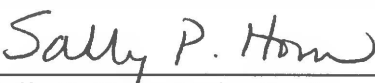


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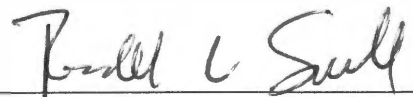
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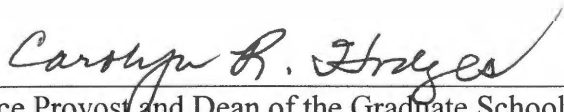


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**Middle to Late Holocene Environmental Change and
Human Impacts in Seasonally Dry Neotropical Forest of
Northwestern Costa Rica:
Sedimentary Evidence from Six Lakes**

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Martin R. Arford
August 2007

DEDICATION

This dissertation is dedicated to my parents, Cynthia Jane Arford and the late Oliver Martin Arford, my siblings, their spouses, and my nieces and nephews.
Thanks for your endless encouragement, love, and support.

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ABSTRACT

This dissertation presents evidence of long-term changes in climate, fire, and vegetation in northwestern Costa Rica, as revealed by sediment profiles from lakes on the seasonally dry, lower Pacific slope of Miravalles volcano in Guanacaste province (10.7° N, 85.2° W). Sediment cores were recovered for pollen and charcoal analysis from six lakes formed by volcanic activity approximately 8200 years ago.

Six regional pollen zones were delineated based on changes in pollen and sediments, and dated by AMS radiocarbon determinations on macrofossils. The basal pollen zone (Zone 6, prior to 8000 cal yr BP) comprises clastic sediments that correspond to the interval of lake basin formation. Zone 5 (8000–7500 cal yr BP) represents a transition to lacustrine sedimentation and shows increasing tree pollen percentages and abundant microscopic charcoal. During Zone 4 (7500–6800 cal yr BP) pollen assemblages indicate drier conditions, and the development of *Myrica* bogs in two basins; charcoal concentrations are highest in this zone. In Zone 3 (6800–5500 cal yr BP), tree pollen generally increases, but there is evidence of an episode of drier climate prior to 5500 cal yr BP. Zone 2 (5500–3700 cal yr BP) represents a period of prehistoric agriculture, punctuated by a dry period around 4000 cal yr BP. Maize pollen first appears at the base of the zone and is present throughout. Herbaceous pollen increases at the expense of tree pollen, and charcoal concentrations are high. Zone 1 (3700 cal yr BP to the present) also contains maize pollen, but charcoal concentrations decrease, and tree pollen remains low until modern times. Sediment characteristics indicate a drought interval at 2500 cal yr BP.

The analysis of cores from multiple lakes made it possible to interpret regional as well as local changes, including shifts in climate and several drought episodes. Maize pollen grains deposited at 5500 cal yr BP constitute the earliest evidence of agriculture in Costa Rica, and document human occupation of the region 1500 years earlier than previously known. Charcoal profiles show that natural and anthropogenic fire has been part of this ecosystem for the past 8000 years.

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CHAPTER 1

INTRODUCTION

STUDY CONTEXT

A fundamental geographic quest is to understand the dynamic interactions between people and the constantly changing natural environment (Cutter *et al.*, 2002). As human population has increased and technology has advanced, anthropogenic alterations of physical landscapes, biotic distributions, and atmospheric and aquatic chemistry have also increased. Climate change, anthropogenic and natural, is a serious modern concern, as are environmental degradation, loss of biodiversity, and ecosystem fragmentation. Understanding past human activities and ecosystem responses to environmental change can help scientists and policymakers develop better models and management plans. Yet in many places, such as the neotropics, large gaps exist in our knowledge of the cultural impacts and climate history that have shaped the biotic patterns we see today.

In tropical Latin America, early human disturbance has been documented but the degree of impact remains disputed. Brown and Lugo (1990) proposed that forty percent of the tropical forest had been cut before European contact, while Denevan (1992) stated that all forests had previously been cut. It seems likely that some areas were more heavily disturbed than others because of differences in human population sizes and distributions, and in local resources available for exploitation. Paleoecological studies, together with archaeological research, provide key data for determining past patterns of population distribution, resource use, and environmental impact.

Neotropical lake sediment records, derived from analyses of sediment chemistry, pollen, charcoal, and diatoms, have revealed changes in climate extending back into the Late Pleistocene. Lake cores from highland sites reveal the advance and retreat of glaciers, and sites at lower elevation show marked temperature depression during glacial times (Bush *et al.*, 2001). Holocene droughts have been documented in many neotropical studies (Piperno *et al.*, 1990; Hodell *et al.*, 1991; Bush *et al.*, 1992; Bush and Colinvaux, 1994; Leyden *et al.*, 1994; Hodell *et al.*, 1995; Curtis *et al.*, 1996; Islebe *et al.*, 1996; Leyden *et al.*, 1996; Marchant *et al.*, 2001, 2002; Berrío *et al.*, 2002; Vélez *et al.*, 2003, 2005; Dull, 2004), although the geographic extent of drought impacts and their timing and duration are not yet well established.

The influence of past fire regimes on vegetation and landscapes is receiving increased attention. Modern natural fires are rare in the wet tropics, but lightning fires are known from some seasonally dry areas, and fires are frequently used to clear and maintain extensive areas of pasture where forests once stood. In North America, early Americans used fire to maintain open fields and to encourage changes in woodland species composition. Prehistoric humans across the globe used fire for domestic purposes, and through escaped fires or intentional burning have influenced vegetation patterns. The ecological role of past fires in the neotropics, of human or natural origin, is not well understood, but may they have had significant effects on past vegetation. Modern fires play an important role in maintaining the boundaries between savanna and forest areas (Binkley *et al.*, 1993; Stocks and Trollope, 1993).

This dissertation focuses on the sediment records of six lakes on the seasonally dry, lower pacific slope of Miravalles volcano in the Province of Guanacaste,

northwestern Costa Rica. The following literature review outlines the context for this work, focusing in turn on the vegetation of seasonally dry tropical environments; what we know already about fire-vegetation dynamics and fire history in Guanacaste Province, and other seasonally dry areas of the neotropics; the reconstruction of fire history from sediment records; and previous paleoecological studies documenting climate history in the seasonally dry tropics. I follow this literature review with specific research objectives I will address through analysis of the Miravalles lake sediments, which derive from my review of the relevant literature.

Seasonally Dry Neotropical Forests and Savannas

Seasonally dry neotropical forests occur where annual precipitation is less than 1600 mm and where a pronounced dry season of 5–6 months occurs with less than 100 mm of monthly rainfall (Gentry, 1995). Vegetation is primarily deciduous, ranging from tall forest to cactus scrub, and is lower in stature and has lower basal area than more moist tropical forests (Pennington *et al.*, 2000). Seasonally dry forest is less species-rich than tropical wet forest (Gentry, 1995). In general, seasonally dry forests occur on soils that are more fertile than savanna soils (Pennington *et al.*, 2000). A moisture gradient extending from the wet equatorial zone toward the subtropics creates a vegetation gradient in which tropical rainforest (wet) gives way to more open semi-deciduous and deciduous forest (seasonally dry) and finally grass savanna (drier) (Goldammer, 1993; Hopkins, 1965).

Savanna landscapes include true grassland as well as ecosystems in which grasses dominate but some trees occur (Begon *et al.*, 1996). Hopkins (1965) described four

broad categories of savanna vegetation along a climate gradient: (1) savanna woodland with trees and shrubs forming a light canopy, (2) tree savanna with scattered trees and shrubs, (3) shrub savanna without trees, and (4) grass savanna that lacks trees and shrubs. Tropical savannas extend over 23 million km², or 20% of earth's land surface (Cole, 1986). Savannas cover over 65% of Africa, 60% of Australia, 45% of South America, and 10% of India and Southeast Asia (Cole, 1986). These high numbers reflect modern savannization of semi-arid lands that once supported more forest (Cole, 1986). Neotropical savannas cover large areas in Venezuela and Colombia (llanos of the Orinoco River area), millions of square kilometers in interior Brazil (the cerrado), and various areas in Bolivia, the coastal Guyanas, and Central America including the Mosquito coast (Sarmiento, 1984). Murphy and Lugo (1995) reported that 49% percent of Central America and the Caribbean is "dry forest," but they also included savanna vegetation in this classification.

Modern seasonally dry tropical forest is disappearing at alarming rates due to human clearing for pasture and agriculture, yielding large expanses of anthropogenic or derived savanna. Janzen (1988) stated that tropical dry forest is the most threatened habitat in the lowland tropics, with only 0.1% of dry forest remaining in Pacific Central America. In Costa Rica, most pre-1940 forest cutting was done in the tropical dry and moist forests, and by 1961 all dry forest had been cut as well as more than 99% of the original moist forest in Guanacaste Province (Sader and Joyce, 1988).

Various conservation and restoration efforts are under way to protect remaining fragments and to restore tropical dry forest. In Costa Rica, large expanses of seasonally dry vegetation have been protected in the Guanacaste Conservation Area, which includes

Santa Rosa, Guanacaste, and Rincon de la Vieja National Parks and the Junquillal Bay Recreational Area. Gillespie *et al.* (2000) found that Santa Rosa National Park had the highest species richness of seven tropical dry forests studied in Costa Rica and Nicaragua. Relationships between dry forest and savanna vegetation are complex and depend on variables such as the seasonality of rainfall, available soil moisture, soil structure, soil fertility, human activities, and fire (Hopkins, 1965; Sarmiento, 1984; Mooney *et al.*, 1995). Elucidating past relationships between dry forest and savanna, including the roles of climate change and fire, both natural and anthropogenic, in maintaining these systems, may potentially benefit modern forest management and restoration efforts.

Neotropical Fire Regimes

Fires are less common in wet tropical forests than in other forests, but can occur during droughts (Stott, 2000) or other times when humidity is low and abundant dry fuel is available for combustion (Uhl and Kauffman, 1990). The most common fuel source for tropical fires is dry grass and leaf litter, both of which are more abundant in savanna and dry forest areas where seasonal drying occurs (Stott, 2000). Savanna vegetation is more fire adapted than many woody dry forest species, and fire helps to maintain savanna vegetation (Sarmiento, 1984; Cole, 1986; Stocks and Trollope, 1993; Mooney *et al.*, 1985; Mueller-Dombois and Goldammer, 1990; Scholz and González, 2000). But even in fire-prone savanna systems, fire-intolerant woody species can be widespread, although their distributions depend on the timing and intensity of fires (Frost and Robertson, 1987). It is less clear whether seasonally dry forests are fire adapted. Many researchers

do not consider fire to be a natural part of disturbance regimes in seasonally dry areas of Central America (Koonce and González-Cabán, 1990; Murphy and Lugo, 1995). Janzen (1988, 2002) considered all modern fires in the Guanacaste Conservation Area of Costa Rica to be human in origin and stated there are no natural fires here. Some potential exists for fires that are not anthropogenic, though. At least one recent fire outside the conservation area can be attributed to a lightning strike in Guanacaste (Middleton *et al.*, 1997). In addition, volcanoes have been considered additional natural sources of ignition in dry and seasonally dry areas (Wilmschurst *et al.*, 1999; Horn, 1998). In Guanacaste, volcanic activity has been present for several million years and may have been a source of natural ignitions (Alvarado, 2000). However, Janzen (2002) stated that these fires only occurred in the far distant past.

Fire-vegetation interactions in Guanacaste have recently come under study, revealing a dynamic relationship. Pastures in the area are typically a monoculture of an introduced African grass, jaragua (*Hyparrhenia rufa*), which is burned off each dry season to maintain the pasture (Kramer, 1997). Janzen (1988, 2002) stated that most pasture fires do not burn into the dry forest when the canopy is dense enough to shade out grasses and herbs. In the presence of cattle, which reduced fuel loads, Janzen (1988, 2002) found that equilibrium was established between pasture and dry forest in Guanacaste National Park. Pasture advanced into the edges of the dry forest during dry years, while wet years resulted in expansion of dry forest (Janzen, 1988). When cattle were removed in 1978–1979, dense stands of tall jaragua grass not only shaded out young dry forest tree seedlings, but also resulted in more intense fires that damaged dry forest

fragments around the burning pastures (Janzen, 1988). Cattle have been used to help reduce the fuel loads created by jaragua in the Guanacaste Conservation Area.

However, the presence of grazing cattle may not reduce the incidence of fire, and may negatively affect woody species. Stern *et al.* (2002) questioned whether cattle consume tall, dry jaragua grass during the dry season, or instead eat greater proportions of small woody stems. In Palo Verde National Park and Reserva Biológica Lomas Barbudal, in the Tempisque watershed of Guanacaste, more plant species and larger woody stems were identified in ungrazed area of jaragua grass when compared to intermittently grazed areas (Stern *et al.*, 2002).

A preliminary study in Palo Verde National Park, Costa Rica, found that fires not only directly affected the dry forest vegetation, but also affected regeneration capacity by significantly reducing the number of seeds able to germinate within the soil (Scholz and González, 2000). The study found that fire reduced plant diversity and increased the occurrence of grasses and sedges. The study by Scholz and González (2002) recommended that fire should be excluded for restoration of the dry forests, the approach recommended for restoration of dry forests of the Guanacaste Conservation Area by Janzen (1988, 2002).

Another recent study in the Río Escalante-Chacocente Wildlife Refuge of southwestern Nicaragua examined the direct effect of fire on vegetation density and diversity (Otterstrom, 2004). The effect of fire on vegetation was quantified through three years of post-fire measurements in dry forest plots burned by a wildfire and in an experimentally burned plot. Results indicated that species responded individually, and that the strongest effect was within the first post-fire year. Woody plants with stems over

6 cm diameter had low mortality rates (<20%). Some tree species responded favorably, especially canopy trees, with higher recruitment and increased seedling density.

Fire frequency may have significant consequences for vegetation structure in neotropical forest areas. Cochrane *et al.* (1999) conducted field studies and used remote sensing images to evaluate the extent and effect of accidental fires in the eastern Amazon. They concluded that no more than 45% of trees with dbh >20 cm are fire susceptible for initial fires. For recurrent fires, which create more fuel, open the canopy, and promote faster drying, up to 98% of the trees are susceptible.

More studies are needed to evaluate both modern and prehistoric relationships between fire and vegetation in seasonally dry neotropical forests. Understanding this dynamic will help in developing more effective plans for habitat management and restoration. Anthropogenic fire, whether harmful or beneficial to the dry forest ecosystem, plays an important role in modern vegetation patterns in Guanacaste Province. But the role of prehistoric fires, natural or anthropogenic, in maintaining or modifying vegetation patterns throughout the Holocene is not yet known.

Fire History from Paleoecological Data

Most paleoecological studies in the neotropics have been conducted in lowland wet (rain) forests, in high elevation forests, or in treeless tropical alpine areas, while dry forests have received little attention in comparison (Mooney *et al.*, 1995; Pennington *et al.*, 2000). Many paleoecological studies in the neotropics have focused on vegetation and climate change inferred from changes in pollen percentages, without much attention to past fire occurrence. Fire history has, however, been a central focus of sediment core

studies at several neotropical sites, including many sites in the Dominican Republic (Horn *et al.*, 2000; Kennedy *et al.*, 2006; Lane, 2007) and in Costa Rica (Horn and Sanford, 1992; Horn, 1993; Northrop and Horn, 1996; Kennedy and Horn, 1997 and in press; League and Horn, 2000; Arford, 2001; Clement and Horn, 2001; Horn and Kennedy, 2001; Anchukaitis and Horn, 2005; Schlachter, 2005).

The most common technique used by paleoecologists to infer past fire regimes is quantifying the changes in abundance and sizes of charcoal fragments in dated sediment profiles. One problem associated with fire reconstruction from sedimentary charcoal is determining the spatial relationship between fire source and sediment basin. Researchers generally agree that larger charcoal particles remain airborne for shorter durations of time, and therefore travel shorter distances from the fire source (Millspaugh and Whitlock, 1995; Whitlock and Millspaugh, 1996; Clark *et al.*, 1998). However, Pitkänen *et al.* (1999) and Ohlson and Tryterud (2000) demonstrated that small charcoal fragments have not necessarily traveled far, but may have been from low-intensity local fires. Pisaric (2002) concluded that during high intensity fires in Montana, convection currents transported macroscopic plant remains, burned and unburned, over 20 km from the fire site. My own personal observation suggests that macroscopic charcoal fragments may sometimes travel long distances in windy conditions. In March 2001, I watched a grass charcoal fragment 5–6 cm long settle at least 10 km from its source on the slope of Miravalles volcano. However, most large fragments probably do not travel this far.

Microscopic charcoal fragments (<125 μm) in pollen preparations from lake sediment cores are commonly quantified on microscope slides during pollen analysis to reveal periods of increased/decreased burning in the general region of the lake basin

(Clark, 1982; MacDonald, 1989; MacDonald *et al.*, 1991; Horn, 1993; Whitlock and Larsen, 2001). Macroscopic charcoal fragments ($\geq 125 \mu\text{m}$) from lake sediments, quantified by sieving, are generally used to reconstruct fire history within a lake basin or watershed (Clark and Hussey, 1996; Whitlock and Millspaugh, 1996; Laird and Campbell, 2000; League and Horn, 2000; Whitlock and Larsen, 2001; Schlachter, 2005). Macroscopic charcoal in soil profiles has also been studied, but limitations to this method exist in comparison with lake sediment analyses (Sanford and Horn, 2000). Lake sediments provide better temporal control for interpreting fires from charcoal evidence. They accumulate in stratigraphic sequence and are not affected by treefalls and other terrestrial processes that can result in younger charcoal occurring below older charcoal in soil.

Even with problems of fossil charcoal interpretation, such as determining the source area, relative changes in sedimentary charcoal abundance are important indicators of changes in fire regimes over time. Pollen-slide analysis of microscopic charcoal also has poor temporal resolution, especially when samples are not contiguous (Whitlock and Larsen, 2001). For my study area, which lacks trees and remnant wood suitable for dendrochronological reconstructions of fire history, sedimentary charcoal analysis provides the only opportunity to interpret relative changes in fire regimes over long temporal scales.

In a companion study to the present dissertation, Schlachter (2005) studied the macroscopic charcoal stratigraphy of one of the six Miravalles lakes, Estero Blanco, at high-resolution (1-cm increments). He used charcoal analysis programs written by P. Bartlein (Long *et al.*, 1998) to determine peak and background fire values and to provide

smoothed curves of 10-year averages of fire intervals. Schlachter (2005) found significant changes in macroscopic charcoal that reflect major changes in fire frequency throughout the sedimentary record.

Past Climates and Climate Change

Late Quaternary climate history has been inferred from many paleoecological records in the American tropics. Researchers have attempted to synthesize individual records to reconstruct paleoclimate patterns across the Americas (Bradbury *et al.*, 2001; Fritz *et al.*, 2001); reconstruct combined Holocene climate and vegetation change (Grimm *et al.*, 2001); and reconstruct temperatures in the lowland neotropics at the Last Glacial Maximum (Bush *et al.*, 2001). Some patterns are beginning to emerge.

In Central Mexico, paleolimnological records indicated wetter conditions in the early to mid-Holocene followed by a shift to arid conditions prior to 5000 BP (Metcalf *et al.*, 1991; Metcalf, 1995; Fritz *et al.*, 2001). In Laguna Verde, El Salvador, discontinuous sedimentation was attributed to drier conditions between 8500–3300 BP (Dull, 2004). Data from Lake La Yeguada, Panama, indicated a relative dry phase between 8200–5500 BP (Bush *et al.*, 1992). Drier conditions existed in the Petén, lowland Guatemala, around 5000 BP (Islebe *et al.*, 1996). Other Central American records suggested a drier mid-Holocene followed by wetter conditions (Piperno *et al.*, 1990; Bush and Colinvaux, 1994; Leyden *et al.*, 1994). Several studies in South America have found drier conditions during the mid-Holocene, as well. In Colombia, mid-Holocene dry intervals have been described from multiple studies (Marchant *et al.*, 2001, 2002; Berrio *et al.*, 2002; Vélez *et al.*, 2003, 2005). Other studies in Colombia reported a lack of sedimentation or loss of sediments during the mid-Holocene (Behling *et al.*, 1999; Willie *et al.*, 2000). Sediment

cores from Lake Titicaca, in Peru and Bolivia, reveal the driest conditions were between 8000 and 5000 cal yr BP (Baker *et al.*, 2001). In nearby Lago Taypi Chaka Khota, Bolivia, drier conditions were reported from 6200–2300 BP (Abbott *et al.*, 2000).

Several studies conducted in the Yucatán revealed wet conditions throughout the mid-Holocene (7100–3000 BP) followed by drier conditions in the late Holocene (Hodell *et al.*, 1995; Curtis *et al.*, 1996; Leyden *et al.*, 1996). At Lake Miragoâne, Haiti, pollen and isotope data indicated moist conditions between 7000 and 4000 BP (Hodell *et al.*, 1991), and in Cuba, Peros (2007) found wetter conditions between 4800 and 4200 cal yr BP. A period of dry climates at about 1200 BP, has been documented in areas including Costa Rica (Horn and Sanford, 1992), and the Yucatan Peninsula of Mexico, coincident with the decline of the Mayan civilization (Hodell *et al.*, 1995; Curtis *et al.*, 1998; Haug *et al.*, 2003; Neff *et al.*, 2006).

Many other lacustrine sediment records from the neotropics are not as useful for paleoclimate reconstruction. Many have dating problems or have sediment records that cover short time spans. Others, including many late Holocene records from Costa Rica, have evidence of human activity that complicates reconstruction of Holocene climate change (Horn, 2007). My sediment records from lakes in northwestern Costa Rica that extend to the early Holocene may yield records that are not as strongly dominated by human signals in earlier periods, when it is believed that human activity had less environmental impact, and may yield important additional data for use in reconstructing Holocene climate.

RESEARCH OBJECTIVES

The presence of multiple natural lakes on the south slope of Miravalles volcano offered the opportunity to develop sediment-based records of vegetation, fire, and climate history that complement and extend previous studies. My objectives in this study were:

1. Develop a sediment chronology for each of six lakes based on radiocarbon dating of macrofossils in sediment cores.
2. Compare/contrast the six lake records to understand the types and rates of sediment accumulation as a context for pollen and charcoal interpretation.
3. Construct a vegetation history by analyzing changes in pollen and spore assemblages as a proxy for vegetation change.
4. Look for evidence of climate change and/or human impacts such as forest clearance and agriculture in the pollen records.
5. Document changes in microscopic charcoal abundance as a way of reconstructing past fire history.
6. Compare fire history, vegetation history, and inferred climate history with archaeological records to evaluate climate change and human impacts over time.

Specific research questions I hoped to answer with my study include:

1. Has the landscape that surrounds the lakes remained forested over time?
2. Do the pollen records indicate changes in forest composition or structure?
3. Do the sedimentary proxies indicate changes in climate over time, and, if so, how do these changes compare with regional paleoclimate reconstructions?

4. Has fire been an integral part of the ecosystem in the past, or is it a more recent human introduction in northwestern Costa Rica?
5. Has fire occurrence been constant or episodic? Are periods of increased fire associated with volcanic activity, climate change, or human influence?
6. What are possible implications of the findings on fire and vegetation history for current forest reconstruction efforts in northwestern Costa Rica?
7. Does evidence of prehistoric land use, such as maize agriculture, exist in the sedimentary record? If so, during what periods, and how does the pollen evidence of agriculture and of possible agricultural abandonment compare with the archaeological record?
8. Do the lakes all record the same events/changes? What regional history emerges from the combination of the records?

This dissertation is divided into six chapters. I follow this introductory chapter with a chapter on the environmental and cultural setting of the lakes. In Chapter 3, I describe laboratory and field methods. Chapter 4 presents results of sediment, pollen, spore, and microscopic charcoal analysis, and lake chronologies based on AMS radiocarbon dates. I discuss these results in Chapter 5, and present conclusions in the final chapter.

CHAPTER 2

ENVIRONMENTAL AND CULTURAL SETTING

PHYSICAL SETTING

The six study lakes are located on the lower southwest (Pacific) slope of Miravalles volcano in the Cordillera de Guanacaste of northwestern Costa Rica (Figures 2.1 and 2.2). The lakes lie at 330–570 m elevation in an area of undulating topography that surrounds the town of La Fortuna de Bagaces, between Cuipilapa and Guayabo (Figure 2.3). The lakes' presence was recorded as early as 1892 (Montero, 1892). The area includes many other small, permanent lakes, permanent wetlands, and bowl-shaped depressions that hold standing water only during the wet season. Weathering boulders of igneous origin are scattered across the landscape, which has been converted from seasonally dry forest to cattle pastures, or derived savanna, in recent decades. According to Gómez (1986), natural vegetation in this area would be semi-deciduous lowland forest. Remnant forests remain on steep slopes and in riparian areas, and abandoned fields contain early successional woody growth. Lower in elevation, toward the town of Bagaces (Figure 2.2), are thick sequences of ignimbrites (welded deposits of fine volcanic ash) deeply incised by rivers and streams that create a badlands-like topography, where dry edaphic conditions probably maintain true savanna/scrub vegetation. Wetter conditions prevail on the upper slopes of Miravalles and adjacent Tenorio volcanoes, which reach heights of over 2000 m. Here, cloud spillover from the moist Atlantic slope allows for the growth of dense, evergreen forests.

The local climate regime at the lakes is marked by a five month dry season from November to April when the northeast trade winds produce a rainshadow effect on the

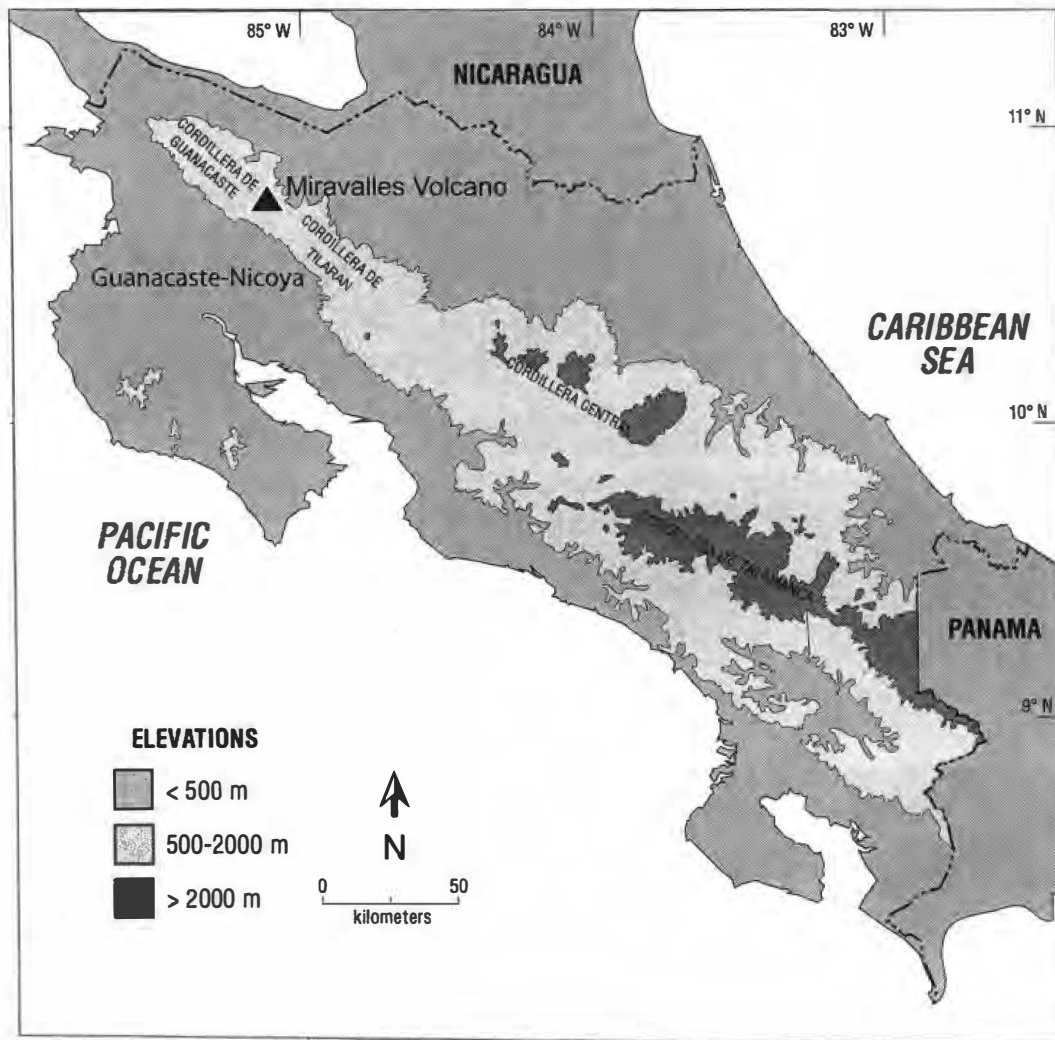


Figure 2.1. Location of Miravalles Volcano, Costa Rica. Modified from a map produced by the Cartographic Services Laboratory at the University of Tennessee.

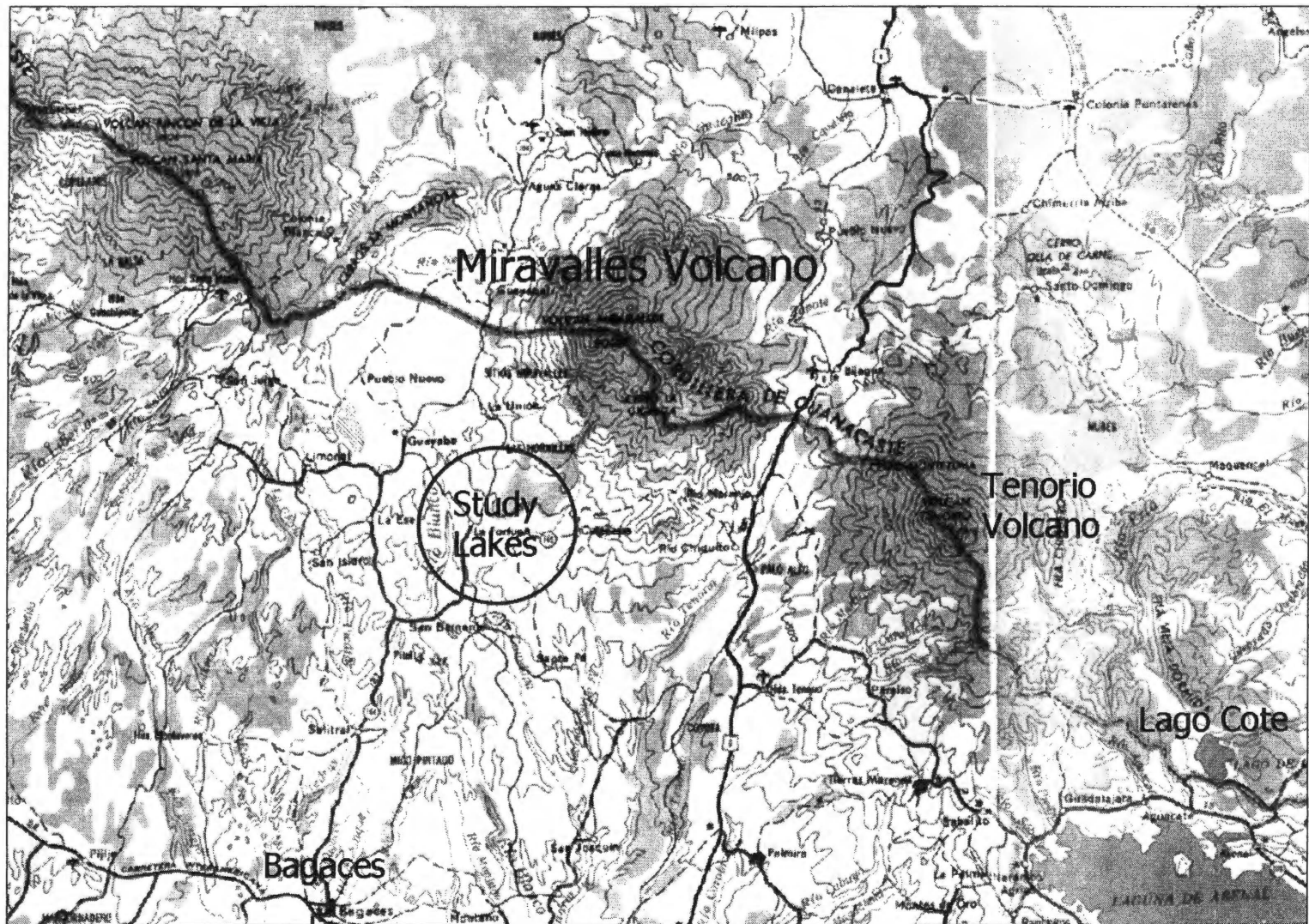


Figure 2.2. Location of the Miravalles Lakes in Guanacaste, Costa Rica. (From the Miravalles and San Carlos maps, 1:200,000 series, 1970, Instituto Geografico de Costa Rica 1:200,000 map, Costa Rica Series.

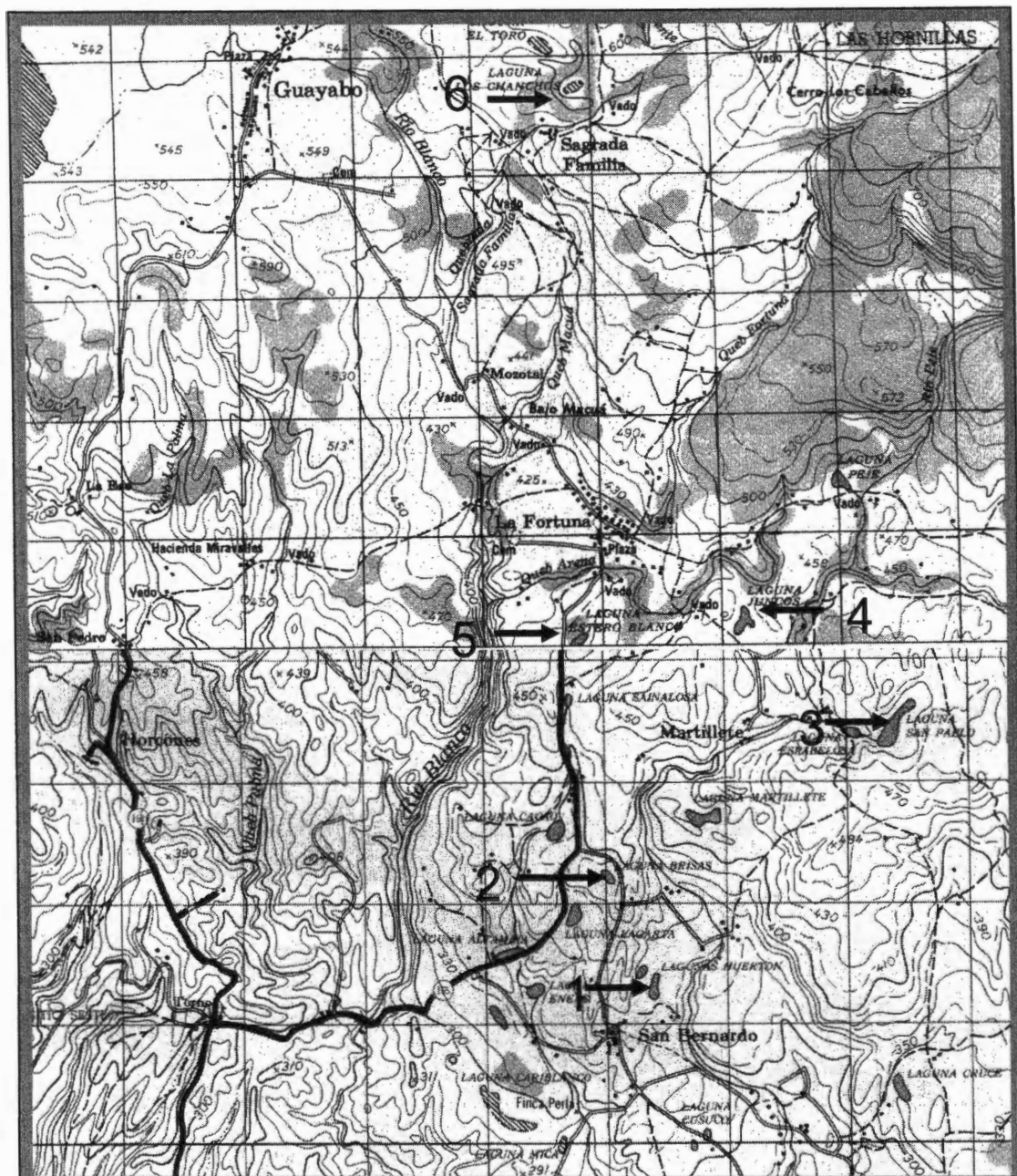


Figure 2.3. Topography of the Study Area and Locations of Sampled Lakes. From 1:50,000 Miravalles and Tierras Morrenas topographic quadrangle maps, Instituto Geográfico de Costa Rica, 1966 Edition. North is at the top of the map. Each grid square is 1 km². Study lakes are (1) Martínez, (2) Las Brisas, (3) San Pablo, (4) Los Juncos, (5), Estero Blanco, and (6) Sorpresa.

Pacific slope (Coen, 1983). The study area is classified as Subhumid-humid, having a very long dry season, in the Herrera system of climates in Costa Rica (1985). Annual precipitation in the region ranges between 1500–2000 mm (Coen, 1983; Bergoeing, 1998). Mean annual temperature is between 22.5–25.0° C (Bergoeing, 1998), with the highest temperatures during the dry season (Coen, 1983). A map of Holdridge life zones (Zonas de Vida de Costa Rica, 1988; Figure 2.4) places the study site within the Premontane Moist Forest-Basal Belt Transition zone. This classification is based on climate parameters, but life zones are named after expected mature vegetation, and life zone terms are used also for vegetation classification in Costa Rica (Holdridge *et al.*, 1971). Continuing up the slopes of Miravalles are bands of moist premontane transition, Premontane Wet Forest, Premontane Rain Forest, and in the highest elevations, Lower Montane Rain Forest. At slightly lower elevations is Tropical Dry Forest which extends from San Bernardo through Bagaces and southward.

During our visits from 1998–2003, we observed rapid changes in the lakes as floating and emergent aquatic vegetation encroached on the lake surfaces. Some lakes that had mostly open water in 1998 or 1999 were by 2003 completely covered with dense mats of *Eichornia* (water hyacinth), *Azolla*, *Pistia stratiodes* (water lettuce), ferns (including *Acrostichum*), and grasses and sedges. Why the lakes, which formed thousands of years ago, are presently filling in so rapidly is an interesting question. Many floating plants are rooting in the littoral zone, with dense tangles of roots. Livestock walk through the shallowest water creating a zone of bioturbation in from the lake margins, with disturbance reaching farther offshore in dry years when lake levels are lower.

Figure 2.4. Approximation of Holdridge Life Zones. Adapted from Liberia 1:200,000 map, Zonas de Vida de Costa Rica Series, 1988. Base map from the Miravalles and San Carlos maps, 1:200,000 series, 1970, Instituto Geográfico de Costa Rica.

Eutrophication from animal waste is likely contributing to the plant growth and organic deposition, and may be changing the water chemistry.

Preliminary water chemistry of the Miravalles lakes has been conducted (Haberyan *et al.*, 2003) as part of a larger limnological research project in Costa Rica (Horn and Haberyan, 1993; Umaña *et al.*, 1999; Haberyan *et al.*, 2003). In ANOVA analysis of water chemistry of all 51 lakes studied, the Miravalles lakes clustered together well. However, the lakes showed substantial variation in water chemistry, not only between lakes (Table 2.1), but for samples taken from the same lake during different years (Haberyan *et al.*, 2003).

Petroglyphs were identified near most of the lakes by Tennessee and/or University of Costa Rican researchers, but I do not report locations pending further study and protection of these archaeological resources by Costa Rican scientists and government authorities.

LAKE BASIN ENVIRONMENTS

Laguna Martínez (10.642° N, 85.197° W, 330 m.a.s.l.) is the larger of two lakes labeled as “Lagunas los Huerton” on the 1966 Miravalles 1:50,000 topographic map, but local residents call it Laguna Martínez and I used the same designation. It is the lowest in elevation of the six study lakes. Topography is undulating, with a small hill separating the two lakes. A small gallery forest on the edge of Laguna Martínez consists mostly of large trees, including *Ficus*, *Coccoloba* and several species of Fabaceae (*Samanea*, among others). Pastures occupy most of the area surrounding the lakes, where “coyol” palms (*Acrocomia aculeata*) are common. Some pastures have been abandoned

Table 2.1. Limnological Data for Six Miravalles Lakes. Chemical data are for surface water samples, analyzed using inductively-coupled plasma emission spectroscopy (ICP) and ion chromatography (IC). Lake areas are estimated from topographic maps or field observation. (Haberyan *et al.*, 2003 and Horn, unpublished data) n.d. = no data. Secchi depth indicates visibility through water column.

