bay-berry (*Myrica cerifera* L., Myricaceae) also peaks near the bottom of Zone I. Hardwood taxa such as *B. salicifolia*, *E. paniculata*, *M. toxiferum*, and *Myrsine floridana* A. DC. (Myrsinaceae) persist in the pollen spectra and are found around Church's today as root-sprouting shrubs. Coincident with the increase in pine is a peak in several pteridophytes. Bracken fern (*Pteridium aquilinum* (L.) Kuhn, Pteridaceae) is of particular interest as it is a characteristic species of frequently burned areas on Andros. Above the 30 cm level, the percentage of pine and grass pollen decreases and the percentages of pteridophytes spores are lower; then there is a second increase in *M. cerifera* and a slight rise in trema (*Trema lamarkianum* (Roem. Y Schlult.) Blume, Ulmaceae), *Pteris* spp. and *P. aquilinum.*

Charcoal

Optically counted charcoal is variable, but less than 6700 pieces per cm^3 below the 90 cm level, with the exception of the middle portion of Zone III where a distinctive sediment type is present (Fig. 2). From 90 to 55 cm the concentration of charcoal pieces varies between 13 600 and 7200 fragments per cm^3, at 50 cm the concentration increases to 46 300 followed by a gradual decline to 6500 at 20 cm and a second increase to 10 200 at 10 and 0 cm. The TGA results show that charcoal makes up only a small percentage of the dry sediment mass in any part of the core (Fig. 2). Charcoal has a peak of 2.5% in the distinctly different sediment type in the 180 cm level. Above 145 cm, charcoal is 1.1% or less until 100 cm where it is 2.1%. Above this level, it is 1.3% or less until 55 cm where it is 1.8%. At 50 cm it reaches 2.1% again then drops to 0.9% at 20 cm. Charcoal reaches its highest percentage (2.7%) at 10 cm and is 1.4% at 0 cm. The pattern of changes in percent charcoal is similar to that in charcoal concentration above 60 cm, but is different below 60 cm.

Discussion

Radiocarbon chronology

The seven ^{14}C dates from Church's Blue Hole do not show an internally consistent depth-age relationship (Table 1). Two different depth-age models can be constructed from the seven dates (Fig. 4). The carbon for the 1530 date was extracted from a 10 cm length of sediment and that for the 2980 date was extracted from a 23 cm length of sediment. Both dates were obtained on collections of many small leaf litter fragments. If these dates are out of stratigraphic order, many young carbon fragments must have somehow been moved below older sediments, but the sediment between 209 and 145 cm has several layered stratigraphic units and the very finely laminated sediments above 145 cm show no evidence of large-scale mixing. Also the dated material was extracted from the center of the core and did not appear to have been disturbed during coring. Perhaps sediment slumped off a shelf and settled out of the water column in an age-inverted stratigraphy. If so, this must have occurred *c.* 1530 radiocarbon yr BP or later.

If the 1530 and 2980 yr BP dates are in correct stratigraphic order, old carbon must have been incorporated into younger sediments above 145 cm. Redeposition of old carbon is quite possible in blue holes, since the vertical walls have numerous shelves and openings that accumulate leaf litter, branches, and even whole trees (pers. obs.) which could fall to the bottom at a later time and be incorporated into the sediment. The 4630 yr BP date was obtained on a single fragment of wood, the 3290 yr BP date was obtained on a bark fragment and small pieces of leaf litter extracted from 4 cm of sediment, and the 3250 date was obtained on a collection of many leaf litter fragments extracted from 11 cm of sediment. The 4630 date may represent a single redeposition event, but the 3290 and especially the 3250 yr BP dates suggest that the majority of the terrestrial organic matter in the 144 to 87 cm unit is over 3000 radiocarbon years old. The dates obtained on mixtures of organic fragments may have included older and younger carbon, yielding younger dates than the single piece of wood. There is little terrestrial organic matter in any portion of the core, so a small amount of old carbon could affect the average age.

