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I am submitting herewith a thesis written by Zachary Paul Taylor entitled "Environmental History at Laguna Yaguarú, Bolivia: Evidence from Pollen, Stable Carbon Isotopes, and an Embedded Mineral Facies." I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Masters of Science, with a major in Geography.

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Environmental History at Laguna Yaguarú, Bolivia: Evidence from Pollen, Stable Carbon Isotopes, and an Embedded Mineral Facies

A Thesis
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Master of Science
Degree
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Zachary Paul Taylor
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Dedication

This thesis is dedicated to the wonderful group of people who are with me at every turn. I have been extraordinarily lucky to have excellent teachers at every level and I proudly bear the legacy of John Kistler and Don Sullivan, as well as many others. My friends from high school and college have always encouraged me to pursue my studies and I would not be the student I am if not for you. My family has been unbelievably supportive. My parents, Doc and Norma Taylor, have always been behind me in everything I have done and I am forever grateful for the freedom I have had to choose my field. My sister, Betsy Taylor, is a great friend and an even greater source of support.

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Abstract

Lowland eastern Bolivia is an important area for paleoenvironmental research because of its location near the climatically controlled boundary between the Amazon basin rain forest and the seasonally dry savannas to the south. I present a multiple proxy study from Laguna Yaguarú (15°36'S, 63°13'W, 195 m), a large (250 ha) lake located in the forest-savanna ecotone. A 2.4 m long core recovered in May 2003 spans approximately the last 5000 years. Chronological control is based on excess ^{210}Pb sedimentation in the uppermost sediments and three AMS dates on plant macrofossils in deeper sediments. I undertook pollen and microscopic charcoal analysis of the Yaguarú core, supplemented with stable carbon isotope analysis, to provide a more complete history of vegetation and of possible climate shifts. Stable carbon isotope ratios in the lake sediments record the relative dominance of C3 and C4 plants in the watershed, and may reveal shifts in grassland communities not apparent in pollen spectra. The most notable feature of the sediment core is a 15 cm layer of gray clay which dates to ~5000 BP. Particle size analysis indicates that this layer represents a flood deposit. Pollen percentages changed significantly following the deposition of the clay layer. Pollen assemblages prior to the flood interval are dominated by *Typha* pollen, whereas subsequent assemblages contain mainly grass and forest pollen. Stable carbon isotope values within the flood deposit show high variability, perhaps indicating extra-basin carbon input. An increase in forest taxa beginning about 3000 BP correlates with nearby records and is attributed to southward migration of the ITCZ due to increased summer insolation in the southern hemisphere.

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Chapter 1

Introduction

Lake sediments provide paleoenvironmental researchers with archives of information about past climates, vegetation patterns, fire regimes, and human activities. Some of these records extend back to the Pleistocene with a high degree of resolution, enabling researchers to reconstruct the climatic transitions from full glacial conditions, through the Holocene, to modern times. One location in which this climatic transition has been studied extensively over the past 30 years is central South America, where research has focused on the Andean highlands (especially around Lake Titicaca) and the Amazon basin. Numerous paleoenvironmental records now exist for these locations, but the seasonally dry forests and savannas that surround the Amazon rainforest remain little studied. Paleoenvironmental histories from sites within this zone of transition between forest and savanna, such as the dry forest of eastern Bolivia, are important for understanding the long-term environmental history of central South America.

In this thesis, I use multiple proxy indicators in a lake sediment record from Laguna Yaguarú, in lowland Bolivia, to reconstruct Late Holocene environmental history. As is the case for sites recently investigated by Mayle et al. (2000) and Burbridge et al. (2004), Laguna Yaguarú is in the Bolivian dry forest. Paleoenvironmental reconstructions from this area are useful because it lies near the location of the intertropical convergence zone (ITCZ) during the austral summer. The mean ITCZ position is an important control on precipitation, which defines the boundary between forest and savanna. The location of Laguna Yaguarú makes it potentially sensitive to changes in this boundary. I use multiple proxies in this thesis to create a

more complete paleoenvironmental history. I performed pollen analysis, counted charcoal fragments, and measured stable carbon isotope ratios in the Yaguarú sediment record to provide histories of vegetation and fire that might indicate changes in this boundary over time. Pollen analysis can provide a good record of local vegetation in many environments, but the dominance of grass pollen in savanna and many dry forest environments can reduce the usefulness of pollen analysis. Grass pollen is a poor paleoenvironmental indicator (Bush, 2002), and cannot generally be identified below the family level (Ficken et al., 2002). Stable carbon isotope analysis adds information to pollen records because it can distinguish between photosynthetic pathways, providing another layer of paleoenvironmental information. I used charcoal analysis to reconstruct past fire regimes. The Laguna Yaguarú sediment core also shows evidence of a significant past hydrologic disturbance. I used particle size analysis to determine the characteristics of this event.

Good paleoenvironmental records from this location may also be useful in the future. Ecotonal areas such as the Bolivian dry forest are important in efforts to maintain biodiversity (Smith et al., 1997). This is especially true in areas of great biodiversity that are as diverse and as threatened by human activity as is the Bolivian dry forest (Killeen et al., 1998). Knowledge of past environments can help land managers make informed policy decisions to best conserve this important area.

With this thesis, I address the following questions: Does the combination of pollen analysis and stable carbon isotope analysis reveal savanna incursion in lowland Bolivia during the Late Holocene? Does the record reveal evidence of prehistoric agriculture at Laguna Yaguarú? To what extent does the Yaguarú record parallel

paleoecological records from highland Bolivia, other records from lowland Bolivia, and records from adjacent areas of the Amazon basin? Does this lake show evidence of radiocarbon anomalies such as those described in Amazon floodplain lakes by Räsänen et al. (1991) and Bush (M. Bush, pers. comm. to S. Horn).

This thesis is divided into six chapters. I summarize literature relevant to this thesis in Chapter 2. I provide an overview of the climate, vegetation, and physical setting in Chapter 3. Chapter 4 describes the field and laboratory methods used in this study including radiocarbon dating, ^{210}Pb dating, pollen analysis, stable carbon isotope analysis, and particle size analysis. In Chapter 5, I present the results of these analyses in a series of diagrams. In Chapter 6, I discuss my results and place them in the context of other South American climate records. Chapter 7 contains my conclusions about the environmental history of Laguna Yaguarú and its significance.

Chapter 2

Literature Review

The impact of past climate changes on the Amazon rainforest and adjoining segment of the Andes has been viewed with differing perspectives. Researchers initially thought that equatorial South America experienced a very steady climate with little change, even during worldwide periods of significantly different climate, such as the Last Glacial Maximum (LGM) (Colinvaux, 1989). A wide range of paleoenvironmental data from both these locations has refuted this hypothesis. Here I present a review of paleoenvironmental studies from the Andean highlands, the Amazon lowland rainforest, and the fringe areas of the Amazon basin, including the Bolivian dry forest. I follow this with a brief mention of radiocarbon dating anomalies that have been detected in Amazonian lake cores, and with a discussion of stable carbon isotope ratios as proxies for climate and vegetation. The studies reviewed here are relevant to my analysis and interpretation of a sediment core from Laguna Yaguarú, Bolivia.