Lake	Lat./Long. Location	Elev. (m)	Area (ha)	Date of Visit	Water Depth (m)	Secchi Depth (m)	Chemical Data (mg l ⁻¹)					
							Ca ⁺² ICP	Mg ⁺² ICP	K ⁺ ICP	Na ⁺ ICP	Si ICP	Cl ⁻ IC
San Pablo	10.661 N, 85.180 W	450	4.5	3/98	2.48	0.7	10.7	6.5	8.0	12.9	19.9	8.2
Martinez Grande	10.642 N, 85.197 W	330	1.5	3/01	3.56	1.3	28.0	8.9	5.7	24.5	n.d.	4.8
Estero Blanco	10.667 N, 85.204 W	430	1.5	3/99	3.15	1.6	16.0	7.2	4.0	7.3	14.0	4.8
Las Brisas	10.650 N, 85.201 W	390	0.8	3/99	2.96	1.3	15.7	5.8	6.5	6.4	14.7	2.1
Los Juncos Near	10.668 N, 85.191 W	440	0.8	3/98	3.0	0.3	10.8	5.0	0.1	8.4	15.7	5.5
La Sorpresa	10.711 N, 85.211 W	570	0.5	3/01	0.8	>0.8	8.9	2.7	4.1	12.2	n.d	5.4

for several years and are grown over with dense, often thorny, shrubs including *Mimosa pigra*. The 1966 topographic map shows the surface of the lake to be about 1.5 ha, but in 2003 it was completely covered with dense floating vegetation (grasses, sedges, *Eichornia*, *Utricularia*, *Hydrocotyle*, and ferns including *Achrostichum*). For coring in 2001 we accessed a small (10 m diameter) patch of open water after chopping/wading through about 8 m of the vegetation and removing the tangled plant material. Water depth at the coring site was 3.6 m.

Laguna Las Brisas (10.650 N°, 85.204 W°; 390 m.a.s.l.) is the second lowest in elevation of the study lakes. It has a surface area of about 0.8 ha, and water depth was 3.0 m in both March 1999 and January 2000. Las Brisas occupies a small, bowl-shaped depression with a moderately steep slope on the west and northwest. A floating mat of vegetation covers most of the water surface (Poaceae, Cyperaceae, *Eichornia*, and ferns including *Acrostichum*). In some dry seasons there is no open water visible. Except for a few large trees (*Enterolobium* and other Fabaceae, *Coccoloba*), the surrounding area is pasture with grasses, *Acrocomia aculeata*, forbs, and some small shrubs including *Mimosa pigra*.

Laguna Estero Blanco (10.667 N°, 85.204 W°; 430 m.a.s.l.) has a surface area of about 1.5 ha. The lake is deepest to the southwest and becomes gradually shallower toward Miravalles volcano to the northeast. The lake level fluctuates at least a meter between the wet and dry seasons; water depth was 3.15 m in March 2001. Rocky pasture occupies rolling hills around the lake where Coyol palms (*Acrocomia aculeata*) and other trees are scattered. In 2001, during coring, lake water was turbid with a secchi depth of 87 cm, and submergent aquatic plants were abundant.

Los Juncos Near (10.668 N°, 85.191 W°; 440 m.a.s.l.) is half of a pair of adjoining lakes. During the dry season when water level drops more than a meter, the lakes are separated into Los Juncos “Near” and “Far” (Haberyan *et al.*, 2003). All further reference to Los Juncos will be about Los Juncos Near. The lake is quite small (0.8 ha) but maintains a water depth of 3 m during the dry season. Pasture surrounds the lake, with a few mature trees at lake edge. Patches of secondary forest grow on nearby rolling hills.

Laguna San Pablo (10.661° N, 85.180° W; 450 m.a.s.l.) is the largest of the six study lakes (4.5 ha). The lake is located in a long northwest to southeast trending basin with low, rolling hills surrounding the lake. Water is deepest (2.54 m) in the southwest end of the lake, while the northeast end becomes gradually shallower into a wetland area. The surface area of the lake changes between wet and dry seasons, when water level varies by more than a meter. According to J. Ramos (personal communication), a local landowner, slopes around the lake were converted to pasture around 1960, but previously had been forested. Coyol palms are the most common pasture tree. Higher on the southeast slope are patches of secondary forest and a small plantation of “pochote” (*Bombacopsis quinata*).

Laguna La Sorpresa (unofficial name) (10.711 N°, 85.211 W°; 570 m.a.s.l.) is small (0.5 ha) and highest in elevation of the study lakes. Only part of the original lake remains on the eastern side of a constructed dike. The western part was excavated as part of a test well during development of the geothermal field of Miravalles volcano. A steep slope abuts the northern edge of the lake; otherwise, the topography consists of gently rolling hills. Water depth was 80 cm in 2001 when we cored from a floating platform. In

2003 we recored the lake to obtain deeper sediments. By then, floating and emergent vegetation, mostly grasses, had spread from the eastern shore to cover most of what was open water in 2001, an area including our previous core site. Our 2003 core site was the western margin of the existing lake at the edge of the dike, because this location would have been closer to the center of the original lake prior to the construction of the dike. While the uppermost sediments had surely been disturbed during dike construction, we were re-coring to obtain deeper and older sediments which we were unable to core recover in 2001.

VOLCANIC HISTORY

Miravalles volcano rises 2028 m above sea level as one of a series of volcanoes that make up the northwest to southeast trending Cordillera de Guanacaste (Figure 2.1). Miravalles' past activity, briefly summed here, is from Alvarado (2000). About 1.8 million years ago (mya), three separate volcanoes existed where Miravalles now exists: La Montañosa to the southwest, Guayabo to the north, and Espíritu Santo to the southeast. Cataclysmic explosions destroyed most of the volcanic complex, and produced a succession of ignimbrites and nuées ardentes (superheated clouds of gas and ash) from about 1.5 to 0.6 mya. Peripheral remnants of the former volcanoes still exist: Cerro Espíritu Santo to the southeast, Cerros La Montañosa to the west of Guayabo, and the large Guayabo caldera containing Laguna Mogote. A new volcano, Cabro Muco, formed in the interior of the depression as volcanic activity continued, but this volcano also exploded and collapsed, about 0.2 mya, leaving the remnant Cerro Cabro Muco to the south-southeast. Volcán Miravalles developed in the ruins. About 0.1 mya, the

volcanic activity shifted to its southwest flank, creating double cones. Activity around 8200 BP produced lava flows and avalanches that generated lahars. Products from the various explosions and mass wasting accumulated to the south-southwest, creating the undulating topography that surrounds and impounds the lakes of the area. Additional lava flows and pyroclastic flows extended from the west and southwest flanks of Miravalles about 8000 BP. (Alvarado, 2000)

On September 14, 1946, a small phreatic explosion occurred on the southwest flank of Miravalles that sent detritus 100 m in the air and created a crater 20 m in diameter (Alvarado, 2000). This eruption resulted from the release of geothermal fluids beneath the surface. Venting of hot fluids and gases, sulfur fumaroles, and bubbling mud are observable at Las Hornillas (Figure 2.3). The Instituto Costarricense de Electricidad (ICE) began investigating the geothermal energy potential of the Miravalles area in 1975, and by 1994 the Planta Geotérmica Miravalles began producing electricity. Development of this resource continues to expand (Alvarado, 2000), and the local landscape is transected by many stainless steel steam pipes and associated wells and holding ponds.

HUMAN PREHISTORY

Archaeological evidence of the first human inhabitants in Costa Rica is extremely limited (Ferrero, 2000). Radiocarbon dates of 10,000 BC from sites in Patagonia, southern Argentina, suggest that humans passed through Central America on their migration from North America at some earlier time, although no evidence exists of their trek in Costa Rica (Snarskis, 1981). Clovis-type projection points have been discovered in the Turrialba Valley, along the Río Reventazón (Snarskis, 1979, 1984). Though the

site is undated, Snarskis (1979, 1984) considered these points evidence of human arrival by at least 10,000 BC. Two Clovis-type points were discovered in the Guanacaste area, suggesting a similar occupation time (Sheets, 1994), but the context of the finds is uncertain. These points are similar to ones found in the United States, Mexico, Guatemala, and El Salvador. One of these points, made of local chalcedony and found in the area of Arenal, was not in stratigraphic sequence, but is thought to be the oldest artifact in northwestern Costa Rica (Hoopes, 1992–1993). Paleoindians in Costa Rica were probably hunter gatherers who lived in small bands, and moved about using temporary residences (Ferrero, 2000). Subsequent Archaic peoples also left little trace in the archaeological record. From the end of the Archaic (~3000 BC) onward, there is increasing archaeological evidence of human presence in Costa Rica.

Three major archaeological regions are recognized in Costa Rica: the Guanacaste-Nicoya Region, the Diquís Region (southwest Pacific coast), and the Central Highlands-Atlantic Watershed (Snarskis, 1981). The lakes studied in this project are located near the border of the Guanacaste-Nicoya and the Central Highlands-Atlantic Watershed archaeological regions, but most references include the area of the Miravalles lakes in the Guanacaste-Nicoya Region.

The Guanacaste-Nicoya region in Costa Rica is the southernmost portion of the area defined as Mesoamerica, which includes Nicaragua, Honduras, El Salvador, and Guatemala, and extends into Mexico. Initial assignment to this region was made because northwestern Costa Rica, basically Guanacaste, had more prehistoric contact with and influence from Mexico and the Pacific Coast of northern Central America than the rest of Costa Rica, and had trade routes with southern Mexico by the late Olmec Period (800–

400 BC) (Lange, 1982–83; Snarskis, 1981). However, there was also interchange between the Guanacaste region and other archaeological areas of Costa Rica (Corrales, 1992–93; Snarskis, 1981). Many archaeological studies have been conducted in the lowland Guanacaste area (Santa Elena and Nicoya Peninsulas, Tempisque River valley, Gulf of Nicoya) as well as in the volcanic cordilleras and foothills (Miravalles, Tenorio, and Arenal volcano areas) (Norr, 1982–83; Ryder, 1982–3a and b; Sheets, 1982–83, 1994; Hurtado de Mendoza and Alvarado, 1988; Sheets *et al.*, 1991; Bishop, 1992–93; Guerrero *et al.*, 1992–93; Odio, 1992; Alvarado, 2000). Funerary and habitation sites were examined, with evaluations of pottery, stone tools, shell middens, human remains, and subsistence strategies. Vázquez *et al.* (1992–93) established local archaeological periods for the Guanacaste-Nicoya region (Table 2.2). A rich prehistory has emerged that shows influences from both South America and Mesoamerica, but also the maintenance of unique, Costa Rican cultural aspects (Snarskis, 1981).

Early human evidence was found at three sites south of the modern town of Guayabo, on the rim of the old caldera, from a paleosol developed over a culturally sterile volcanic tuff (Alvarado, 2000). Evidence included stone flakes from tool making and other rock fragments, and abundant charcoal associated with hearth fires dating to 1500–1800 BC (3750–3450 BP) (Alvarado, 2000).

At the La Pochota site, between the lower part of the Río Tempisque and the Cordillera de Guanacaste, a new complex of ceramics was found that predated Zoned Bichrome and extended into the Middle Formative (1500–500 BC/3450–2450 BP) (Odio, 1992). Based on ceramic analysis, the agriculture had been similar to the Tilarán Cordillera and the Caribbean plains to the northeast, with more dependence on grain

Table 2.2. Archaeological Periods for the Guanacaste-Nicoya Region and Tempisque River Valley

BC/AD	SAR Periods ¹	New Chronology Guanacaste- Nicoya ²	Old Regional Periodization ³	Tempisque River Valley ^{3,4}	BP
1600	Period VI			Bebedero B	950
1400		Ometepe	Late Polychrome	Bebedero A	
1200					
1000	Period V	Sapoa	Middle Polychrome	Palo Blanco B	
800				Palo Blanco A	
600		Bagaces	Early Polychrome	San Bosco	
400	Period IV		Linear	Ciruelas	1950
200					
AD--BC		Tempisque	Zoned Bichrome	Catalina	
200					
400					
600	Period III	Orosí	Formative		2950
800					
1000					
2000					3950
4000	Period II	Archaic	Archaic		5950
6000					7950
8000					9950
	Period I	Paleoindian	Paleoindian		?
?10,000					?11,950

¹ School of American Research

² (Vázquez *et al.*, 1992–1993)

³ (Snarskis, 1981)

⁴ (Snarskis, 1981; Lange, 1982–83)

crops, including corn, than in the Central Highlands-Atlantic Watershed and South Pacific regions, where root crops were more significant (Odio, 1992).

In the Rio Naranjo-Bijagua Valley in the “Guanacaste-San Carlos Corridor,” a radiocarbon date of 3500 ± 60 ^{14}C BP was obtained just below a burial mound at the Méndez site (Norr, 1982–83). Construction of the mound was dated to about 2250 ± 60 ^{14}C BP, suggesting that the first occupation occurred sometime between the two dates. The earliest settlement was in the southern portion of the study area, and moved northward through time. Ceramics from the Zoned Bichrome show contact with both the Tempisque Valley and the plains to the north and east (Central Highlands-Atlantic Watershed). Later, by the Early to Mid Polychrome, no apparent contact was evident with the Pacific Coast region, and the sites were probably nearing abandonment (AD 100–1000) (Norr, 1982–83). Many sites in the region date to the Zoned Bichrome and Early Polychrome periods (500 BC–AD 800). These include Hacienda Jerico, on the southwestern slopes of Tenorio volcano (Finch, 1982–83), Hacienda Mojica, 10 km west of Cañas, where abandonment occurred at end of the Zoned Bichrome or shortly afterward (Ryder, 1982–83a), and Guayabo de Bagaces, between Cuipilapa, Fortuna, and Guayabo, where mostly mortuary sites were found with a few habitation sites and a few petroglyphs (Ryder, 1982–83b). One site from Guayabo de Bagaces had some Middle Polychrome artifacts, but these may not have been *in situ* (Ryder, 1982–83b).

These archaeological studies demonstrate that early peoples were living in the greater Miravalles area by 4000 BP, although not continuously at all sites. Populations generally increased through time, with a notable decrease around AD 300–800. Snarskis (1981) reported that population declined in the volcanic foothills during Period VI (AD

1000–1500), while population levels remained high along the coasts. In contrast, Hurtado de Mendoza and Alvarado (1987) reported a population increase during the Late Polychrome (AD 1200–1550). In the Guanacaste lowlands, population and the number of sites continued to increase along the coast, especially after AD 800, with more exploitation of marine resources and probably less agriculture (Snarskis, 1981). Occupation continued through Spanish contact in 1522 (Snarskis, 1981), when the Spaniards encountered three groups of peoples living there: the Corobicí, Chorotega-Mangue, and the Nicarao (Stone, 1977).

Available archaeological studies, though mostly preliminary surveys, provide regional context for interpreting my pollen and charcoal analyses at the Miravalles lakes. Professors Sergio Chávez and Maureen Sánchez, together with their students in the Laboratory of Archaeology at the University of Costa Rica, have visited the Miravalles lakes with the intention of developing additional, local archaeological research. Evidence of agriculture and other human activity, natural disturbance, and climate history preserved in the Miravalles lake sediments will add to archaeological evidence of human prehistory and human-environment interactions in the Guanacaste-Nicoya region.

CHAPTER 3

METHODS

FIELD METHODS

Sediment cores were collected from the Miravalles lakes during field expeditions in March 1999, January 2000, March 2001, and June 2003. Working from an anchored platform, we used a 5 cm diameter Colinvaux-Vohnout (C-V) locking piston corer (Colinvaux *et al.*, 1999a) to collect sediments in ca. one-meter long, nearly contiguous sections. During our first coring expedition we encountered a problem with sediments falling out of the core tubes during recovery. To eliminate this problem, I designed and made an aluminum core catcher that we used for most subsequent coring (Figure 3.1). Use of the core catcher resulted in gaps of 5 cm or more in sediment recovery between core sections. We collected softer samples near the sediment-water interface using a 5 cm diameter plastic pipe fitted with a rubber piston (except at Laguna Las Brisas, where the plastic tube was lost prior to collecting the soft sediments). These “plastic tube core” (PTC) sediments were extruded in one or two cm intervals in the field and placed into labeled plastic bags. All PTC samples and longer core sections were returned to the Laboratory of Paleoenvironmental Research at the University of Tennessee for cold storage and analysis. C-V core sections were transported to the laboratory in their original aluminum coring tubes.

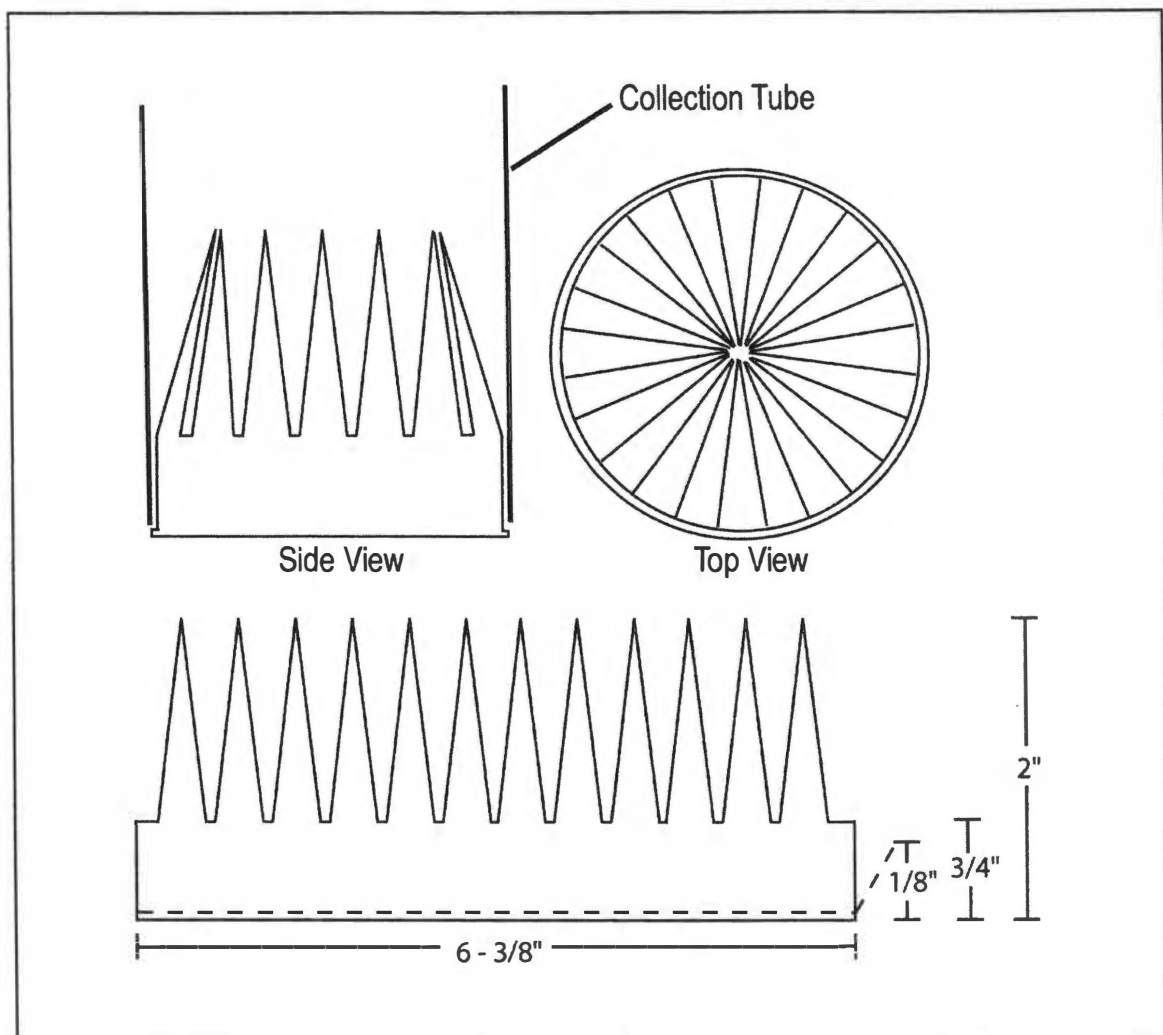


Figure 3.1. Homemade Core Catcher Design.

The core catcher is made from thin, flexible aluminum sheet metal. In use, the catcher is inserted into the bottom of the collection tube prior to attaching the core shoe. The lug at the bottom keeps the catcher from being pushed into the core tube during collection. As sediment is pushed into the tube the bent "fingers" are forced toward the tube wall. Sediment movement downward causes the prongs to fold inward, trapping sediments in the tube. Similar core catchers, made of plastic, are available commercially but are less robust than my aluminum core catchers.

LABORATORY METHODS

Sediment coring tubes were opened lengthwise using a router mounted on a stand, and sediment core sections were sliced longitudinally with a wire and/or knife. Cores were immediately photographed to document pre-oxidation colors. The stratigraphy of each core section was described on core logs in terms of sediment texture, particle/clast size, and Munsell color. Subsamples for pollen in analysis and loss-on-ignition (LOI) varied from 1.25 cm³ to 0.5 cm³ depending on water content. I initially removed subsamples at about 16 cm intervals and later at finer intervals. For LOI, samples were first dried at 100° C for ≥16 hours to determine water content, and were then ignited at 550° C for one hour to estimate organic content and at 1000° C for one hour to estimate carbonate content (Dean, 1974). I processed samples for pollen analysis with standard palynological techniques (HCl, HF, KOH, acetolysis, safranin stain; Berglund, 1986; Appendix A). One tablet of *Lycopodium* spores was added to each sample as a control, to allow calculation of pollen and charcoal concentrations (Stockmarr, 1971). I mounted pollen residue on microscope slides using silicone oil and examined the slides using a Leitz Laborlux microscope. I scanned a minimum of two slides per level in their entirety at low magnification (100x) to determine the presence or absence of maize pollen (*Zea mays* subsp. *mays*) (Horn, 2006). After scanning, I identified and counted a minimum of 250 pollen grains at 400x magnification from each sample level, excluding spores and indeterminate pollen grains. I used a modified version of CalPalyn (Bauer *et al.*, 1991) running on a Linux platform to make pollen, charcoal, and LOI diagrams. In the diagrams, I show Cyperaceae pollen as a percentage of total pollen excluding fern spores and indeterminates. Because Cyperaceae pollen is so abundant, I excluded it from the

pollen sum used to calculate percentages of all other taxa, following Northrop and Horn (1996).

I identified pollen to the lowest taxonomic level possible (usually family or genus) by comparison with pollen reference samples prepared from herbarium specimens from Costa Rica and other neotropical areas. In addition, I used published pollen and spore keys and descriptions (Heusser, 1971; Markgraf and D'Antoni, 1978; Hooghiemstra, 1984; Horn, 1986; Moore *et al.*, 1991; Palacios-Chávez *et al.*, 1991; Roubik and Moreno, 1991; Tryon and Lugardon, 1991; Colinvaux *et al.*, 1999b). I followed the taxonomy used by the Instituto Nacional de Biodiversidad, Costa Rica, in their list of plants of Costa Rica (INBio, 2004).

Some pollen types are difficult or impossible to separate because of their morphological similarities. These types, which I grouped together, include Melastomataceae/Combretaceae, Sapotaceae/Meliaceae, and the order Urticales. The order Urticales includes the families Cecropiaceae, Moraceae, Ulmaceae, and Urticaceae, which mostly have small, wind-dispersed pollen grains. I distinguished several genera including *Cecropia*, *Dorstenia*, *Trema*, *Celtis*-type, and *Ficus*. Other Urticales types were classified by pore number (diporate, triporate, 4- or more porate). In the *Ficus* category, I included only grains that were lozenge-shaped and diporate (Horn and Ramirez, 1990).

I separated maize pollen from other grasses based on the maximum diameter of the pollen grains. Poaceae grains with a diameter $\geq 65 \mu\text{m}$ and annuli $\geq 12 \mu\text{m}$ across were classified as maize. Based on work by other researchers in Central America and Mexico (Ludlow-Wiechers *et al.*, 1983; Sluyter, 1997), these are expected sizes for maize pollen

grains. They are consistent with sizes of prehistoric maize grains from other sites in Costa Rica (Horn, 2006). These maize grains overlap in size with some teosintes (*Zea perennis*, *Zea mays* subsp. *parviglumis*, and other *Zea*; Sluyter, 1997) and the Asian grass *Coix lacryma-jobi* (Anchukaitis and Horn, 2005), but these taxa are not known to have grown in prehistoric Costa Rica.

Pollen grains I could not identify, but which were potentially identifiable, were classified as “unknown.” For each unknown morphotype I recorded microscope coordinates for representative grains, drew and described each morphotype, and assigned a morphotype number. Pollen grains that were not potentially identifiable were counted as indeterminates, and assigned to one of four categories based on the reason they could not be identified: exine corrosion, exine degradation, mechanical damage, or concealment by detritus or authigenic minerals (Delcourt and Delcourt, 1980). I classified fern spores by morphology (monolete vs. trilete) and exine characteristics (psilate, scabrate, verrucate, coarsely verrucate, striate, echinate, rugulate, bacculate, or clavate). I counted microscopic charcoal fragments during regular pollen counts, and classified them into two size categories (50–125 μm and $>125 \mu\text{m}$) based on longest dimension. Only fragments which were black, opaque, and angular were identified as charcoal.

To establish chronologies for the lake sediment cores, Sally Horn and I submitted 40 organic samples to Beta Analytic, Inc., and to the University of Arizona AMS Laboratory for accelerator mass spectrometry (AMS) radiocarbon dating. Most of the samples consisted of fragments of charcoal, although a few were dicotyledonous leaf fragments. Macrofossils were collected under low power magnification with a stereozoom microscope, then were rinsed with distilled water and dried at 100° C before

submission. Radiocarbon dates were calibrated using the program CALIB v4.4.2. (Stuiver and Reimer, 1993) and the INTCAL98 dataset (Stuiver *et al.*, 1998). I used the weighted mean of the calibration probability distribution to assign a single calendar age to each sample (Telford *et al.*, 2004). Use of the weighted mean to assign a single date is a more reliable method when estimating a single age than using intercept methods (Telford *et al.*, 2004). I calculated sedimentation rates, and estimated ages for each sediment interval, using linear interpolation between the weighted means of the calibrated dates, assuming a constant sedimentation rate between dated intervals.

CHAPTER 4

RESULTS

Eight sediment cores, ranging in length from 2.5 to 6.5 meters, were recovered from the six study lakes (Figure 4.1). Five of the cores (one from each site except Sorpresa) terminated atop or within volcanic deposits associated with pyroclastic flows that formed the lake basins. Neither of two cores recovered from Sorpresa reached this depth. The core recovered from San Pablo in 1999 also terminated above the basal volcanic deposits. The lowest macrofossils submitted for radiocarbon dating from the longest cores ranged from about 7100 to about 8400 calibrated years in age. Forty radiocarbon determinations were in correct stratigraphic order. Each of the six lake basins revealed similar sedimentation histories, with more rapid sedimentation in the lower portions of the cores (Figure 4.2). All radiocarbon dates were calibrated using CALIB 4.4.2 (Stuiver and Reimer, 1993) and the dataset of Stuiver *et al.* (1998). The probability that the true calendar age falls within the 2-sigma calibrated range is 95.4%. Henceforth, single calibrated dates for sediment intervals in figures and text are the weighted means of the probability distributions of the radiocarbon dates (Telford *et al.*, 2004), or ages linearly interpolated from the weighted means of dates above and below the interval in question.

Many of the core sections had less than a meter recovery, even though one meter was cored. This may have been due to compaction of sediments within the core tubes, during collection, or more likely from the core tube “plowing” through some sediments instead of collecting them. The core catcher I designed generally accomplished the

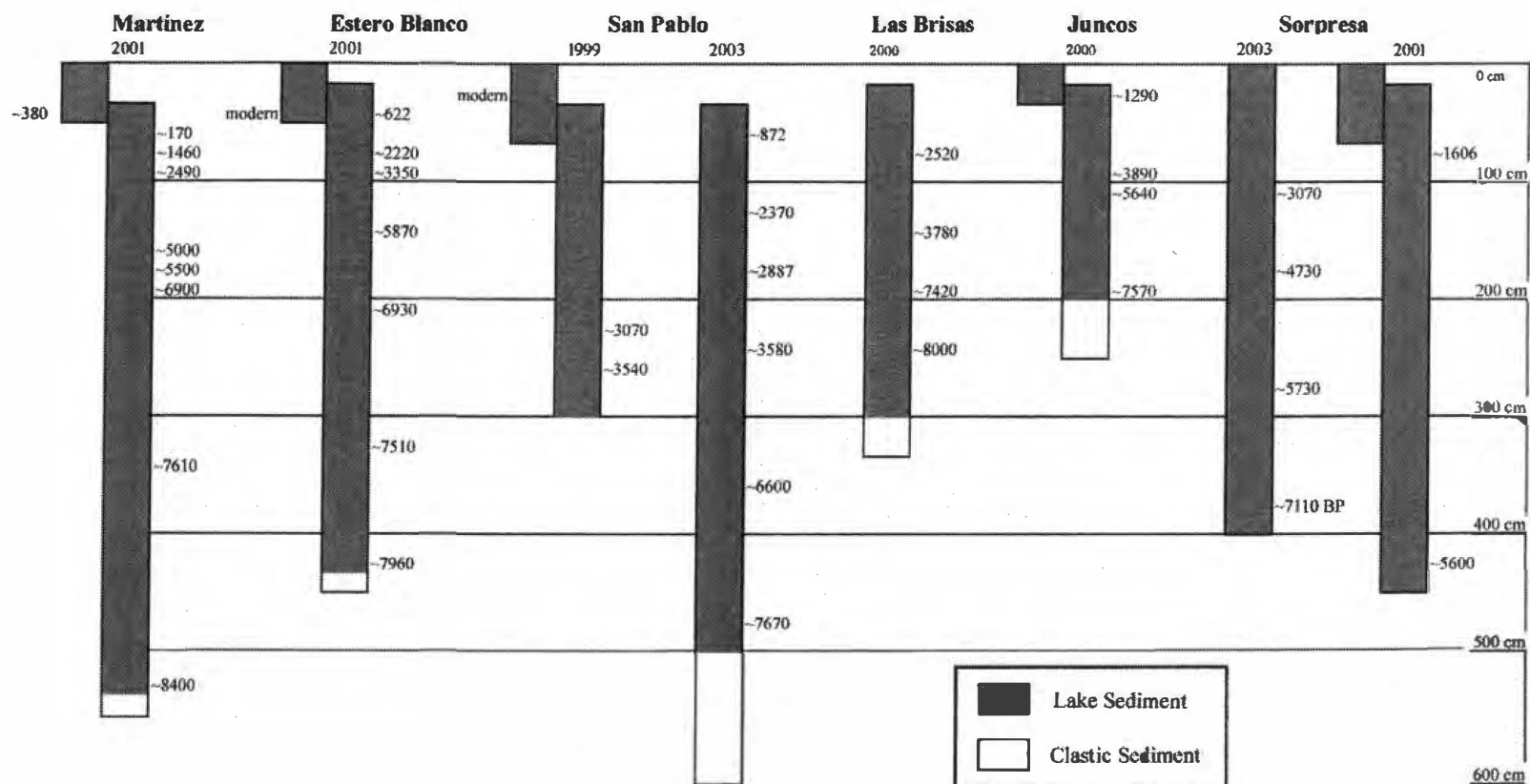


Figure 4.1. Sediment Core Depths and Radiocarbon Dates from the Miravalles Lakes.
(Dates are the weighted mean of the probability distribution, given as calibrated years BP)

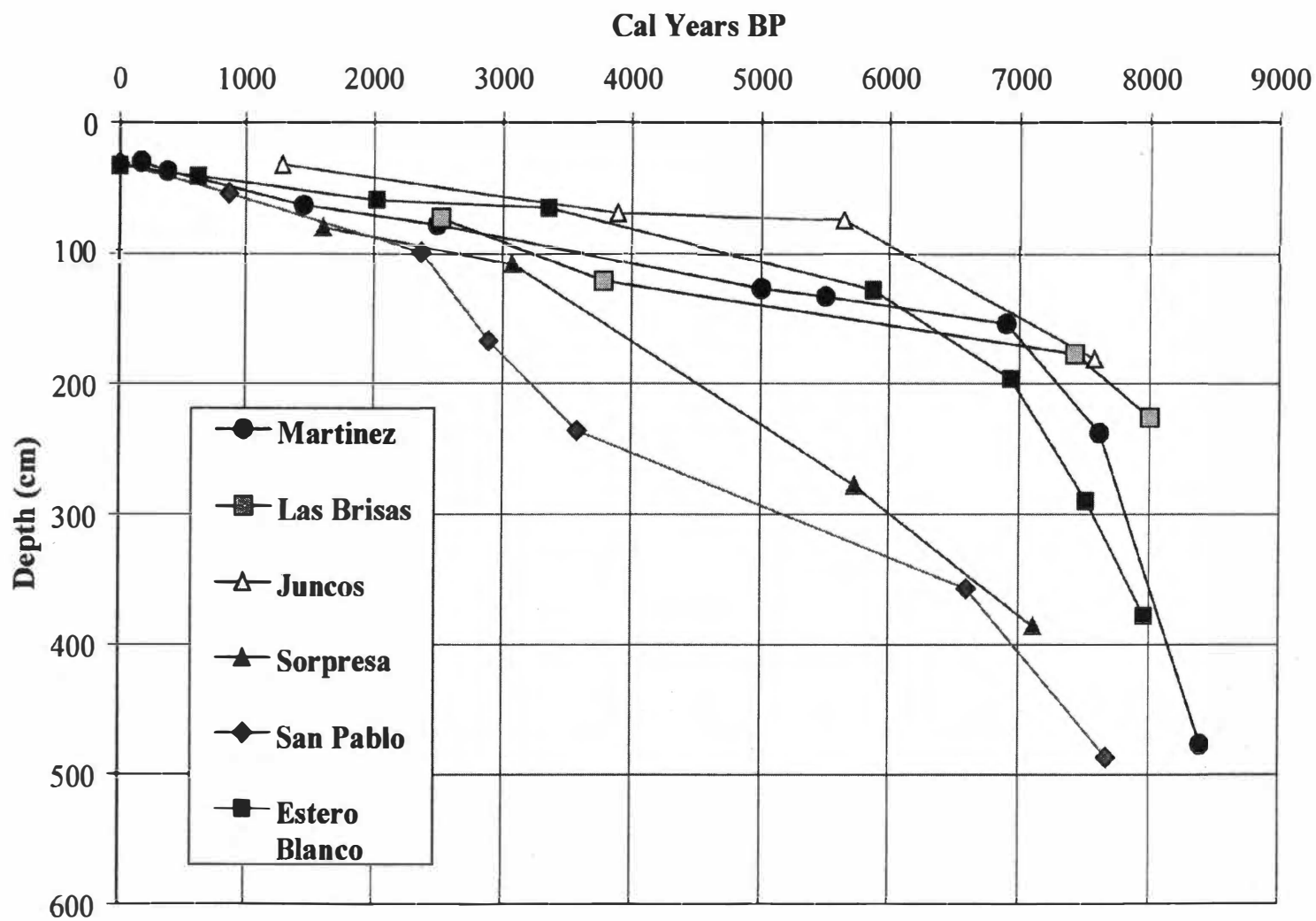


Figure 4.2. Age-Depth Relationships for the Miravalles Lakes Sediment Cores.

objective of retaining loose sediments during recovery. However, the core catcher also reduced the length of core recovery to 95 cm. Because I did not make adjustments for this 5 cm difference during the coring process, gaps of at least 5 cm exist between all core sections.

The sediment cores from the six lakes include intervals indicative of drying, peaty layers, invertebrate burrows, and clastic debris indicative of environmental disturbances or changes (Figure 4.3). Basal sediments at five lakes included clay- and silt-rich deposits, in some cases laminated, that were deposited shortly after the lake basins were formed.

LAGUNA MARTÍNEZ

Sediment Stratigraphy and Radiocarbon Chronology

Sediments in the 5.8 m sediment core recovered from Laguna Martínez in 2001 are dense and mineral-rich throughout most of the profile (Table 4.1; Figure 4.4). Nine radiocarbon range from 8400–170 yr cal BP (Table 4.2). There is a gap in sediment recovery from 99–117 cm depth representing a missing age range of 3620–4540 cal yr BP (interpolated). Mottling of sediment colors exists in intervals 76–94 cm (2353–2310 cal yr BP interpolated) and 156–180 cm (7120–6910 cal yr BP interpolated) consistent with redoximorphic changes associated with drying episodes or bioturbation.