The much younger radiocarbon ages obtained above and below the 144 to 87 cm unit suggest that the redeposition process was primarily confined to this unit. It is different in color than the units above or below, so perhaps the limnology of the blue hole was different at the time it was deposited and a different limnology, perhaps with more active water circulation may have favored the redeposition of old carbon. If old carbon was being incorporated into the sediments, old pollen must also have been redeposited off

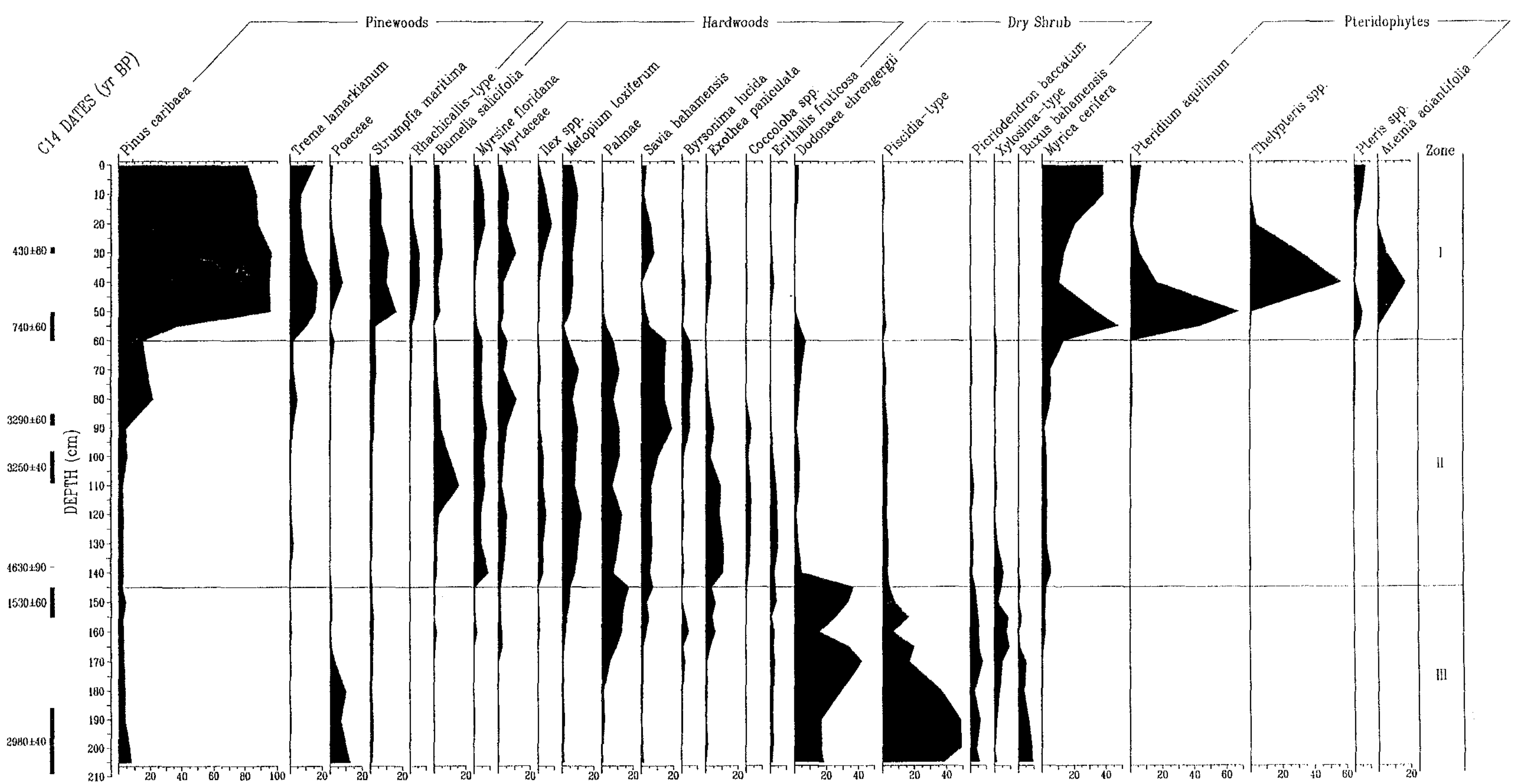

Fig. 3. Percentage data for selected pollen and spore taxa from Church's Blue Hole sediment core. Pine pollen was calculated as a percentage of total pollen. All other pollen types were calculated as a percentage of non-pine pollen. Pteridophyte spores were excluded from the pollen sum and were calculated as a percentage of non-pine pollen.