Andean Paleoenvironmental Records

Ice cores from several locations in the Andes have provided long and detailed climate records. Tropical glaciers are very sensitive to climate change and can provide oxygen isotope, dust accumulation, elemental concentration, and pollen records (Thompson et al., 1998; Thompson, 2000; Ramirez et al., 2003; Reese, 2004). The ice cores indicate that the LGM was ~8 °C cooler than modern conditions. The cores show a general warming around 22,000 BP and then a return to glacial-like conditions from ~15,000 BP–11,500 BP. Oxygen isotope values increased and dust concentrations rose

after 11,500 BP, a change attributed to less snow cover (Thompson et al., 1998; Thompson, 2000; Ramirez et al., 2003). The early Holocene brought warmer conditions which ended ~ 9000 BP, when dry conditions led to high concentrations of dust. This dry phase lasted until 3400 BP, when modern, moist conditions set in. All of the records show this general pattern, but the precise timing of these periods varies between the different ice cores. This is a function of their different geographical locations and their position relative to lakes and paleolakes on the Bolivian Altiplano.

These lakes and paleolakes have also provided important paleoenvironmental records. Lake Titicaca is the world's highest large lake (Fritz et al., 2004) and its sediment record, which goes back 25,000 years, has been studied intensely. Lake Titicaca is part of a hydrologic arrangement that is ideal for paleoenvironmental research. Lake Titicaca overflows at high water levels into Lago Poopo, which in turn overflows into two salt flats, the Salar de Uyuni and the Salar de Coipasa. This system makes Lake Titicaca especially sensitive to fluctuations in water level, with consequences for salinity, evaporation, and other lake variables that have been exploited by researchers as paleoenvironmental indicators. Tapia et al. (2003) used diatoms and Baker et al. (2001) used diatoms and carbon isotopes to reconstruct precipitation over the Late Quaternary. Like the ice cores, the records documented the change from Pleistocene glacial conditions to the Holocene interglacial. Both records suggested that the LGM was wetter then today and that Lake Titicaca continuously overflowed. Wet conditions persisted until 11,000 BP, giving way to drier conditions when the lake reached its lowest level between 8000–5500 BP. Lake levels began to rise at 4000 BP and reached modern levels around 1500 BP. Both authors connected these changes with orbitally forced

strengthenings and weakenings of the South American monsoon. Greater summer insolation in the Southern Hemisphere led to a stronger monsoon and greater precipitation over northern and central South America. Paduano et al. (2003) presented the vegetation and fire history component of this study. Pollen first appeared in the record around 21,000 BP, coincident with the climate amelioration. The pollen data generally followed the pattern described above. Fires were first detected starting at 17,700 BP and became more important as vegetation cover increased. No Younger Dryas or other climate reversals were seen in the data. A separate oxygen isotope study correlated lake level with archeological records from the shore of Lake Titicaca, and tied a drought between 1100–1400 AD to cultural collapse (Binford et al., 1997). Fritz et al. (2004) cored the Salar de Uyuni and obtained a 170,000 year record of hydrology in the Altiplano, providing information on long-term climatic variations well into the Pleistocene.

Numerous studies have been done on other high elevation lakes in the central Andes. Abbott et al. (1997) studied sediments of lakes directly below glaciers to date deglaciation and neoglaciation. Their records indicated a dry early Holocene with wetter conditions beginning around 2300 radiocarbon years BP. Wolfe et al. (2001) reconstructed paleohumidity from two lake sediment cores using oxygen isotopes. These records matched the ice core and Lake Titicaca archives, also showing a wet late Pleistocene, a dry early Holocene (20 % less humid conditions), a variable mid-Holocene, and modern high humidity conditions setting in around 2000 BP. Analyses of high elevation wetlands allowed a more detailed reconstruction of Holocene precipitation patterns. Convective rainfall was differentiated from frontal precipitation using lenses of

different particle size in the sediment (Servant and Servant-Vildary, 2003). Low intensity frontal rainfall was most common until ~1500 BP when convective precipitation became more important. Servant and Servant-Vildary (2003) related this to the weakening of the Bolivian high, which allowed the trade winds to reach the Altiplano. The most comprehensive study from this region investigated a transect of lakes along the central Andes. Abbott et al. (2003) used a suite of proxy indicators in sediment cores to refine the climate record and detect interbasin variation in climate shifts. Their findings were similar to the studies mentioned above, but the researchers found some discrepancy between lake levels and precipitation. This was attributed to a gradual southward expansion of moisture in the late Holocene and to inter-basin variability in the relationship between lake level and precipitation. A study by Hansen et al. (1994) in Peru used pollen to interpret vegetation change over the last 40,000 years. They reported vegetation changes that appear consistent with the other climate records.

The Funza-2 core from the high plain of Colombia provides a 450,000 year record of pollen, bulk carbon isotopes, and compound specific stable carbon isotopes in the northern Andes (Boom et al., 2001; Boom et al., 2002; Marchant et al., 2002). This record is long enough to permit observations of long-term climate cycles and CO_2 concentration changes. Last Glacial Maximum cooling at this location is estimated at 5.5 °C.

Lowland Paleoenvironmental Records

Paleoenvironmental records from the lowlands of South America tend to rely more heavily on pollen and to focus on vegetation reconstruction. As a whole, lowland lake records are shorter and less concentrated geographically than their high elevation counterparts. The main impetus for paleoenvironmental studies in the Amazon was the Pleistocene refugia hypothesis. Initially, it was believed that tropical locations were essentially immune to climate change (Colinvaux, 1989). In 1969, it was observed that there were hotspots of diversity within the Amazon rainforest (Haffer, 1969). The Pleistocene refugia hypothesis held that colder and drier conditions during the Pleistocene fragmented the Amazon rainforest into smaller segments separated by savanna. These segments created geographic isolation between populations, which led to speciation and subsequent hotspots of diversity.

Permanent and old lakes that can be used to test the Pleistocene refugia hypothesis are rare in the lowland Amazon due to high erosion rates and the fluvial nature of the environment. Colinvaux et al. (1985) first reported the presence of permanent lakes in the Amazon basin. Pollen analysis from these lakes was reported by Frost (1988) and Colinvaux et al. (1988). Paleoenvironmental studies from these sites did not support the refugia hypothesis (Colinvaux, 1987).