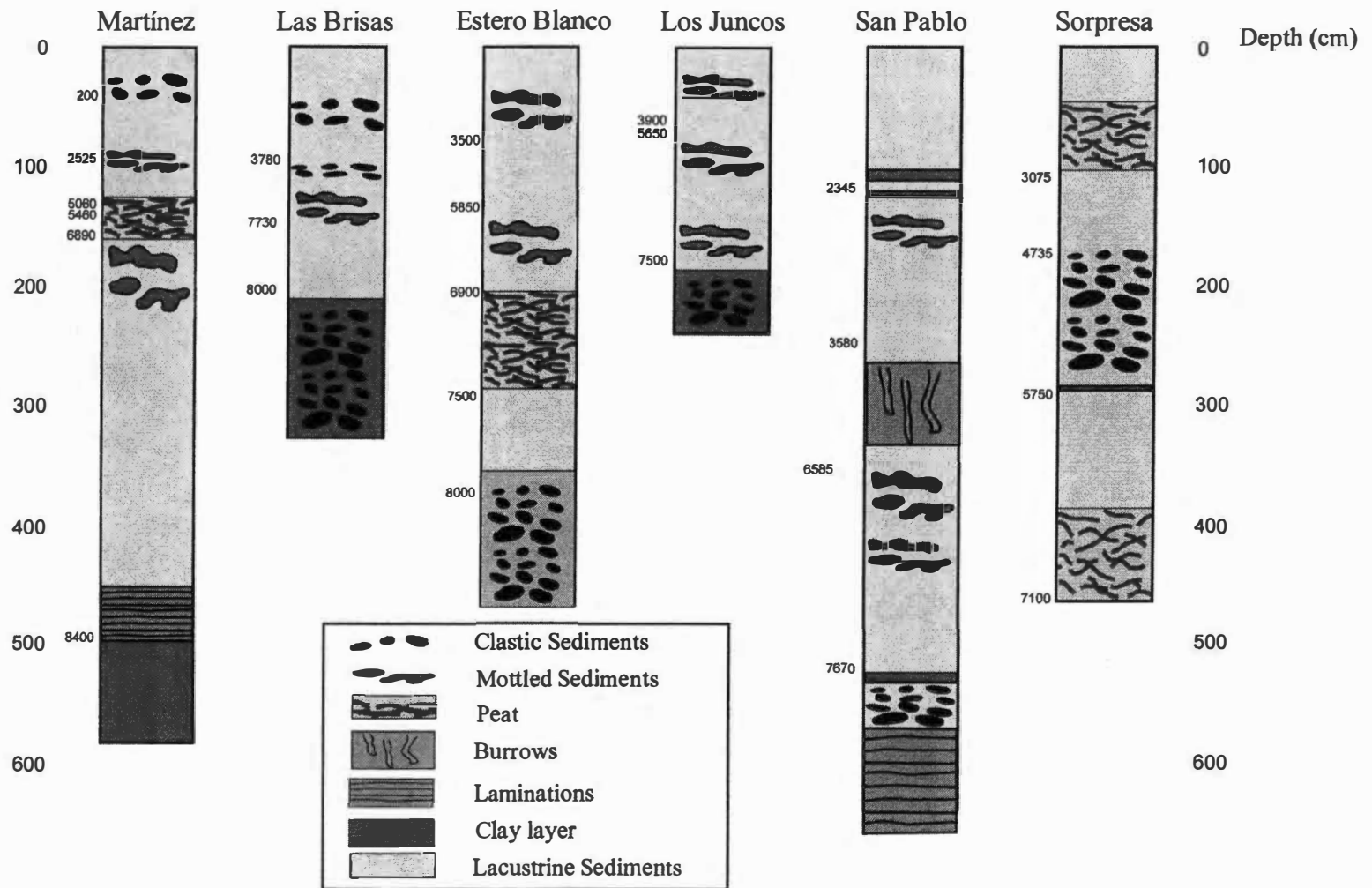


Figure 4.3. Sedimentary Evidence of Environmental Disturbance or Change in the Miravalles Lakes Sediment Cores

Table 4.1. Sediment Description for Laguna Martínez

Depth (cm)	Munsell	Description
0–10	10YR 3/1	watery
11–23	10YR 3/1	firm, mineral matrix, organic fragments
24–51	10YR 3/2	mineral matrix, but organic-rich
52–75	10YR 3/1	very firm, mineral-rich
76–94	7.5YR 2/0	fibrous organic-rich, mottling of 10YR 3/1
94–99	10YR 2/1	clay-rich dense inorganics
100–117	--	gap in sediment recovery
118–143	10YR 3/2 & 2/1	peaty/fibrous but mineral-rich
144–155	10YR 2/1	very dense, tightly packed layers of organics & minerals, diatoms, charcoal; compressed
156–180	10YR 3/2	dense, gritty, mineral-rich, mottling
181–205	10YR 2/1	gritty mineral-rich
206–217	--	gap in sediment recovery
218–306	10YR 2/1	firm, smooth
307–316	--	gap in sediment recovery
317–398	10YR 3/1	smooth mineral-rich mud
399–402	10YR 2/1	firmer, darker, finer grained
403–409	--	gap in sediment recovery
410–440	10YR 2/1 & 3/1	slightly banded fine grained mud
441		thin tephra layer
442–471	10YR 3/1 & 2/1, 5Y 2.5/1 & 3/1 GLEY 3/10Y, 2.5/N, & 4/10Y	discrete banded sediments, fine-grained occasional thin diatomaceous layers
472–477	5Y 4/1 & 10YR 4/1	clay
478–482		coarse sand and gravel-sized clastics
483–488	10YR 4/1	clay
489–498		coarse sand and gravel-sized clastics
499–507		gap in sediment recovery
508–582	10YR 4/1, 5Y 4/1	silty-clay, very dense

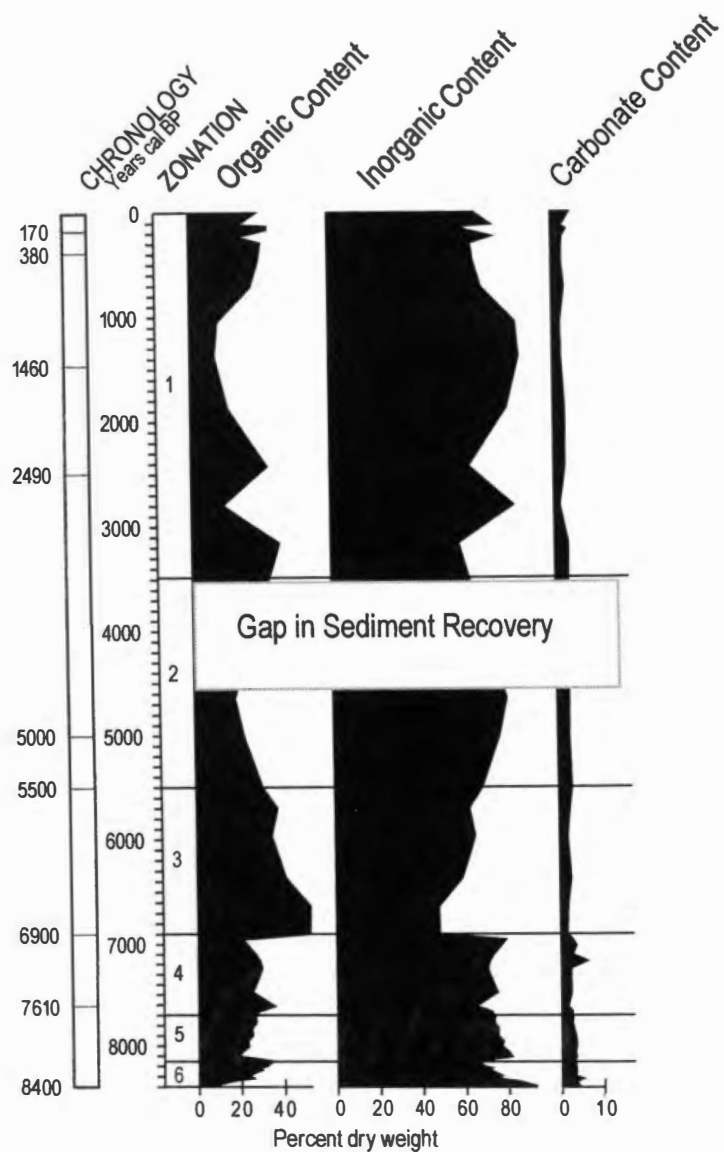


Figure 4.4. Loss on Ignition Results for Laguna Martínez

Table 4.2. AMS Radiocarbon Dates for Laguna Martínez¹

Lab Number	Depth (cm)	Material Dated	Radiocarbon Date	Weighted Mean yr cal BP	Calibrated 2 Sigma Range BP	Calibrated 2 Sigma Range AD/BC
β-167804	30	Single Charcoal piece	190 ± 40	170	3652–3594	AD 1644–1702
					3765–3672	AD 1722–1815
					3831–3780	AD 1830–1881
					3900–3864	AD 1914–1950
AA-60654	37	Dicot leaf	301 ± 38	380	463–293	AD 1487–1657
AA-60655	63	Charcoal fragments	1572 ± 39	1460	1363–1353	AD 587–597
					1382–1369	AD 568–581
					1537–1385	AD 413–565
β-184799	78	Charcoal fragments	2410 ± 40	2490	1270–1190	AD 680–760
					1318–1283	AD 632–667
					1373–1359	AD 577–591
					1554–1391	AD 396–559
β-179844	127	Charcoal fragments	4410 ± 40	5000	5276–5270	3326–3320 BC
					5264–5182	3314–3232 BC
					5123–5110	3173–3160 BC
					5068–5058	3118–3108 BC
					5054–4864	3104–2914 BC
β-176224	133	Charcoal fragments	4760 ± 40	5500	5592–5453	3642–3503 BC
					5379–5330	3429–3380 BC
β-172357	154	Dicot leaves	6060 ± 40	6900	7136–7135	5186–5185 BC
					7008–6790	5058–4840 BC
					6770–6757	4820–4807 BC
β-188888	238	Charcoal fragments	6750 ± 50	7610	7679–7563	5729–5613 BC
					7537–7510	5587–5560 BC
β-157205	477	Charcoal fragments	7610 ± 50	8400	8538–8530	6588–6580 BC
					8520–8493	6570–6543 BC
					8481–8332	6531–6382 BC
					8231–8221	6281–6271 BC

¹ Analyses were performed by Beta Analytic Laboratory, Miami FL (β-numbers), or the University of Arizona AMS Laboratory (AA-numbers).

Pollen and Charcoal Zones

Microfossil results are presented in a series of diagrams, including a summary diagram (Figure 4.5), and separate diagrams for trees (Figure 4.6), non-arboreal taxa (Figure 4.7), fern spores (Figure 4.8), and microscopic charcoal (Figure 4.9). Six pollen zones were designated based on the pollen and sediment stratigraphy at Laguna Martinez and in the records from other study lakes as well. This same zonation is used for all subsequent lake results.

The sediments of the lowest zone, Zone 6 (8400–8200 cal yr BP), consist of clays and clastic material that infilled the newly formed lake basin. The basal sample contains mostly *Pityrogramma* fern spores, indicative of landscape disturbance, and few pollen grains (primarily *Typha*, Poaceae, and Urticales). Pollen concentrations increase upcore, with *Cecropia*, Poaceae, Cyperaceae, Asteraceae, and Amaranthaceae common. Charcoal fragments are abundant, reaching the highest concentration outside of Zone 1, perhaps due to volcanic eruptions that followed lake basin formation by about 200 years (Alvarado, 2000) or drier conditions. Zone 6 represents landscape disturbance following volcanic/landslide activity followed by an increase in weedy and early colonizing vegetation.

Sediments in Zone 5 (8200–7700 cal yr BP) represent the transition from clastic infilling to true lacustrine sedimentation. Banded, fine-grained mineral sediments increase in organic content throughout the zone. Tree pollen percentages increase at the expense of Cyperaceae and Poaceae. *Cecropia* and *Ficus* pollen shows greatest percentage increases, and *Guazuma ulmifolia*, *Bursera* and Sapotaceae/Meliaceae also increase. *Ceratopteris*, a floating aquatic fern that requires seasonality for its annual life

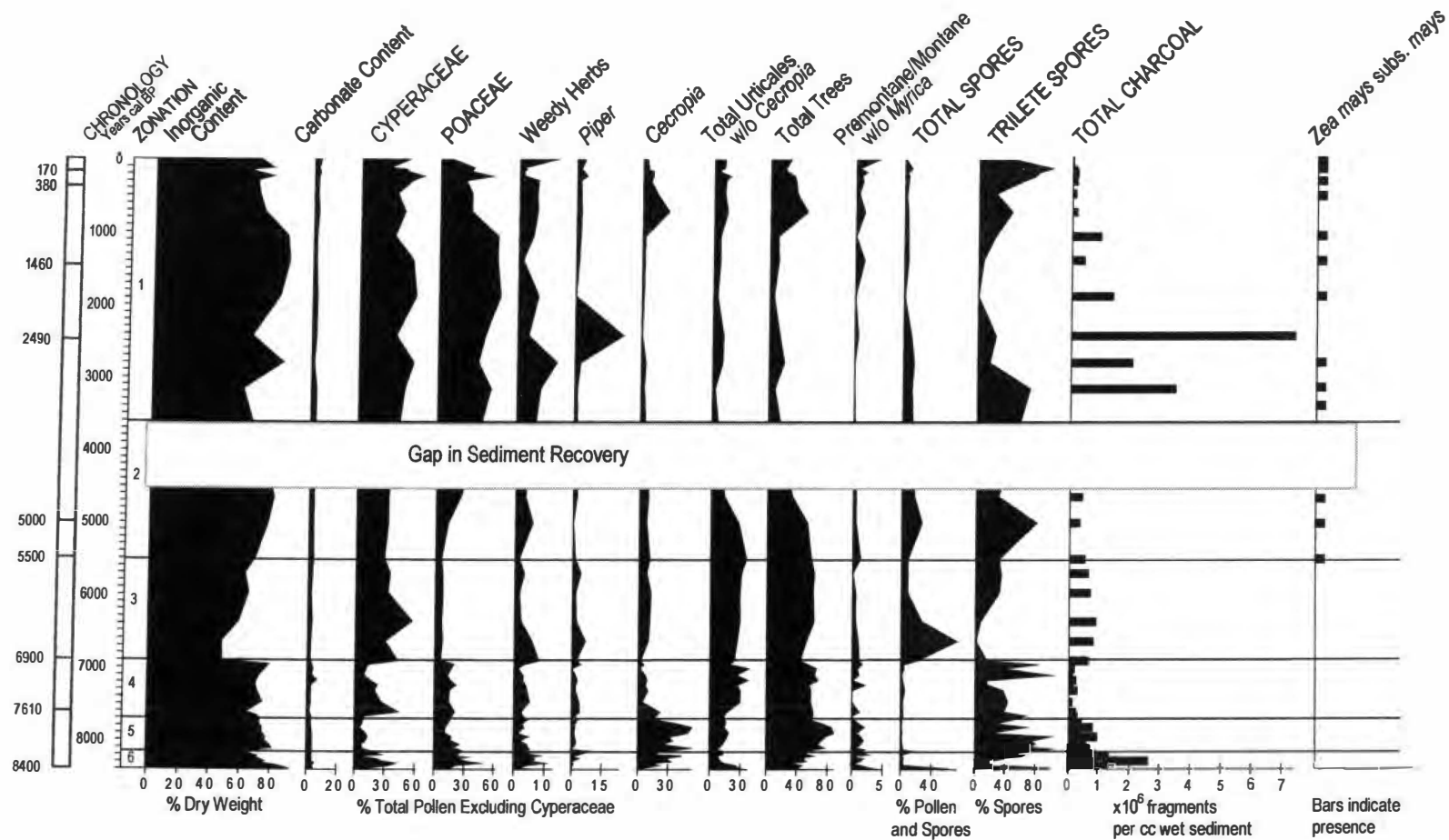


Figure 4.5. Pollen Summary for Laguna Martínez

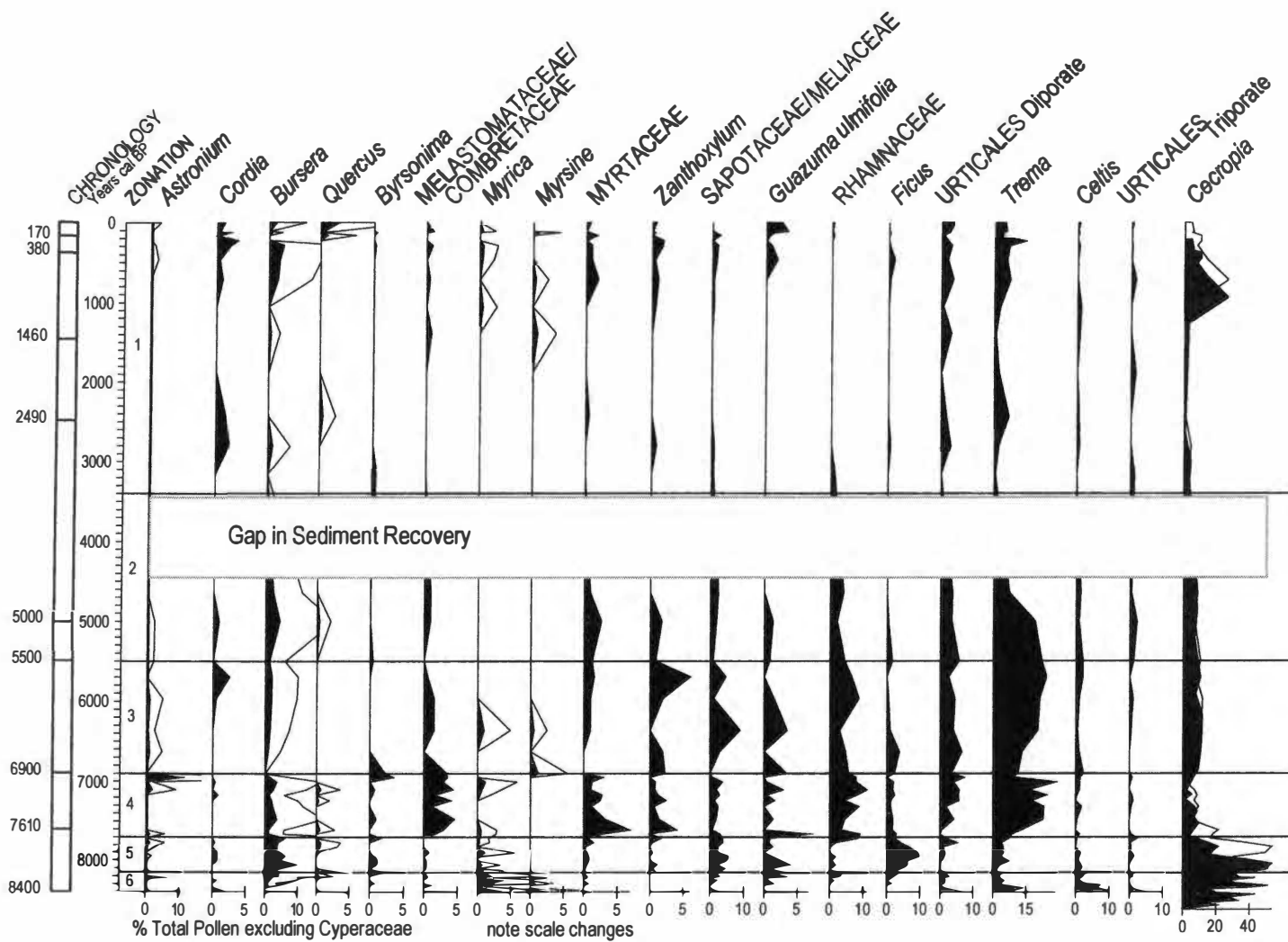


Figure 4.6. Tree Pollen Results for Laguna Martínez

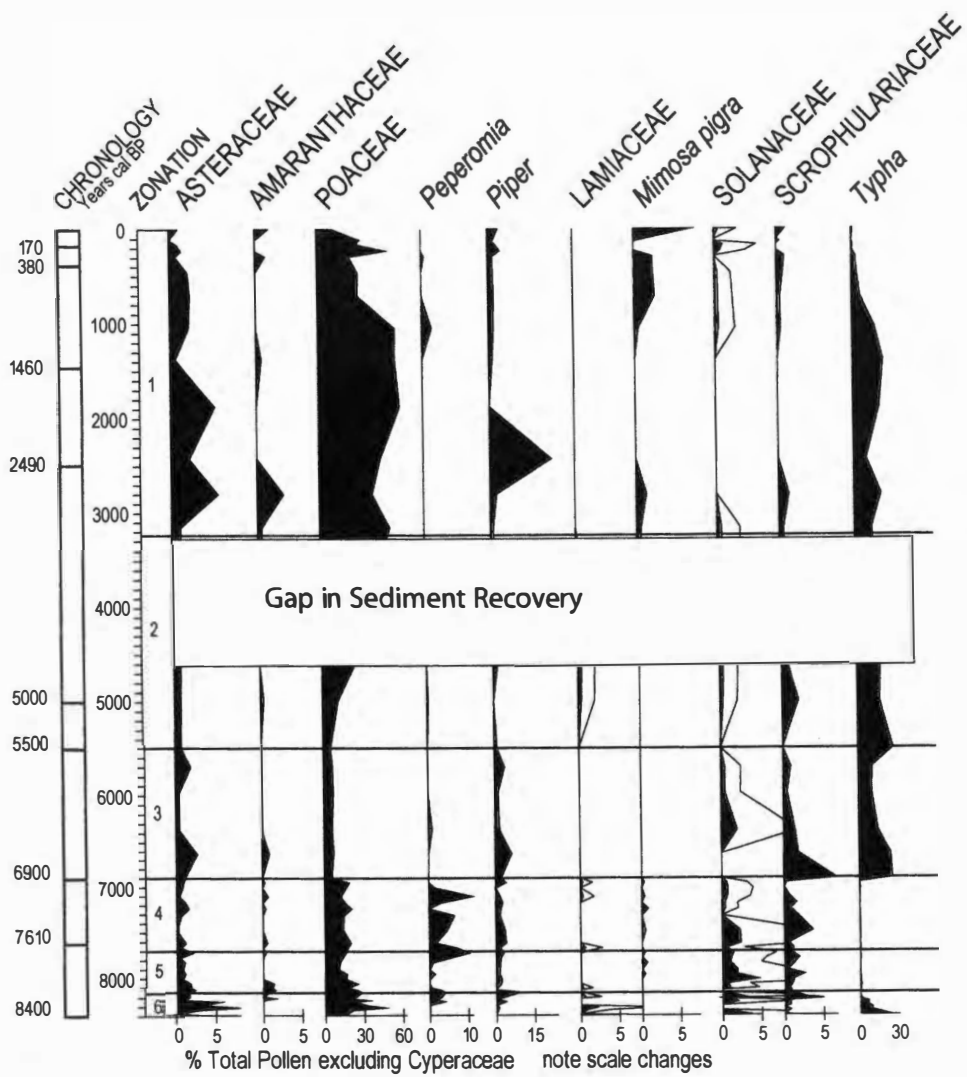


Figure 4.7. Non-Arboreal Pollen Results for Laguna Martínez

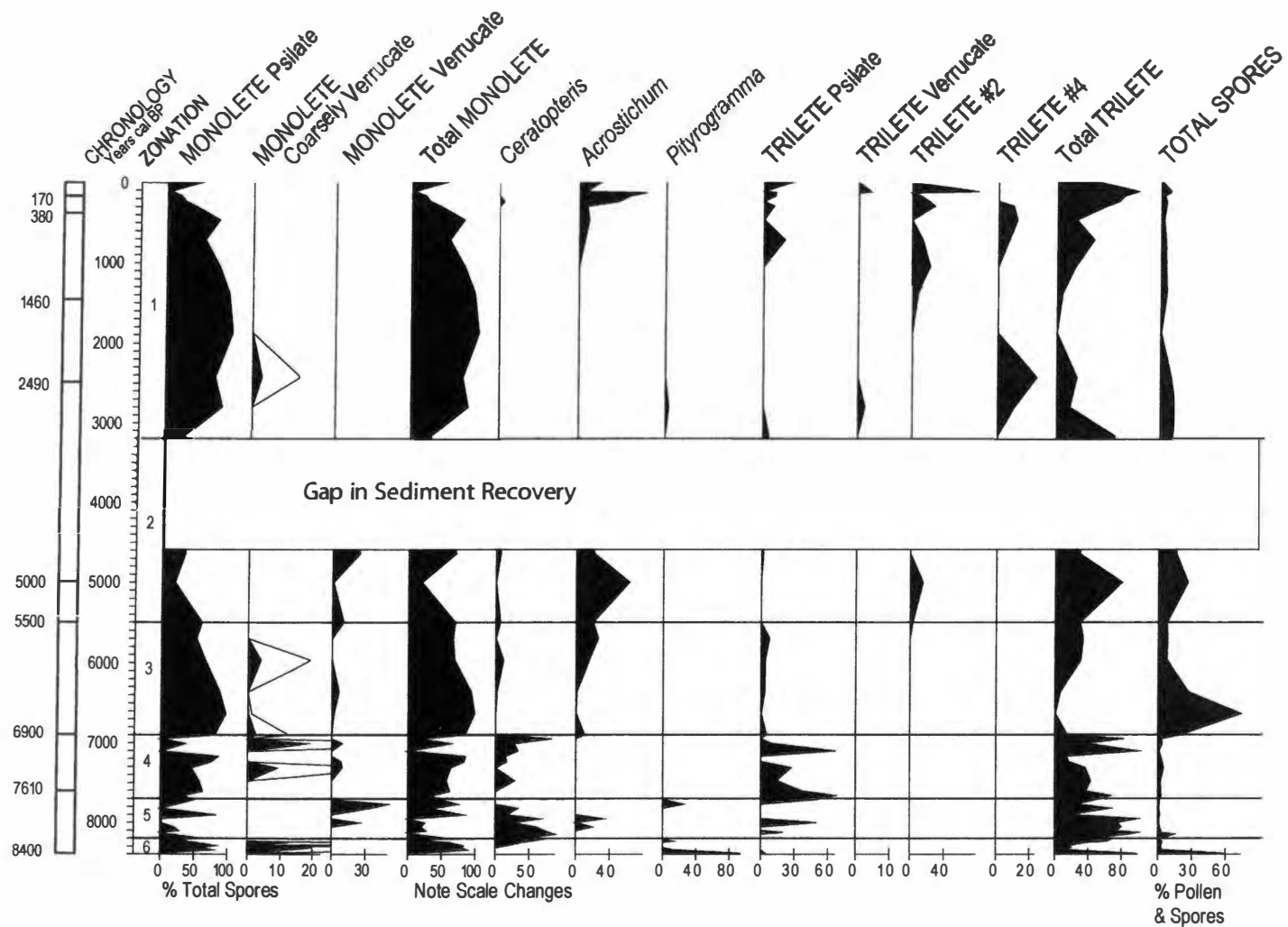


Figure 4.8. Fern Spore Results for Laguna Martínez

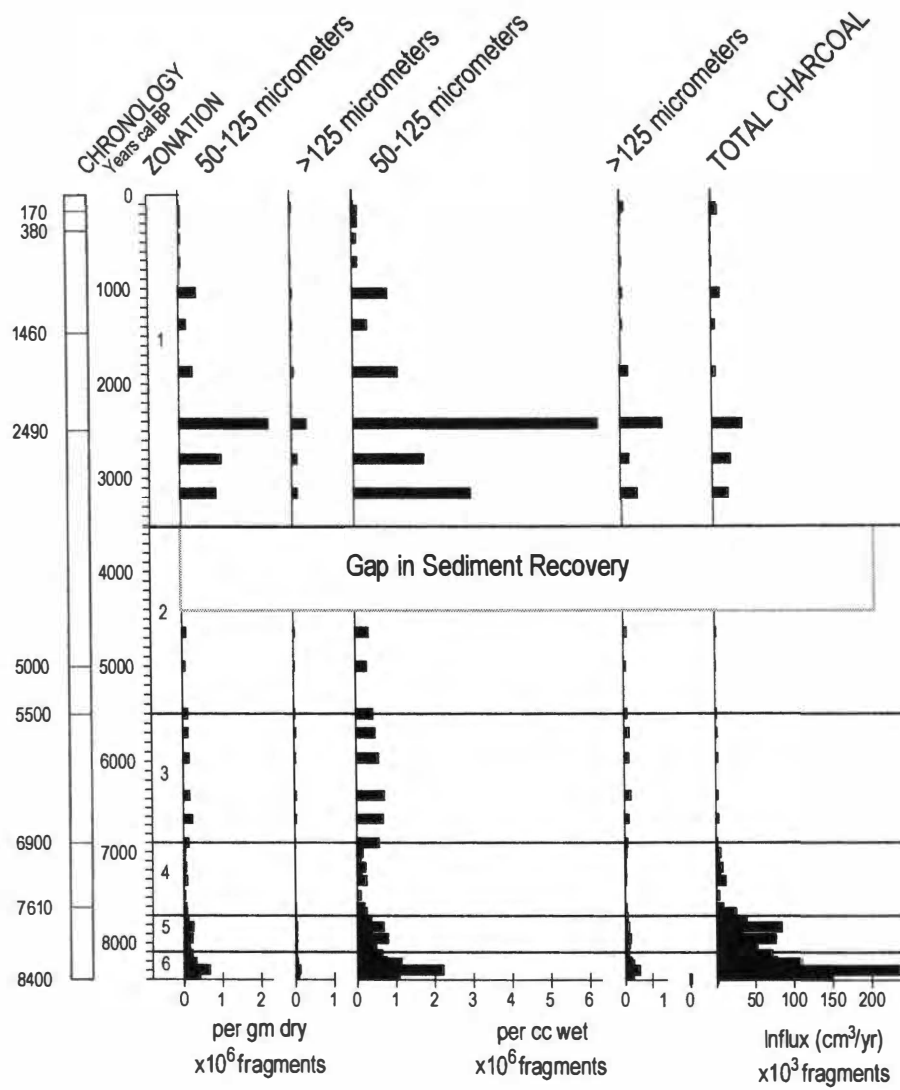


Figure 4.9. Microscopic Charcoal Results for Laguna Martínez

cycle (Tryon and Tryon, 1982), dominates the spore signal at the beginning of this zone, but monolete fern spores increase by the upper zone boundary. This may suggest a decrease in water level. Microscopic charcoal decreases in abundance (Fig. 4.9).

In Zone 4 (7700–6900 cal yr BP), sediments remain nearly 80% inorganic. Mottling of the sediments from ~6910 to 7130 cal yr BP indicates at least intermittent drying out of the sediments. Tree pollen decreases to about 60% of total non-Cyperaceae pollen and represents a shift from mostly *Cecropia* and *Ficus* to Melastomataceae, Myrtaceae, Rhamnaceae, and *Trema*. Percentages of Poaceae, Cyperaceae, and *Peperomia* increase, but by the top of this zone Cyperaceae decreases. *Ceratopteris* spores increase throughout this zone. Pollen and spore changes suggest a more mature forest. Charcoal is much less abundant throughout Zone 4 than in the previous zones.

Zone 3 (6900–5500 cal yr BP) begins with densely packed organics including leaves, seeds, and charcoal. Organics initially account for >50% of the sediment dry mass, but by the upper zone boundary have decreased to nearly 30%. I also noticed abundant diatoms in the organic matter while removing macroscopic samples for AMS radiocarbon dating. Cyperaceae and tree pollen dominate this zone. *Typha* percentages increase, with a corresponding decrease in grass pollen. An initial decrease in the percentage of tree pollen may be an artifact of the overwhelming amount of *Typha* pollen. Pollen from Melastomataceae/Combretaceae, *Bursera*, and Myrtaceae decrease, and pollen from *Zanthoxylum*, Sapotaceae/Meliaceae, and *Guazuma ulmifolia* increase. At ~6800 cal yr BP (interpolated), spores, almost all psilate monolete, comprise 70% of the pollen and spore total. By the top of Zone 3 tree pollen is about 70% of total non-

Cyperaceae pollen. This zone is characterized by forest taxa, and standing water in the lake basin.

Within Zone 2 (5500–3620 cal yr BP), inorganic content of sediments increases from about 70 to 80%. A gap in sediment recovery exists from 4540–3620 cal yr BP (interpolated), and I used the top of the gap to define the upper limit of Zone 2, which contains only two samples. The lowest sample has a marked increase in spores of *Achrostichum* from the top of Zone 3. Total tree pollen drops from about 40% in the lower sample to 30% in the upper one, and may indicate landscape disturbance associated with maize agriculture. Charcoal occurs at slightly lower concentrations than in Zone 3. The lowest maize grains appear in the same level that yielded an AMS radiocarbon date on charcoal of 4760 ± 40 BP (weighted mean of calibration probability distribution 5495 cal yr BP) (Figure 4.10). The AMS date on charcoal obtained 6 cm upcore (4410 ± 40 , weighted mean 5000 cal yr BP) also is from an interval with maize pollen. This first occurrence of maize pollen occurs prior to increases in sedimentary charcoal and other evidence of widespread landscape disturbance. Zone 2 represents the first evidence of agriculture in the sediments.

Throughout Zone 1 (3620 cal yr BP–present) sediment composition averages about 70% inorganic material. Sediment mottling is present from 2353–2310 cal yr BP, suggesting episodes, or a period, of drying. Tree pollen remains low until ~700 cal yr BP (interpolated), when total tree pollen increases to about 40% (mostly *Cecropia*, also *Bursera* and *Trema*) with corresponding decreases in grass pollen and microscopic charcoal. Maize pollen occurs throughout most of Zone 1 except in the interval from ~700 cal yr BP–present. The lowest sample in this zone, interpolated to ~3200 cal yr BP,

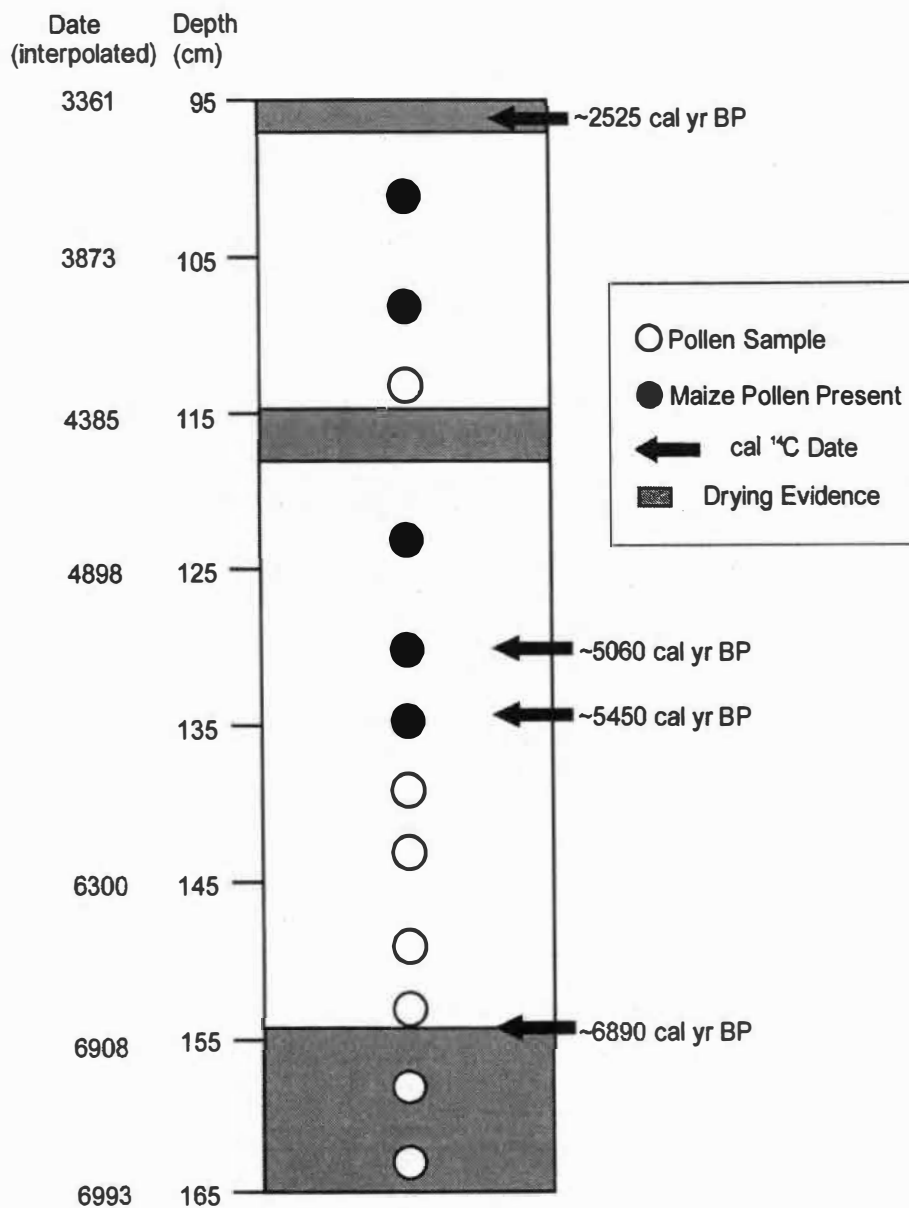


Figure 4.10. Section of the Martínez Core Showing Positions of Early Maize Pollen

has a classic pollen signal that represents agriculture: a significant decrease in pollen from trees and an increase in grass pollen to about 60%. Charcoal concentration increases considerably over Zone 2, although charcoal influx does not show such a dramatic increase.

has a classic pollen signal that represents agriculture: a significant decrease in pollen from trees and an increase in grass pollen to about 60%. Charcoal concentration increases considerably over Zone 2, although charcoal influx does not show such a dramatic increase.

LAGUNA LAS BRISAS

Sediment Stratigraphy and Radiocarbon Chronology

Sediments in the 2.85 m sediment core recovered in 2000 are very mineral rich and include several igneous rock clasts (Table 4.3, Figure 4.11). Basal sediments consist of banded clastics ranging from clay to sand size. Four radiocarbon dates range from 8001–2523 cal yr BP (Table 4.4). There is a partial gap in sediment collection between 25 and 66 cm because some of the sediments slid out of the tube during collection (Table 4.3). Eight cm of sediment was missing from the end of the final core tube which apparently fell out during the retrieval. We did not take a PTC core from Las Brisas. Sediments from 130–116 cm (3649–5470 cal yr BP, interpolated) exhibit heavy mottling, consistent with intermittent drying of the sediments. Less mottling is observed in deeper sediments to 199 cm (7515 cal yr BP interpolated).

Table 4.3. Sediment Description for Laguna Las Brisas

Depth (cm)	Munsell	Description
0–14	---	
14–20	---	wood
20–25	2.5 YR 2.5/0	firm, dark
25–66	10YR 2/1 and 2.5YR 2.5/1	sediments only partially filled tube, some sliding. soft, mineral rich.
66–69	---	4 cm diameter clast
69–92	2.5YR 2.5/0	soft
92–96	---	rock
96–101	10YR 4/1	
101–114	---	gap in sediment recovery
114–118	10YR 2/1	dense, clayey, “rubbery”
118–125	10YR 2/2	dense, clayey, “rubbery”
125–126	10YR 2/2	dense, clayey, “rubbery”
126–130	10YR 2/2	several clasts
130–116	10YR2/1, 3/1	heavily mottled w/10YR 4/2, dense, firm
161–199	10YR 2/1	dense, firm, less mottling of 10YR 4/2
199–112	---	gap in sediment recovery
112–229	10YR 2/1	firm, dense, smooth
229–237	10YR 2/1	soft, gelatinous
237–255	---	tephra or clastics, mixed colors
255–262	---	banded black, gray, very soft w/tephra
265–299	---	coarse, banded clastics w/thin silt & clay layers
299–307	---	missing sediments

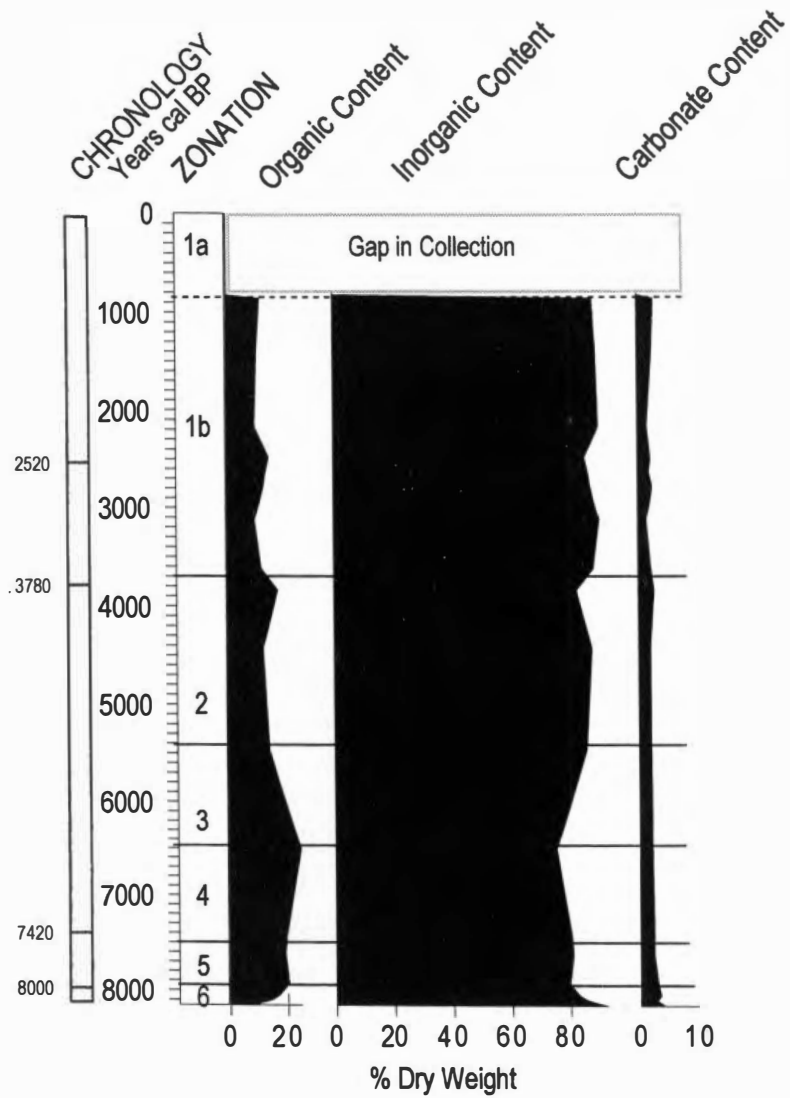


Figure 4.11. Loss on Ignition Results for Laguna Las Brisas

Table 4.4. AMS Radiocarbon Dates for Laguna Las Brisas¹

Lab Number	Depth (cm)	Material Dated	Radiocarbon Date	Weighted Mean cal yr BP	Calibrated 2 Sigma Ranges BP	Calibrated 2 Sigma Ranges AD/BC
β-188887	73	Charcoal fragments	2440 ± 40	2523	2711–2629	761–679 BC
					2619–2562	669–612 BC
					2544–2354	594–404 BC
β-172355	121	Charcoal fragments	3510 ± 40	3775	3888–3877	1938–1927 BC
					3874–3688	1924–1738 BC
					3657–3645	1707–1695 BC
β-176222	177	Charcoal fragments	6890 ± 40	7417	7791–7658	5841–5708 BC
					7636–7615	5686–5665 BC
β-158435	226	Charcoal fragments	7190 ± 40	8001	8147–8143	6197–6193 BC
					8111–8087	6161–6137 BC
					8057–7937	6107–5987 BC
					7891–7877	5941–5927 BC

¹Analyses were performed by Beta Analytic Laboratory, Miami FL.

Pollen and Charcoal Zones

Microfossil results are presented in a series of diagrams, including a summary diagram (Figure 4.12), and separate diagrams for trees (Figure 4.13), non-arboreal taxa (Figure 4.14), fern spores (Figure 4.15), and microscopic charcoal (4.16). This core was analyzed at a coarser resolution than those from most other Miravalles lakes due to the site's poor temporal resolution: less than 3 meters of sediment represent over 8000 years (calibrated).

The sediments in Zone 6 (8200–8000 cal yr BP) contain clastic material that infilled the newly formed lake basin. In the basal sample *Pityrogramma* spores, indicative of landscape disturbance, represent nearly 80% of total spores, and tree pollen is over 40% of total non-Cyperaceae pollen. Poaceae pollen then increases to over 50% and pollen from tree taxa declines. Microscopic charcoal is very abundant, reaching the highest values in the profile. Results from this zone indicate fire and landscape disturbance.

Sediments in Zone 5 (7500–8000 cal yr BP) are mostly inorganic (80%) and represent early lacustrine sedimentation. Pollen of non-arboreal taxa dominates. Asteraceae and *Piper* pollen each increase to over 25% of total pollen by the top of the zone and, while grass pollen decreases, it remains around 30%. Microscopic charcoal decreases slightly from Zone 6, but remains high. During the time period included in Zone 5 landscape disturbance and fire remained high.