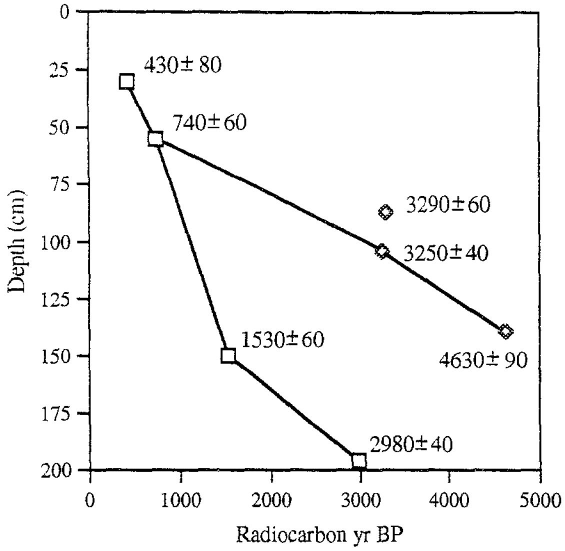

Fig. 4. Plot of radiocarbon yr BP *vs* depth in Church's Blue Hole sediment core.

of shelves. The pollen spectrum in the 144 to 87 cm unit, therefore, may represent a mixture of pollen from over 3000 yr BP and less than 1500 yr BP. Most of the species represented in the pollen spectrum in Zone II of the pollen diagram show little change in percentage as the sediment type changes around 87 cm, suggesting that, if old pollen was being incorporated, it did not have a major effect on the relative percentages of new pollen being incorporated at the time the sediment was deposited. Caribbean climate was wetter than present before 3200 yr BP, so the vegetation around Church's Blue Hole may have been hardwood thicket, which could have produced a pollen spectrum indistinguishable from that produced by the vegetation growing around Church's between 1500 and 740 yr BP.

Given the available evidence, there is no clear choice of which carbon dates to accept. In a blue hole system with vertical walls and a relatively flat sediment surface, redeposition of older carbon is more probable than down-mixing of younger carbon, but parsimony alone is not sufficient to make a decision. However, other evidence favors the 1530 and 2980 yr BP dates. The 1530 yr BP date was obtained on carbon extracted from a section of sediment between 145 and 155 cm. The pollen spectra in this sediment indicate that a transition from dry to mesic conditions occurred at the time the sediment was deposited. There is widespread evidence of a period of dry climate in the Caribbean between *c.* 3200 and 1500 yr BP. (Brown & Cohen, 1985; Hodell *et al.*, 1991; Goman, 1992; Gleason & Stone, 1994; Burney *et al.*, 1994). If the 2980 and 1530 yr BP dates from the Church's core are correct, the changes in the sediment and pollen spectra between 145 and 155 cm correlate well with a widespread climatic change which occurred in the Caribbean around 1500 yr BP. If the 4640, 3250 and 3290 yr BP dates are correct, there is no record of the Caribbean dry period in the Church's core and the dry shrub pollen spectrum was deposited at a time when Caribbean climate was wetter than present (Hodell *et al.*, 1991). Given the available evidence, it appears that the depth-age chronology using the 430, 740, 1530 and 2980 yr BP. dates is more reasonable. Therefore this is the chronology that will be used in the discussion.

Vegetation and fire history

The pollen and sediment in the Church's Blue Hole core indicate that several dramatic changes have occurred around the site in the past 2000 years (Figs 2 & 3). Zone III of the pollen diagram reflects unique conditions that ended approximately 1500 yr BP. The pollen spectra in this zone are composed primarily of shrub species that currently grow in dry, rocky, open sites. Though all of these species still grow on Andros Island today, this combination of them is found nowhere on the island. Grass pollen is also prevalent in the bottom half of this zone, indicating a relatively open canopy, but pteridophytes are not represented.

The limnology of Church's Blue Hole must have been distinctly different when the pollen in Zone III was deposited. The current anoxia in the lower saltwater layer prevents any mollusks from living there today, yet they are abundant in the sediment below 148 cm. Although these mollusks have not been positively identified to species, they all appear to be from genera which are found in brackish or saltwater marshes or mud flats. It is unlikely that the mollusk shells were delivered by a storm, for there is no terrestrial debris mixed with them and the shells show no signs of damage below 160 to 148 cm. Sea level changes could affect the limnology, but sea level in the Bahamas has been within 0.5 m of present for the past 1500 years and within 3 m of present for the past 5000 years (Boardman *et al.*, 1989). The water level in Church's Blue Hole is controlled by sea level and is currently 6 m below the rim. A 0.5 m or even a 3 m difference in sea level could not affect the limnology and vegetation simultaneously.