Research has continued in the Amazon basin to understand the ecological response to climate change in tropical rainforest. A 40,000 year record in northwestern Brazil showed the continuous presence of rainforest at the site (Colinvaux et al., 1996). Upland species in the pollen record suggested a cooling of 5–6 °C during the Pleistocene. Lago Consuelo, in the lower montane forests of Ecuador, contains a 48,000 year record

of vegetation (Bush et al., 2004). Its location in the montane zone makes it ideal for detecting species movement due to climate change. The record suggests a Pleistocene cooling of 5–9 °C and an 8000 year transition to modern conditions beginning ~18,000 BP. Vegetation was reconstructed for the entire Amazon basin using pollen data from a deep sea core taken on the Amazon fan (Haberle and Maslin, 1999). The 50,000 year record revealed no evidence for extensive drying in the basin throughout the Pleistocene. Oxygen isotope data from this core indicated precipitation trends over the past 14,000 years (Maslin and Burns, 2000). Discharge of the Amazon was estimated at 60 % of current levels during the Younger Dryas period, gradually increasing to modern conditions through the Holocene. Another estimate of Pleistocene cooling in the Amazon came from analysis of noble gases dissolved in groundwater (Stute et al., 1995). Radiocarbon-dated water samples suggested LGM cooling of 5.4 ± 0.6 °C throughout the Amazon basin. Based on a multiple proxy sediment record from Lagoa do Caçó in Northern Brazil, Ledru et al. (2001) and Siffedine et al. (2003) estimated a similar amount of cooling along with moist conditions, which they attributed to changes in the position and/or strength of the Intertropical Convergence Zone. Several synthesis papers disagree on the LGM Amazon. Colinvaux et al. (2000), Heine (2000), and van der Hammen and Absy (1994) agreed that the Amazon experienced a 5–6 °C cooling during the LGM. Reductions in precipitation are not agreed upon. A drier, fragmented Amazon is favored by van der Hammen (1994), while Colinavaux et al. (2000) and Heine (2000) contend that the drying was minimal and that the Amazon remained largely intact throughout the Pleistocene. All three of the synthesis papers agree that there is no

evidence of a late glacial, Younger Dryas-type climate reversal from the Amazon basin, in contrast to Maslin and Burns (2000).

Most Holocene sediment archives from the Amazon show some evidence of climate change, but are primarily records of local paleoecology. The Lagoa do Caçó record indicated a relatively dry early and mid-Holocene, with moister conditions beginning around 7000 BP (Sifeddine et al., 2003). A further increase in moisture was reported from the central Amazon at 2800 BP by Behling et al. (2001). These changes were not seen in the Eastern Amazon, where conditions remained largely the same during this period (Behling and da Costa, 2000). Fire history has been reconstructed in two locations (Turcq et al., 1998; Behling and da Costa, 2000). Turcq et al. (1998) connected their record closely to climate and detected no evidence of humans. Behling and da Costa (2000) found an increase in charcoal in the last 2500 years, and attributed it to anthropogenic fires.

There is significant variation in the details of the Holocene records, a result of the enormous size of the Amazon region and its dynamic environment. Disturbance is the rule and many of the lakes alternate between open water and swampy conditions (Behling and da Costa, 2000; Behling et al., 2001; Ledru, 2001). Authors variously attribute these changes to climate shifts and to changes in local hydrology. Hydrologic disturbance seems to have played an important role in a number of these lakes (Colinvaux et al., 1985; Frost, 1988). Anañgucocha is one of several lakes with sedimentary lenses recording a period of intense flooding from 1300–800 BP (Frost, 1988). These deposits were laid down by the flooding of several rivers that drain the Andes. Two hypotheses were offered to explain this period of flooding. The first is that it corresponds to a wet

period in some parts of the Amazon. The second is that it may be related to tectonic uplift which rejuvenated the streams. These floods not only created a disturbance in the local vegetation, but also changed swamps to lakes when flood water ponded.

Sediment records from the dry forest and savanna ecotones that surround the Amazon are also important sources of paleoclimate data. Behling and Hooghiemstra (1999) reconstructed the history of the savanna north of the Amazon back to the LGM based on two lake sediment records from the Colombian llanos. The region has been dominated by savanna conditions with frequent droughts and fires since the LGM, but changes in lake level indicated variations in moisture regimes. Dry Late Pleistocene conditions slowly grew wetter with the Holocene transition, with noticeable increases in moisture at 10,700, 5600, and 3800 BP. The savannas on the southern side of the Amazon have also been studied. Like the Colombian llanos, the Brazilian campos were 5–7 °C cooler and significantly drier during the LGM (Behling, 2002; Behling et al., 2004). Grasslands were also more extensive, reaching farther north than at present. Fires were rare until 7400 BP, when they became more frequent, possibly as the result of human occupation (Behling et al., 2004). Beginning in the mid-Holocene, wetter conditions and less frequent fires allowed the expansion of *Araucaria* forest into campos areas (Behling et al., 2004). This expansion had two pulses at 3000 and 1500–1000 radiocarbon years BP.

Stable carbon isotope analysis has also been used in Brazil to reconstruct the location of the forest–savanna ecotone. Carbon isotope ratios of soil cores taken from a transect of environments across the southwestern boundary of the Amazon in Brazil indicated that there had been significant contraction of the forest through the Holocene

(Pessenda et al., 1998). A carbon isotope record from a paleosol in southeastern Brazil showed one pulse of forest expansion at 4000 BP and suggested that fire was more important than climate in determining the location of the forest-savanna ecotone (Alexandre et al., 1999). Though these data are in general agreement with other records, tropical soils are less desirable than lake sediments as sources of paleoecological records, owing to possible downwashing of microfossils and to soil overturn, and to the fact that soils do not steadily accumulate as do lake sediments (Horn et al., 1998; Lane et al., 2004).

Between the Amazon rainforest proper and the savanna to its south is a transitional zone of seasonally dry forest. The location of this transitional zone is controlled by the seasonal migration of the Intertropical Convergence Zone, which makes it useful for detecting past climate changes (Mayle et al., 2000; Burbridge et al., 2004). Much of what is known about the last 50,000 years in this area comes from two lake records in the seasonally dry forest of northeastern Bolivia that document changes in species composition over this time (Mayle et al., 2000; Burbridge et al., 2004). Paleoenvironmental records suggested that during the Last Glacial Maximum, vegetation assemblages existed that have no modern analogue. The band of dry forest south of the Amazon rainforest arrived at its current location during the Holocene when the Amazonian forest complex expanded to the south (Mayle, 2004). This expansion slowed during a dry period with more fires from 8000–3600 BP (Mayle et al., 2004). This was followed by an expansion of forest, which is attributed to increased summer insolation in the southern hemisphere due to Milankovitch forcing (Mayle et al., 2004). The present day southern limit of the forest is at its southernmost location of the last 50,000 years.