Zone 4 (7500–6500 cal yr BP) includes only two samples, with a 13 cm gap in sediment recovery, so zonal interpretation is difficult. Sediments remain highly inorganic

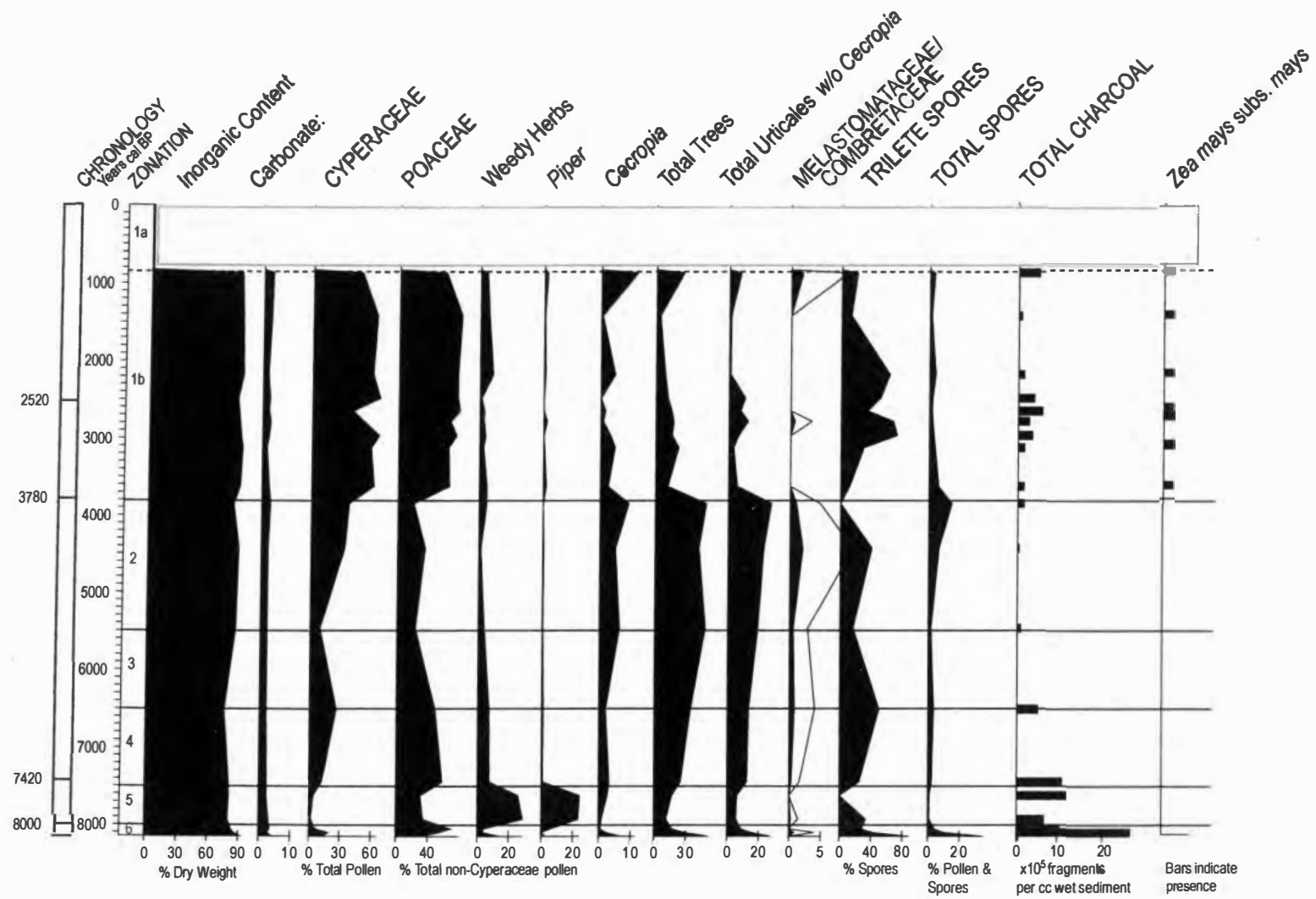


Figure 4.12. Pollen Summary for Laguna Las Brisas

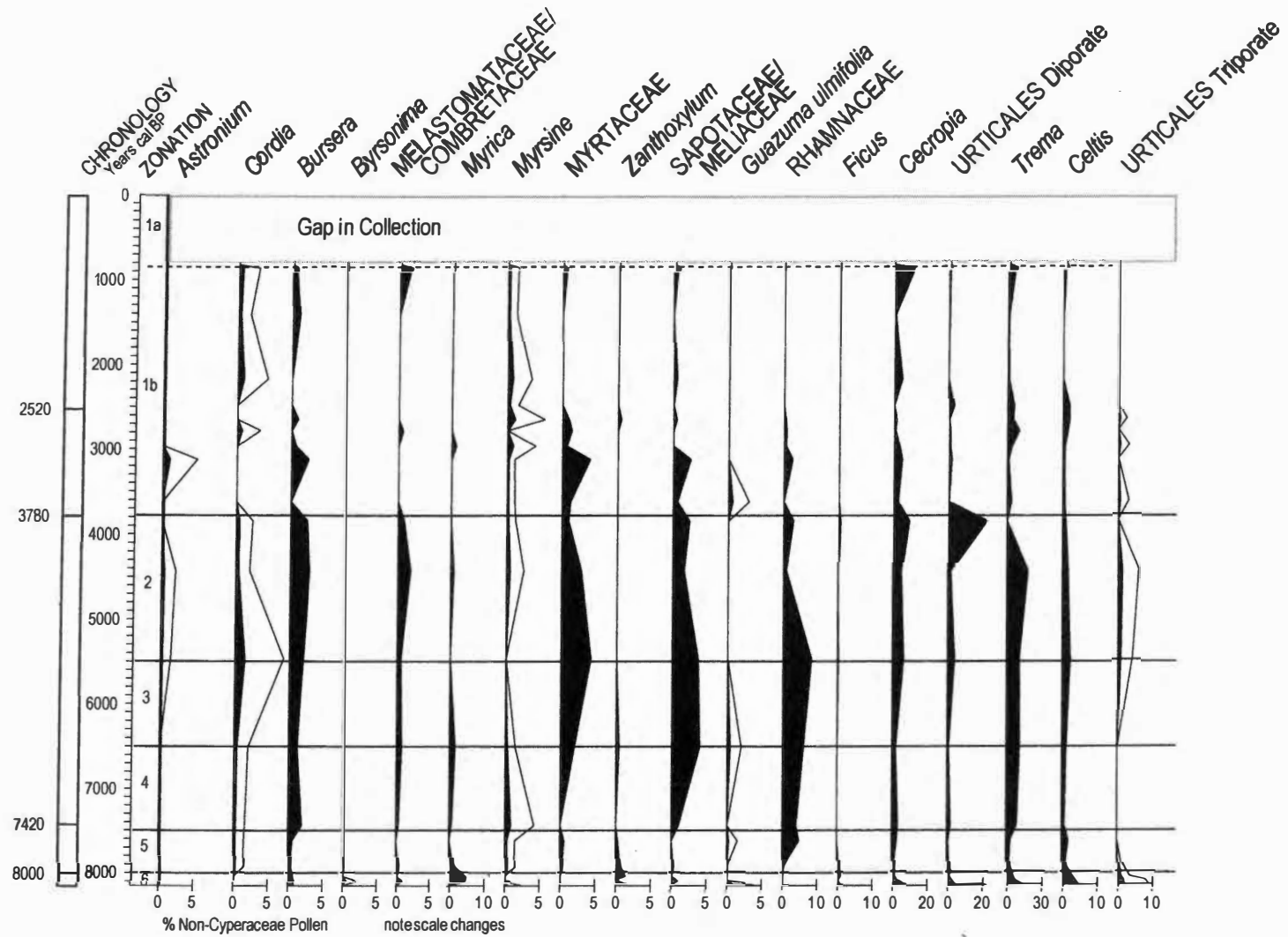


Figure 4.13. Tree Pollen Results for Laguna Las Brisas

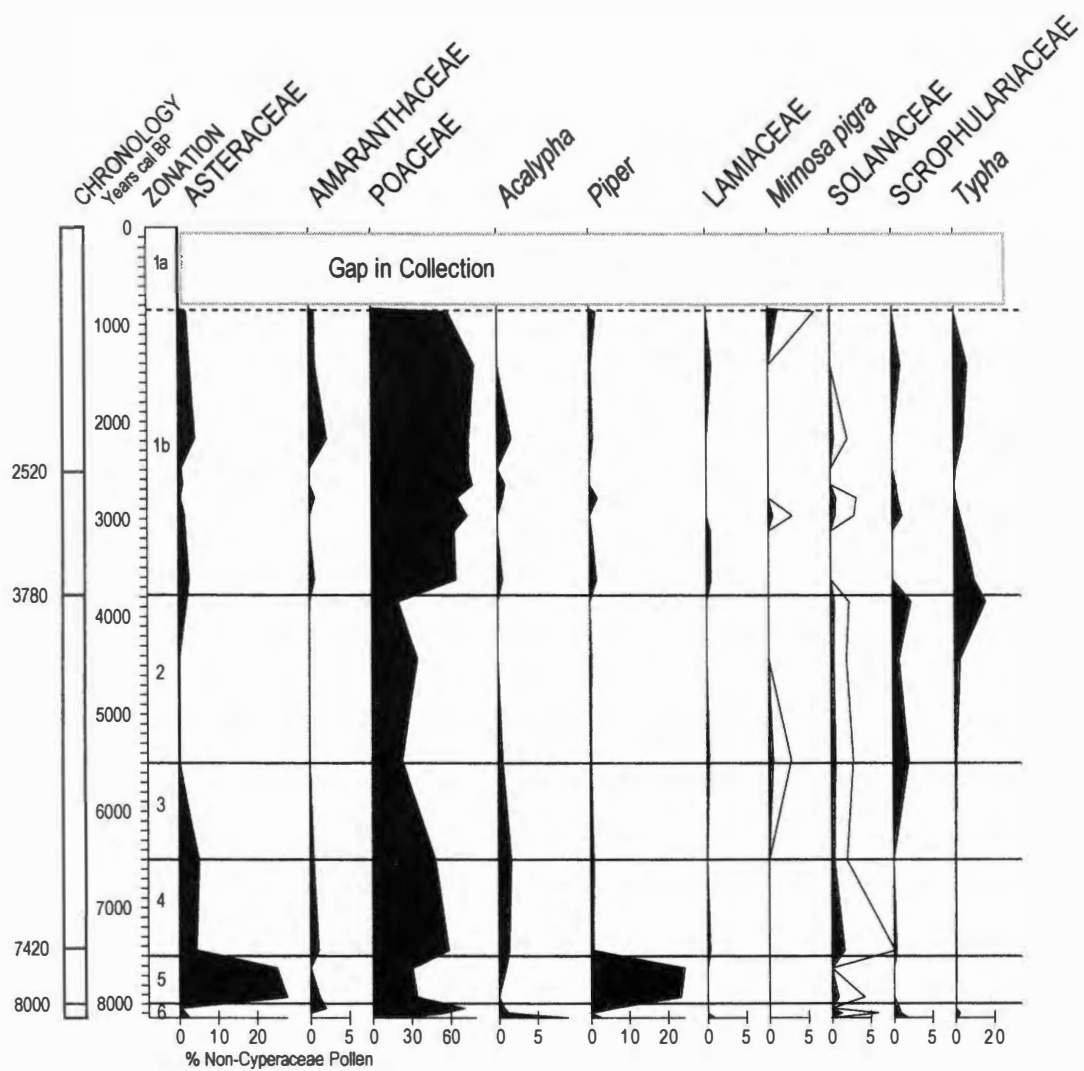


Figure 4.14. Non-Arboreal Pollen Results for Laguna Las Brisas

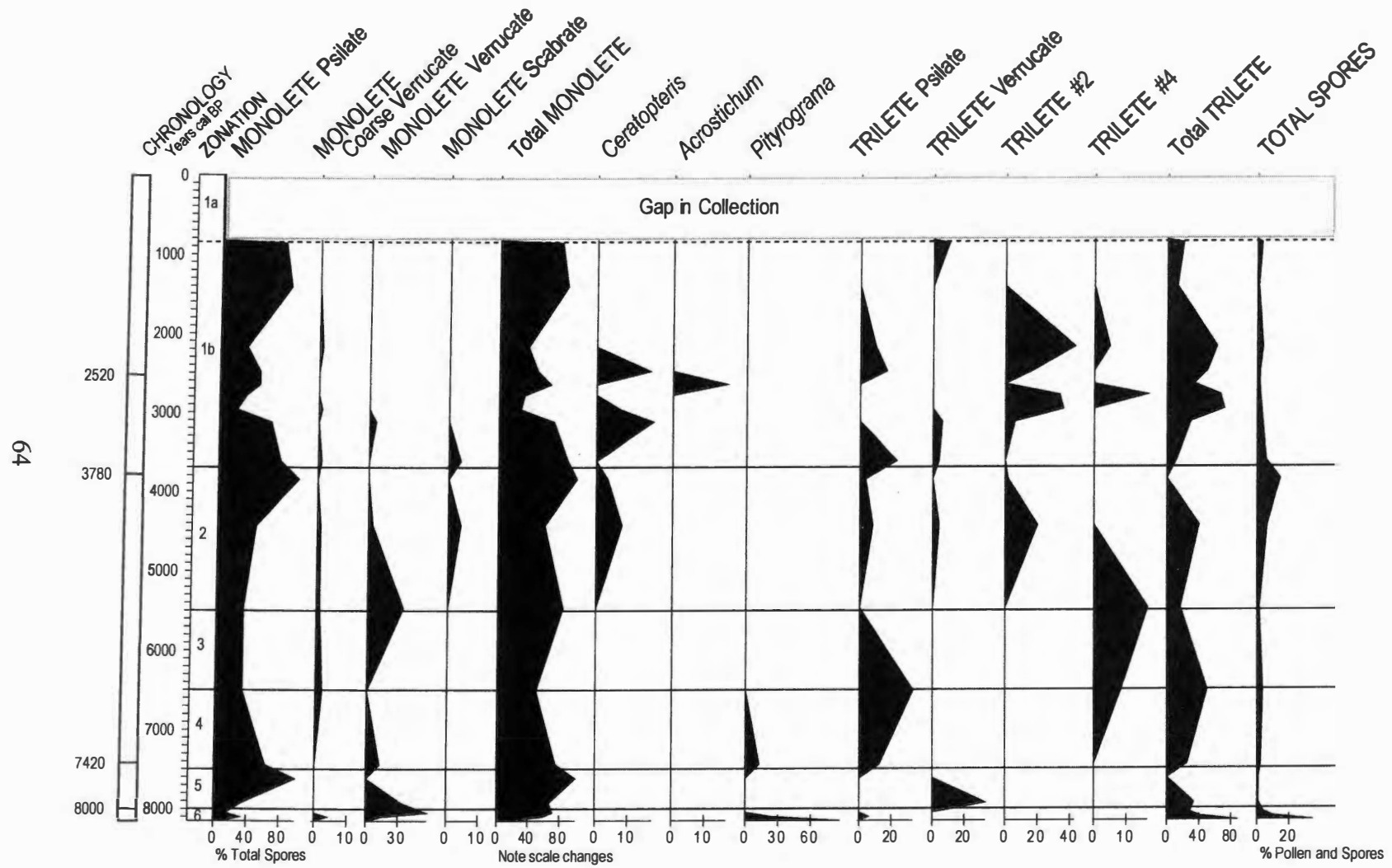


Figure 4.15. Fern Spore Results for Laguna Las Brisas

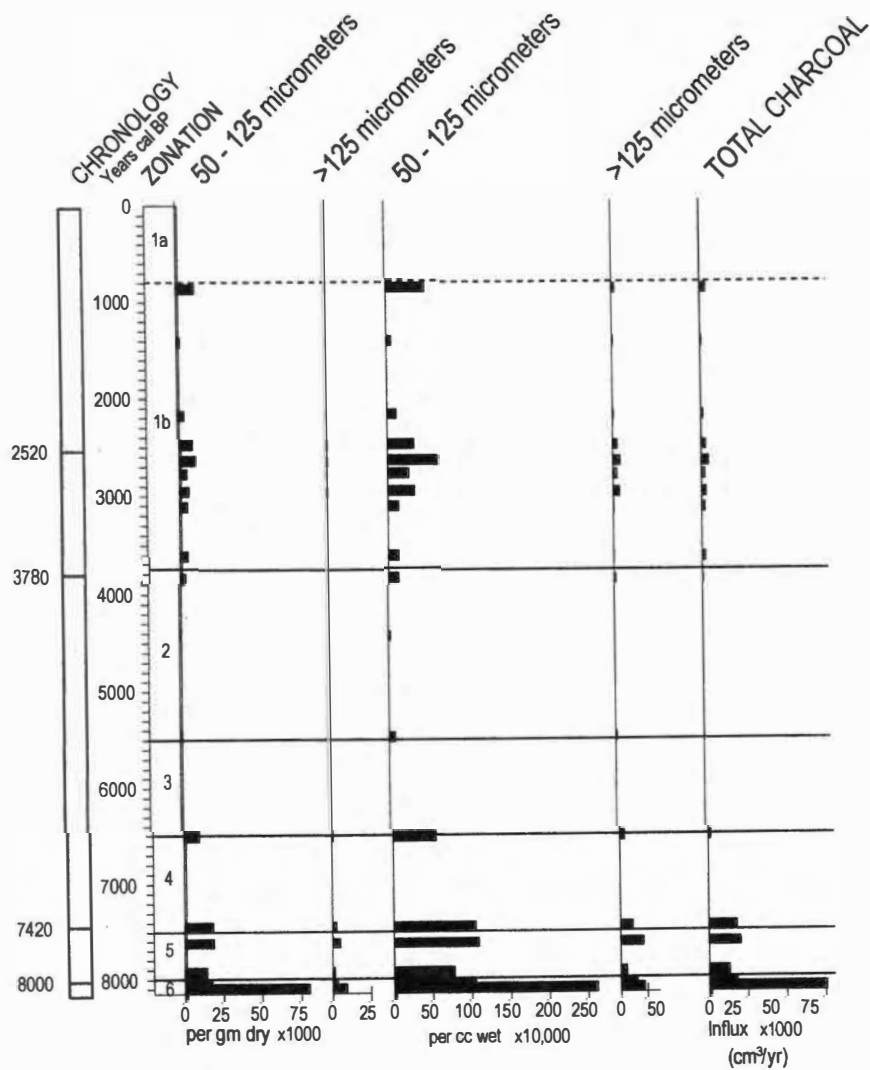


Figure 4.16. Microscopic Charcoal Results for Laguna Las Brisas

and dense. Tree pollen increases to about 30% of total pollen. Poaceae pollen increases from 30% to 60% of pollen, but this may be an artifact of the nearly 20% decreases in *Piper* and Asteraceae over the values in Zone 5. A small spike of *Pityrogramma*, a disturbance indicator, occurs at the base of the zone. Microscopic charcoal concentrations decrease slightly at the top of this zone. Pollen changes indicate the establishment of more mature-forests with Sapotaceae/Meliaceae, Rhamnaceae, *Bursera*, and *Trema*.

Zone 3 (6500–5500 cal yr BP) is represented by only 16 cm and two pollen samples, and sediments contain mottled areas. Pollen shows another slight increase in tree taxa, mostly Myrtaceae and *Cecropia*, and a further decrease in Poaceae pollen from Zone 4. Microscopic charcoal concentrations are low at the top of the zone.

Zone 2 (5500–3800 cal yr BP) sediments are characterized by mottling features consistent with desiccation and several lithic clasts up to about 1 cm in diameter. Cyperaceae pollen increases through this zone. *Ceratopteris* spores are higher, especially in the middle of the zone, indicating some standing water. *Typha* and Urticales diporate pollen percentages both increase in the uppermost sample, but Myrtaceae, Rhamnaceae, and Sapotaceae/Meliaceae decrease slightly toward the top of the zone. Microscopic charcoal abundance remains quite low.

Zone 1a represents the top 14 cm of sediment which was not cored (483 cal yr BP interpolated to present), because we did not take a PTC core. Zone 1b (3800 to 483 cal year BP interpolated) sediments are dense, inorganic, and contain several areas with heavy mottling and lithic inclusions several cm in diameter. At the base of Zone 1b tree pollen decreases dramatically from about 40% to 15%, while Grass and Cyperaceae

pollen increase significantly. Maize pollen is present in six of nine of these samples. Peaks in *Ceratopteris* and *Acrostichum* fern spores exist in the lower half of Zone 1b. Microscopic charcoal increases in the middle of Zone 1b, but not to the levels seen in Zones 4 and 5. Zone 1b represents maize agriculture and human disturbance.

LAGUNA ESTERO BLANCO

Sediment Stratigraphy and Radiocarbon Chronology

The 4.48 m sediment core collected in 2001 from Estero Blanco shows major changes in type of sediments from coarse to fine clastics, firm mineral sediments, peat, and ped-like crumbles (Table 4.5). Organic content varies from less than 20% to greater than 80% (Figure 4.17). AMS dates range from 622–7959 cal yr BP (Table 4.6). A gap in sediment recovery extends from 99–120 cm depth (4710–5549 cal yr BP, interpolated). The interval from 41–65 cm (622–3353 cal yr BP) has mottling indicative of intermittent drying or bioturbation.

Pollen and Charcoal Zones

Microfossil results are presented in a series of diagrams, including a summary diagram (Figure 4.18), and separate diagrams for trees (Figure 4.19), non-arboreal taxa (Figure 4.20), fern spores (Figure 4.21) and microscopic charcoal (Figure 4.22).

Zone 6 (>7900 cal yr BP) sediments included gravels and sands in a gray silty matrix of clastic material that infilled the newly formed lake basin. Palynomorphs are consistent with landscape disturbance and include Poaceae, Asteraceae, and *Cecropia* pollen, and *Pityrogramma* fern spores. Tree pollen constitutes about 50% of the total

Table 4.5. Sediment Description for Laguna Estero Blanco

Depth (cm)	Munsell	Description
0–21	10YR 3/1	Soft, brown organic sediments
22–31	10YR 2/2	Firmer, more mineral content
32–40	10YR 2/1	Black, crumbly, peaty organic rich
41–64	10YR 3/1	Very firm, dense, mottled
65	7.5YR 4/4	Orange clay inclusion
66–99	7.5YR 2/0	Crumbly, chunky. Chunks contain mineral matrix with charcoal and organic pieces
100–125	---	Gap in sediment recovery
126–134	10YR 2/1	Fibrous, organic rich
135–156	10YR 2/1	Dense slippery mud with fine organics
157–183	10YR 2/1	Fibrous, peaty organics
184–208	10YR 2/1	Coarse organic peat
209–221	---	Gap in sediment recovery
222–270	10YR 2/1	Very coarse organic peat
271–296	5Y 2.5/1	Finer-grained organics, more mineral rich
297–309	5Y 2.5/1	Denser, fewer and finer organics
310–318	---	Gap in sediment recovery
319–342	5Y 2.5/1	Smooth, dense clay-rich mud
343–378	5Y 2.5/1 & 5/1	Dense clay-rich, thin horizontal bands
378–448	5Y 2.5/1 to 3/1	Gravels in silty sandy matrix

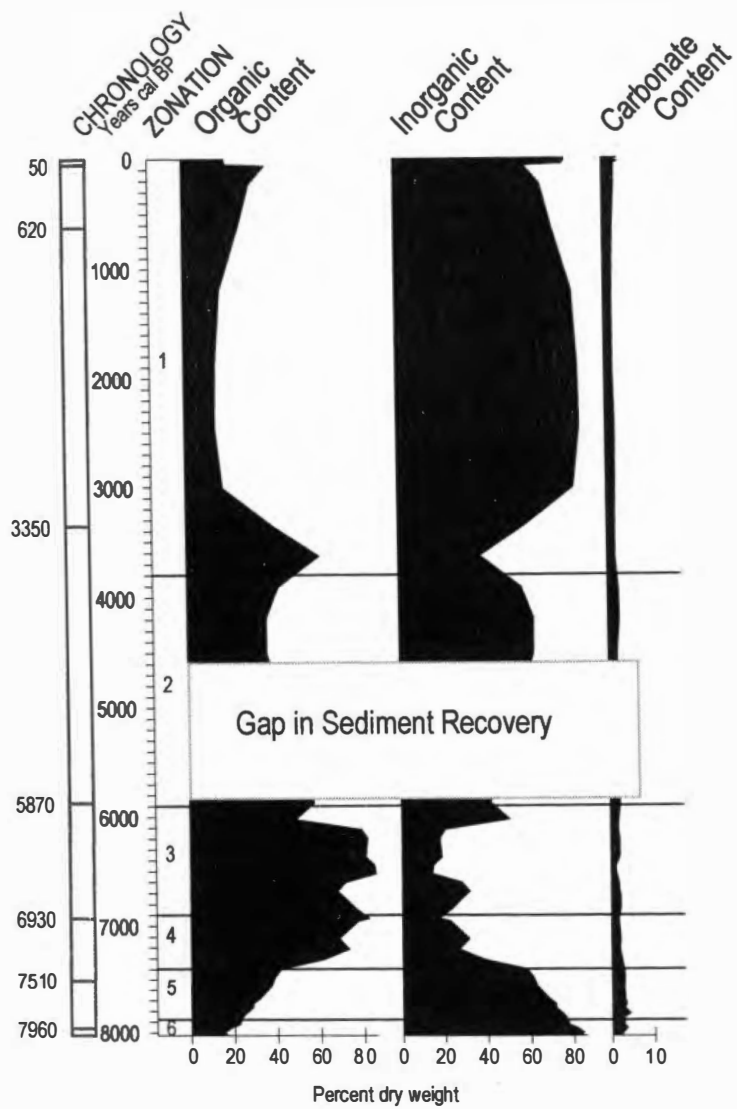


Figure 4.17. Loss on Ignition Results for Laguna Estero Blanco

Table 4.6. AMS Radiocarbon Dates for Laguna Estero Blanco¹

Lab Number	Depth (cm)	Material Dated	Radiocarbon Date	Weighted Mean cal yr BP	Calibrated 2 Sigma Ranges BP	Calibrated 2 Sigma Ranges AD/BC
AA-60651	33-34	Leaves and Charcoal Fragments	Post bomb	*	*	*
AA-60652	41	Charcoal Fragments	682 ± 37	622	605–556 679–623	1394–1345 AD 1327–1271 AD
β-205877	59	Charcoal Fragments	2200 ± 40	2224	2331–2118	381–168
β-169602	65	Charcoal Fragments	3140 ± 60	3353	3470–3210 3180–3170	1520–1260 BC 1230–1220 BC
β-176223	128	Charcoal Fragments	5140 ± 40	5868	5988–5970 5948–5858 5830–5751	4038–4020 BC 3998–3908 BC 3880–3801 BC
β-155065	196	Charcoal Fragments	6080 ± 40	6927	7155–7130 7087–7082 7021–6850	5205–5180 BC 5137–5132 BC 5071–4900 BC
β-155066	290	Wood Fragment	6630 ± 50	7510	7579–7431	5629–5481 BC
β-158437	378	Charcoal Fragments	7150 ± 50	7959	8108–8094 8032–7925 7900–7866	6158–6144 BC 6082–5975 BC 5950–5916 BC

¹Analyses were performed by Beta Analytic Laboratory, Miami FL (β-numbers), or the University of Arizona AMS Laboratory (AA-numbers).

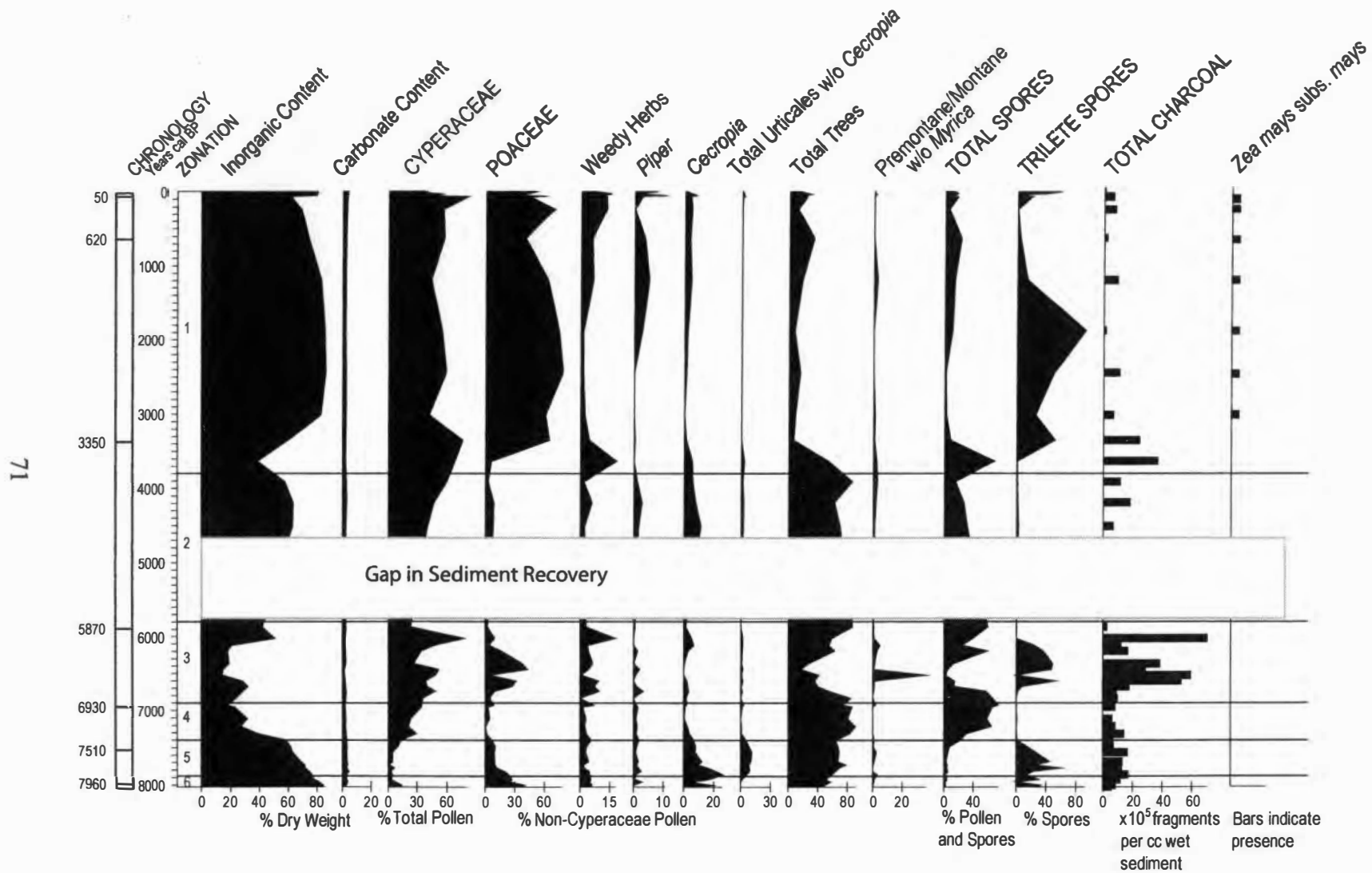


Figure 4.18. Pollen Summary for Laguna Estero Blanco

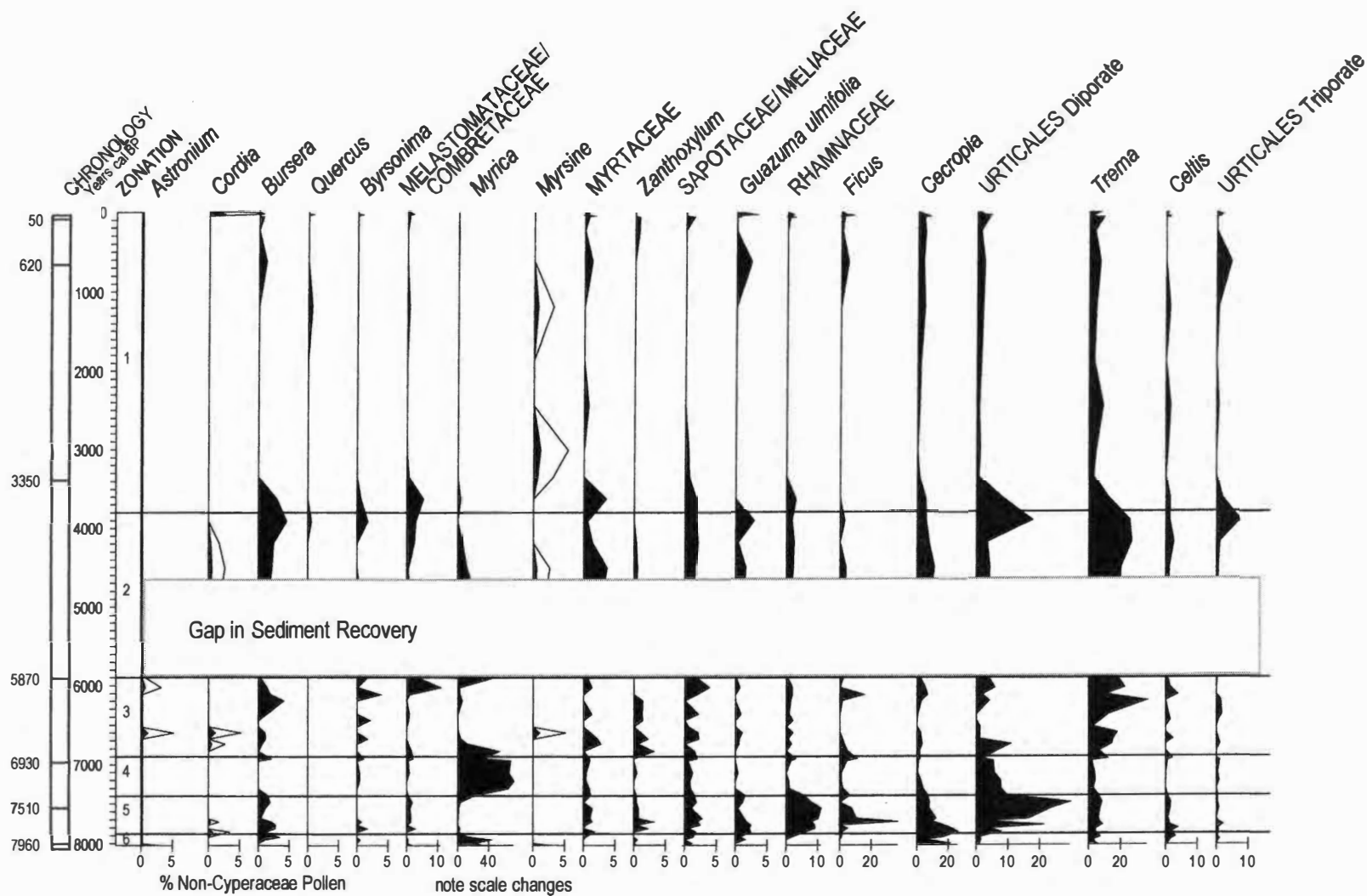


Fig. 4.19. Tree Pollen Results for Laguna Estero Blanco

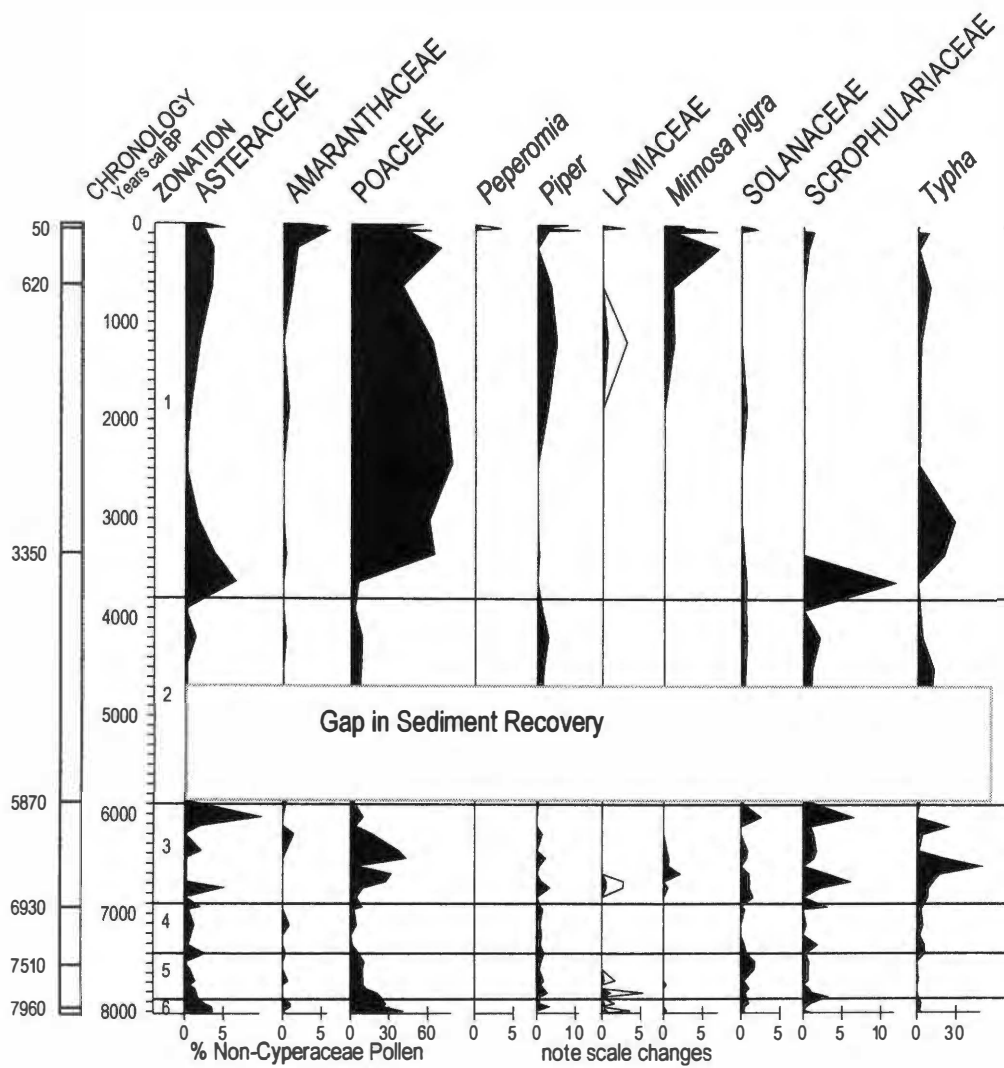


Figure 4.20. Non-Arboreal Pollen Results for Laguna Estero Blanco

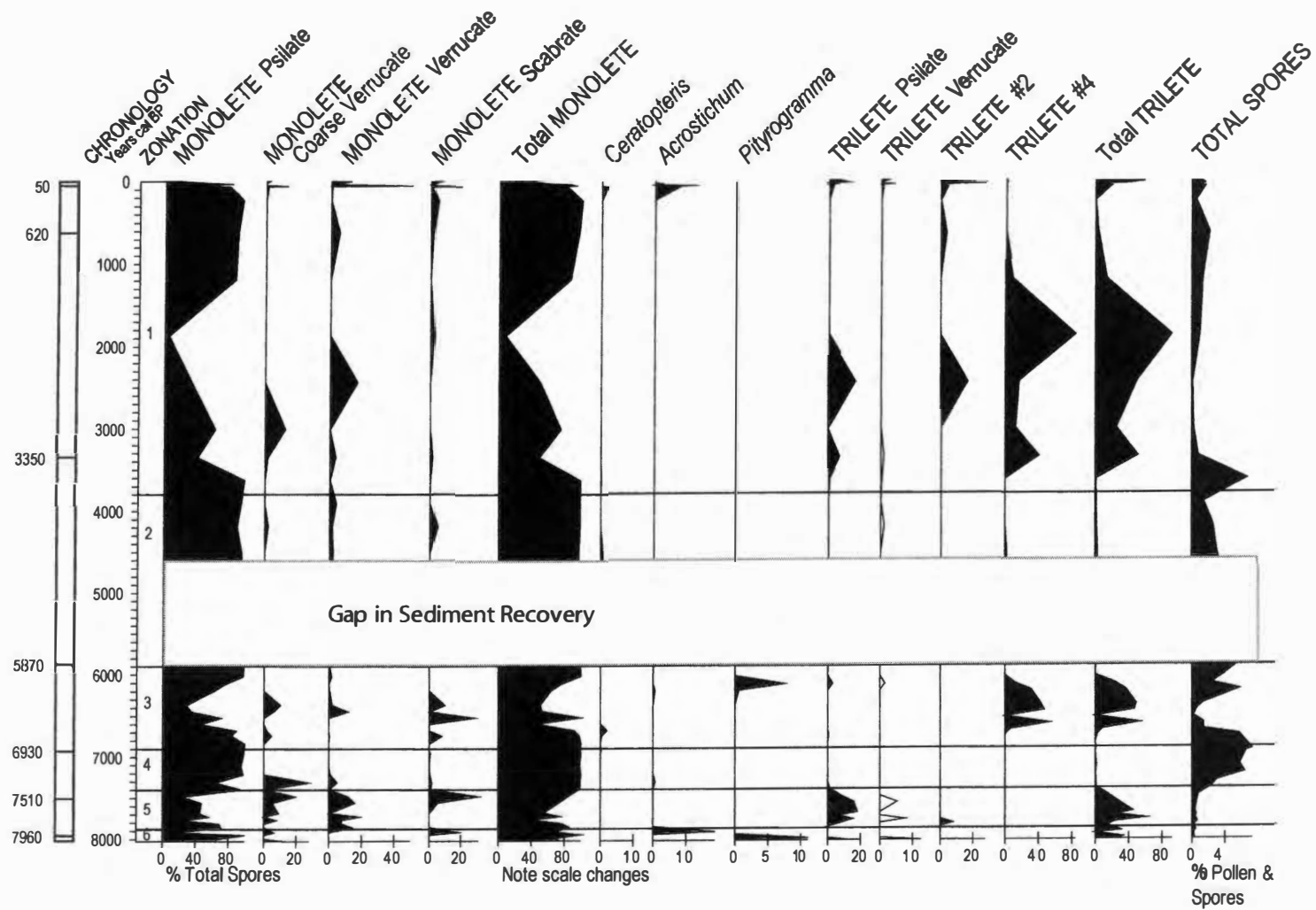


Figure 4.21. Fern Spore Results for Laguna Estero Blanco

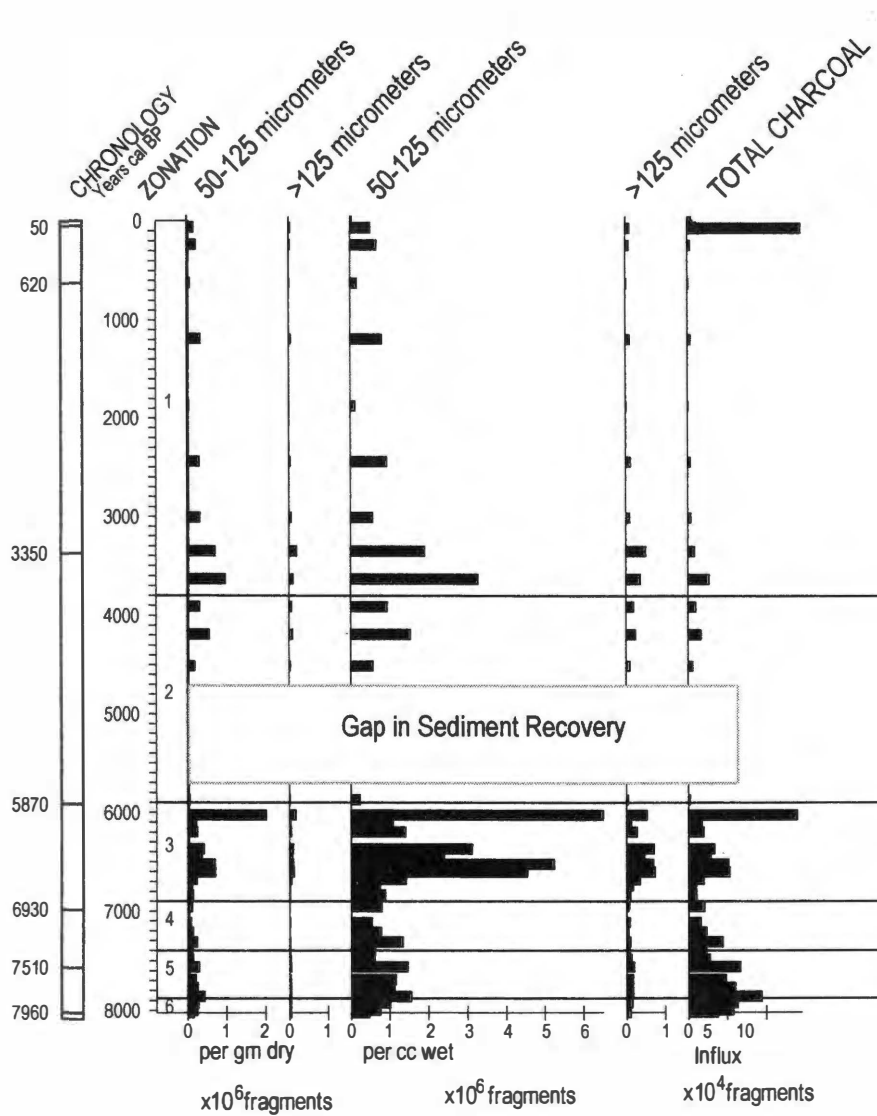


Figure 4.22. Microscopic Charcoal Results for Laguna Estero Blanco

pollen (excluding Cyperaceae), with *Myrica* and *Cecropia* as the most abundant tree types. Microscopic charcoal is moderately abundant in this basal zone.