The period of dry climate prior to 1500 yr BP is the most probable explanation for the unusual sediment and pollen in Zone III. Using oxygen isotope ratios, Hodell *et al.* (1991) demonstrated that the climate of Hispaniola was unusually dry between *c.* 3200 and 1500 yr BP. Dry climate during this period has also been found in Puerto Rico (Burney *et al.*, 1994), Central America (Horn & Sanford, 1992; Goman, 1992) and Florida (Brown & Cohen, 1985; Gleason & Stone, 1994) so it is reasonable to assume that the climate of Andros Island was also dry at this time. The dry climate indicated by the pollen spectrum may have reduced the fresh water lens enough to allow full mixing to occur throughout the water column. Church's Blue Hole is much wider than it is deep so wind mixing could bring oxygenated waters in contact with the bottom substrate if the water column was not strongly stratified.

The state of preservation of the mollusk shells declines between 160 and 148 cm and the amount of algal gyttja in the sediment is very low. The pollen spectra indicate that mesic hardwood vegetation was increasing and dry scrub species and grasses were declining when the sediment was deposited. This may reflect the onset of a wetter climate which supported a denser vegetation canopy, shading out the grasses and lower shrubs. The wetter climate may have established some degree of stratification and anoxia in the blue hole, perhaps on a sporadic or seasonal basis before a final strong stratification took place around the time the 145 cm level was deposited. Changing from a stratified to a mixed system and back may have reduced the algal productivity and thereby slowed the sedimentation rate, allowing the mollusk shells to lie exposed and eroding on the sediment surface longer before they were incorporated.

The dry period may have affected more than the vegetation and sediments. It was probably a primary factor in delaying human colonization of the Bahamas. Humans were in the Greater Antilles at least by 7000 yr BP (Rouse, 1989), but the earliest known archaeological site in the Bahamas dates to *c.* 1100–1200 yr BP (Berman & Gnivecki, 1994). Colonists would need a source of fresh water even if they were only making short visits to the islands. Water is scarce in the Bahamas, even in the current climate. If the climate were much drier than today, it is unlikely that the islands could support a human population.

The dry shrub pollen spectra in Zone III are replaced in Zone II by pollen spectra which reflect an assemblage of hardwood species similar to that found in the hardwood thickets on Andros today (Fig. 3). This assemblage begins to develop prior to *c.* 1500 radiocarbon yr BP. At an age interpolated to be *c.* 900 to 1000 radiocarbon yr BP there is an increase in percent pollen from pine and several pinewoods species and a slight presence of *P. aquilinum* and *Pteris* spp. spores, while percent pollen from *Exothea paniculata* and *Coccoloba* spp., characteristic taxa of the hardwood canopy, decline. At the bottom of Zone I, *c.* 740 radiocarbon yr BP, the hardwood thicket is displaced by pinewoods as indicated by the dominance of pollen and spores from pinewoods species. This change in vegetation could have resulted from a climatic shift since Hodell *et al.* (1991) found that Caribbean climate has been drying progressively from *c.* 900 yr BP to the present. However, the current climate of Andros supports an extensive hardwood stand in the vicinity of Church's Blue Hole on the same topography and substrate, so climate changes have not eliminated hardwood stands. Furthermore, if drier climate were solely responsible for the conversion to pinewoods, it would appear that pinewoods should have succeeded the dry shrub vegetation prior to 1500 yr BP and then been displaced by hardwoods as the climate became wetter with the reverse happening toward the present.

The increase in *M. cerifera* in Zone I is noteworthy because it is not a common species in the pinewoods. It occurs more frequently in low-lying mesic areas or around the edge of wetlands (pers. obs.). *Myrica cerifera* is wind pollinated so its pollen could have come from some distance away. There is a shallow marsh in the vicinity of Church's Blue Hole and the loss of dense hardwood cover around the site may have allowed more *M. cerifera* pollen to blow into the blue hole. Perhaps the hardwood canopy around the marsh was also reduced allowing *M. cerifera* to become more abundant and expand into areas that were formerly too densely shaded to support this species.