Amazonian Radiocarbon Anomalies

Räsänen et al. (1991) reported the occurrence of anomalously old radiocarbon dates in lakes in the Peruvian Amazon that are subject to seasonal flooding. For example, a macrofossil date of 225 ± 80 and a date on bulk organics of 3230 ± 150 were obtained from the same level of a sediment core from Lago Turku, Peru. Other lakes in the region showed a similar order of magnitude difference between AMS data on macrofossils and conventional dates on bulk sediment. This phenomenon was noticed in several floodplain lakes in the Peruvian Amazon, but only in floodplain lakes. Räsänen et al. (1991) attributed this effect to old carbon being reincorporated as part of channel migration in the floodplain. Anomalously old dates were also noticed in floodplain lakes of the Brazilian Amazon (M. Bush, pers. comm. to S. Horn). Floodplain records that may be questionable due to their reliance on bulk dates include Frost (1988), Behling and Hooghiemstra (1999), Mayle et al. (2000), and Burbridge et al. (2004) (M. Bush, pers. comm. to S. Horn). The latter two studies were conducted near Laguna Yaguarú.

Controls on Stable Carbon Isotope Ratios

Carbon isotopes can identify the dominant photosynthetic pathway of the plants in an environment, aiding greatly in detecting changes from savanna to forest. Carbon isotopes can be especially useful in a lake like Laguna Yaguarú, where the pollen record may be distorted by a variety of factors. Analysis of stable carbon isotope ratios is also useful in grass-dominated environments because, unlike pollen, stable carbon isotope ratios can differentiate between C3 and C4 species.

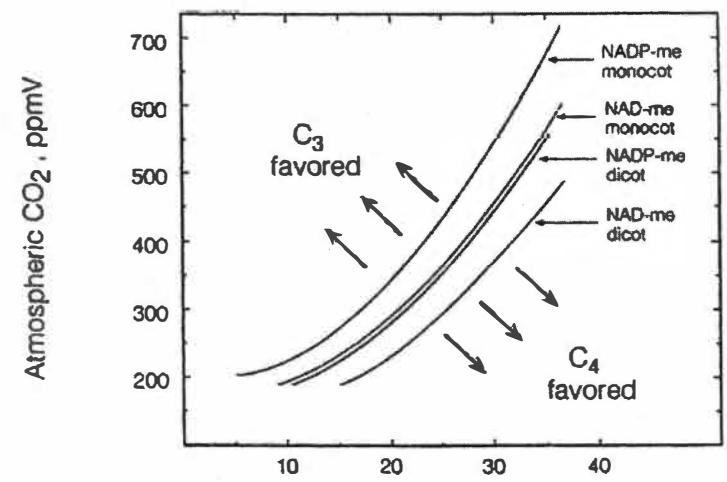
Plants have evolved three forms of photosynthesis. C3 (Calvin Cycle) photosynthesis is most prevalent, especially in dicots. Many monocots, including many genera in the Poaceae and Cyperaceae families, utilize the C4 pathway or Hatch-Slack photosynthesis (Ehleringer et al., 1997). CAM (Crassulacean Acid Metabolism) photosynthesis is typically limited to succulents and other species of arid environments. Some aquatic species also employ CAM photosynthesis. Each photosynthetic pathway produces a known range of carbon isotope composition in plant tissues and in lake or bog sediments into which decayed plant matter is incorporated. The photosynthetic pathway of C3 plants discriminates strongly against ^{13}C, producing $\delta^{13}C$ values from –32 to –20 ‰ (PDB), with an average value of –27 ‰ (PDB). C4 species do not discriminate significantly against ^{13}C and have a $\delta^{13}C$ range of –17 to –9 ‰ (PDB), with an average of –12 ‰ (PDB). Because of the distinct isotopic composition of these groups, the carbon isotope compositions of organic carbon preserved in lake sediments can indicate shifts in the dominant photosynthetic pathway in a watershed over the duration of the sediment record.

The factors that control photosynthetic dominance in an ecosystem are complex. Most authors agree that pCO_2 levels, temperature, and precipitation play the largest role in determining C3-C4 plant abundance (Ehleringer et al., 1997). The location of Laguna Yaguarú at the lowland forest-savanna boundary, and the age of the record (~5500 years) make precipitation and temperature the most likely causes for past variations in the occurrence of C4 plants that may be recorded in Yaguarú's sediments. Human land clearance may have also played a role in opening the forest and increasing the amount of

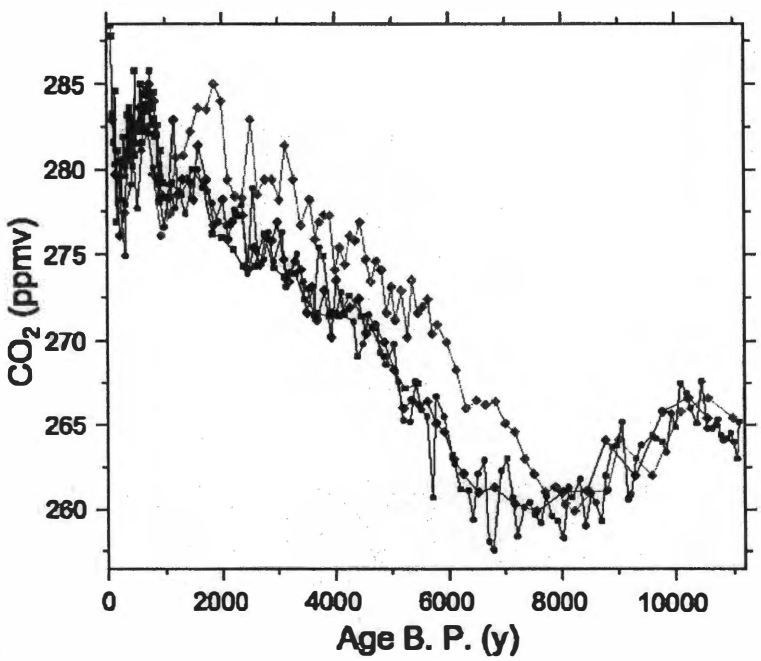
C4 vegetation through an increase in grasses or the cultivation of maize (Lane et al., 2004).