In Zone 5 (7900–7400), sediments have subtle color changes within finely laminated clayey layers. Organic content increases from <20% to nearly 40% at the top of the zone. Microfossils include high percentages of tree pollen, mostly Urticales diporate, *Cecropia*, Rhamnaceae, and *Ficus*, and decreasing Poaceae pollen. Trilete fern spores rise to about 50% of total spores, then decrease to nearly zero at the top of the zone. Microscopic charcoal gradually decreases moving upcore.

In Zone 4 (7400–6800 cal yr BP), basal sediments are higher in mineral content (60%), but peaty and coarse organic material increases to 80% by the top of the zone. Greater than 60% of the total pollen (excluding Cyperaceae) is *Myrica* pollen; Urticales diporate adds another 10%. Cyperaceae pollen increases in abundance, as does the percentage of monolet psilate fern spores as a percentage of total pollen and spores. Pollen percentages for non-arboreal and weedy taxa remain very low. In the lowest sample microscopic charcoal increases slightly, but decreases moving upward.

Zone 3 (6800–5800 cal yr BP) sediments remain highly organic (nearly 80%), but fluctuate and decrease to about 50% at the top. The percentage of tree pollen drops from 80% to about 20% in the center of the zone, then recovers to 80% again. Poaceae pollen has an inverse signal, increasing significantly mid-zone. *Typha* pollen percentage peaks at over 40% in the center of Zone 3 along with a spike in premontane/montane tree pollen (Melastomataceae/Combretaceae and *Hedyosmum*). Cyperaceae pollen has a general increasing trend. Trilete fern spores also increase, primarily unknown trilete type #4.

Microscopic charcoal shows the highest concentrations and influx rates of the entire core.

Zone 3 includes evidence of major environmental change.

Zone 2 (5800–3800 cal yr BP) contains a gap in sediment recovery of approximately 29 cm (125–100 cm; 5800–4750 cal yr BP). Sediments decrease in organic content (40–50%), have mottled coloring, and contain crumbly, ped-like structures. Total tree pollen averages about 70%. Urticales pollen and *Myrica* dominate the bottom of Zone 2, below the gap. Above the gap *Myrica* pollen decreases while there are slight increases in *Bursera*, Myrtaceae, *Guazuma ulmifolia*, and Rhamnaceae pollen percentages. Microscopic charcoal increases above the sediment gap through the top of Zone 2.

In Zone 1 (3800 cal yr BP–present), organic content is much lower than in other zones (about 20%) except for a peak at about 3700 cal yr BP. Organic content increases near the top of the core to nearly 40%. The bottom of this zone shows a sharp decline in the percentage of tree pollen, and dramatic increases in pollen of grass and weedy herbs, monolete psilate spores, and microscopic charcoal. These microfossil changes happen just prior to the first occurrence of maize pollen. Cyperaceae pollen averages about 50% of total pollen, and Poaceae represents nearly 60% of the non-Cyperaceae pollen. Trilete spores, especially unknown trilete type #4, remain high throughout most of this zone. After 620 cal yr BP, tree and grass pollen percentages show reciprocal shifts. In the base of the zone, microscopic charcoal concentrations increase, but influx remains relatively low. Even though maize pollen is present, most of the levels do not include high levels of charcoal. At the top of the zone, during modern times, a spike in charcoal influx occurs.

LAGUNA LOS JUNCOS

Sediment Stratigraphy and Radiocarbon Chronology

A 2.5 m sediment core, collected in 2000, consists mostly of dense mineral-rich sediments (Table 4.7). Inorganic content is about 80% through most of the profile, except in the basal sediments, which contain about 40% organic material (Figure 4.23). Four AMS radiocarbon dates range from 1284–573 cal yr BP (Table 4.8). There is an apparent depositional hiatus between 3888 and 5644 cal yr BP, in which two dates separated by ~1750 years were obtained on charcoal fragments separated by only 5 cm. A gap exists in sediment recovery from 109–127 cm.

Pollen and Charcoal Zones

Microfossil results are presented in a series of diagrams including a summary diagram (Figure 4.24), and separate diagrams for trees (Figure 4.25), non-arboreal taxa (Figure 4.26), fern spores (Figure 4.27) and microscopic charcoal (Figure 4.28). This core, like Laguna Las Brisas, was analyzed at a coarser resolution due to the poor temporal resolution (less than 2 meters represents over 7500 cal yr), a gap in sediment collection, and a depositional hiatus of ~1750 years.

The basal Zone 6 (>7500 cal yr BP) contains mostly the pre-lacustrine part of the record including nearly a meter of tephra and clastic sediments. This zone contains only one sample, analyzed for pollen, microscopic charcoal, and LOI, taken from the uppermost part of this zone where organic content is highest (about 45%). Tree pollen approaches 38%, mostly composed of *Trema* and *Celtis*. Non-arboreal pollen is dominated by Poaceae (28%), Asteraceae (about 20%), and *Typha* (7%).

Table 4.7. Sediment Description for Laguna Los Juncos

Depth (cm)	Munsell	Description
0–21		soft, organic sediment
21–68	10YR 2/1	fine dark, mineral sediments, slightly gritty
69–72	10YR 2/1	very dense, rubbery mineral sediments
73–108	10YR 3/1	slightly gritty mineral seds, mottling of 10YR 4/1
109–127	---	gap in sediment recovery
128–137	10YR 3/1	slightly gritty mineral seds, mottling of 10YR 4/1
138–177	10YR 2/1	firmer, not gritty
178–183	10YR 2/1	fibrous, organic-rich
184–186		tephra, coarse-sand sized
187–192	10YR 2/2, 3/1, 4/1	Banded clays and v. fine tephra
193–246		med.–coarse grained tephra

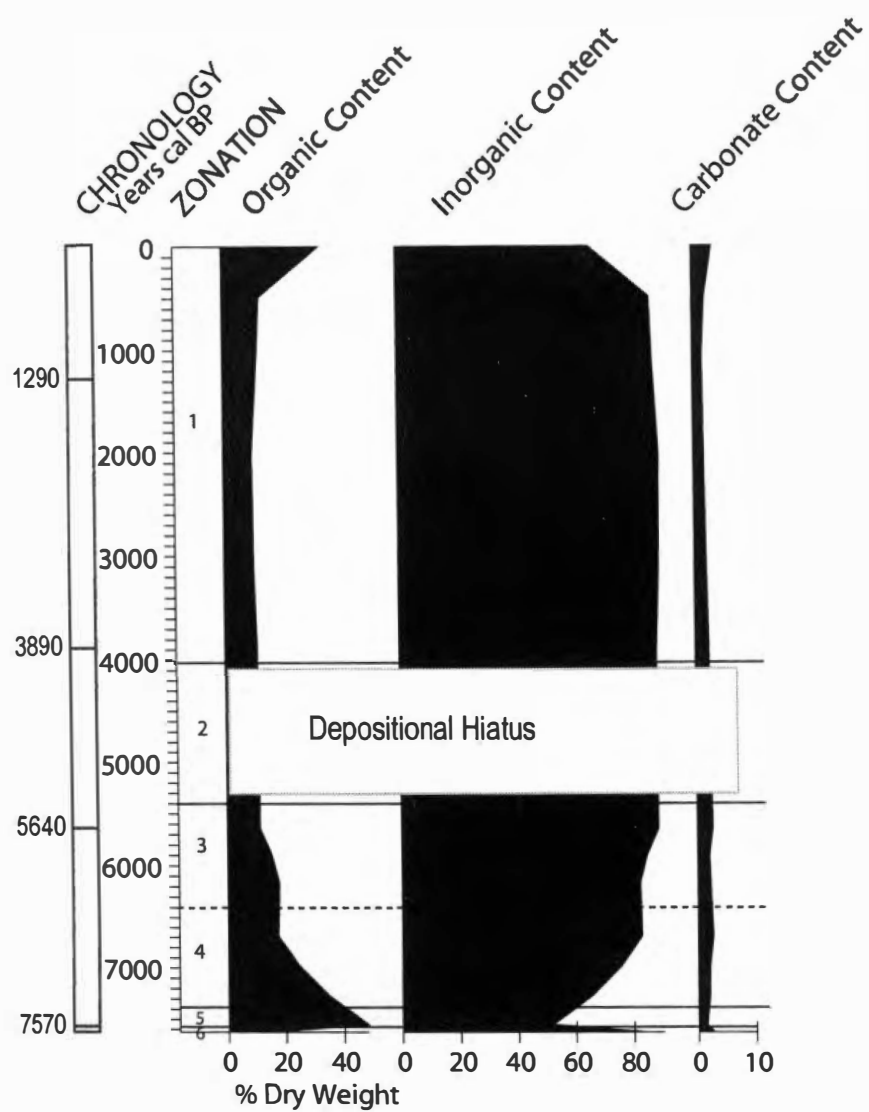


Figure 4.23. Loss on Ignition Results for Laguna Los Juncos

Table 4.8. AMS Radiocarbon Dates for Laguna Los Juncos¹

Lab Number	Depth (cm)	Material Dated	Radiocarbon Date	Weighted Mean cal yr BP	Calibrated 2 Sigma Ranges BP	Calibrated 2 Sigma Ranges AD/BC
AA-60653	32	Charcoal fragments	1380 ± 38	1294	1200–1188 1251–1235 1350–1257	762–750 AD 715–699 AD
β-179843	69	Wood and Grass Charcoal fragments	3590 ± 40	3888	4064–4050 3987–3824 3793–3760 3750–3726	2114–2100 BC 2037–1874 BC 1843–1810 BC 1800–1776 BC
β-172356	74	Charcoal fragments	4910 ± 40	5644	5719–5592	3769–3642 BC
β-167803	181	Charred material	6710 ± 50	7573	7669–7547 7544–7481	5719–5597 BC 5594–5531 BC

¹Analyses were performed by Beta Analytic Laboratory, Miami FL (β-numbers), or the University of Arizona AMS Laboratory (AA-numbers).

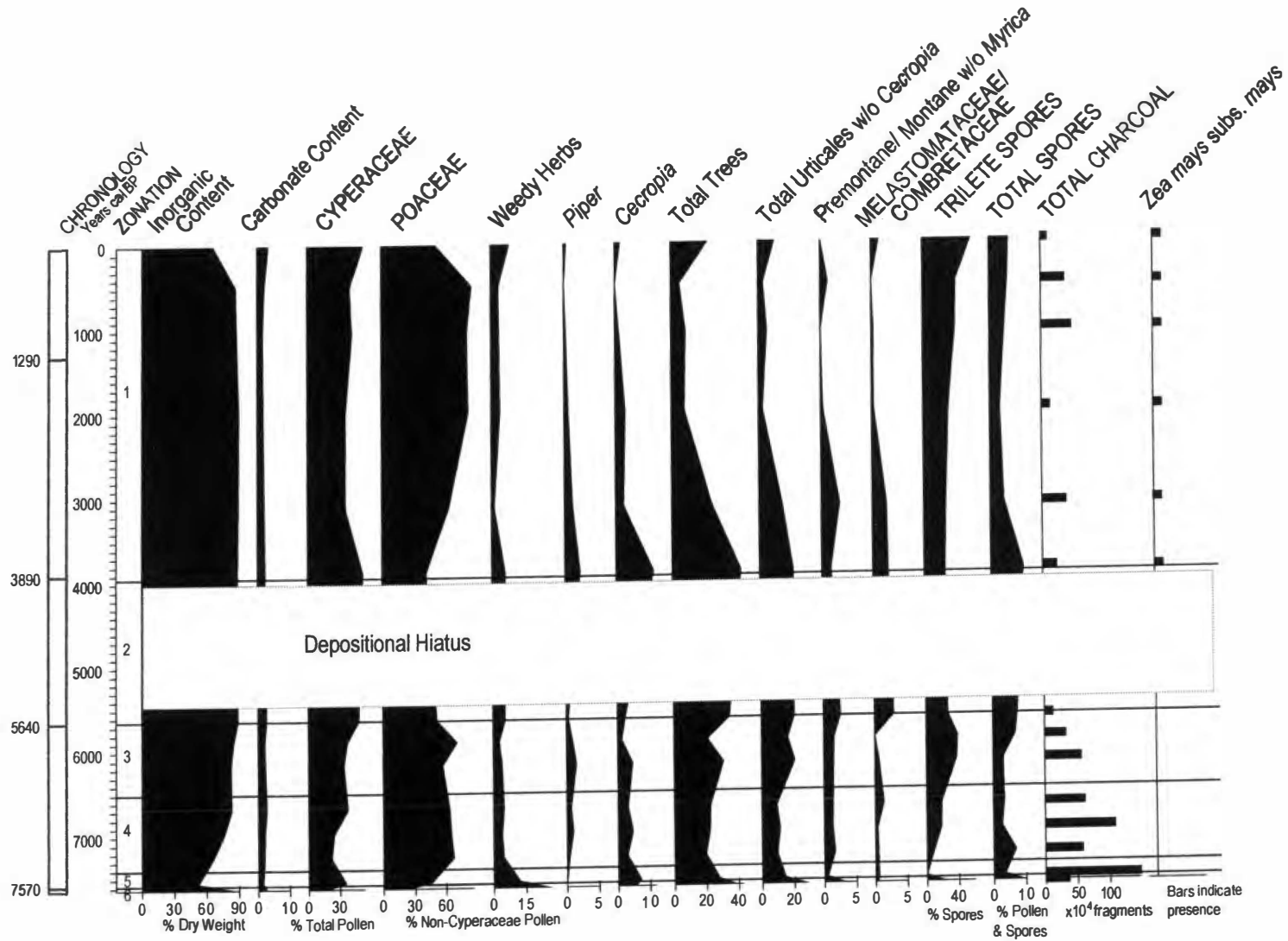


Figure 4.24. Pollen summary for Laguna Los Juncos

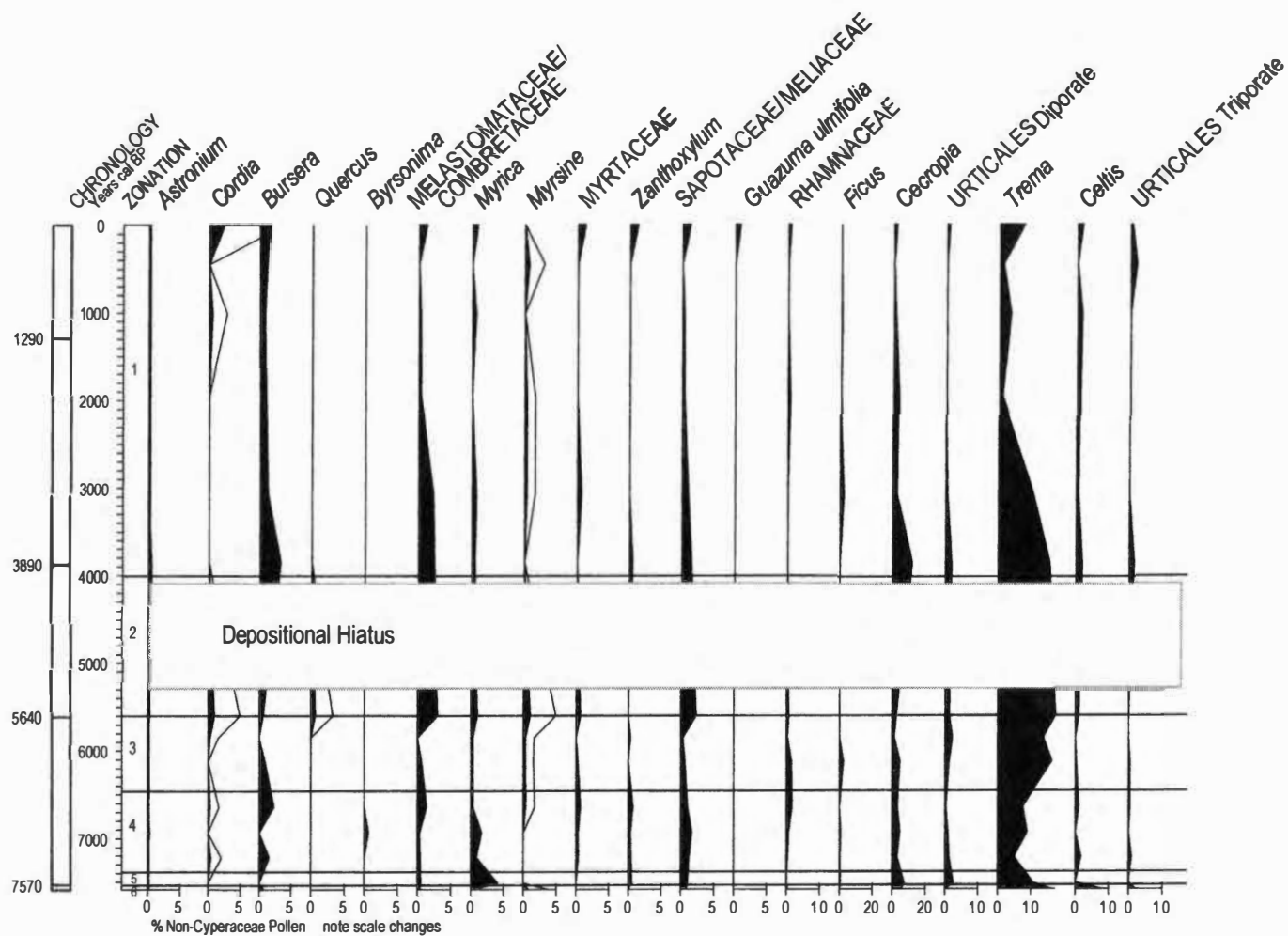


Figure 4.25. Tree Pollen Results for Laguna Los Juncos

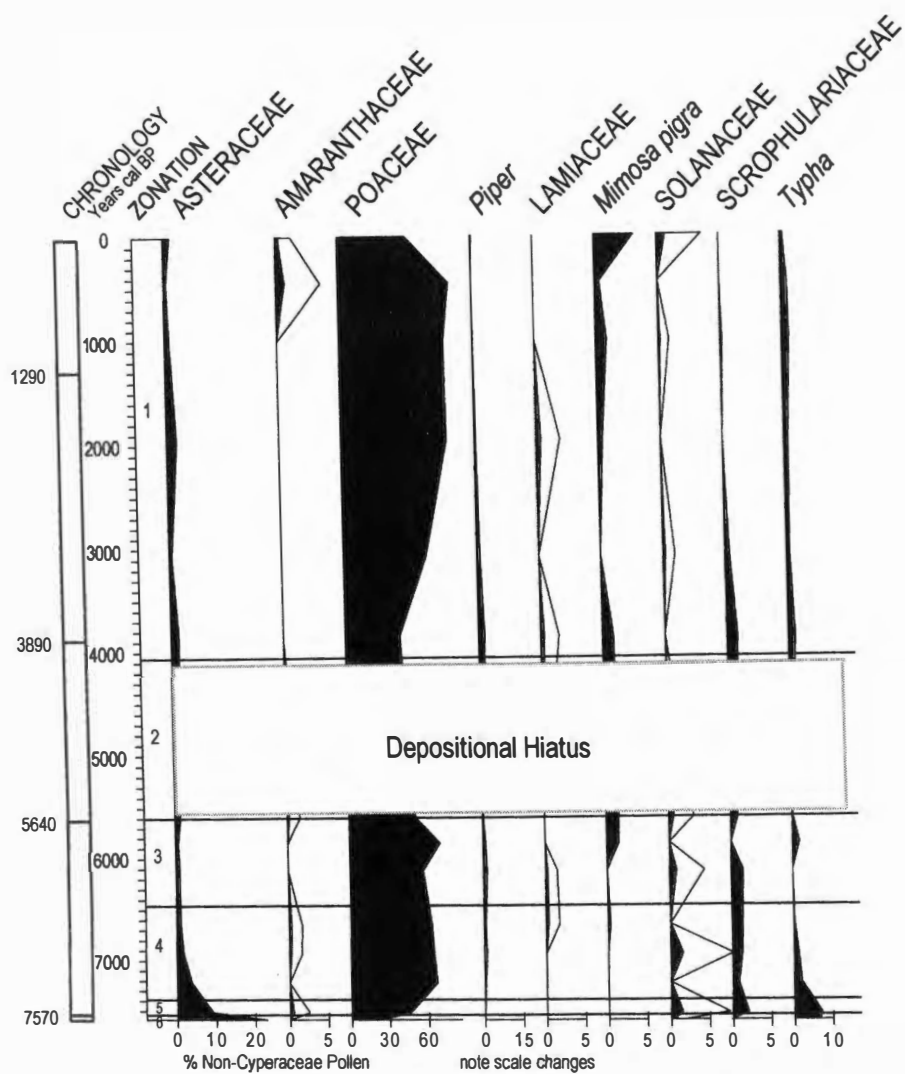


Figure 4.26. Non-Arboreal Pollen Results for Laguna Los Juncos

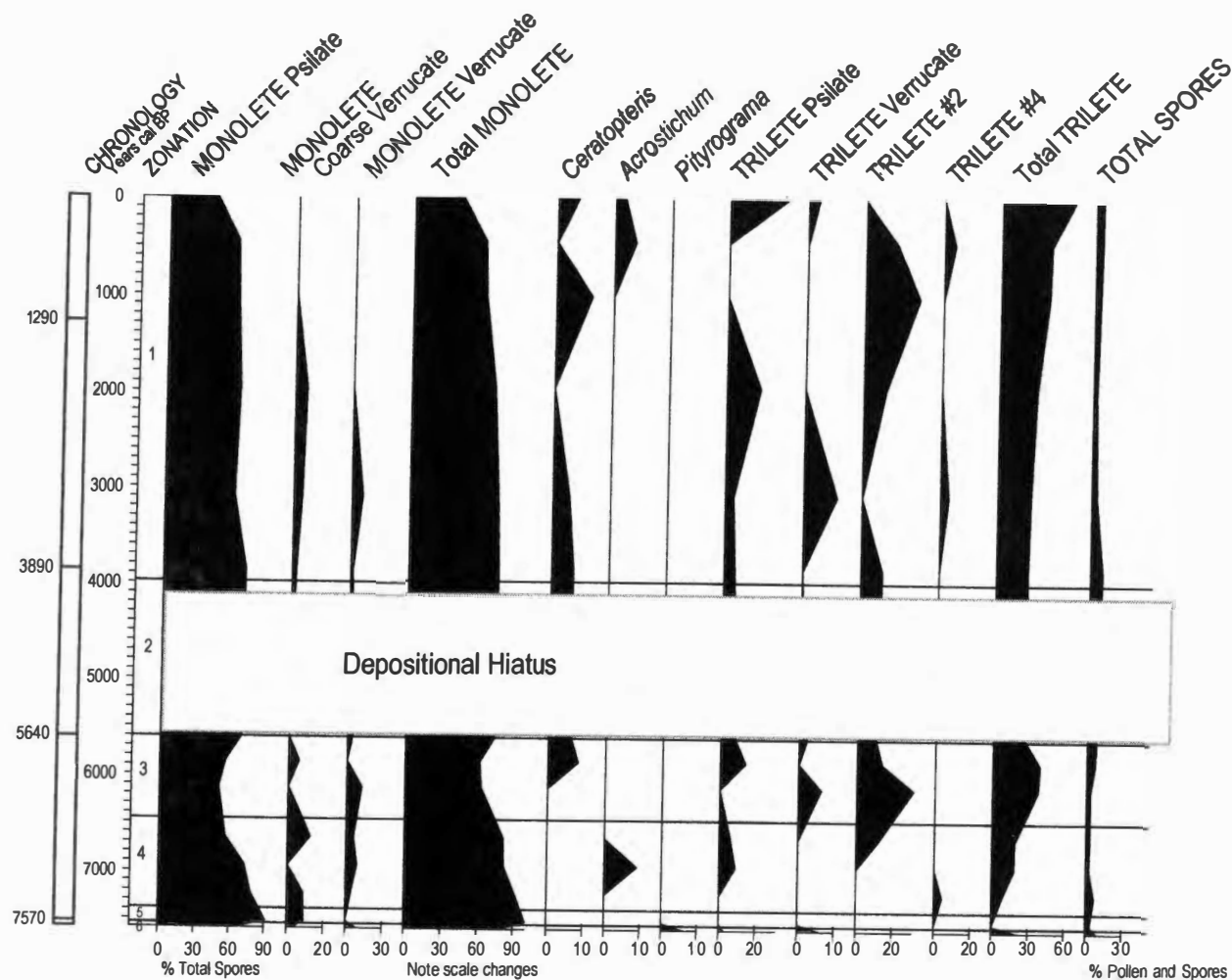


Figure 4.27. Fern Spore Results for Laguna Los Juncos

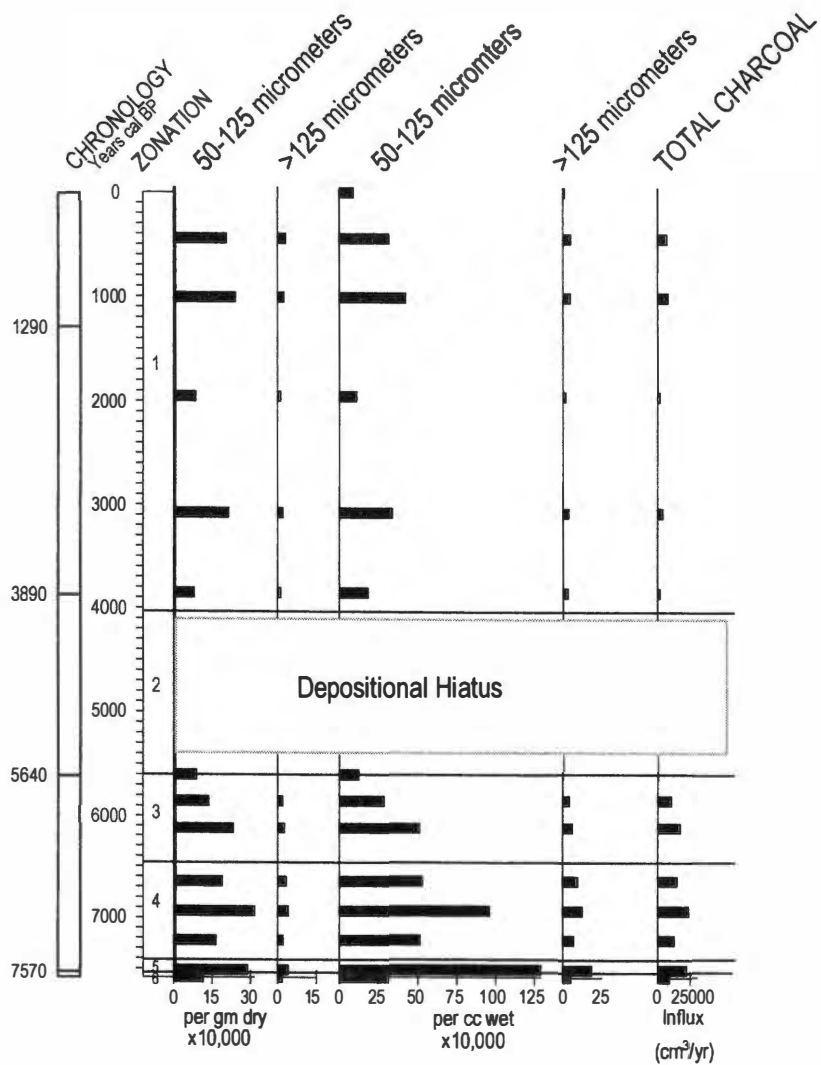


Figure 4.28. Microscopic Charcoal Results for Laguna Los Juncos

Zone 5 (7500–7400 cal yr BP) sediments are higher in organic content than Zone 6 at about 45%. Only one sample was analyzed from this zone. *Trema* and *Myrica* are the most abundant tree pollen types, but total tree pollen is lower than Zone 6. Poaceae and Cyperaceae increase, *Typha* increases slightly, while Asteraceae pollen and *Pityrogramma* spores decrease. Charcoal concentration is the highest of any zone.

In Zone 4 (7400–6500 cal yr BP) organic content declines from 40% to 20%, and there is some mottling of sediments at the top of the zone. The percentage of tree pollen initially decreases, then gradually increases due to an increase in *Trema* pollen; grass pollen has an inverse signal. *Myrica* pollen drops off toward the top of the zone, while *Typha* and Asteraceae pollen decrease. Charcoal concentrations remain high.

Zone 3 (6500–5640 cal yr BP) contains slight gritty mineral sediments (>80% inorganic). Mottling of the type associated with desiccation and/or root traces occurs around 5900–5800 cal yr BP (interpolated). Tree pollen increases except for one sample level that has increases in Poaceae and *Typha* pollen. At this same level, spores of *Ceratopteris*, a floating fern, appear in the record. Near the top of the zone, an increase occurs in pollen from Melastomataceae/Combretaceae and Sapotaceae/Meliaceae. An AMS date from charcoal from the top of Zone 3, at 74 cm sediment depth, yielded a date of 5640 cal yr BP. Microscopic charcoal decreases from moderate amounts at the bottom of the zone to low amounts at the top.

Within Zone 2 (5640–3900 cal yr BP), a sample 5 cm above the lower boundary of Zone 2 (5640 cal yr BP) yielded a calibrated date of 3890 cal yr BP, a time difference of 1750 years. This probably represents a hiatus in sediment deposition within Zone 2, or a loss of sediments during a drying period. Sediments remain highly inorganic. Tree

pollen, mostly non-*Cecropia* Urticales, increases slightly to 40% of total non-Cyperaceae pollen. *Bursera* and *Cecropia* pollen also increase. Microscopic charcoal amounts remain low. A noticeable change in the pollen signal does not occur until Zone 1.

In Zone 1 (3900 cal yr BP–present) sediments remain over 80% inorganic until the uppermost sample when inorganics decrease to 60%. Maize pollen first appears in the same sample interval that yielded the date of 3890 cal yr BP, and is present in all other sampled levels in Zone 1. Tree pollen markedly declines while Poaceae pollen increases. Other than a few changes in types of trilete spores, no other remarkable changes in pollen and spore types were found until the uppermost level. This youngest sample contains a decrease in Poaceae pollen, a slight increase in most tree taxa, and an increase in pollen from *Mimosa pigra*. Microscopic charcoal concentration remains relatively low, much lower than in the three lowest zones.

LAGUNA SAN PABLO

Sediment Stratigraphy and Radiocarbon Chronology

We first cored San Pablo in March, 1999. We recovered a 2.4 meter long core, but deeper sediments repeatedly fell out of the bottom of the core tubes. In 2003, we recored the lake using a custom core catcher that allowed us to recover a 6.5 m core. For sediment and pollen analyses I used the PTC core from 1999 and the deeper, more complete 2003 C-V core. Sediments in the 2003 core were mostly dense and mineral-rich (Table 4.9), with inorganic content 80% or greater throughout most of the core (Figure 4.29). Three AMS radiocarbon dates were obtained from the 1999 core, and 6

Table 4.9. Sediment Description for Laguna San Pablo

Core	Depth (cm)	Munsell	Description
PTC	0–22	10YR 2/1	soft mud, organic fibers
	23–32	10YR 2/1	firmer
2003	33–43	10YR 2/1 and 3/1	mottling, crumbly, ped-like
	44–54	10YR 3/1	crumbly, ped-like
	32–94	10YR 2/1	firm, dark, organic rich
	95–97	10 YR 4/2	silty clay
	98–103	10YR 2/1	black silty sediment
	104–106	10YR 4/2	mottled, silty
	106–112	10YR 2/1	silty, gravel inclusion
	113–131	---	gap in sediment recovery
	132–197	10YR 3/1	very dark gray, silty, mottles of 10YR 2/1
	198–213	10YR 2/1	clay-rich, black
	214–232	---	gap in sediment recovery
	233–236	10YR 4/1	dark gray, silty-clay, charcoal chunks
	237–270	10YR 4/1	dark gray, firm, burrows
	271–275		rock
	276–313	7.5 YR 4/1	silty dark gray
	314–332	---	gap in sediment recovery
	333–362	2.5Y 4/1	clay-rich, dark gray
	363–383	2.5Y 4/1	mottling of 10YR 3/1, clay-rich
	384–392	2.5 Y 4/1	firm, dark, clay-rich
	393–407	2.5Y 4/1	mottling of 10YR 3/1
	408–420	10YR 3/1	very dark gray, silty-clay
	421–432	---	gap in sediment recovery
	433–449	2.5Y 3/1	silty dark brown
	450–489	10YR 2/1	very dark brown, silty
	489–493	2.5Y 3/1	slightly gritty
	494–495		tephra
	496–505	2.5Y 6/1	gray clay
	506–517		clastics
	518–532	---	gap in sediment recovery
	532–650		clastics

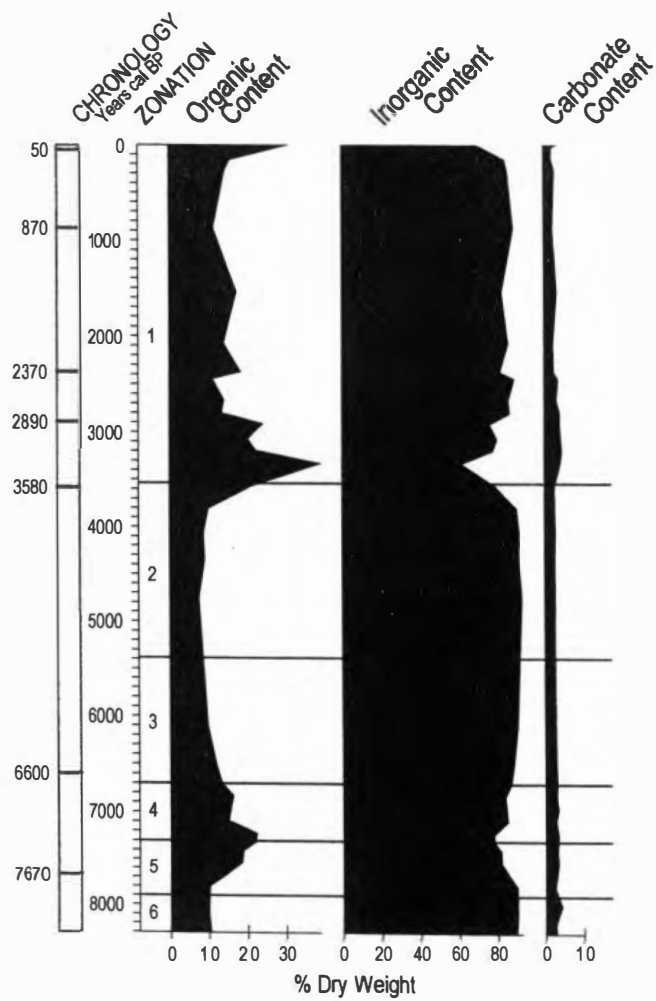


Figure 4.29. Loss on Ignition Results for Laguna San Pablo

from the 2003 core yielding a range 7671 cal yr BP to modern (post-bomb) (Table 4.10). Mottling of sediments was present in the intervals of 383–363 cm (6813–6648 cal yr BP, interpolated) and 407–393 cm (7011–6896 cal yr BP, interpolated), suggesting intermittent drying during those time periods. In addition to the radiocarbon dates, photographic analysis, loss-on-ignition and preliminary pollen work was completed on the 1999 core in order to match the 1999 and 2003 cores. The PTC (1999) core was then placed in correct stratigraphic position with respect to the 2003 C-V core.

Pollen and Charcoal Zones

Microfossil results are presented in a series of diagrams including a summary diagram (Figure 4.30), and separate diagrams for trees (Figure 4.31), non-arboreal taxa (Figure 4.32), fern spores (Figure 4.33), and microscopic charcoal (Figure 4.34)

Sediments in Zone 6 (>7900 cal yr BP) consist of pre-lacustrine clastic material that infilled the newly formed lake basin. Pollen is very scarce in this zone.

Pityrogramma fern spores are abundant, and are nearly 80% of total pollen and spores near the upper part of the zone. Cyperaceae pollen averages about 30% of total pollen. *Typha* pollen percentages remain at 10–15% throughout this zone. Pollen from premontane/montane taxa, such as *Myrica* and *Hedyosmum*, account for half of the total tree pollen. Most of the remaining tree pollen is *Zanthoxylum* and Urticales (primarily *Celtis*). Microscopic charcoal fragments are rare in this zone.