The initial decline in pollen from some hardwood species and increase in pollen and spores from pinewoods species at the top of Zone II occurs just as charcoal concentration in the sediment begins to increase (Figs 2 & 3). The abrupt conversion to pinewoods is coincident with a peak in charcoal concentration and percent charcoal in the sediments. The changes in charcoal concentration could reflect higher amounts of charcoal fragmentation during the processing of some samples, but the close correlation of the peak in charcoal concentration with a peak in percent charcoal and changes in the pollen spectra suggest a real change in charcoal concentration in the sediments. If so, this suggests an increase in fire frequency and/or intensity. The increased burning must have played a pivotal role in changing the vegetation because the current pinewoods of Andros are maintained by frequent fires (Kjellmark, 1995). Most of the canopy trees of the hardwood thickets are common in these pinewoods, but they are kept in a low, root sprouting form by frequent burning. In the absence of fire the root sprouts could quickly grow into canopy trees and eventually replace the pines (Kjellmark, 1995).

The increase in charcoal and transition to a pyrogenic vegetation type on Andros begins shortly after human colonization of the Bahamas and is probably a result of human alterations in fire frequency. The current inhabitants of Andros still practice slash and burn agriculture and hardwood thickets are preferred garden sites as they have a greater accumulation of organic litter over the limestone rock than the frequently burned pinewoods. It is reasonable to assume that the Lucayan Arawaks on Andros would have made a similar choice of garden sites and preferentially cleared and burned hardwood stands such as that growing around Church's Blue Hole between *c.* 1500 and 740 radiocarbon yr BP. Even if the hardwood stands around Church's were not cleared and burned directly, fires that escaped from garden sites or habitations would have increased the overall fire frequency on Andros, and this, in combination with a slowly drying climate, would have favored the expansion of pinewoods at the expense of hardwood vegetation.

Andros is not the only island where an increase in charcoal and a transition to pyrogenic vegetation is associated with human arrival. Burney (1993) found a very similar pattern near the southwestern coast of Madagascar, in central Madagascar (Burney, 1987), and perhaps also in Puerto Rico (Burney *et al.*, 1994). Drier climate or an increase in lightning strikes could have caused these changes in fire ecology, but in Puerto Rico, the high charcoal influx declines *c.* 3200 cal. yr BP, just as Caribbean climate begins to become drier (Burney *et al.*, 1994). Similarly, on Andros the high concentration of charcoal declines after 430 radiocarbon yr BP, even as the climate continues to become drier (Hodell *et al.*, 1991).

Burney *et al.* (1994) state that a sudden increase in charcoal influx in sediments may be one of the earliest indicators of human colonization of oceanic islands. Sediments from Madagascar, Puerto Rico and Andros, 3 widely separated islands, all show a sudden increase in charcoal influx or concentration, but at different times and under different climatic conditions. On Andros and Puerto Rico, this increase post-dates archaeological evidence of human colonization of nearby islands. On Madagascar it is coincident with early evidence of human presence near the southwest coast, but occurs in the interior well after human colonization of the island. Although climatic explanations cannot be ruled out, the role of humans in altering the fire ecology and vegetation of these three islands must be considered.

Sediments from Church's Blue Hole that date to *c.* 430 radiocarbon yr BP contain a lower percentage of pollen and spores from most of the pinewoods species (Fig. 3) and a lower concentration and percent of charcoal (Fig. 2). The pinewoods vegetation may have been undergoing a period of succession since its early expansion and finally reached a new stable equilibrium, but this change occurs shortly after humans were removed from the Bahamas (Byrne, 1980; Watts, 1987). Perhaps the removal of humans returned the fire ecology to its 'natural' regime and the pinewoods were beginning to convert back to hardwood thickets. If so, the understory ferns and grasses would be the first species to be shaded out. Toward the top of core, the percentage of pteridophyte spores and pollen from some pinewoods species is higher and charcoal concentration increases, perhaps reflecting increased burning after humans recolonized Andros. The precise date of the recolonization of Andros is unclear, but the earliest permanent colonies in the Bahamas were established on Eleuthera in 1648 and New Providence in 1666 (Byrne, 1980). However, it was not until 1783 that people began to recolonize the Bahamas in earnest and this period is the most probable time that humans returned to Andros.