Unlike C3 plants, C4 plants concentrate CO_2 from the atmosphere in bundle sheath cells before it is used in photosynthesis, allowing them to be more successful during times of low CO_2 concentration (Collatz et al., 1998). Expansions of C4 plants during the Cretaceous, Miocene, and Pleistocene have been attributed to decreases in pCO_2 (Huang et al., 2001). Models designed by Collatz et al. (1998) and Ehleringer (1997) have simulated the effects of changes of pCO_2 levels on plants and determined crossover points where C4 plants become dominant over C3 plants (Figure 2.1 A). Huang et al. (2001) and Boom et al. (2001) have examined lacustrine sediment records from tropical locations extending back to glacial times. Stable carbon isotope analyses of these records provided evidence of past C3-C4 distribution changes, only some of which can be tied to changes in pCO_2. Huang et al. (2001) compared their record with the Taylor Dome CO_2 record, and suggested that climate factors may be more important controls on C3-C4 distribution than pCO_2 levels. The record at Laguna Yaguarú reaches back ~5,500 years, during which time the pCO_2 has changed little, compared to the magnitude of fluctuations that had a large effect on C3-C4 ratios worldwide (Figure 2.1 B).

Temperature also has an effect of C3-C4 dominance ratios (Figure 2.1 B). C4 plants tolerate high temperatures better than C3 plants. According to Ehleringer et al. (1997), C3 plants have higher rates of carbon gain when average growing season temperatures are below 22° C. Above this point, C4 plants have higher carbon gains, but the crossover temperature is dependent on CO_2 concentration. In the Laguna Yaguarú



A



B

Figure 2.1 CO_2 Levels and Temperature as Controls on C3-C4 Dominance, and Holocene CO_2 Fluctuations. (A) Diagram of how CO_2 levels and temperature affect C3-C4 dominance (Ehleringer et al., 1997.) (B) CO_2 levels over the Holocene based on air bubbles in Antarctic ice core records from Dronning Maud Lane (black squares), Dome C (black dots), and Taylor Dome (gray diamonds), (Monnin et al., 2004).

record, temperature should be a large factor because CO_2 values are relatively constant throughout the record. Ice core data from Antarctica indicates that CO_2 values varied from 260-285 ppmV over the past 5500 years (Monnin et al., 2004; Figure 2.1 B).

Aridity also plays a role in determining C3-C4 dominance. C4 plants outcompete C3 plant in hot, dry environments with warm-season precipitation because they have higher water use efficiency (Huang et al., 2001). This originally was thought to be the main factor in controlling C3-C4 dominance until the implications of pCO_2 changes were understood (Huang et al., 2001). However, pCO_2 levels have not fluctuated significantly in the past 5000 years, making it an unlikely driver of change in C3-C4 dominance. In a low elevation, low latitude environment like Laguna Yaguarú, the most important controls over the dominant photosynthetic pathway are expected to be aridity and temperature.

Thus, shifts between C3 and C4-dominance at Laguna Yaguarú were likely controlled by climate, and may record shifts between the proportion of forest and savanna surrounding the lake. These isotopic shifts may provide a proxy of temperature and precipitation variability to compare with the vegetation record based on pollen. To accurately interpret the stable carbon isotopic composition of bulk sediment, the sources of organic material entering the lake must be identified. Carbon from outside the lake (allochthonous carbon) comes from terrestrial sources, including plant material and carbon from soil (Aucor et al., 1999). Autochthonous carbon, that which originates within the lake, comes from algae and other organisms living in the lake. Aquatic vegetation is present within Laguna Yaguarú and is a likely a source of carbon in the sediment. This study uses total organic carbon for isotope analysis, but I take into

account that carbon in the lake comes from both autochthonous and allochthonous sources. Huang et al. (2001) and Ficken et al. (2002) pointed out that using bulk organic samples can lead to inaccurate results if autochthonous carbon distorts the record. By examining other proxies, including pollen and sediment characteristics, I attempted to recognize and account for this possible problem. Lake sediments usually provide excellent organic carbon preservation because of the anaerobic nature of the lake sediment. However, diagenesis, most often from biological processes or superimposed oxidation, can impact the isotopic signature. It may be possible to identify diagenesis by carbon isotope compositions that are inconsistent with the pollen assemblage and/or pollen degradation and changes in sediment color that typically accompany oxidation.

Chapter 3

Study Area

Laguna Yaguarú lies in the lowland region of eastern Bolivia (15°36'S, 63°13'W, elevation of 195 m), between the Andes foothills and the current boundary of the Amazon rainforest. The lake covers an area of ~250 ha and is mostly less then 4 m deep. The size and depth of the lake vary considerably between the wet and dry seasons. Most of the lake is surrounded by a large swampy area with only a small portion of the shoreline well defined. At the time of sampling in May 2003, there were large amounts of macrophytes and floating vegetation. The small village of Yaguarú is located on the southeast shore of the lake.

Geologic and Physiographic Setting

Bolivia can be divided into two major physiographic regions: the Andes and the lowlands. The Andes dominate the western third of the country and reach heights of over 6000 m. The eastern portion of Bolivia has very little relief and is largely dominated by fluvial processes. The area is underlain by Precambrian igneous and metamorphic rocks that are heavily weathered. Oxisols are common and soil fertility is often low (Killeen et al., 1998).

Laguna Yaguarú is one of several lakes near the town of Ascención de Guarayos. It lies in a small, north-south trending basin flanked by two rivers. Total relief around the basin is 5 m. The names of these rivers vary on different maps, but the largest scale map (1:100,000 Defense Mapping Agency "Ascención de Guarayos" Edition 1), identifies the river to the east as the Rio Blanco and the river to the west as the Rio Zapaco. The Rio

Blanco has its headwaters in a series of upland areas southeast of Laguna Yaguarú. The Rio Zapaco is a smaller stream that drains the southwest flank of this same upland. This region of Bolivia has numerous streams flowing to the north, eventually joining the Amazon. These rivers do not have their headwaters in the Andes; they instead arise from the swamps and plains to the south of Yaguarú.

Climate

The Santa Cruz region of lowland Bolivia, where Laguna Yaguarú is located, is generally warm with strongly seasonal precipitation. The region receives ~1400–1500 mm of mean annual precipitation with a ~6 month dry season during the winter months (Mayle et al., 2000; Burbridge et al., 2004). Mean annual temperature is between 25 and 26 °C. Climate data from the town of Concepción (~100 km east of Yaguarú) indicate similar average temperatures to those reported by Mayle et al. (2000) for the region as a whole, with extremes of 3 and 38.1 °C (Killeen et al., 1998). At Concepción, mean annual precipitation is reported at 1129 mm, but with a potential evapotranspiration of 1350 mm, leaving an annual water deficit of 200 mm (Killeen et al., 1998). Killeen et al. (1998) also reported large inter-annual variability in precipitation. Wet years can have as much as 1710 mm precipitation, while dry years as little as 500 mm.