Table 4.10. AMS Radiocarbon Dates for Laguna San Pablo¹

Analyses were performed by Beta Analytic Laboratory, Miami FL (β-numbers), or the University of Arizona AMS Laboratory (AA-numbers)	Lab Number	Core	Depth (cm)	Material Dated	Radiocarbon Date	Weighted Mean cal yr BP	Calibrated 2 Sigma Ranges BP	Calibrated 2 Sigma Ranges AD/BC
	AA-60657	PTC 1999	31	Plant stems	Post bomb	*	*	*
	AA-60658	2003	54	Charcoal fragments	980 ± 38	872	791–953	1159–997 AD
	β-186685	2003	99	Charcoal fragments	2340 ± 40	2370	2705–2667 2664–2654 2487–2481 2471–2306 2238–2207 2196–2183	755–717 BC 714–704 BC 537–531 BC 521–356 BC 288–257 BC 246–233 BC
	AA-60659	2003	167	Charcoal fragments	2790 ± 41	2887	2781–2971 2980–2987	1021–831 BC 1037–1030 BC
	β-135626	1999	197	Charred material	2920 ± 60	3071	3320–3310 3260–3220 3210–2920 2910–2880	1370–1360 BC 1310–1270 BC 1260–970 BC 960–930 BC
	β-167805	1999	230	Charred material	3310 ± 50	3542	3685–3665 3641–3443 3426–3408	1735–1715 BC 1691–1493 BC 1476–1458 BC
	β-182612	2003	236		3350 ± 40	3578	3687–3660 3643–3473	1737–1710 BC 1693–1523 BC
	β-184801	2003	357	Dicot leaves	5800 ± 40	6599	6723–6699 6675–6494	4773–4749 BC 4725–4544 BC
	β-181323	2003	487	Charcoal fragments	6840 ± 50	7671	7786–7779 7755–7587	5836–5829 BC 5805–5637 BC

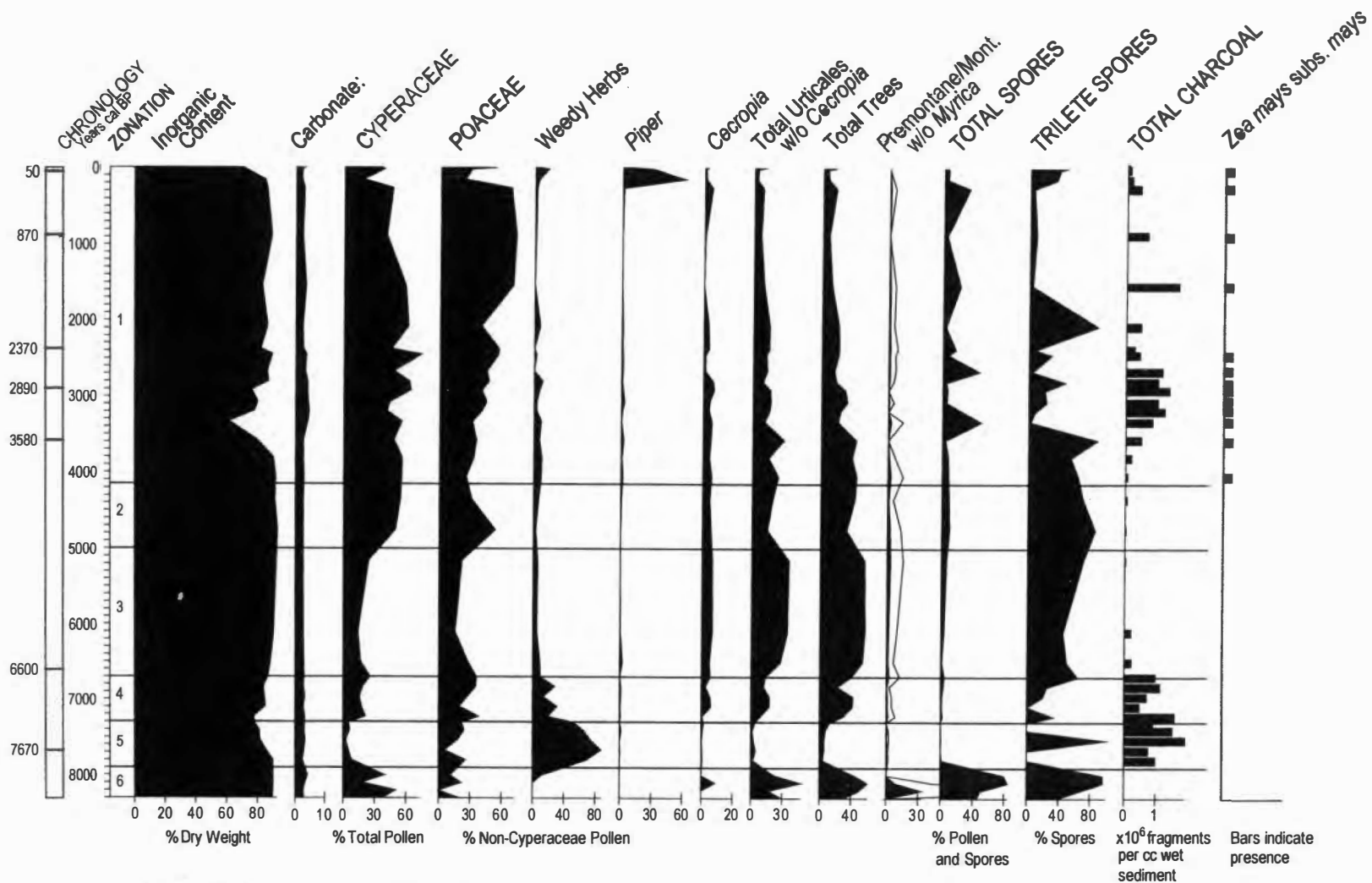


Figure 4.30. Pollen Summary for Laguna San Pablo

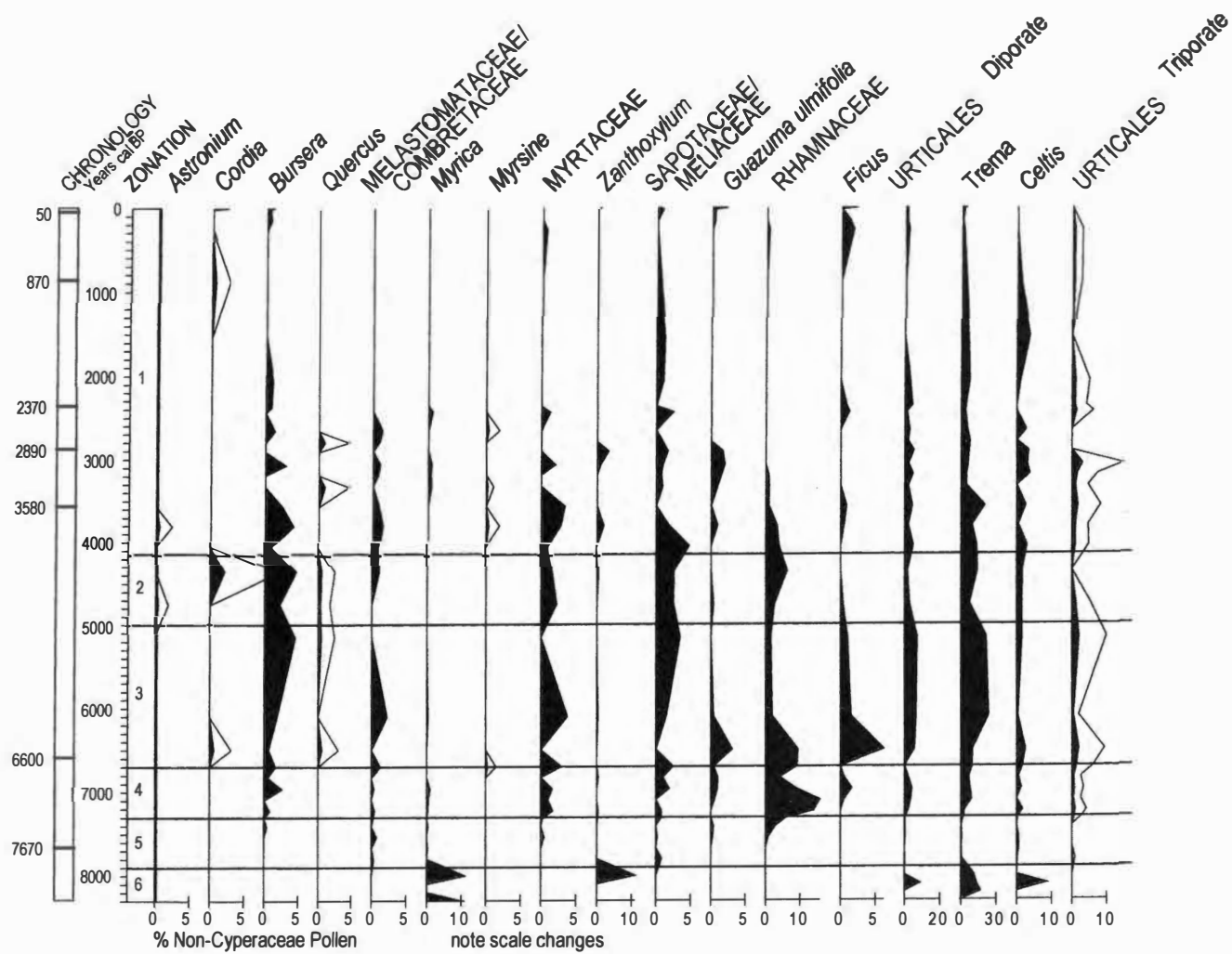


Figure 4.31. Tree Pollen Results for Laguna San Pablo

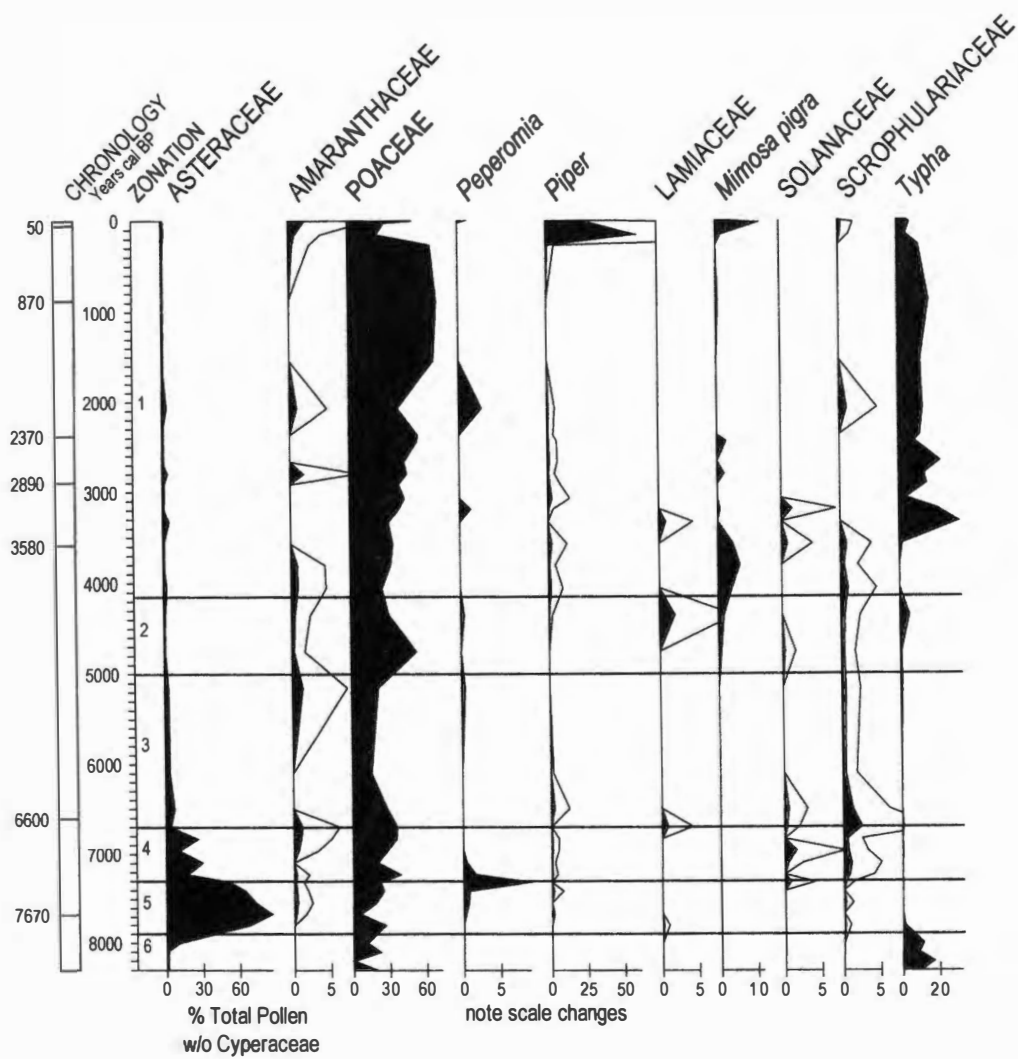


Figure 4.32. Non-Arboreal Pollen Results for Laguna San Pablo

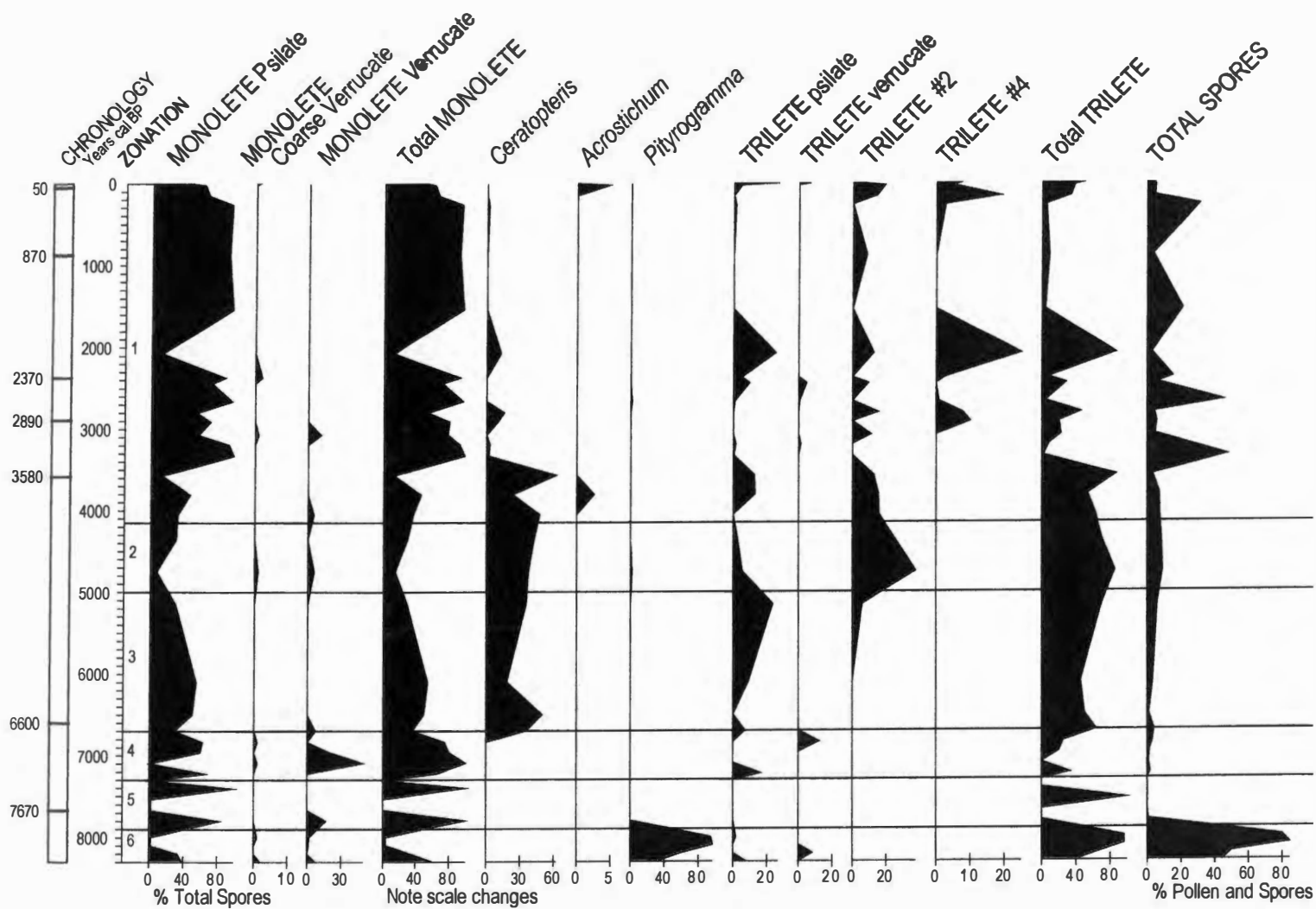


Figure 4.33. Fern Spore Results for Laguna San Pablo

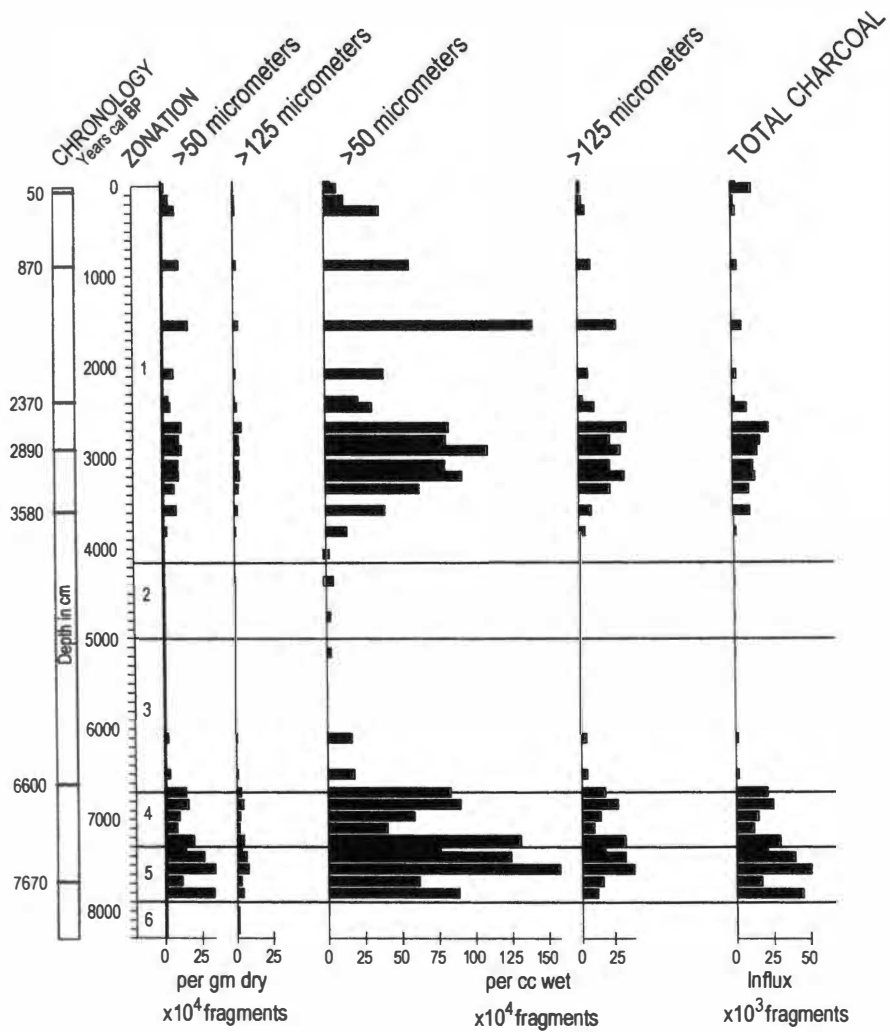


Figure 4.34. Microscopic Charcoal Results for Laguna San Pablo

The sediments at the base of Zone 5 (7900–7300 cal yr BP) are highly inorganic (90%) and contain clays and silts, but transition to slightly more organic (20%) near the top. Pollen is dominated by Asteraceae (>60%) and Poaceae, which overwhelm pollen from tree taxa. Fern spores are rare, and one sample contained no fern spores. Typha and aquatic ferns disappear, and Cyperaceae decreases significantly. Microscopic charcoal is abundant with the highest influx rates of all zones.

In Zone 4 (7300–6700 cal yr BP), sediments increase slightly in inorganic content (90%). Tree pollen rises to 40% including a large increase in Rhamnaceae. Other taxa that increase in Zone 4 are *Bursera*, Myrtaceae, Sapotaceae/Meliaceae, and *Trema*. Asteraceae pollen fluctuates between 15% and 30%. Charcoal influx remains quite high.

Zone 3 (6700–5500 cal yr BP) sediments remain 90% inorganic. There is a gap in sediment recovery of 19 cm (6025–5600 cal yr BP). In the remainder of the zone, tree pollen averages 50% of the non-Cyperaceae pollen. At the bottom of the zone there are peaks in abundance of *Guazuma ulmifolia*, Rhamnaceae, and *Ficus*. Later, increases in *Bursera*, *Trema*, and Sapotaceae/Meliaceae occur. Most of the non-arboreal pollen is grass (20–30%). Spores, poorly represented, are mostly *Ceratopteris*, a floating aquatic fern, and unknown trilete type #2. Microscopic charcoal occurs in very low concentrations.

Zone 2 (5500–3600 cal yr BP) sediments remain 90% inorganic. An increase in grass pollen at the expense of tree pollen marks the beginning of the zone. Throughout Zone 2, Cyperaceae and grass pollen remain high. Several other weedy herbs are represented, although their abundances are low. Near the top of Zone 2, *Mimosa pigra*

pollen increases to nearly 5%. *Ceratopteris* percentages remain high. Microscopic charcoal occurrence is the lowest of all zones.

In Zone 1 (3600 cal yr BP–present), sediments vary considerably in texture, but remain mostly inorganic. Organic content is highest soon after the beginning of this zone, then climbs again in modern sediments. Most sediments are silty and dark brown, but some intervals contain mottling (3200–2600 cal yr BP, interpolated; 2370 cal yr BP). The transition sediments between Zones 3 and 2 have traces like those produced by burrowing invertebrates. Most sampled levels contain maize pollen. Pollen of tree taxa declines shortly after a rise in charcoal begins and remains low throughout the rest of the zone, while Poaceae and Cyperaceae pollen remain high. Near the top of Zone 1 a peak occurs in *Piper* pollen to over 50% of non-Cyperaceae pollen. The uppermost, modern samples include a noticeable increase in pollen from *Mimosa pigra*. By ~3400 cal yr BP, microscopic charcoal concentration increases considerably, coincident with a rise in *Typha* pollen.

LAGUNA SORPRESA

Sediment Stratigraphy and Radiocarbon Chronology

In 2001 we recovered a 3.8 m core from Laguna Sorpresa, but we did not believe it contained the basal sediments. In 2003, we re-cored Laguna Sorpresa near the edge of the dike and recovered 3.9 m of sediment. I compared the sediment stratigraphy (photos and sediment color/texture), preliminary pollen counts, and loss-on-ignition data for the 2001 and 2003 cores. As suspected, because of disturbance from the construction of the dike, the top meter of the 2003 core did not match the stratigraphy, pollen, and LOI from

the 2001 core. However, after the first meter was set aside, the deeper sediments from the 2003 core matched the 2001 core nearly identically. I used the PTC and top two meters from our 2001 cores for sediment, charcoal and pollen analysis. Below this level is a gravel layer that occurred in both cores. I switched to the 2003 core at the top of the gravel interval and used the deeper and older sediments from this core for the remainder of the analyses (Table 4.11). Organic content is highest, around 80%, at the bottom of the core, but near the middle of the profile drops to as low as about 5% (Figure 4.35). Sediments vary considerably, from soft organic peat to silt and clays and coarse clastic layers (Table 4.11). This range is greater than the other lakes in this study. Two AMS radiocarbon dates were obtained from the 2001 core, and four from the 2003 core (Table 4.12). Dates range from 7110–1606 cal yr BP (Table 4.12).

Pollen and Charcoal Zones

Microfossil results are presented in a series of diagrams including a summary diagram (Figure 4.36), and separate diagrams for trees (Figure 4.37), non-arboreal taxa (Figure 4.38), fern spores (Figure 4.39) and microscopic charcoal (Figure 4.40). The 2003 sediment core from Laguna Sorpresa did not reach the basal sediments due to breakage of equipment during the coring process (but this core was deeper and older than the 2001 core). Therefore, the basal sediments date to 7110 cal yr BP, and my analysis begins in Zone 4.

Sediments in Zone 4 (7110–6300 cal yr BP) are peaty and highly organic (70–80%), with coarsest particles near the base. Pollen in the basal sediments is nearly 90% trees, with *Myrica* at 60% and *Urticales* about 25% (of which *Ficus* is nearly half). Percentages of fern spores, and pollen from *Cyperaceae*, *Poaceae*, and weedy herbs, are

Table 4.11. Sediment Description for Laguna Sorpresa.

Core	Depth (cm)	Munsell	Description
PTC	0–18	10YR 2/1	soft organic-rich, organic fragments
	18–58	10YR 2/1	firm organic-rich, organic fragments
2001	19–76	7.5YR 2/0	chunky, v. soft, organic-rich
	76–91	10YR 2/1	dense, peaty, fibrous
	91–110	7.5YR 2/0	chunky, organic-rich
	110–121	---	gap in sediment recovery
	121–175	7.5YR 2/0	soft, organic-rich
	175–181	10YR 3/1	firm, smooth, mineral-rich
	181–196	10YR 4/1, 3/1	gravel/sand/silt
	196–199	---	wood
	199–216	---	gap in sediment recovery
	216–298	10YR 3/1	sandy, silty, debris w/gravel-sized clasts
	298–306	---	gap in sediment recovery
***	306–371	7.5YR 2/0	soft, chunky (firm lumps)
	371–379	7.5YR 2/0	streaks of 7.5YR 5/2, coarse clasts
	379–401	---	gap in sediment recovery
2003	0–4	---	sediment transposed during coring process
	4–6	10YR 4/1	gritty silt with clasts
	6–13	10YR 2/1	slightly gritty silt/clay, organic-rich
	13–16		
	16–34	10YR 3/1	lighter mottled patches
	34–38	10YR 3/1	mottled with 10YR 4/1, dark specks
	38–47	10YR 3/1	fine (smooth) dark brown
	47–50	10YR 3/1	dense, rubbery
	50–52.5	10YR 3/1	fine, dark brown
	52.5–100	---	gap in sediment recovery
	100–103	GLE Y1 2.5/N	
	103–125	10YR 2/1	soft, silty
	125–160	10YR 2/1	chunky, organic-rich
	160–176	10YR 4/1	sandy, silty, debris w/gravel-sized clasts
	176–214	---	gap in sediment recovery
	214–230	10YR 3/1	clastic – gravel, sand, silt
	229–233	---	woody inclusion
	233–265	10YR 3/1	gritty, sandy, mineral rich
***	265–272	10YR 2/1	soft, smooth, organic
	272–275	10YR 4/1	clay-rich
	275–278	10YR 2/1	soft, smooth, organic
	278–284	GLE Y1 2.5/N	soft, smooth, black
	284–304	---	gap in sediment recovery
	304–325	10YR 2/1	dense, organic-rich, slightly gritty
	325–389	10YR 2/1	coarse organic particles (CPOM)
	389–395	---	gap in sediment recovery

*** Represents the same gravel layer within the 1999 and 2003 cores

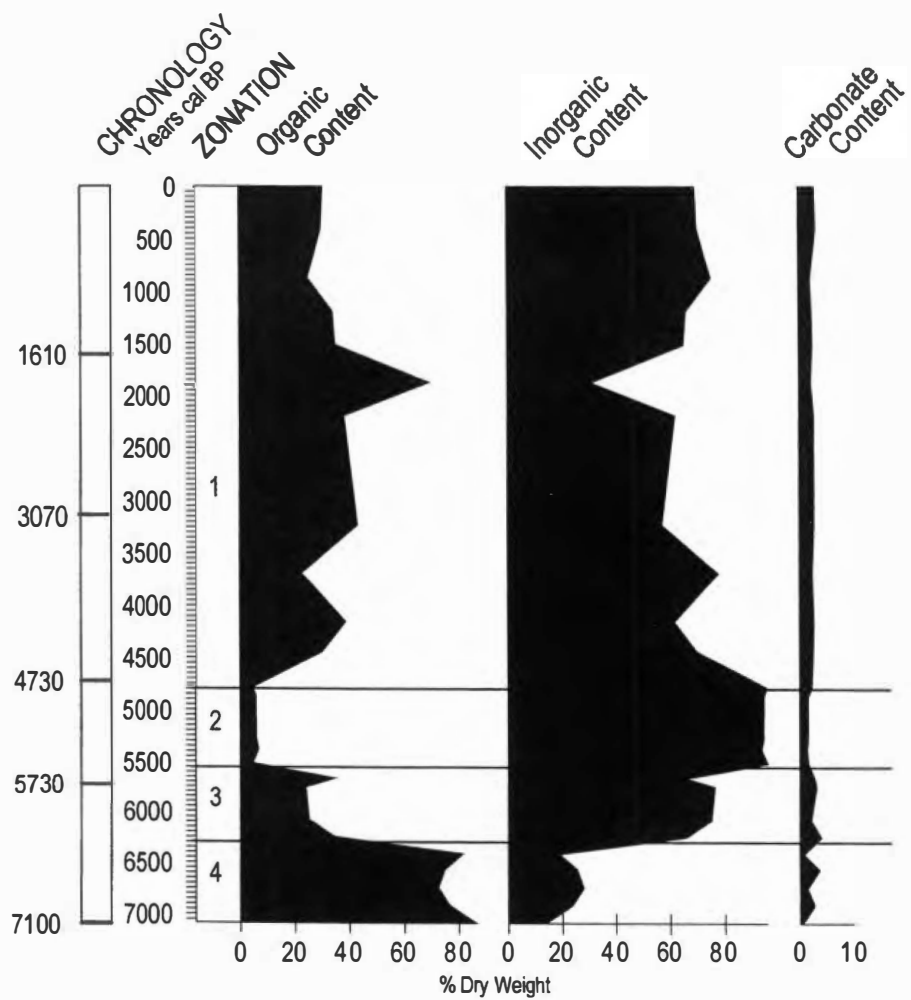


Figure 4.35. Loss on Ignition Results for Laguna Sorpresa

Table 4.12. AMS Radiocarbon Dates for Laguna Sorpresa¹

Lab Number	Core	Depth (cm)	Material Dated	Radiocarbon Date	Weighted Mean BP	Calibrated 2 Sigma Ranges BP	Calibrated 2 Sigma Ranges BC/AD
AA-60656	2001	80-81	Charcoal Fragments	1695 ± 41	1606	1525–1701	
β-158438	2001	371	Charcoal fragments	4860 ± 40	5596	5661–5576 5535–5478	
β-186683	2003	108	Charcoal fragments	2920 ± 40	3067	3210–3177 3173–2949	
β-186684	2003	172	Charcoal fragments	4210 ± 40	4731	4850–4787 4768–4614 4597–4587	
β-184800	2003	278-279	Charcoal fragments	4990 ± 40	5731	5888–5810 5762–5612	
β-181322	2003	386-387	Leaf Fragments	6210 ± 50	7110	7251–6987 6959–6953	

¹Analyses were performed by Beta Analytic Laboratory, Miami FL (β-numbers), or the University of Arizona AMS Laboratory (AA-numbers).