Conclusions

The results of this study indicate that the vegetation around Church's Blue Hole has undergone two major transitions in the past two millennia. The earliest vegetation type around the site was composed of shrub species that currently grow in dry, open areas. Coincident with the dry shrub pollen assemblage is a unique sediment type composed primarily of shells from small gastropods and bivalves. Church's Blue Hole is currently strongly stratified with 18 m of fresh water overlying 15 m of anoxic salt water, so the past limnology of the blue hole must have been quite different when mollusks were living at the bottom. The dry shrub pollen profile and different limnology may have resulted from a dry climate and low rainfall. If the dry climate did not produce a thick enough fresh water layer to maintain strong stratification, the water in the blue hole could be mixed by wind, bringing oxygen to the bottom.

A mesic hardwood thicket similar to those growing on Andros Island today succeeded the dry shrub vegetation and persisted until it was displaced by pinewoods vegetation, which currently surrounds Church's Blue Hole. The transition to pinewoods is coincident with a peak in charcoal concentration indicating a change in fire ecology. Charcoal concentration, and percent pine pollen drop off above 30 cm, then charcoal concentration and percentage of pollen and spores from pinewoods species increase again near the top of the core.

The timing of the vegetation and sediment changes recorded in the lower portion of the Church's Blue Hole core is uncertain, because the seven radiocarbon dates obtained on the core do not show an internally consistent depth-age chronology. The bottom portion of the core, from 209 to 186 cm, dates to 2980 radiocarbon yr BP and the top of the mollusk shell sediment unit from 145 to 155 cm dates to 1530 radiocarbon yr BP, coincident with the end of a dry period that occurred throughout the Caribbean from 3200 to 1500 yr BP. However, the 139 cm level of the core dates to 4630 radiocarbon yr BP, the 109 to 98 cm level of the core dates to 3250 radiocarbon yr BP, and the 85 to 89 cm level dates to 3290 radiocarbon yr BP. If the three older dates are correct, a previously unknown period of dry climate occurred on Andros Island prior to 4630 yr BP, at a time when the rest of the Caribbean was apparently wetter than present.

A peak in charcoal concentration and transition to pinewoods dates to 740 radiocarbon yr BP. This postdates human colonization of the Bahamas and may signal human arrival or an increase in human-set fires on Andros Island. The earliest known date for human presence in the Bahamas is 1100 yr BP, quite late compared to the rest of the Caribbean Islands. It is probable that the dry climate between 3200 and 1500 yr BP made the Bahamas too dry to support a human population, thus delaying their colonization.

Near the top of the core from 30 to 20 cm there is a decrease in percent pine and grass pollen and pteridophyte spores and a drop in charcoal concentration which dates to 430 radiocarbon yr BP, then, in the top 10 cm of the core, charcoal concentration increases once again and there is a slight rise in pteridophyte spores and pollen from pinewoods species. This pattern may reflect the removal of the Lucayan Indians *c.* 1530 cal. yr AD and the recolonization of Andros by humans *c.* 200 years later.

Climate shifts cannot be ruled out as the cause of the vegetation changes recorded in the upper portion of the Church's Blue Hole core, but the coincidence of these changes with known events in the human colonization, depopulation and recolonization of the Bahama Islands strongly suggests that humans played a major role in altering the vegetation of Andros Island.

Acknowledgments

I thank Pauline Vaas of Duke University and Dr Luther Brown, Dr Bob Jonas, and their students from George Mason University for their invaluable assistance in obtaining the sediment core. Additional thanks to Dr George DeBusk for his technical assistance in making the coring device and thanks to the staffs of Forfar Field Station and International Field Studies, Inc. for providing facilities, transportation, and assistance on Andros Island. I also thank Dr Maurice Isaacs of the Bahamas Department of Lands and Surveys for his assistance in obtaining plant collecting permits.

I wish to acknowledge Dr Daniel Livingstone, Dr George DeBusk, Michelle Goman, and Pauline Vaas for their valuable comments on the manuscript. I also thank Dr Norman Christensen, Dr Daniel Livingstone, Dr James Clark, and Dr Mark Bush for their advice on this research.

Funding was provided by Dr Norman Christensen, and by grants from the Duke University Department of Botany, Sigma Xi, The Explorer's Club, and NSF Grant BSR-9107272 to Dr James S. Clark.

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