The dominant control of precipitation in lowland Bolivia is the seasonal migration of the Intertropical Convergence Zone (ITCZ) (Killeen and Hinz, 1992; Martin et al., 1997; Burbridge et al., 2004). During the austral summer, the ITCZ moves southward. This allows the northeast trade winds to blow from the Atlantic across the Amazon in to northern Bolivia, with the Amazon forest as the predominant moisture source. The

warm, moist, and extremely unstable air creates strong convective activity over the region. According to Mayle et al. (2000), this is such an important source of precipitation that it is the dominant control of the Amazon rainforest's southern boundary (Figure 3.1). This low pressure area centered over the Amazon basin is one of three major pressure systems that interact to control the summer climate over lowland Bolivia. In addition to the low pressure over the Amazon, low pressure forms over the southeastern portion of Brazil. The South Atlantic Convergence Zone or "Noreast" low is a result of warm, unstable air from the warm South Atlantic and adjacent coast (Lenters and Cook, 1995). Between these two lows resides the Bolivian high over the Altiplano. Models run by Lenters and Cook (1997) indicated that the Bolivian high's location is not caused by the Andes. Instead, it is the result of these two lows, especially the Amazonian low, creating an area of subsiding air. These three systems change slightly in relative strength throughout the summer, controlling which areas get precipitation.

During the austral winter, the ITCZ moves to the north, taking with it the northeast trade wind belt. The Andes serve as an effective barrier to the mid-latitude westerlies that would otherwise have a strong influence over eastern Bolivia (Lenters et al., 1995), allowing the southeast trade winds to create an anticyclonic circulation during the austral winter that brings dry, northerly winds to lowland Bolivia. They lack the moisture source of the northeast trades, resulting drier conditions even though the circulation pattern is similar to that of the austral summer. These winds are occasionally interrupted by advective flows from the South Pacific anticyclone. Known locally as "surazos," these cold winds can bring temperatures as low as 5 °C (Mayle et al., 2000).

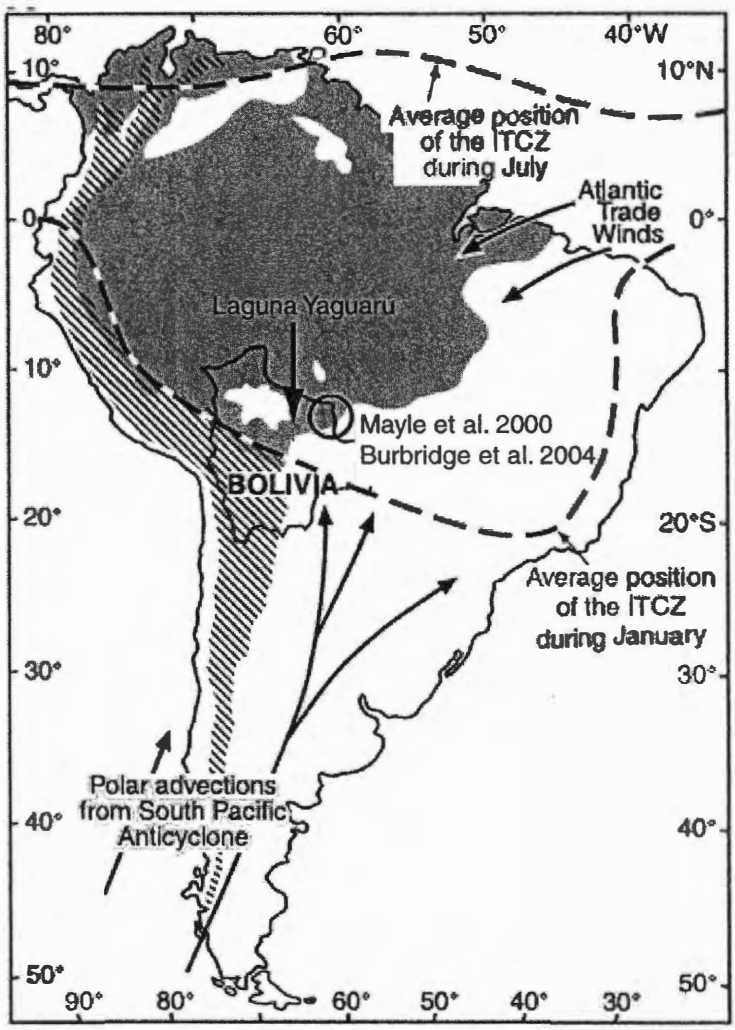


Figure 3.1: Map Showing Location of Laguna Yaguarú. Dominant winds, seasonal positions of the ITCZ, and study sites of Mayle et al. (2000) and Burbridge et al. (2004) also shown. Map adapted from Mayle et al. (2000).

Vegetation

Laguna Yaguarú lies in the transition zone between evergreen (Amazonian) rainforest to the north, and savanna to the south. Diverse terms have been applied to the vegetation of this transition zone, including dry forest, humid forest, seasonally dry tropical forest, and semi-deciduous forest (Killeen et al., 1998). Mayle (2004) used the term "seasonally dry tropical forest" (SDTF) as a catchall term for the neotropical forests south of the Amazon rainforest itself and north of the savanna region. These areas receive less than 1600 mm annual precipitation, with a 5–6 month dry period with less than 100 mm of precipitation. SDTFs range from tall, closed canopy forest in more mesic sites to cactus scrub in drier habitats. The species present in the SDTFs are a subset of those found in the rainforest, but with much lower diversity, and include species from the savanna region to the south (Mayle, 2004). Basal area, canopy height, net primary production, and biomass are lower than true rainforests. SDTFs have a higher percentage of flowering trees and lianas that require specific pollinators than do rainforests. As SDTFs occupy areas with the same climatic parameters as cerrado (non-flooded savannas), soil conditions exert a control over their distribution. More fertile and basic soils support SDTFs, while savannas are relegated to nutrient-poor, acidic soils (Mayle, 2004).

There are four primary SDTF areas south of the Amazon basin in South America: the Caatinga, Misiones, Chiquitano and Andean Piedmont (Mayle, 2004). The Chiquitano forest covers the northeastern portion of Bolivia. Laguna Yaguarú is located in the eastern portion of the Chiquitano forest. Within the area designated as the Chiquitano, there are a range of environments encompassing forest, savanna, and

pantanal wetlands. Killeen et al. (1998) compiled a floristic inventory of a 400-ha block of Chiquitano forest, near the town of Concepción, ~100 km east of Laguna Yaguarú. They identified 501 total species, making it one of the most species-rich neotropical dry forests on record. Trees (124 spp.), herbs (101 spp.), lianas (85 spp.), and shrubs (66 spp.) made up most of the species. Overall, the forest is characterized by being relatively open and having high stem density. This openness led to more species richness on the forest floor than the rest of the vertical strata combined. Lianas were extremely common. In some cases, lianas were more abundant than trees over 2 m in height. Lianas covered over 25 % of the trees' crowns and less than 25 % of the trees were free of lianas. Statistical analysis of plant distributions suggested three distinguishable microhabitats with characteristic floral assemblages. Valley bottoms and upland areas were significantly different, but each supported a large number of species. Plots that included granite outcrops harbored a unique collection of species, including cacti and other xeromorphic species, which were found nowhere else.