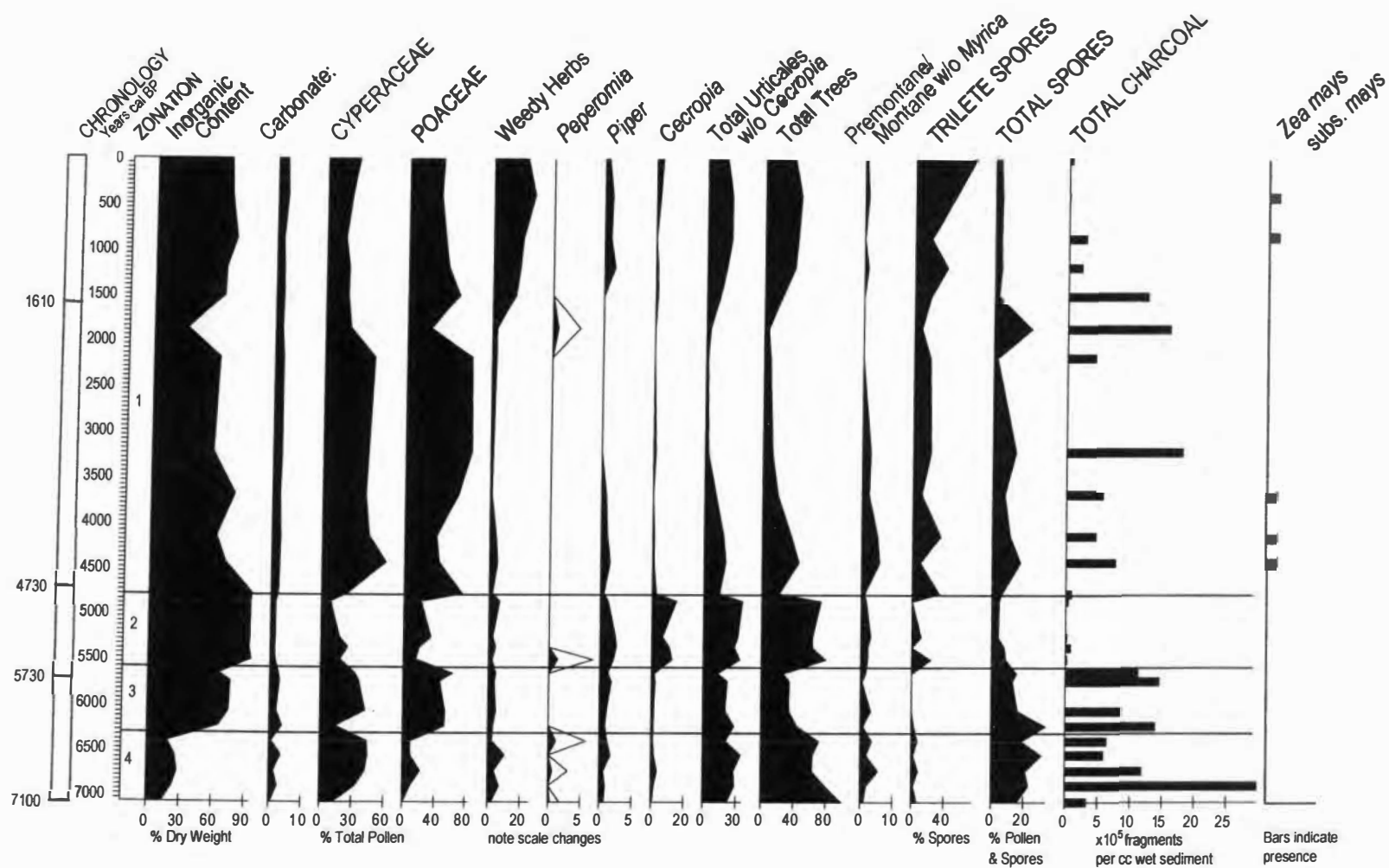


Figure 4.36. Pollen Summary for Laguna Sorpresa

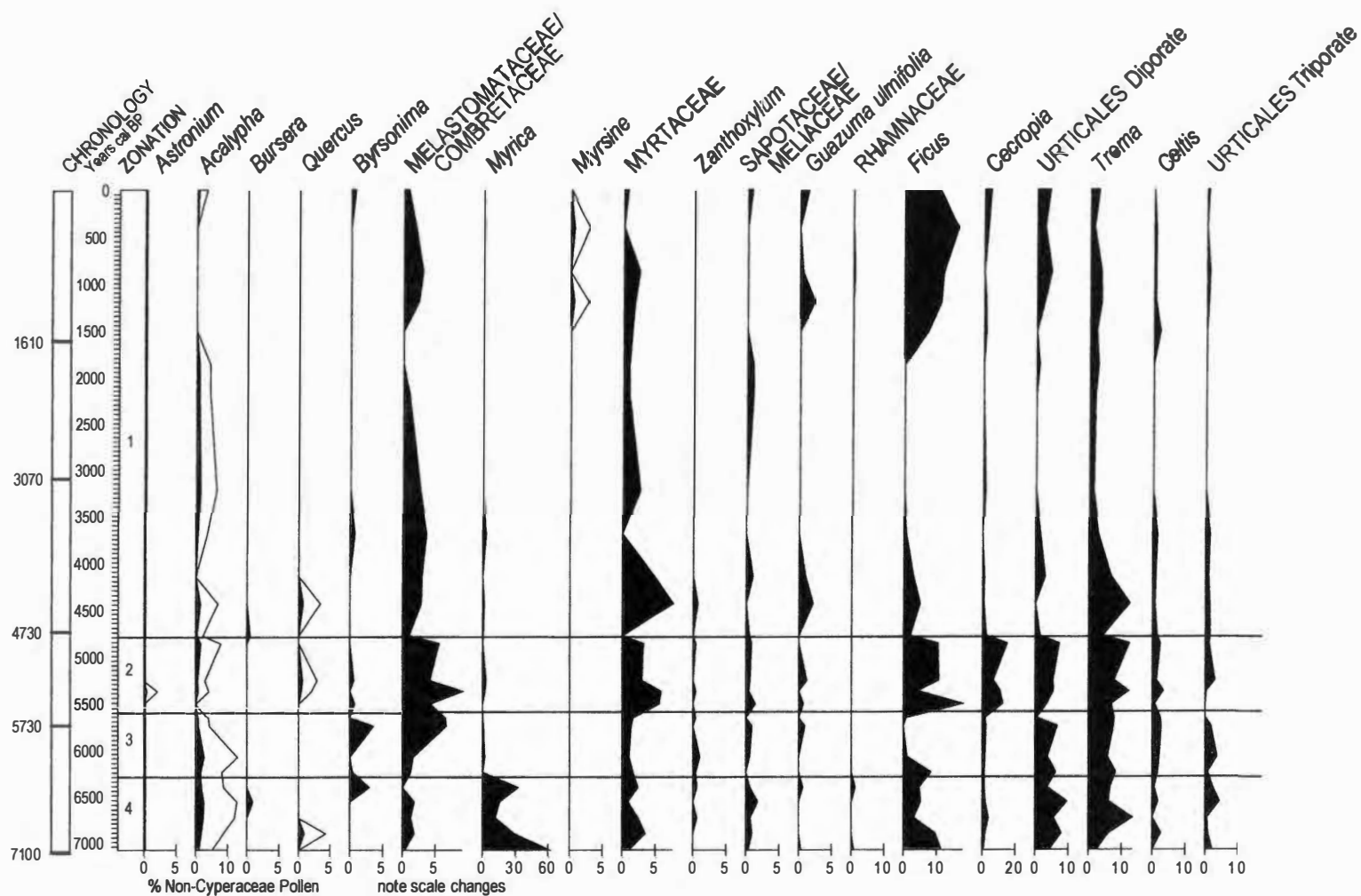


Figure 4.37. Tree Pollen Results for Laguna Sorpresa

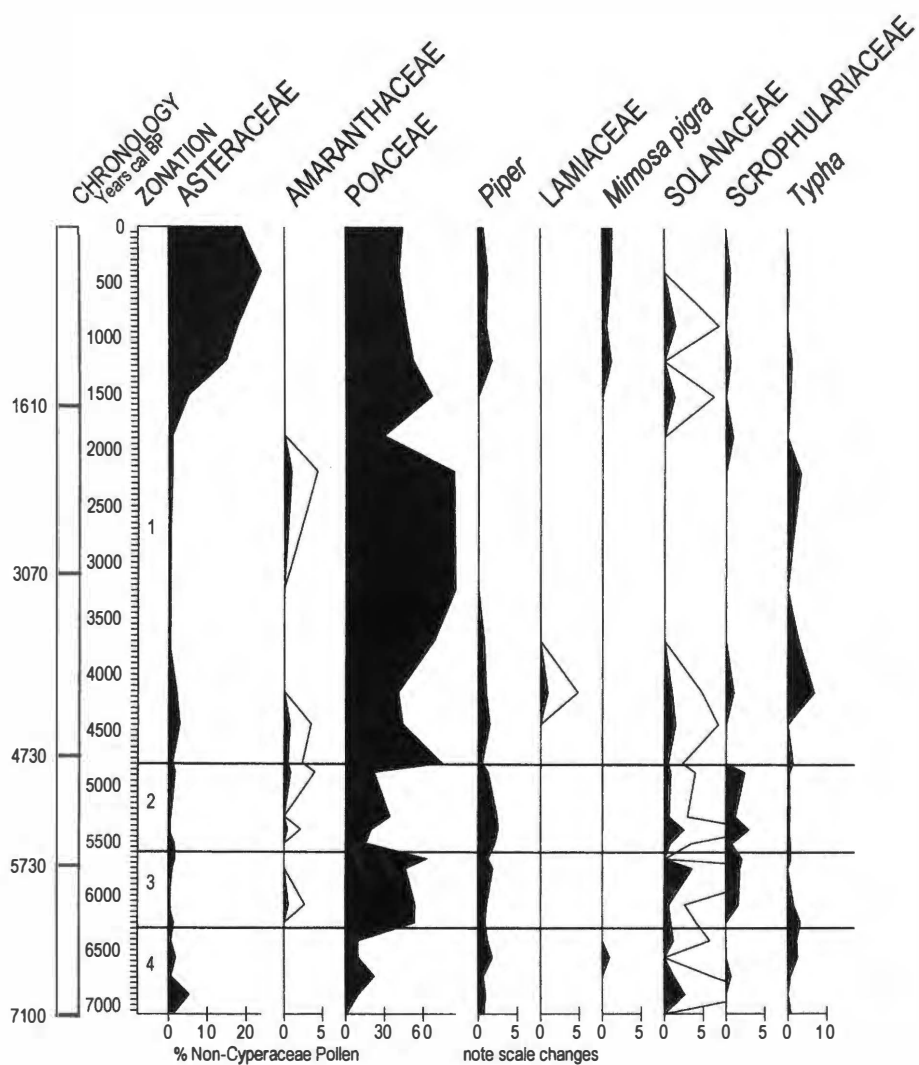


Figure 4.38. Non-Arboreal Pollen Results for Laguna Sorpresa

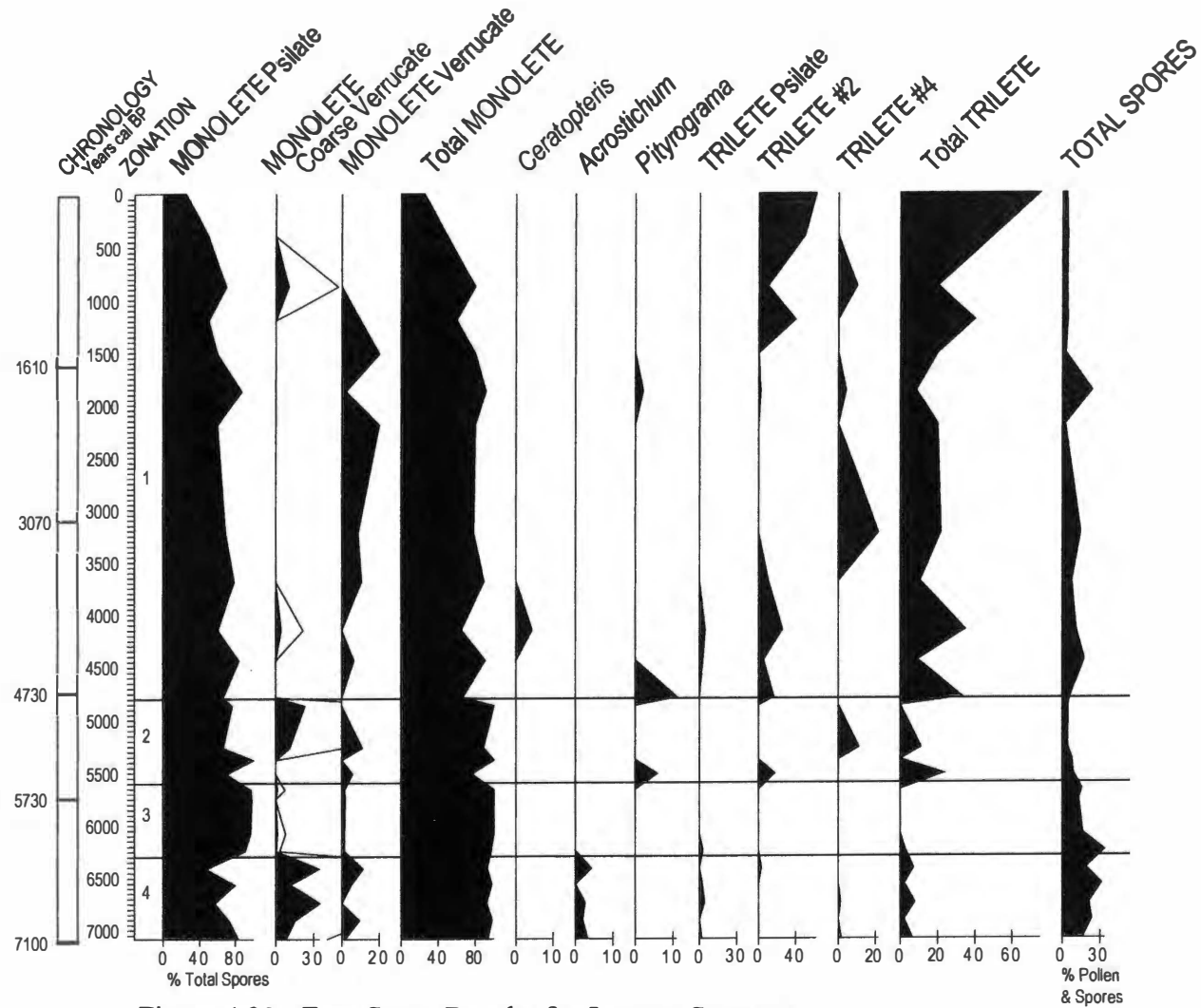


Figure 4.39. Fern Spore Results for Laguna Sorpresa

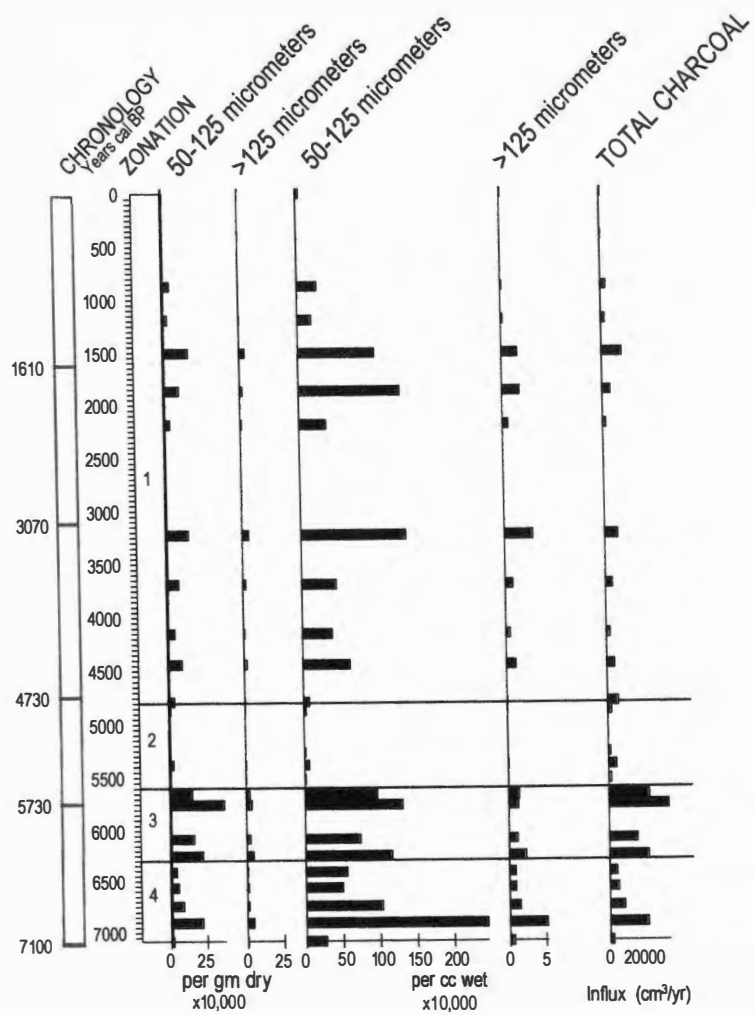


Figure 4.40. Microscopic Charcoal Results for Laguna Sorpresa

low. Moving upcore, tree pollen decreases and Cyperaceae increases. *Myrica* decreases some, but peaks again near the top of the zone. Microscopic charcoal concentration is very high throughout Zone 4, especially near the base of the zone where it is highest of any zone.

The base of Zone 3 (6300–5500 cal yr BP) marks a distinct change in sediment type, from 80% organic to 75% inorganic. Mottling occurs just after 5700 cal yr BP, and sediments above are less peaty and contain rock fragments. Grass pollen rises significantly in Zone 3, while the amount of tree pollen declines. *Ficus* pollen nearly disappears. A small increase occurs in *Byrsonima* and Melastomataceae/Combretaceae pollen. Cyperaceae pollen remains high after a decline at the base of the zone. Charcoal concentration remains high through this zone.

In Zone 2 (5500–4700), the sediments from ~5500–4700 cal yr BP are over 90% inorganic, and contain coarse clastic material (gravels, sands, silts) Pollen from tree taxa increases, mostly *Cecropia*, *Ficus*, Myrtaceae, and diporate Urticales; Melastomataceae/Combretaceae pollen fluctuates but remains around 5%. Grass and Cyperaceae pollen both decrease, Peaks of *Pityrogramma* spores bracket this clastic interval. Microscopic charcoal falls to the lowest concentrations in the core.

Zone 1 (4700 cal yr BP–present) sediments increase to 30–40% organic, with ample organic fibers visible. At about 2000 cal yr BP (interpolated) there is a peak of organic-rich sediments (80%). Maize pollen occurs intermittently through Zone 1. Tree pollen remains low, and Poaceae and Cyperaceae pollen remain high until 1610 cal yr BP. After 1610 cal yr BP, there is a large increase in Asteraceae and *Ficus*, and smaller increases in *Piper*, *Guazuma ulmifolia*, *Mimosa pigra*, Melastomataceae/Combretaceae,

and Urticales diporate. Trilete fern spores increase significantly near the top of the core as well. Microscopic charcoal concentrations show peaks near 3200 and 1800 cal yr BP, but decline after 1500 cal yr BP. In the past ~1000 years, charcoal concentrations are extremely low.

CHAPTER 5

DISCUSSION

REGIONAL ENVIRONMENTAL RECONSTRUCTION

In this section I present a regional synthesis of environmental change, based on my analyses of pollen, spores, and microscopic charcoal contained in the sediment cores from the six lakes studied. I examine and interpret the combined results by using the pollen zones I defined in Chapter 4. Changes in zonal boundaries represent changes in both sediment types and pollen and spore assemblages. The timing of changes varies slightly across the lake basins (Table 5.1). These differences may indicate varying rates of response to climate shifts or differences in the timing of human activities in the individual lake watersheds. Some uncertainty is also inherent in the radiocarbon dating process, which yields ranges of probable years rather than a single date. Use of linear interpolation assumes that sedimentation rates remained constant between dated intervals, yet changed abruptly at dated intervals. However, changes in sedimentation rates will occur between dated intervals, and can be expected between pollen zones. Pollen zone boundaries vary in age slightly between the lakes, as well. Therefore, I designate “regional pollen zone periods,” based on average timing of pollen/sediment changes, and use these regional periods when making comparisons between and among the six lake records (Table 5.1). Key differences between records show how climate change was expressed at sites with slightly different environmental conditions, and how human activities and impacts differed at the six sites.

Table 5.1. Pollen Zones and Dates for Miravalles Lakes¹

Lake	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Martinez	0–3620	3620–5500	5500–6900	6900–7700	7700–8100	8100–8400
Las Brisas	0–3800	3800–5500	5500–6500	6500–7500	7500–8000	8000–8200
Estero Blanco	0–3800	3800–5800	5800–6800	6800–7400	7400–7900	>7900
Los Juncos	0–3900	3900–5640	5640–6500	6500–7400	7400–7500	>7500
San Pablo	0–3600	3600–5500	5500–6700	6700–7300	7300–7900	>7900
Sorpesa	0–4700	4700–5500	5500–6300	6300–7100	not represented	not represented
Regional Periods	0–3800	3800–5500	5500–6800	6800–7500	7500–8000	8000–8400

¹Dates are expressed as approximate cal yr BP.

Considerations for Interpretation

Use of Poaceae and Cyperaceae Pollen

Poaceae (grass) pollen is a common component of sedimentary pollen assemblages. Its abundance is often used as an indicator of past climate or vegetation structure, for example drier climate or more open vegetation. However, Bush (2002) presented evidence that Poaceae pollen should be used with caution when interpreting pollen records. Poaceae pollen may be overrepresented in sediments because grass produces abundant pollen which is widely dispersed by wind, whereas many other tropical plants, especially trees, are not wind-pollinated and produce much less pollen (Bush 2002). Bush (2002) also cautioned against the use of Poaceae pollen to indicate aridity where seasonal flooding occurs, or where lake size varies seasonally. In such sites, increased pollen from Poaceae may reflect more grass pollen coming from the marshy area around the shoreline, not more coming from regional sources (Bush, 2002). During the driest periods, when a lake may be reduced to a seasonal swamp, grass pollen may be low, and other swamp taxa, such as *Typha* and ferns, may dominate. Floating islands of grassy vegetation may also alter the signal of Poaceae pollen recorded in sediments (Bush, 2000; 2002). In his study of pollen rain in Panama and Costa Rica, Bush (2000) found high Poaceae pollen only in samples from lakes with large marshy areas or floating mats of Poaceae. In modern pollen samples from dry, open-canopy *Quercus* forest in lowland Costa Rica, Bush (2000) found only 3% Poaceae pollen. Poaceae pollen in high percentages may sometimes indicate dry conditions, but not necessarily. The story seems to be more complex.

Poaceae pollen is abundant in the sediment of all Miravalles lakes, and is the dominant pollen taxon within certain intervals. The changing amount of Poaceae pollen is significant to the paleoclimate interpretation. The problem is determining the signal. During modern conditions, seasonal changes in precipitation cause water level to change by up to a meter or more in the Miravalles lakes. Several lakes have broad, shallow areas that are seasonally inundated but support grass and other herbs during the dry season. Floating vegetation, which includes abundant grass, nearly covers the surface of Las Brisas. Laguna Martinez had some open water when we cored, but is now completely covered, as are many other lakes in the area that we did not core. Floating islands of grassy vegetation shift across Laguna San Pablo with changes in wind direction. Because grass pollen may have been contributed from the littoral area, or from floating mats, I used caution when interpreting Poaceae pollen as evidence of regional environmental change.

Changes in Cyperaceae pollen are sometimes used to infer changes in water level from sedimentary pollen records, and for paleoenvironmental reconstructions. Cyperaceae is often treated as a swamp or aquatic taxon (Willie *et al.*, 2000; Berrio *et al.*, 2002; Bush *et al.*, 2004; Vélez *et al.*, 2005), but sometimes it is interpreted as a signal of human disturbance (Piperno and Jones, 2003.) In the Miravalles study area, sedges occur along lake edges and in floating vegetation mats. They are also common in pastures, grassy fields, and even in the forest understory along disturbed forest edges. I attempted to control for the abundance and varying ecological roles of Cyperaceae at the lakes by excluding this pollen type from the pollen sum used for determining pollen percentages for all types but itself.

Lake Size and Pollen Source Area

The amount of open water may affect the pollen signal of lake sediments by biasing the local versus regional accumulation of pollen (Jacobson and Bradshaw, 1981; Bush, 2002). Larger lakes with more open water may receive a higher proportion of airfall pollen than pollen from vegetation immediately surrounding the lake, while smaller lakes with less open water may receive a higher proportion of local pollen from adjacent vegetation (Jacobson and Bradshaw, 1981; Bush 2002). However, these observations may not hold true in tropical areas, where few trees are wind pollinated.

Arranged in order of size, the Miravalles lakes include Laguna Sorpresa (currently 0.5 ha, but originally ~1.0–1.5 ha), Lagunas Las Brisas and Los Juncos (0.8 ha), Estero Blanco and Martínez (1.5 ha), and the largest, San Pablo (4.5 ha). Las Brisas and Los Juncos have very similar pollen records. Poaceae and Cyperaceae pollen are more abundant throughout more of the record than at other lakes, and tree pollen never reaches 40% of the total pollen. Fern spores are consistently low, rarely reaching more than 10%. Sediments are nearly all inorganic, and show very little change throughout the length of the cores. These cores are shortest, have the slowest sedimentation rates, and appear to have the most complacent pollen records. However, some of this complacency is a consequence of fewer levels being analyzed, especially at Los Juncos.

The records of Lagunas Estero Blanco, Martínez, and Sorpresa share certain characteristics, as well. While Sorpresa is currently smaller than the other two lakes, recent excavation by the Instituto Costarricense de Electricidad, as part of developing its geothermal energy plants on Miravalles volcano, has reduced the surface area of the lake to half or less of its previous size. Prior to excavation, it may have been close in size to

Martínez and Estero Blanco. These three lake records reveal the most dramatic changes in pollen and spore percentages. Fern spores reach levels of 80% of total pollen and spores in both the Martínez and Estero Blanco cores, and 30% in the La Sorpresa cores, much higher than in the cores from the smaller lakes. Large changes were found in inorganic and organic percentages in these cores.

Laguna San Pablo, the largest lake, seems to have recorded a slightly different signal. Tree taxa pollen is always less than 60% and, like Los Juncos and Las Brisas, Poaceae and Cyperaceae constitute a larger percentage of the pollen throughout the record. Shortly after lake formation, Asteraceae pollen approaches 80% of the total pollen. Like the small lakes, little change was found in the proportions of organic and inorganic sediment. Unlike the small lakes, however, San Pablo has consistently high fern spores percentages.

In summary, the smallest lakes (Las Brisas and Los Juncos) may have recorded a pollen and spore record indicative of edge effect and local vegetation. The medium-sized lakes (Estero Blanco, Martínez, and paleo-Sorpresa) were better at recording local environmental change, as reflected in the changes of pollen and spore percentages and inorganic content of the sediments. San Pablo, the largest lake, received much of its pollen and spores from the lake edge, and changes in pollen and spore abundance may be more indicative of edge effect. According to the model of Jacobson and Bradshaw (1981), based on studies of temperate pollen distribution, a larger surface of open water should yield a more regional pollen signal. I propose that the model does not work at San Pablo because of the low incidence of anemophily in this tropical regional flora as compared to the temperate, more anemophyllous, pollen studied by Jacobson and

Bradshaw (1981). Even with a larger area of open water, there simply was less transport and deposition of “regional” pollen than that of temperate lake studies.

Bunting *et al.* (2004) modeled combinations of pollen taxa variations within a lake basin, holding other basins variables constant, and concluded that vegetation patterning was the most important determinant factor for the “relevant” pollen source area. They suggested that changes in vegetation patterns over time may directly influence the relative pollen source area, and this must be considered when interpreting paleorecords (Bunting *et al.*, 2004). Perhaps factors in addition to basin size contribute to the different pollen signal recorded at Laguna San Pablo. Type of vegetation, and changes in vegetation, may have also played a role in determining the effective pollen source area, and the different signal recorded in the San Pablo sediments.

Discussion of Pollen Zones

Pollen Zone 6 (≥ 8000 cal yr BP)

This interval represents initial clastic sedimentation into the newly formed lake basins. Volcanic activity from Miravalles volcano, including pyroclastic flows and lahars, is dated to about 8200 yr BP (uncalibrated) (Alvarado, 2000). The oldest basal date from the Miravalles lakes is from Laguna Martínez, where a charcoal fragment in the basal clastic sediments yielded an age of 7610 ± 50 BP (8400 cal yr BP). Pollen from tree taxa averaged about 40% of total non-Cyperaceae pollen, with both *Myrica* and *Cecropia* pollen relatively high. Other taxa indicated landscape disturbance, particularly *Pityrogramma* fern spores and Asteraceae pollen. *Pityrogramma* is an early colonizer on disturbed sites such as landslides (Tryon and Tryon, 1982). Spores from *Pityrogramma*

occur at the base of all lake cores that extend into the basal clastic layer. Sediments are highly inorganic, and contain sand- and gravel-sized clasts as well as silts and clays, sometimes banded. Overall, charcoal concentration is low to moderate across the lake cores, with highest relative concentrations at Lagunas Los Juncos and Las Brisas. Fires during this period may have resulted from volcanic activity, although lightning strikes have ignited fires in Guanacaste Province in modern times and cannot be ruled out as a source (Middleton *et al.*, 1997; R. Sanford, pers. comm., to S. Horn). Fires were unlikely to be anthropogenic in this region around 8000 years ago, unless set by roaming hunter-gatherers, since no evidence of occupation exists for that time period. These findings are all consistent with regional landscape disturbance, and match well with the volcanic history (Alvarado, 2000).

Pollen Zone 5 (8000–7400 cal yr BP)

Sediments from this zone have increasing organic content, and represent a switch to lacustrine sedimentation. At Lagunas Estero Blanco and Martínez, tree pollen percentages are generally high, averaging about 70%. These tree taxa include *Cecropia*, *Rhamnaceae*, *Ficus*, *Bursera* and *Acalypha*. The aquatic ferns *Acrostichum* and the floating fern *Ceratopteris* are well represented in the spore record from Martínez and indicate standing water.

Las Brisas and San Pablo show a signal quite different from Estero Blanco and Martínez, with higher microscopic charcoal concentrations, lower tree pollen percentages, and high percentages of weedy taxa. Asteraceae pollen reaches 80% at San Pablo. At Las Brisas, Asteraceae pollen approaches 30%, and *Piper* pollen is over 20%.

Cyperaceae pollen is very low in this zone at both Las Brisas and San Pablo. No pollen or spores from aquatic taxa, which indicated standing water, were present in this zone.

Laguna Los Juncos contains only one sample in this zone, limiting interpretation. Tree pollen represents about 30% of total pollen, and the charcoal concentration is high. *Typha* pollen is about 8% of total non-Cyperaceae pollen, indicating wet conditions. The core from Laguna Sorpresa did not extend deep enough to contain sediments from this zone.

The pollen record from Zone 5 includes mixed signals of continuing disturbance and landscape/vegetation recovery, probably due to variation in local environmental conditions surrounding and within the individual lake basins. The magnitude of volcanic disturbance, as well as the pace of recovery, may have varied from lake to lake.

Pollen Zone 4 (7400–6800 cal yr BP)

The general picture from microfossils in Zone 4 is one of high percentages of tree pollen, moderate to high concentration of microscopic charcoal, and lower water levels in the lake basins. The record from Estero Blanco shows *Myrica* pollen at nearly 60%, and peaty organic sediments, indicating a *Myrica* bog, with lower water levels. The base of the Sorpresa core starts in this *Myrica* bog zone, with a high but declining percentage of *Myrica* pollen, and a small amount of *Typha* pollen and *Acrostichum* spores, again indicating lower water levels. Charcoal concentration is highest of any zone in the Sorpresa core. Martínez, however, has low charcoal concentrations and continues to have high percentages of tree pollen, especially *Trema*, Rhamnaceae, and Melastomataceae/Combretaceae. Sediments in the upper part of this zone of the Martínez core have mottling suggestive of root traces and/or desiccation. In the San Pablo record,

Zone 4 contains high amounts of Asteraceae (30%), but less than the previous zone, and an increase in both tree and grass pollen. Charcoal concentration and influx continue to remain high as in Zone 5. Both the Los Juncos and Las Brisas records have a slightly increasing trend in the amount of tree pollen and slightly decreasing amount of grass pollen moving upcore, with charcoal concentrations remaining high.

Environmental change, based on microfossils, was not consistent between lakes, but there may be patterns of change based on lake size and/or basin characteristics. Los Juncos and Las Brisas both have high percentages of grass and sedge pollen, and relatively high concentrations of microscopic charcoal. They are the smallest lakes and their pollen records should therefore be more susceptible to edge effects. The larger lakes Estero Blanco and Martínez and higher elevation lake Sorpresa may have maintained moist basins with closed gallery forest, causing the higher percentages of tree pollen. San Pablo, the largest of the study lakes, has a pollen and charcoal signal much more like that of the smaller lakes Los and Las Brisas. It may be that the large area of open water received a strong regional signal of charcoal but, because most regional trees are not wind pollinated, the pollen of edge plants (Poaceae, Cyperaceae, and fern spores) may have overwhelmed the regional pollen signal.

One explanation for increased tree pollen and charcoal is a stronger seasonality of precipitation, with a wetter wet season that produced more growth and fuel for fire during the dry season. The resulting large fluctuations in lake levels would have enhanced the edge-effect, increasing the input of Poaceae and Cyperaceae pollen. Schlachter (2005) attributed high macroscopic charcoal at Estero Blanco during this zone to increased seasonality. However, the lower lake levels indicated by the presence of *Myrica* bogs at

two sites more likely indicates overall drier conditions. My interpretation is that regional climate conditions were more arid during this period, with a drier wet season, but that the lakes maintained moist conditions due to groundwater availability which supported gallery forest. The groundwater recharge area is the upper Atlantic slope of Miravalles volcano and the cloud spill-over on the uppermost Pacific slope. As long as adequate precipitation occurred on the windward and wetter slope, the study lakes on the rainshadow side may have maintained high enough moisture levels to support gallery forest at Lagunas Martínez, Estero Blanco, and Sorpresa while the regional Pacific climate regime was more arid, with increased regional fires.

Pollen Zone 3 (6800–5500 cal yr BP)

Zone 3 is in general a period of increased tree pollen. Grass pollen and charcoal concentrations remain high but decline somewhat in the Los Juncos and Las Brisas records. Tree pollen represents about 60% of the Martínez non-Cyperaceae pollen, although Cyperaceae does remain high. The base of Zone 3 in the Martínez core contains a dense layer of coarse organics within mineral sediments that probably represent the transition from dry conditions in Zone 4 to a wetter environment. Tree pollen and fern spores are both abundant in the San Pablo core, but a gap exists in sediment recovery from about 6000–5500 cal yr BP. During this zone at Sorpresa a general decline occurs in tree pollen (including *Ficus*) while grass pollen increases, although Melastomataceae/Combretaceae pollen does increase. Charcoal concentrations remain high at Sorpresa and Estero Blanco. Estero Blanco has other evidence of disturbance. Large swings occur in the percentages of Cyperaceae, Poaceae, tree pollen, weedy herbs (Asteraceae, Scrophulariaceae, and *Typha*), and fern spores. The changes in vegetation and fire

frequency in this zone may have resulted from a change in the amount or seasonality of precipitation. However, despite evidence of forest disturbance, the general trend is one of increased tree pollen.

Pollen Zone 2 (5500–3700 cal yr BP)

In Zone 2, strong variability was evident in the pollen signals within and between the six lake records, and the first evidence of human presence was found. An apparent hiatus, or sediment discontinuity, exists in the Los Juncos core with only 5 cm of sediment between dates of 5640 and 3890 cal yr BP (^{14}C dates of 4910 ± 40 and 3590 ± 40). Mottling of the sediments occurs below the older of the two dated intervals. In the Sorpresa core, there is nearly a meter of coarse gravels, sands, and pieces of wood that probably were deposited during a landslide event. Dates below and above this interval are 5731 and 4731 cal yr BP, respectively. A steep slope abuts the lake to the northeast and could have been the source of the landslide. The general pollen trend is one of higher tree pollen early in Zone 2, then a rapid decrease in tree pollen and a large increase in both Poaceae and Cyperaceae, and increasing charcoal concentrations, by the end of the zone. Timing of this shift, based on interpolated ages, varies between lake records, but ranges from about 4700 to 4000 cal yr BP.

Of particular significance is the presence of maize pollen during this time period from the Martínez (5500 cal yr BP), Sorpresa (4557 cal yr BP; Sorpresa Zone 1), and San Pablo (4052 cal yr BP) cores (Figure 5.1). Maize appears in the Martínez record prior to significant increases in microscopic charcoal and the pollen shift from trees to grasses and sedges. The shift from tree to grass pollen occurs simultaneously with the first maize pollen in the Sorpresa sediments. Other lakes show a decrease in tree pollen and increases

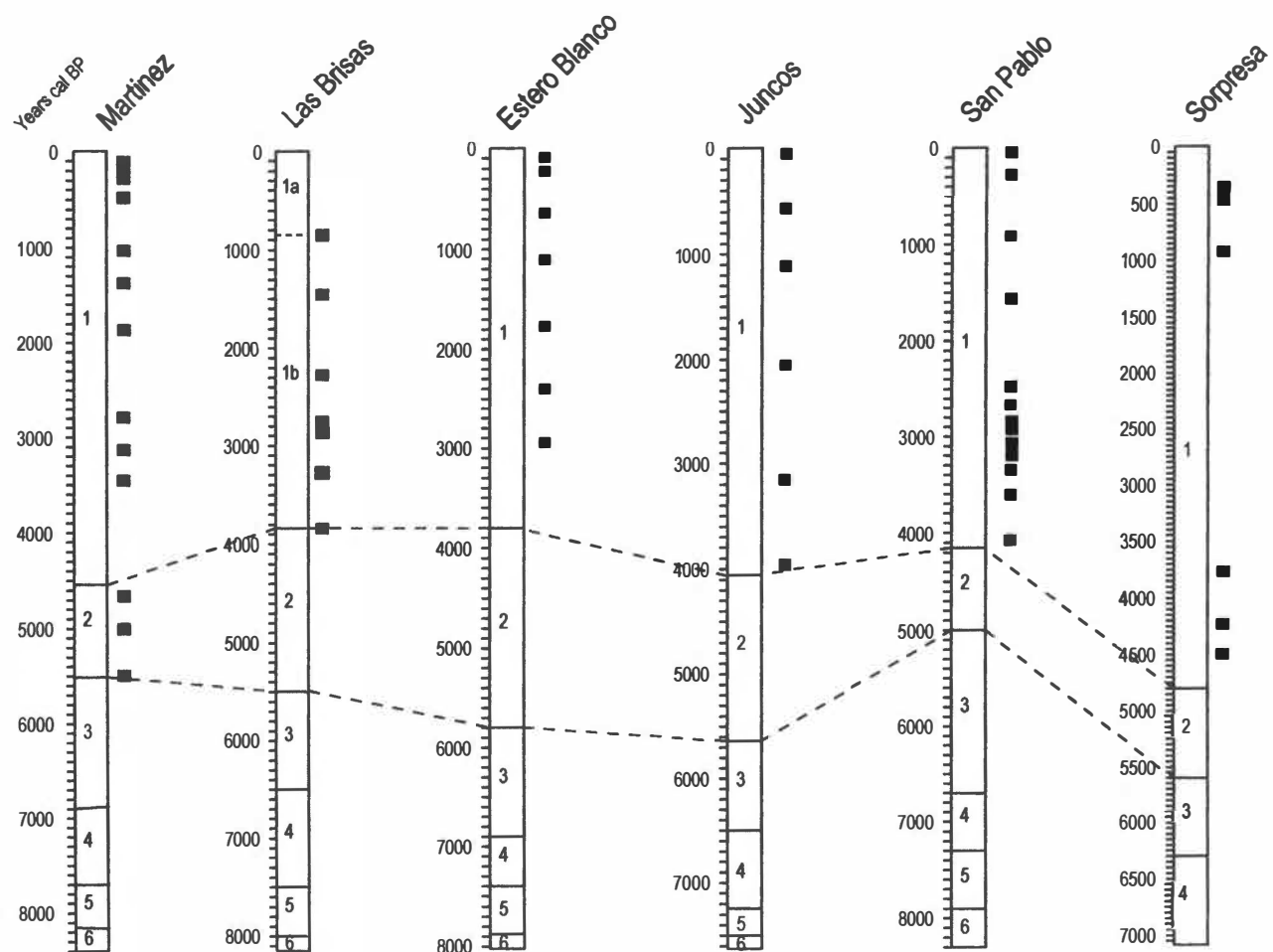


Figure 5.1. Schematic Comparison of Maize Pollen Presence in Sediment Cores from Six Miravalles Lakes

in charcoal in this zone in the absence of maize pollen. However, these changes may still be the result of human activity, including agriculture, near the lake basins. The regional environment represented by the upper part of Zone 2 was probably beginning to see strong impacts of human activity.

Pollen Zone 1 (3800 cal yr BP to Present)

Human activity dominates Zone 1. Maize pollen occurs in many levels from all six lake cores (Figure 5.1). Peaks in microscopic charcoal concentration occur at most lakes between 2800 to 1600 cal yr BP, most likely a result of anthropogenic fire. The pollen record continues to be dominated by Poaceae and Cyperaceae, with low percentages of tree pollen, until the upper part of the zone. Increases in tree pollen, which may indicate cessation of agriculture or abandonment of the lake sites, occur at different times. An increase in tree pollen begins just after 1000 cal yr BP at Martínez, about 1200 cal yr BP at Las Brisas, 600 cal yr BP at Estero Blanco, 1300 cal yr BP at Sorpresa, and not until modern times at Los Juncos. Tree pollen never increases much at San Pablo, but within the last few hundred years Cyperaceae and Poaceae decrease, and fern spores and pollen from *Piper* increase. The high percentage of *Piper* pollen (30–50%) may overwhelm the pollen signal and mask an increase in pollen from other tree taxa.

COMPARISON TO ARCHAEOLOGICAL RECORDS

My analyses of sediments, pollen, spores, and microscopic charcoal has revealed patterns of human occupation and agriculture that add to interpretations made from archaeological data. The first maize pollen occurs at 5500 cal yr BP (4760 ± 40 ^{14}C) at

Laguna Martínez, and occurs in each succeeding five-century period at at least one lake (Table 5.2). This is the earliest pollen evidence of maize agriculture in Costa Rica (Arford and Horn, 2004; Appendix B). Because maize requires cultivation, the presence of pollen from this plant in the lake sediments indicates that humans were present at the site, either settled permanently or visiting the site frequently to tend maize fields. Prior archaeological research suggested that humans occupied the region by about 1500–1800 BC (3450–3750 BP) (Alvarado, 2000). The pollen evidence from Laguna Martínez pushes back occupation time by over 1500 years. This finding indicates that further research should reveal archaeological evidence for earlier human occupation in the Miravalles region.

Human abandonment of archaeological sites in the greater Miravalles area is suggested by about AD 100–1000 (1950–950 BP) (Rio Naranjo-Bijagua Valley; Norr, 1982–83), and at the end of the Zoned Bichrome Period, 500 BC–AD 300 (2450–1650 BP) (Hacienda Jerico, Finch, 1982–83; Hacienda Mojica, Ryder, 1982–83a; Guayabo de Bagaces, Ryder, 1982–83b). Snarskis (1981) reported declining population in the volcanic foothills around AD 1000–1500 (950–450 BP), while Hurtado de Mendoza and Alvarado (1987) reported a population increase between AD 1200–1550 (750–400 BP). Interpretation of abandonment from the sediment records is difficult, especially with the poor resolution and few radiocarbon dates of the last several hundred years. But, some intriguing patterns emerge when proxy indicators are considered in light of those archaeological interpretations.

Increases in the percentage of tree pollen in the sediment records and decreases in charcoal concentration could suggest abandonment of agriculture and subsequent forest

Table 5.2. Comparison of Dates of Maize Pollen Occurrence from the Miravalles Lake Records¹.

Martínez	Las Brisas	Estero Blanco	Los Juncos	San Pablo	Sorpresa
modern	863	modern	modern	modern	298
155	1415	213	484	267	398
163	2175	622 ²	1048	758	875
290	2651	1067	1993	872 ²	3690
505	2783	1601	3117	1538	4152
1045	3124	2224 ²	3890 ²	2438	4557
1377	3623	2788		2659	
1872				2796	
2797				2907	
3156				3067	
3412				3187	
4641				3327	
5000 ²				3568	
5500 ²				4052	

¹ Dates are interpolated cal yr BP except as noted.

² Date is the weighted mean age in cal yr BP of organic material removed from the same sediment interval as the pollen sample.

regrowth around AD 950 at Laguna Martínez, about AD 750 at Las Brisas, about AD 1350 at Estero Blanco, and about AD 650 at Sorpresa. These rough dates are within the ranges suggested by previous archaeological studies. However, a significant finding of this study is that sites were not completely abandoned at these times. The presence of maize pollen in nearly all Zone 1 samples from all lakes indicates that maize agriculture continued through Archaeological Period V and into Period VI (Table 2.2). Continued maize agriculture at the lakes indicates the presence of at least small populations despite evidence for concurrent forest regrowth. Agriculture may have been conducted on a smaller scale, and agricultural practices may have changed to involve less reliance on fire and less disturbance to vegetation to maintain fields than earlier maize agriculture. A similar interpretation was drawn from a study of Lagunas Bonillita and Bonita, in the Atlantic lowlands of Costa Rica (Northrop and Horn, 1996). Perhaps small agricultural plots were located on the very shores of the Miravalles lakes, where seasonal changes in lake level provided fertile and open space for growing maize without the need for fire. My results indicate that further archaeological investigation in the region will yield new evidence of human occupation patterns that contradicts regional interpretations of site abandonment in Archaeological Period V.

PALEOCLIMATE INTERPRETATION AND COMPARISON WITH OTHER PROXY RECORDS

My results suggest there were significant changes in climate patterns on the Pacific slope of Volcán Miravalles during the past 8000 years, based on inferred water levels in the lake basins and changes in pollen assemblages. Shortly after the basins

formed following pyroclastic flows, lake bottoms were sealed with fine-grained material such that they could hold water and accumulate lacustrine sediments. During the period 7900–7400 cal yr BP, adequate precipitation maintained water in the lakes. Between 7400 and 6800 cal yr BP, water levels dropped, yielding boggy conditions and intermittent drying of some of the lake basins. From 6800–5500, tree taxa increased around standing water in the basins, but water levels may have fluctuated considerably. From this period on, the water levels are difficult to infer, especially because human activity, including agriculture, was beginning. An apparent sediment hiatus occurs in the Laguna Los Juncos and Las Brisas records around 5500–4000 cal yr BP, and probably represents a drying interval. This time interval is represented in the Laguna Martinez record with a short core section where sedimentation was very slow or intermittent. Mottled sediments, representing dry periods, occur just before 5800 cal yr BP in cores from Estero Blanco and Los Juncos, and prior to 4000 cal yr BP in the cores from Las Brisas, San Pablo, and La Sorpresa. Sedimentary evidence from all lakes shows a drying interval around 2500 cal yr BP, with peat accumulation at Sorpresa, sediment mottling at Los Juncos, Estero Blanco, San Pablo and Martínez, and clasts and mottling at Las Brisas.

The general pattern from the Miravalles lakes is low water levels between 7400–6800 cal yr BP, fluctuations in water levels until about 5500 cal yr BP, and drier conditions with drying episodes around 4000 and 2500 cal yr BP. This is consistent with findings from some paleoecological studies in the neotropics, and in opposition to others.

A number of records from the circum-Caribbean area show evidence of dry climates at about 1200 cal yr BP (Lane, 2007), including records from Costa Rica (Horn

and Sanford, 1992; Horn, 1993 and unpublished data; Haberyan and Horn, 1999). This period is coincident with the decline of the Mayan civilization (Hodell *et al.*, 1995; Curtis *et al.*, 1996; Haug *et al.*, 2003; Neff *et al.*, 2006), and is an example of a possible impact of prehistoric climate on human culture. The time resolution in this part of my lake records is poor, preventing an accurate assessment whether this drought episode also affected northwestern Costa Rica. In general, 1200 cal yr BP falls within a period of slight increases in tree pollen in the Estero Blanco and Sorpresa records, and high Poaceae and low tree pollen in the other lake records. One sample from Los Juncos is dated at 1294 cal yr BP, but disturbance in this pollen record or the sediments is not evident.

A period of drought was documented around 2500 cal yr BP in the Yucatan Peninsula (Hodell *et al.*, 1995), and on the island of Hispaniola (Hodell *et al.*, 1991). Possible evidence for drier climate at this time also exists in the Caribbean lowlands of Costa Rica (Horn and Sanford, 1992), in the highlands of the Cordillera de Talamanca (Horn, 1993; Haberyan and Horn, 1999), and at Laguna Gamboa in southern Pacific Costa Rica (S. Horn, unpublished data).

A number of records show these drought intervals at ~2500 and 1200 cal yr BP to be embedded within a general trend towards drier conditions beginning between about 5000 cal yr BP and 3000 cal yr BP, apparent in records from the wider circum-Caribbean region, including Hispaniola (Hodell *et al.*, 1991; Higuera-Gundy *et al.*, 1999), the Yucatan Peninsula (Hodell *et al.*, 1995, 2000), Venezuela (Bradbury *et al.*, 1981; Binford 1982; Leyden 1985; Curtis *et al.* 1999), the Bahamas (Kjellmark, 1996), and the Cariaco Basin (Haug *et al.*, 2001). The studies that show the replacement of wetter mid-Holocene

conditions by dry conditions were all conducted at sites on the eastern side of the mountainous central cordilleras of Mexico and Central America.

In the circum-Caribbean region, earlier (around 7000–5000 cal yr BP) wetter conditions are attributed to a more northerly summer position of the Intertropical Convergence Zone (ITCZ), which created warmer and wetter conditions during the mid-Holocene. However, results from the Miravalles study, on the western (Pacific) side of Central America, indicate that drier conditions began much earlier, by 7400 cal yr BP, and occurred intermittently thereafter (6800, 5800, 5500–4000, and 2500 cal yr BP).