Environments in the Chiquitano that are more xeric or subject to seasonal flooding are inhabited by a wide variety of grass species assemblages. Killen and Hinz (1992) described 113 grass species and associated vegetation patterns near Concepción, Bolivia; the rest of this paragraph is based on their study. Species richness, dominant morphology, and percentage of total grass cover were determined for seven different habitats. In the semideciduous forest, grasses are common, but usually contribute 5 % or less of total cover and have low species diversity. In the cerrado habitat—wooded savanna with woody vegetation less than 25 % cover—the importance of grasses fluctuates seasonally. Annual fires remove much of the woody material, allowing grasses

to dominate during the rainy season. The cerrado has high species diversity. The ecotone between the semideciduous forest and the cerrado—called the cerradão—has 50–100 % grass cover and has an intermediate level of diversity. On xeric ridge tops is the campo rupestre, or treeless savanna. This has the lowest species richness of any of the environments. The wetland areas were divided into two categories: valley-side campos and pantanal complexes in the valley bottoms. The valley-side campos form where a perched water table seasonally intersects the surface. Grasses and sedges each contribute about 50 % of the cover. The high grass species diversity has been attributed to the large moisture gradient. The pantanal wetlands have the highest number of grass species, a condition also attributed to extreme moisture gradients. Grasses make up 50–70 % of the cover and have an extremely heterogeneous distribution. These areas often have hummocks, seasonal ponds, and other features that contribute microtopographic variability. Here, species from the valley-side campos and drier locations can grow adjacent to species constrained to seasonally flooded areas. The region's granite outcrops supported a species-poor but unique grass community. The extremely xeric conditions severely limited the number of species. Percent grass cover was below 50 % because of competition from cacti and bromeliads. A second study by Killeen and Hinz (1992) made general observations about the photosynthetic pathway preferred by the grasses in these environments. The C3 pathway was used almost exclusively by grasses in the semideciduous forest and in other locations with a closed canopy. C3 grasses were also important in wetland areas. C4 grasses were dominant in the drier, more open areas.

Human History

The human history of the Chiquitano region is poorly understood. The area is inhabited today by the Guarayo Indians. Little is known about the group, except that they migrated to the area from what is now Paraguay around 1400 (Paz-Rivera, 2003). Spaniards first visited the area in 1548, but there was no consistent European presence until missions were set up around 1700. In 1794, a Franciscan priest estimated the population in the Yaguarú region to be around 3000. This is probably extremely low as it included only those living in missions (Paz-Rivera, 2003). It took until 1845 to successfully integrate the native population into Jesuit missions (Killeen et al., 1998; Paz-Rivera, 2003).

Literature on lowland Bolivian archeology is sparse, but evidence exists of large scale environmental modification by prehistoric humans (Paz-Rivera, 2003). Paz-Rivera (2003) found anthropogenically modified soils at the BOLFOR field station of La Chonta (located in the Yaguarú area). Portions of the forest had dark soils that contained large amounts of charcoal and pottery shards. These soils, known as *tierra-negra*, had higher nutrient levels and likely supported some form of prehistoric agriculture. Human use of these soils stopped abruptly 400 years ago and current vegetation is no different from nearby plots without *tierra-negra* soils (Paz-Rivera, 2003)

In addition to agriculture, there is evidence to suggest that prehistoric peoples built earthworks to form fish weirs (Erickson, 2000). Fish protein supplemented diets and the weirs provided habitats for fruiting palm trees.

Currently, the Chiquitano is under threat from forestry, grazing, agricultural expansion, and mineral exploitation (Killeen et al., 1998). These activities are beginning

to change species compositions and threaten one of the neotropics' most intact and diverse dry forest ecosystems.

Chapter 4

Methods

Field Methods

I was part of a field team from the University of Tennessee that cored Laguna Yaguarú in May 2003. We were supported by a grant from The A.W. Mellon Foundation to Sally Horn and Robert L. Sanford, Jr. and were assisted while in Bolivia by staff of the Proyecto de Manejo Forestal Sostenible (BOLFOR), a joint Bolivia-U.S. project focused on the ecology and management the forests of the Chiquitano region.

We collected one sediment core working from an anchored platform in 1.12 m of water. Using a plastic tube corer (PTC), which is a piece of 5 cm diameter PVC pipe fitted with a rubber piston, we recovered 76 cm of flocculent upper sediments. We extruded and sampled the sediments in 2 cm increments on the shore, where we placed them in plastic bags for transport to the University of Tennessee. For deeper sediments we used a Colinvaux-Vohnout (C-V) locking piston corer which samples sediments in one meter aluminum tubes (Colinvaux et al., 1999). We recovered a total of 4.75 m of sediment. Cores were sealed in the aluminum collecting tubes and returned to the University of Tennessee. They were stored in a cold room at 6° C from May until they were opened in August 2003.

Laboratory Methods

We opened the aluminum tubes lengthwise using a specially modified router. The cores were then sliced longitudinally into two equal halves using a thin wire. One half was used for sampling and the other was archived. We immediately photographed both

core halves and described the stratigraphy in terms of sediment texture and Munsell color. The upper two core sections and PTC contained sediment suitable for analysis (see Results).

Loss-On-Ignition

I sampled the cores for pollen and charcoal analysis at 4–8 cm intervals. For both pollen and loss-on-ignition (LOI) analyses I used 1 cm^3 volumes. LOI samples were placed in preweighed crucibles, weighed, dried for 24 hours at 100° C, and then reweighed to determine water content. Samples were then ignited in a muffle furnace at 550 °C for 1 hour and 1000 °C for 1 hour, to estimate organic and carbonate content, respectively (Dean, 1974).

^{14}C Dating

Chronological control on C–V core sections was provided by three Accelerated Mass Spectrometry (AMS) radiocarbon dates from Beta Analytic, Inc. Each date was on macrofossil material (predominantly charcoal) I took from the core. To obtain these samples, I rinsed sediment through a sieve, and, using a dissecting microscope, picked out pieces with small tweezers. I calibrated the dates using CALIB rev. 4.4.1 (Stuiver and Reimer, 1993) and the dataset of McCormac et al. (2004), and calculated the weighted means of the calibration probability distributions (Telford et al., 2004) using a spreadsheet. The values were included on diagrams and used to calculate sedimentation rates.

^{210}Pb Dating

To better understand the sedimentation rate in the more recent sediments, samples from the uppermost 40 cm of the core (bagged in the field at 2 cm intervals) were prepared for ^{210}Pb analysis. Each sample was placed in a small plastic dish and dried at 60 °C. The dishes were then refilled, and the process repeated until each small dish was filled with dry sediment. The dishes containing the samples were then scanned for Beta emission in the laboratory of Dr. Lee Cooper of the Department of Ecology and Evolutionary Biology at the University of Tennessee. Only the topmost 7 samples, representing 14 cm, were actually counted because of insufficient amounts of ^{210}Pb in samples from deeper levels. The data were plotted and used to calculate the sedimentation rate.