Some studies conducted on the Pacific slope of Central America also reported drier mid-Holocene conditions as evident in the Miravalles lake records. Dull (2004) reported a sediment hiatus due to drier climate conditions between 8200–3300 cal yr BP at Laguna Verde, El Salvador. Bush *et al.* (1992) reported a similar dry phase between 8200–5500 cal yr BP at Lake Yeguada, Panama. In Colombia, many studies document mid-Holocene aridity (Marchant *et al.*, 2001, 2002; Berrío *et al.*, 2002; Vélez *et al.*, 2003, 2005). Other studies in northern South America indicate warmer and wetter conditions remained during the middle-Holocene (Sandweiss *et al.*, 1996; Rodbell *et al.*, 1999; Haug *et al.*, 2001). An earlier shift to increased aridity prior to 5000 BP was also noted in Central Mexico sites (Metcalf *et al.*, 1991, 1997; Metcalf, 1995).

Some neotropical studies have suggested that current El Niño Southern Oscillation (ENSO) cycles did not begin until around 5000 BP (Sandweiss *et al.*, 1996; Rodbell *et al.*, 1999; Haug *et al.*, 2001). Concurrently, warm coastal waters along Pacific South America switched to cooler water as the ITCZ shifted southward, a stronger gradient developed in sea surface temperature (SST), and increased trade wind strength

lead to more upwelling (Sandweiss *et al.*, 1996; Rodbell *et al.*, 1999; Haug *et al.*, 2001). This change resulted in drier conditions in South America, overall, but with stronger storms and more clastic sedimentation caused by ENSO events.

Summer precipitation in the Province of Guanacaste, Costa Rica, occurs when the ITCZ has shifted northward in the northern hemisphere summer. Precipitation does not come from the moist, warm Caribbean air masses, but from moist air masses that move landward from the Pacific coast. Winter dry conditions result when the strong northeasterly winds prevail, from the Caribbean, but the Pacific slopes are in the rainshadow and receive little to no rainfall. Given the southward shift of the ITCZ that caused drier conditions in South America after 5000 BP (Sandweiss *et al.*, 1996; Rodbell *et al.*, 1999; Haug *et al.*, 2001), this should suggest drier conditions in Guanacaste after 5000 BP. But results from the Miravalles lake study indicate a shift to drier climate conditions around 7400 cal yr BP, about 2500 years earlier than the South American sites. During the early to middle-Holocene, some other mechanism may have been operating that prevented landward movement of wet air masses from the Pacific into Central America. A possibility is that colder eastern Pacific sea surface temperatures influenced regional wind patterns and caused drying on the Pacific side of Central America, while the Caribbean slope remained wetter.

In the circum Caribbean, studies indicate warmer and wetter conditions during the early to middle Holocene due to a more northerly summer position of the ITCZ (Rodbell *et al.*, 1999; Haug *et al.*, 2001), and warmer, not colder, water is indicated off the Peruvian coast from 8000 to 5000 BP (Sandweiss *et al.*, 1996). Mayewski *et al.* (2004) reported in their synthesis of Holocene climates a wetter period from 6000–5000 cal yr

BP in the Caribbean and the Cariaco Basin, while lake levels were lower in Titicaca. This pattern is repeated again, between 4200 and 3800 cal yr BP, when Haiti is wet but lake levels in Titicaca once again fall (Mayewski *et al.*, 2004). Clearly, a need exists for more in-depth evaluation of Holocene paleoclimate patterns in the neotropics to understand the hemispheric and regional changes in climate conditions. The Miravalles sediment records contribute to understanding of regional patterns because they are from an understudied part of Central America and extend well into the Middle Holocene, in contrast to many records in Central America that only begin in the Late Holocene.

TRENDS IN FOREST COMPOSITION AND STRUCTURE

Like other tropical forests, the seasonal forests of the Miravalles region contain many taxa that are unrepresented in pollen records. These “silent taxa” (Bush *et al.* 1992) are present in the vegetation, but not in pollen records owing to their manner of pollination. The high proportion of tropical taxa that show up rarely or never in pollen records makes it impossible to reconstruct the past forest composition in great detail. However, an evaluation of past forest composition is possible by comparing pollen spectra over time to detect possible shifts in floristic composition.

Comparison of the record of forest taxa pollen in the Miravalles lakes revealed reduced percentages of tree pollen since human occupation occurred. Prehistoric land use decreased the amount of tree cover, at least in the pollen catchment of the Miravalles lakes. Only recently has there been any significant increase in tree pollen percentages. The same tree taxa that were frequent prior to human disturbance are part of the modern increase in tree pollen, just at much lower percentages now. Some increases in tree

pollen occurred prior to European arrival. This period of forest regrowth, prior to European conquest, may represent less intense land use by prehistoric peoples. In modern times, much of the land cover is pasture, but there are gallery forests around the lakes, remnant forest patches are found on surrounding slopes, and abandoned fields exist in various stages of secondary succession.

While most of the pre-human disturbance tree taxa are represented in modern pollen samples, one exception to this pattern was found in Zone 4 (7500–6800 cal yr BP). *Myrica* pollen was very high, about 60% of total pollen for this entire zone in the Estero Blanco record, and 60% at the base of Zone 4 in the Sorpresa record. As mentioned previously, this *Myrica* increase is concurrent with peaty sediment accumulation that suggests lowered water levels and the formation of *Myrica* bogs. No modern increase in the amount of *Myrica* pollen was observed.

FIRE HISTORY AND FOREST “RESTORATION” IN GUANACASTE

Variations in microscopic charcoal concentration (number of particles >125 μm per cc) reveal significant changes in fire regimes in the Miravalles area over the 8000-year span of the sediment cores (Figure 5.2). Charcoal concentrations show variability within and between cores. The highest concentrations occur in the Laguna Martínez core with nearly 8×10^6 particles per wet cc of sediments in the most charcoal-rich sample. Overall, the Laguna Los Juncos record has the lowest charcoal concentration. While charcoal profiles from the six lakes differ slightly, together they reveal general patterns in regional fire history, with four main intervals of increased fire.

High microscopic charcoal values occur in the basal sediments that followed lake formation (>8000 cal yr BP, Zone 6), but this initial rise does not show up in the Estero Blanco and San Pablo cores. These earliest fires likely resulted from volcanic episodes and/or lightning.

From 8000 to 6800 cal yr BP (Zones 5 and 4), charcoal concentrations remain moderately high at Lagunas Las Brisas, Los Juncos, and San Pablo; decrease at Laguna Martínez; and remain low at Estero Blanco. In the Sorpresa core, which begins at ~7000 cal yr BP, charcoal concentrations are high. This period of increased fire between about 8000 and 6800 cal yr BP was probably due to drier climate conditions, or possibly stronger seasonality of rainfall. Martínez and Estero Blanco may have maintained moister conditions within their basins, yielding a record of lower charcoal concentrations and higher percentages of tree pollen.

Charcoal concentrations increase in the Martínez, Sorpresa, and Estero Blanco records, and remain moderately high at Los Juncos, during pollen Zone 3 (6800–5500 cal yr BP). During this period the lake records contain other evidence of changing water levels associated with drier episodes, including mottling of the sediments. In the absence of any known occupation this early, increased charcoal likely reflects climate drying and natural fires. Charcoal concentrations decrease in all lakes after 5500 cal yr BP, in Zone 2.

Later increases in charcoal concentrations, associated with human disturbance and maize agriculture (3800 cal yr BP to present, Zone 1), occur in the sediments from all six lakes. Concentrations mainly peak in the early period of maize agriculture, and decline through the late Holocene. This period of increased fire corresponds well with

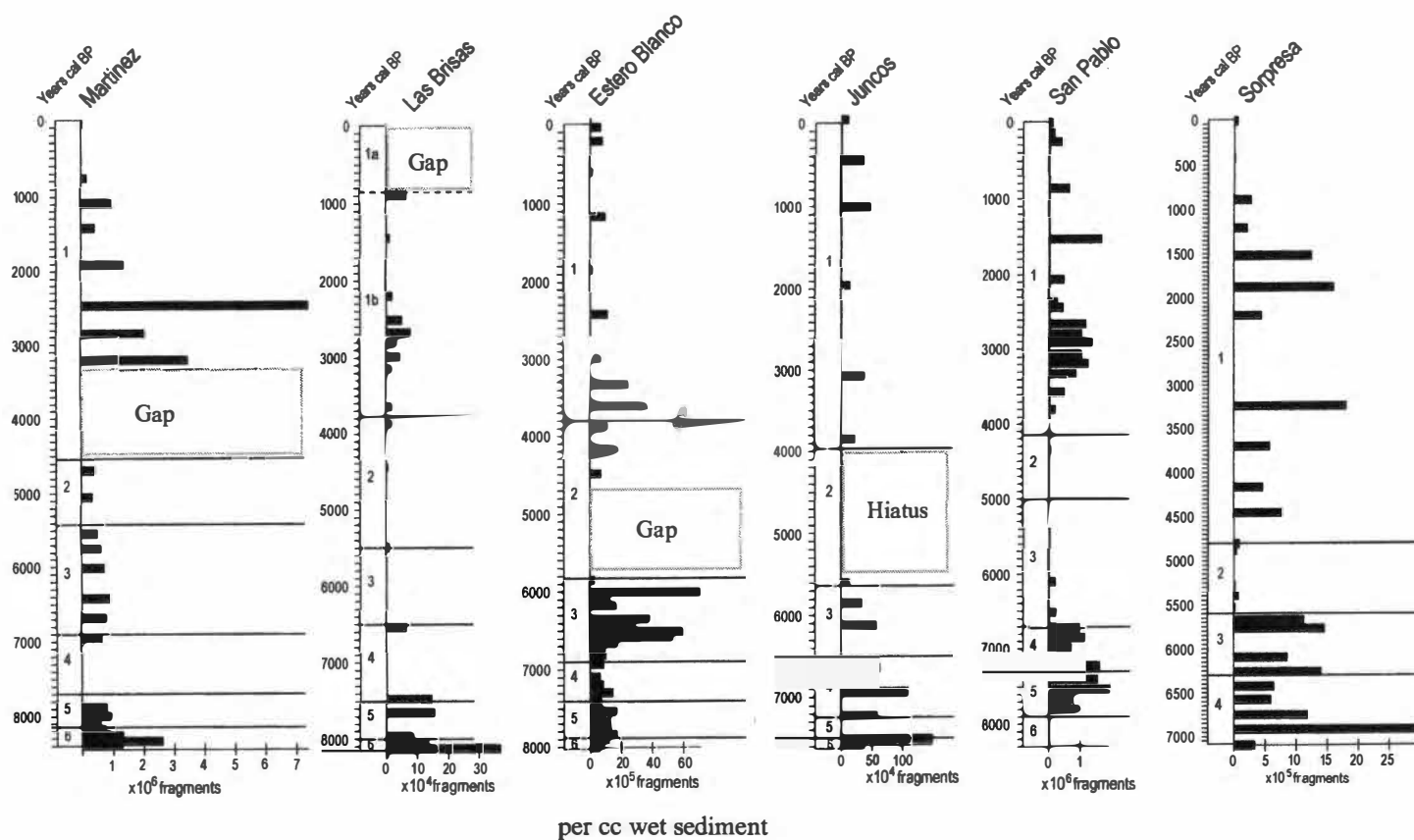


Figure 5.2. Schematic Comparison of Microscopic Charcoal Abundance in Sediment Cores from Six Miravalles Lakes

occupation times cited in archaeological studies. However, this decline in charcoal concentration occurs despite pollen evidence of continuing maize agriculture. This suggests that burning may not have been an important agricultural practice once cultivation areas had been established. Maize pollen is large and poorly dispersed (Horn, 2006), and one would expect charcoal to be at least as well dispersed as maize pollen if fire was used in maize cultivation. Periods of drier climate may have contributed to increased burning during the zone of maize agriculture, as well, but it is difficult to separate the human from climate signals.

A companion study of macroscopic charcoal from the Estero Blanco core (Schlachter, 2005) revealed that the macroscopic charcoal stratigraphy matched very closely with my microscopic charcoal stratigraphy. Macroscopic sedimentary charcoal is used to determine local fire history with the idea being that larger charcoal fragments are transported only short distances and thereby indicate nearby fires (Whitlock and Larsen, 2001). That the micro- and macroscopic charcoal records were so similar at Laguna Estero Blanco suggests that the microscopic charcoal was also recording primarily local fire signals. That microscopic charcoal concentrations appear to represent local fire is significant, and differs from most interpretations of size and source area for sedimentary charcoal. (Schlachter, 2005).

That fire has been part of the Miravalles regional landscape for over 8000 years contrasts with ideas proposed by Janzen (2002) that seasonal forest in the Guanacaste Conservation Area has not been influenced by natural fires, except possibly in the "distant past." Janzen (2002) noted that some hilltops may have been burned off by prehistoric people, but stated that no fire-maintained, natural savannas existed in the

region in prehistoric time. The sedimentary charcoal and pollen data confirm a long history of fire, and suggest that prehistoric fire was detrimental to forest growth and development. For example, during periods of increased charcoal concentrations in the Miravalles sediment records, tree pollen percentages decrease and grass pollen usually increases. This finding may suggest that fires created areas with more open vegetation at the expense of forest. However, as presented earlier, increases in grass pollen may not have indicated open forest, or increased grassland, but may have reflected changes in vegetation at the lake edge. In any event, natural fires did occur in seasonal forest in the Miravalles study area during prehistoric times. Fire was also used for a few thousand years by prehistoric agriculturalists. Unfortunately, in neither period can the areal extent and magnitude of fire be reconstructed from the sediment records of pollen and charcoal. However, my research refutes the idea that fire is an unnatural component of tropical dry forest ecosystems in Costa Rica. Fires set by volcanism, lightning, or humans have occurred for at least 8000 years. Management and restoration efforts that focus on the complete elimination of fire may not produce ecologically desirable outcomes, and are not recreating a prehistoric forest community.

Another finding of my study relevant to management is the evidence of rather continuous ecosystem change preserved in the sediments of the Miravalles lakes. Any management effort directed toward recreating a past ecosystem and set of ecosystem disturbance regimes will need to identify the period of interest, and grapple with the issue that the climate during that past period may be significantly different than today's climate (Horn, 2003). Forest "restoration" efforts in the Guanacaste region may be inherently untenable. If previous forests existed under climate conditions that differ from now, we

may be unable to ever “restore” them. However, we may be able to create new forest communities with desired conditions that can be sustained by active management under the modern climate regime.

CHAPTER 6

SUMMARY AND CONCLUSIONS

This paleoecological study from six Miravalles lakes has revealed an 8000 year history of significant disturbance and environmental change. One key element of my study is the use of six nearby lakes to reconstruct both individual local records of change, and a combined regional history of climatic and anthropogenic changes. This study developed the oldest sediment record from lowland Costa Rica, and provided findings of ecological, archaeological, and climatological interest.

Following lake basin formation, just after 8000 cal yr BP, wet climate conditions existed and the lakes maintained standing water. During the early mid-Holocene (7400–6800 cal yr BP), climate conditions became much drier. In two of the lake basins *Myrica* bogs developed, sediments in other lake basins dried out, and regional fire incidence increased. Climate shifted between wetter and drier conditions through 5500 cal yr BP. This evidence of climate drying during the middle Holocene contrasts with results from several studies in the circum-Caribbean region, where generally wet conditions have been reported throughout this time period. However, some studies from the Pacific side of Central America and northern South America show dry phases during this period.

Reconstructing paleoclimates during the late Holocene at the Miravalles lakes is complicated here as elsewhere in Central America by human impacts that can mask evidence of climate change (Horn, 2007). However, the general picture seems to be one of continuing drought intervals, particularly between 5500–4000 cal yr BP and at 2500 cal yr BP. Evidence for drought at 2500 cal yr BP is present in the sediment records of

all six lakes, and has been noted in other paleoclimate records from the circum-Caribbean. The postulated regional dry phase at 1200 cal yr BP seen in other regional records is not well resolved in the Miravalles records, which have poor time resolution during the latest Holocene.

A significant finding is the occurrence of maize pollen from sediments dated to 5500 cal yr BP at Laguna Martínez. This evidence of prehistoric agriculture occurs 1500 years prior to the earliest human occupation previously documented in the region, and represents the earliest pollen evidence of maize agriculture anywhere in Costa Rica. The maize pollen evidence also extends the time frame of later human occupancy in the region, well into the late Holocene (regional archaeological period V). Previously, archaeologists suggested abandonment of many sites much earlier. Populations may have declined at the sites, but the continued cultivation of maize shows they were not completely abandoned.

Our knowledge of fire history in this region has been strengthened. Fire has been an important part of the landscape for most of the 8000 year history recorded in the lake sediments. Fires were probably ignited by natural sources (lightning and volcanism) as well as by humans. Vegetation may have been negatively impacted by natural fires that occurred during dry climate conditions. Post-occupation tree pollen percentages are a fraction of pre-occupation percentages, even though climate conditions were wetter following human settlement, thus emphasizing the strong impact of prehistoric humans on vegetation. Anthropogenic disturbance has obviously had a major impact on regional vegetation since humans first settled in the area by at least 5500 cal yr BP. Recent increases in tree pollen indicate increased forest growth by some of the same taxa present

prior to human landscape modification. This suggests that the forest taxa may be more resilient than expected.

This study has important implications for management and restoration efforts in the Guanacaste region. Climate change and fire, both natural and human, have strongly impacted vegetation for 8000 years. Any restoration efforts must consider that this was a dynamic landscape, and that it may prove difficult to impose a static postcard view of what the vegetation should be. Efforts to create functioning ecosystems must consider how past environmental change has produced the vegetated landscape we see today, and plan for future change as well.

This analysis of sediment cores from multiple lakes on the Pacific slope of Volcán Miravalles yielded a stronger record of environmental change than could have been developed from a single lake core. Working with cores from multiple lakes allowed me to look at regional as well as local changes, and avoid some of the problems inherent in studies based on single cores, such as missing sediment intervals, or complacent pollen records. This study reinforces the value of using paired lake, or multiple lake studies in study areas where multiple lakes exist.

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APPENDICES

APPENDIX A

MIRAVALLS LAKE SEDIMENT PROCESSING PROCEDURE

I used the following procedure to concentrate pollen in sediment samples from the Miravalles lakes sediment cores. This processing procedure was developed by Drs. Sally Horn and John C. Rodgers III, following standard palynological techniques (Berglund, 1986). This procedure takes about six hours to complete with a batch of six samples, and must be performed in a laboratory fume hood. I use an IEC bench top centrifuge with a 6 x 15 ml swinging bucket rotor set to rotate at about 2500 RPM. All centrifuge times are 2 minutes with time measured from initial start up. Gloves and goggles should be worn for all chemical steps and use of HF also requires use of a respirator and face shield.

1. Place wet sediment in pre-weighed, 15 ml polypropylene centrifuge tubes and reweigh.
2. Add 1 tablet *Lycopodium* spores to each tube (Batch # 710961 = 13,911 spores/tablet).
3. Add a few ml 10% HCl, and let reaction proceed; slowly fill tubes until there is about 10 ml in each tube. Stir well, remove stirring sticks, and place in hot water bath for 3 minutes. Remove from bath, centrifuge, and decant.
4. Add 10 ml hot distilled water, stir, centrifuge and decant. Repeat for a total of two washes.
5. Add about 10 ml 5% KOH, stir, remove stirring sticks, and place in boiling bath for 10 minutes; stir again after 5 minutes. Remove from bath and stir again. Centrifuge and decant.
6. Add 10 ml hot distilled water, stir, centrifuge, and decant. Repeat for a total of 4 washes.

7. Fill tubes about $\frac{1}{2}$ way with distilled water, stir, and pour through 125 μm mesh screen, collecting liquid in a labeled beaker underneath. Use a squirt bottle of distilled water to wash the screen, and to wash out any material remaining in the centrifuge tube.
8. Centrifuge down material in beaker by repeatedly pouring beaker contents into correct tube, centrifuging, and decanting.
9. Add 8 ml of 49–52% HF and stir. Place tubes in boiling bath for 20 minutes, stirring after 10 minutes. Remove from bath and centrifuge and decant.
10. Add 10 ml hot Alconox solution (made by dissolving 4.9 cm^3 commercial Alconox® powder in 1000 ml distilled water). Stir well and let sit for 5 minutes. Centrifuge and decant.
11. Add more than 10 ml hot distilled water to each tube, so that top of water comes close to top of tube. Stir, centrifuge, and decant. Check top of tubes for oily residue after decanting. If present, remove carefully with wadded paper towel. Also at this time, examine the tubes to see if they still contain silica. If silica is present, repeat steps 9–11. Assuming that no samples need retreatment with HF, continue washing with hot distilled water as above for a total of 3 hot water washes.
12. Add 10 ml of glacial acetic acid, stir, centrifuge, and decant.
13. Make acetolysis mixture by mixing together 9 parts acetic anhydride and 1 part concentrated sulfuric acid. Add about 8 ml to each tube and stir. Remove stirring sticks and place in boiling bath for 5 minutes. Stir again after 2.5 minutes. Remove from bath and centrifuge and decant.

14. Add 10 ml glacial acetic acid, stir, centrifuge, and decant.
15. Add 10 ml hot distilled water, stir, centrifuge, and decant.
16. Add 10 ml 5% KOH, stir, remove stirring sticks, and heat in vigorously boiling bath for 5 minutes. Stir again after 2.5 minutes, then remove sticks. After 5 minutes, centrifuge and decant.
17. Add 10 ml hot distilled water, stir, centrifuge, and decant. Repeat for a total of 3 washes.
18. After decanting last water wash, use vortex mixer for 20 seconds to mix sediment in tube.
19. Add 1 drop 1% safranin stain to each tube. Use vortex mixer for 10 seconds. Add distilled water to make 10 ml. Stir, centrifuge, and decant.
20. Add a few ml tertiary-butyl alcohol (TBA), use vortex mixer for 20 seconds. Fill to 10 ml with TBA, stir, centrifuge, and decant.
21. Add 10 ml TBA, stir, centrifuge, and decant.
22. Vibrate samples using the vortex mixer to mix the small amount of TBA left in the tubes with the microfossils. Carefully transfer the liquid to precleaned and labeled glass vials. Centrifuge down residue in vials and decant. Repeat as necessary until all material is transferred from tubes to vials.
23. Add several drops of silicone oil (2000 cs viscosity) to each vial, more if a lot of residue remains. Stir with a clean toothpick.
24. Place uncorked samples in a dust-free cabinet to let the residual TBA evaporate.
25. Stir again after 1 hour, adding more silicone oil if necessary.

26. Check the samples after 24 hours; if there is no alcohol smell, cap the vials. If the alcohol smell persists, allow more time for evaporation.

APPENDIX B

Pollen Evidence of the Earliest Maize Agriculture in Costa Rica

This Appendix is an identical version of a paper by the same name published in the *Journal of Latin American Geography* in 2004 by Martin R. Arford and Sally P. Horn:

Pollen Evidence of the Earliest Maize Agriculture in Costa Rica. *Journal of Latin American Geography* 3:108–115.

The domestication of maize and its spread throughout the Americas has long generated interest. Four symposia on maize at the March–April 2004 meeting of the Society of American Archaeologists in Montreal (1) helped to push research (and debates) forward. While there is at present widespread acceptance that one of the teosintes (likely *Zea mays* subsp. *parviglumis*) is the ancestor of domesticated maize (*Zea mays* subsp. *mays*), many questions remain about where, when, and how domestication took place, and about the subsequent spread of cultivated maize throughout the Americas (Society for American Archaeology 2004a, b; Smalley and Blake, 2003).

Botanical evidence for the presence of maize at different sites and times is key to the debate. This evidence consists of maize macrofossils (usually cobs, kernels, or fragments) and maize microfossils (pollen grains and phytoliths) for which ages can be determined using radiocarbon analysis. Until recently, almost all radiocarbon ages for maize macrofossils or microfossils were based on standard radiocarbon assays of associated charcoal or other organic remains in the soils or sediments from which the maize fossils were recovered. The development of accelerator mass spectrometry (AMS) radiocarbon dating, which requires a much smaller mass of sample, has made it possible

to date individual maize kernels or cob fragments, and has led to the application of more exacting standards to botanical evidence of the history of maize and other New World crops (Smith, 1994–95; Fritz, 1994). Under these new standards, the primary class of botanical evidence consists of seeds or other plants parts that show morphologies indicative of deliberate planting and harvesting (2) and that are directly dated by AMS methods (Smith, 1994–95). Cultigen pollen and phytoliths that are not directly dated constitute less desirable, secondary classes of evidence, as do macrofossils that are not directly dated. Reinterpretation of the history of maize based only on primary botanical evidence, including direct AMS dates on maize cobs from rockshelters in the Tehuacán Valley of Mexico that had previously been dated only indirectly (Long *et al.*, 1989), led Fritz (1994) to question the standard 5000 BC date for maize domestication. The earliest primary botanical evidence she found was for a directly dated cob from the San Marcos (Tehuacán) cave that yielded an AMS date of 4700 ± 110 ^{14}C years BP, a radiocarbon age that corresponds to a calendar age of between 3700 and 3100 BC when corrected for known variations in atmospheric ^{14}C (see Table A1 for calibration methods and for calibrated age ranges for all dates for maize subsequently presented here). More recently, Piperno and Flannery (2001: 2102) dated two “primitive-looking maize cobs” from Guilá Naquitz cave in Oaxaca, Mexico, to 5420 ± 60 ^{14}C years BP and 5410 ± 40 ^{14}C years BP. Based on an analysis by Beadle and Ford, the dated cobs are thought to represent either “maize-teosinte hybrids or a primitive maize that demonstrated strong teosinte influence” (Piperno and Flannery, 2001: 2102).

Table A1. Radiocarbon dates relevant to the history of maize in Mexico and Costa Rica.

Site and material	Reference	Maize dates ¹⁴ C years BP	2-sigma calibrated BC age ranges ¹
Guila Naquitz cave, Oaxaca, Mexico primitive maize cob	Piperno and Flannery (2001)	5420 ± 60	4360–4050 BC
Guila Naquitz cave, Oaxaca, Mexico primitive maize cob	Piperno and Flannery (2001)	5410 ± 40	4340–4050 BC
San Marcos cave, Tehuacán Valley, Mexico maize cob	Fritz (1994) [from Long <i>et al.</i> 1989]	4700 ± 110	3700–3100 BC
Laguna Martínez, Costa Rica charcoal in interval of earliest maize pollen	This paper	4760 ± 40	3640–3380 BC
Arenal Prehistory Project, Costa Rica charcoal associated with excavated maize macrofossil	Bradley, 1994; Mahaney <i>et al.</i> , 1994	4450 ± 70	3340–2920 BC
Laguna Martínez, Costa Rica charcoal in maize interval 5 cm above earliest maize interval	This paper	4410 ± 40	3330–2910 BC.
Lago Cote, Costa Rica charcoal in sediment interval directly below maize interval	Arford (2001)	3630 ± 70	2200–1770 BC

¹Determined using CALIB 4.4.2 (Stuiver and Reimer, 1993) and the dataset of Stuiver *et al.* (1998). The probability that the true calendar age falls within the 2-sigma range is 95.4%.

But what about the record of maize microfossils, in Mesoamerica and beyond? Large grass pollen grains identified as *Zea mays* are routinely found in prehistoric sediments of lakes and swamps in Mexico and Central and South America. In northern Central America and Mexico the reconstruction of ancient maize cultivation from pollen is complicated by the difficulty of distinguishing the pollen of cultivated maize from that of teosinte, for which wild populations have been documented as far south as the Gulf of Fonseca region in the northern Pacific lowlands of Nicaragua (Iltis and Benz, 2000). But in southern Central America and South America, where wild populations of teosinte are unknown, the large *Zea* pollen grains should be strong evidence for the presence of cultivated maize, and we and other pollen analysts have interpreted them as such. Phytolith experts are similarly confident in their ability to document the past presence of maize in southern Central and South America from phytoliths. (e.g., Pearsall *et al.* 2003; Piperno 2003).

An interesting, if sometimes troubling, pattern emerges when one compares the earliest dates on maize macrofossils and microfossils at many sites in this region. Microfossils of maize recovered from sediment cores or archaeological excavations frequently predate by one to many thousands of years maize macrofossils from archaeological sites (Smalley and Blake, 2003). Examples include maize phytoliths and pollen from the Cueva de los Ladrones archaeological site in central Panama that are associated with preceramic deposits dated to ~7000 ¹⁴C years BP (Piperno *et al.*, 1985); maize pollen and phytoliths in ~5300-yr-old sediments from Lake Ayauchⁱ, Ecuador (Bush *et al.*, 1989); and maize phytoliths in archaeological profiles from Las Vegas and

Real Alto, Ecuador, that date to ~ 7000 ^{14}C years BP (Pearsall and Piperno, 1990; Pearsall, 2002).

While some maize macrofossils are directly dated and thus constitute primary evidence in Smith's (1994–95) system, microfossils are almost always indirectly dated via the dating of associated charcoal or other plant macrofossils in the sediment core or archaeological profile. Is the pattern of microfossil dates predating macrofossil dates evidence that the former are suspect, or are other factors at play here?

Our view is that all early dates for maize microfossils (our own included) demand careful scrutiny, but that pollen and phytoliths in lacustrine sediment sequences that have been carefully dated (ideally by AMS dates on charcoal fragments or other terrestrial organic macrofossils) should not be excluded from consideration just because the microfossils are not themselves directly dated. We believe that the age discrepancy between maize microfossils and macrofossils in some areas of southern Central America and South America may be a consequence of different degrees of research effort and/or possibilities for preservation. The considerable interest that exists in unraveling the history of tropical plant communities using analyses of pollen and other proxy indicators in sediment cores has led to the recovery of cores from a large number of lowland lakes and swamps, many of which occupy watersheds that were likely farmed during prehistory, but in which archaeological excavations have yet to be carried out. Maize pollen does not disperse far from its source, but should pollen of nearshore maize plants be deposited in lake sediments, conditions for preservation are often excellent – perhaps far better than conditions for preserving maize macrofossils onshore. In our view, the presence of maize pollen in well-dated lacustrine sediment intervals predating local

archaeological evidence is not a challenge to the veracity of pollen data, but instead evidence that future archaeological work at the site might be worthwhile.

Iltis (2000: 36) recently proposed a novel idea that may provide an additional explanation for the discrepancy between macrofossil and microfossil ages for maize in southern Central America and South America. Iltis suggested that maize was “originally domesticated not for its grain but for its sugary pith or other edible parts.” Smalley and Blake (2003: 675) elaborated on this idea by proposing that “during *Zea*’s initial period of domestication the stalk provided a key source of sugar for many purposes, including the making of alcoholic beverages,” and that “the social importance of alcohol production was a precipitating factor in *Zea*’s early and rapid spread.” If corn stalks, not kernels, were the focus of early maize production at sites in southern Central America and South America, cobs and kernels would be less likely to have been carbonized and preserved with hearth remains. Therefore, we might expect maize kernels and cobs to appear later than pollen even at sites with exceptional preservation of archaeological materials and where detailed excavations have been carried out in the watersheds of sediment coring sites. We look forward to new evaluations of both primary and secondary classes of evidence of maize at sites throughout the Americas that can build upon the ideas of Iltis (2000) and Smalley and Blake (2003), and to new field research in archaeology, paleoecology, and cultural ecology that these ideas may stimulate. It appears to us that Latin Americanist geographers have a potential role to play in assessing the merits of the ‘sugar stalk’ hypothesis and the more general idea that alternate uses of maize were important in the early spread of the cultigen, and in assembling some of the datasets that can provide context (or tests) for these ideas.

Our recent field work and subsequent laboratory analyses have provided new data on the history of maize in northwestern Costa Rica that we share here with the objective of providing context for the reevaluation of the history of the spread of maize through southern Central America and into South America. Our new evidence consists of maize pollen grains that are significantly older than those found previously in Costa Rican sediments, and as old or slightly older than the maize macrofossil that until recently constituted the oldest botanical evidence of maize in the country (Blanco and Mora, 1994). In this case, the maize macrofossil as well as our microfossils are both indirectly dated, but the dates are compatible with direct AMS dates on maize macrofossils from Mexico and we believe them to be correct.

Our new maize data from northwestern Costa Rica derive from detailed investigation of multiple proxies in sediment records from six lakes on the lower Pacific slope of Volcán Miravalles in the NW-SE trending Cordillera de Guanacaste. These lakes formed just over 8000 years ago following pyroclastic flows from Miravalles volcano (Alvarado, 2000). The lakes range in elevation from 340 to 560 m.a.s.l., and in size from 0.5 to 4.5 ha. The climate in this area is warm (mean annual temperature of 22.5–25.0° C), and seasonally dry (annual rainfall of 1500–2000 mm occurring from May to November) (Bergoeing, 1998; Coen, 1983). Modern vegetation is primarily pasture grasses with remnant patches of semi-deciduous forest. No archaeological excavations have been conducted near the lakes, but surveys in the general area suggest occupation dating to 4000 BP or earlier.

Sediment coring was conducted in four field seasons from 1999 to 2003, with laboratory analysis ongoing. We have dated all cores through AMS analyses of charcoal

and leaf fragments, and have carried out detailed analyses of pollen and microscopic charcoal to document changes in vegetation and fire history resulting from climate change and human activity in the lake watersheds. We have found maize pollen in our standard (percentage) pollen counts of samples from all of the lakes, and have supplemented these counts by preparing multiple additional microscope slides and scanning them completely for maize at low-power magnification at additional levels below the lowest occurrences of maize in our standard counts. The large size of maize pollen in comparison to other pollen types makes this type of presence/absence analysis practical.

Maize pollen is present in the late Holocene sections of the cores from all six lakes, with the earliest occurrence at Laguna Martínez (10.642 N, 85.197 W, 340 m elevation). Laguna Martínez has a surface area of 1.5 ha, and a water depth of at least 3.6 m during the dry season. Our core from Laguna Martínez is approximately 5 m long and has a basal date of 7610 ± 50 ^{14}C yr BP. Six AMS radiocarbon dates on charcoal fragments and dicotyledon leaves indicate rapid initial sedimentation followed by much slower sedimentation (or possibly a hiatus) that we associated with dry conditions around 6060 ± 40 ^{14}C yr BP. Maize pollen first appears in the record shortly after this dry period ends, associated with a trend of decreasing percentages of tree pollen, and increased abundance of grass pollen and microscopic charcoal. Pollen grains of *Zea mays* subsp. *mays* in the Laguna Martínez sediments range in size from 62.5 to 92.5 μm with pore annuli diameters of 12.5 to 17.5 μm . These values are within the expected size range for maize pollen from Central America and Mexico (Ludlow-Wiechers *et al.*, 1983), and are similar to the sizes of preColumbian maize grains found at other sites in Costa Rica

(Horn *et al.*, 2004). The lowest occurrence of maize, at 141 cm, dates to 4760 ± 40 ^{14}C BP based on AMS dating of tiny charcoal fragments picked from the maize-containing interval. As a check on this date we obtained another radiocarbon date five centimeters upcore, also on charcoal fragments from an interval with maize pollen. That sample yielded a date of 4410 ± 40 ^{14}C yr. BP. The association of these early maize grains with declining tree pollen percentages and with abundant microscopic and macroscopic charcoal is strong evidence of local forest clearance and maize cultivation, likely on the very shores of the lake. In the Laguna Martínez sediment core, almost all samples above this initial interval of prehistoric agriculture contain maize pollen, until the uppermost section of the core corresponding to the last few hundred years, in which maize pollen is only sporadically present.

Previously, the earliest evidence of prehistoric maize in both northwestern Costa Rica and the country as a whole consisted of a carbonized maize kernel excavated during the Arenal Prehistory Project conducted at the present site of the Arenal reservoir (formerly a natural wetland) approximately 35 km east of the Miravalles lakes (Sheets and McKee, 1994). The maize kernel was not directly dated, but a date of 4450 ± 70 ^{14}C BP was obtained on carbonized wood found in association with the kernel (Bradley, 1994; Sheets, 1994; Mahaney *et al.*, 1994). Earlier dates were obtained for hearth fires in the Arenal excavations, but no evidence older than the above was found for maize cultivation. Until we began working at the Miravalles lakes, the oldest pollen evidence of maize agriculture came from near the base of a sediment core from Lago Cote, located a few km north of the area investigated in the Arenal Prehistory Project. That maize pollen was found just above a sediment interval which yielded an AMS date on macroscopic

charcoal of 3630 ± 70 ^{14}C yr BP (Arford, 2001). Our new data from Laguna Martínez indicates that maize farmers at Lago Cote and Lago Arenal had company. Maize cultivation was occurring at these times and slightly earlier on the lower Pacific slope of Volcán Miravalles.

The dates at hand for both the Arenal maize kernel and the Laguna Martínez maize pollen indicate that the earliest maize now known from Costa Rica overlaps in time with the earliest maize cob from San Marcos (Fritz, 1994) but is ~700–1000 radiocarbon years younger than the primitive cobs from Guilá Naquitz (Piperno and Flannery, 2001) (see table). In our view, the Costa Rican maize dates do not conflict with the history of maize as interpreted from primary botanical evidence alone. We do not need to invoke the ‘sugar-stalk’ hypothesis to explain the Costa Rican dates, and of themselves the dates do not provide a test for the hypothesis. However, the reported occurrence in Panama and South America of maize pollen and phytoliths that predate the Costa Rican evidence as well as the oldest cobs from Guilá Naquitz may be evidence that the spread of maize southward from Mexico was influenced by alternate uses of the plant (Smalley and Blake, 2003). If people to the south were first using maize for its sugary pith or other plant parts, they may also have been doing so in Costa Rica.

Is earlier maize likely to be found in Costa Rica? SPH and collaborators are working at several dozen lakes and swamps in Costa Rica to develop multiproxy records of environmental history that include evidence of the history of maize, but most sedimentary basins at low- to mid-elevation are younger than the earliest maize from Martínez and Arenal. Cores from some of these sites document maize cultivation earlier than as yet documented by local or regional archaeological evidence (e.g., Clement and

Horn, 2001; Horn and Kennedy, 2001), but cannot reveal the initial arrival of maize as the sediment records begin a millennia or more after maize arrived in Costa Rica. However, some of the sites we are presently investigating in Costa Rica may yield older records that are appropriate for determining the timing of initial maize introduction and spread in Costa Rica. Our ongoing analyses of stable carbon isotope signatures of lake and swamp sediments are providing new proxy data for maize agriculture (Lane *et al.*, in press) that could predate the first microfossil evidence at some of our sediment coring sites. On the archaeological front, the study of starch grains on stone tools may provide additional data points on early maize in Costa Rica (as they do in Ecuador; Piperno and Holst, 1998.). Archaeological research carried out in tandem with multi-proxy paleoecological research may offer the best opportunities for refining the ‘maize story’ in Costa Rica, and for perhaps ultimately determining whether early maize agriculturalists were motivated by maize kernels alone or also (or instead) by fermentable stalks.

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Notes:

1. The symposia were organized by Michael Blake, John Staller, John Hart, and Robert Thompson. Presenters and paper titles are listed under sessions 86, 111, 136, and 161 in SAA (2004a) and abstracts are in SAA (2004b). A book is planned, edited by John Staller, Robert Tykot, and Bruce Benz.
2. With domestication, morphological changes are seen that allow differentiation of domesticated plants from their wild forms. For seed crops, for example, such changes include “greater seed size, thinner seed coats, and loss of natural seed dispersal mechanisms such as non-brittle rachis.” (Smith 1994–95: 176).

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VITA

Martin Russell Arford was born in Pennsylvania. Following his graduation from United High School in Armagh, Pennsylvania, he worked for many years in Emergency Medical Services. Martin entered Indiana University of Pennsylvania in 1992 and received his Bachelor of Science degree in 1997, graduating Magna cum Laude with double majors in geology and biology and a minor in geography. He spent a semester aboard the National Oceanic and Atmospheric Administration (NOAA) ship Discoverer in the equatorial Pacific Ocean and participated in field courses in Virginia (oceanography), Pennsylvania (aquatic ecology), Florida Keys and Bahamas (geology), Newfoundland (geology), and Costa Rica (development and planning). During these courses he developed strong interests in paleoecology and biogeography.

Martin entered the graduate program in geography at the University of Tennessee, Knoxville in 1997 with a desire to study environmental history in Costa Rica with Dr. Sally Horn. While at the University of Tennessee, Martin participated in field research in Costa Rica, Bolivia, and the Dominican Republic funded by the National Geographic Society, The A.W. Mellon Foundation, and the National Science Foundation. Martin received his Master of Science degree in August 2001. He studied Tropical Ecology in Costa Rica during a 3-week field course conducted by the Organization for Tropical Studies, and completed a mini-course in Sedimentary Macrofossil Identification at University College London. At the University of Tennessee, Martin taught introductory physical geography, and was a teaching assistant for introductory physical geography and world regional geography. He received the Robert G. Long Outstanding Graduate

Student Award, awards for Extraordinary Professional Promise, and Outstanding Teaching Associate and Teaching Assistant.

Martin is an assistant professor of geography at Saginaw Valley State University in Michigan, and will continue in that position after completing his Ph.D. degree. He will also continue paleoecological research, both in the circum-Caribbean region and in Michigan, where he can involve undergraduates and, hopefully, inspire them to pursue adventures, graduate studies, and careers in physical geography and environmental history.

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