Particle Size Analysis

I used particle size analysis procedures developed for use in the Laboratory of Paleoenvironmental Research by Dr. Ken Orvis, which are based on work by Gee and Bauder (1996). I analyzed 15 samples from a mineral facies in the sediment core. Each level sampled for particle size was also sampled for water content analysis to provide dry weight measurements. I modified the procedure by not removing organic matter to more accurately simulate the depositional environment. I dispersed the samples by shaking them (1 Hz) overnight in a solution of 3.6 % sodium metaphosphate. Once fully disaggregated, I rinsed each sample through 63 and 53 μm sieves. I rinsed the captured

particles into dried, preweighed beakers. They were then dried, weighed, and archived for possible later analysis.

The remaining material, consisting of silt- and clay-sized particles, underwent sedimentation analysis. Each sample was placed into a 1000 ml graduated cylinder that was then filled to 1000 ml with deionized water. I placed all the cylinders in a constant temperature water bath and allowed them to thermally equilibrate. After stirring each column vigorously, aliquot samples were taken from 10 cm depth at specified periods (controlled by temperature) to capture each particle size range (φ). The φ ranges were as follows: 63–32 μm, 32–16 μm, 16–8 μm, 8–4 μm, 4–2 μm, 2–1 μm, and <1 μm. The 63–53 μm values included material that remained on the 63 μm and 53 μm sieves. I placed each aliquot into a dried, preweighed beaker. I then dried them an oven at 100 °C, cooled them in a dessicator, and weighed them. Material that remained in the column was flocculated, centrifuged, and archived for later use.

I entered all weights into a database that determined the percentage of mass made up by each particle size class. These data were then graphed with a modified version of CalPalyn (Bauer et al., 1991).

Pollen Analysis

I processed samples for pollen analysis using standard processing methods (HCl, HF, KOH, acetolysis, safranin stain; (Berglund, 1986; Appendix A) . To each sample, I added one tablet of *Lycopodium* spores (13,911 spores per tablet) to allow calculation of pollen concentrations (Stockmarr, 1971). I used silicone oil as a mounting medium, and I prepared one or two slides for each level processed.

I identified pollen to the lowest possible taxonomic level using the pollen reference collection in the Laboratory of Paleoenvironmental Research at the University of Tennessee and several pollen keys (Herrera and Urrego, 1996; Roubik and Moreno, 2003; Rull, 2003). I also used a plant taxa list provided by BOLFOR of species they have identified in the Laguna Yaguarú area.

I grouped some pollen types together because they have similar morphologies that made distinguishing them difficult or impossible. Melastomataceae/Combretaceae, Saptotaceae/Meliaceae, and the order Urticales were grouped in this way. The Urticales order includes the families Cecropiaceae, Moraceae, Ulmaceae, and Urticaceae. These four families include many taxa that produce pollen grains that are small, and have psilate or scabrate exines. I distinguished *Cecropia*, *Trema*, and *Celtis*-type, and classified the rest according to pore number (diporate, triporate, 4-porate, polyporate, and undifferentiated pore number).

I classified grains as indeterminate if they were unidentifiable because of corrosion, degradation, mechanical damage, or concealment by other materials on the slide (Delcourt and Delcourt, 1980). I only classified the indeterminate grains based on their most obvious characteristic and did not combine categories (Northrop, 1994).

Grains that were potentially identifiable but for which I did not know the taxon were classified as unknowns. I assigned a number to each unknown morphotype, made a rough sketch, and recorded its size. I also recorded the slide number and coordinates of each unknown. I classified fern spores by morphology (monolete and trilete) and exine type (psilate, scabrate, verrucate, coarsely verrucate, echinate, striate, rugulate, bacculate, and clavate).

I counted at least 200 grains excluding indeterminate pollen, Cyperaceae pollen, and fern spores in each of 55 sample levels in the profile. I excluded Cyperaceae pollen from the pollen count because it was present in large enough numbers to overwhelm the signal and because herbs of this family are common in a range of environments, making them poor environmental indicators.

Charcoal Analysis

While counting pollen, I also counted charcoal. I only classified particles as charcoal if they were black, opaque, angular fragments >50 μm in maximum dimension. I divided the charcoal particles into two size ranges, 50–125 μm and >125 μm. I plotted all pollen and charcoal data with a modified version of CalPalyn (Bauer et al., 1991).

Stable Carbon Isotope Analysis

I measured stable carbon isotopes on the same levels sampled for pollen, using the procedure outlined in Boom et al. (2001). I washed sediment samples in HCl to remove any carbonate material and then rinsed them with distilled water until neutralized. I then dried and vacuum-aspirated the samples. I then combusted the samples in quartz tubing at 850°C with platinum, Cu, and CuO in a muffle furnace. I cryogenically purified the CO_2 produced using a vacuum distillation line. The CO_2 produced was analyzed on a Finnigan MAT DeltaPlus mass spectrometer at the University of Tennessee Stable Isotope Laboratory. Results are reported in standard delta-permil notation, relative to the Peedee belemnite (PDB) standard:

$$\delta^{13}C(‰) = 1000[(R_{sample}/R_{PDB}) - 1],$$

where $R = {}^{13}C/{}^{12}C$.

The reproducibility of samples analyzed is 0.05 ‰ based on 20+ months of comparison in the laboratory with the USGS-24 standard.

Chapter 5

Results

Core Stratigraphy

A total of 475 cm of sediment was recovered from Laguna Yaguarú. A fairly complete section was recovered, although there were a few small gaps likely resulting from the coring processes. There also is one 15 cm section that appears to be out of place stratigraphically. The lower two core sections (276–371 cm, 369–475 cm) consist of clean mineral sand, unsuitable for paleoenvironmental analysis. The 234 cm analyzed in this study consist of three main units. The upper unit (0–151 cm) is dominated by fine organic mud with a Munsell color of 10YR 2/1 (Figure 5.1). The middle unit (152–171 cm) is mineral sediment with high clay content and a Munsell color of 10YR 4/1. The lower unit (172–234 cm) with a Munsell color of Gley 2.5/N also consists of organic mud, but is not as dark as the upper unit.

Loss-On-Ignition

The upper unit has the highest organic content, reaching a maximum of 42 % (dry weight basis) in the near surface sediment (Figure 5.1). Organic content drops sharply in the middle unit of mineral material, reaching low values of less than 5 %. The lower unit of the profile has an intermediate organic content. Carbonate content was less than 2 % and varied little throughout the core.

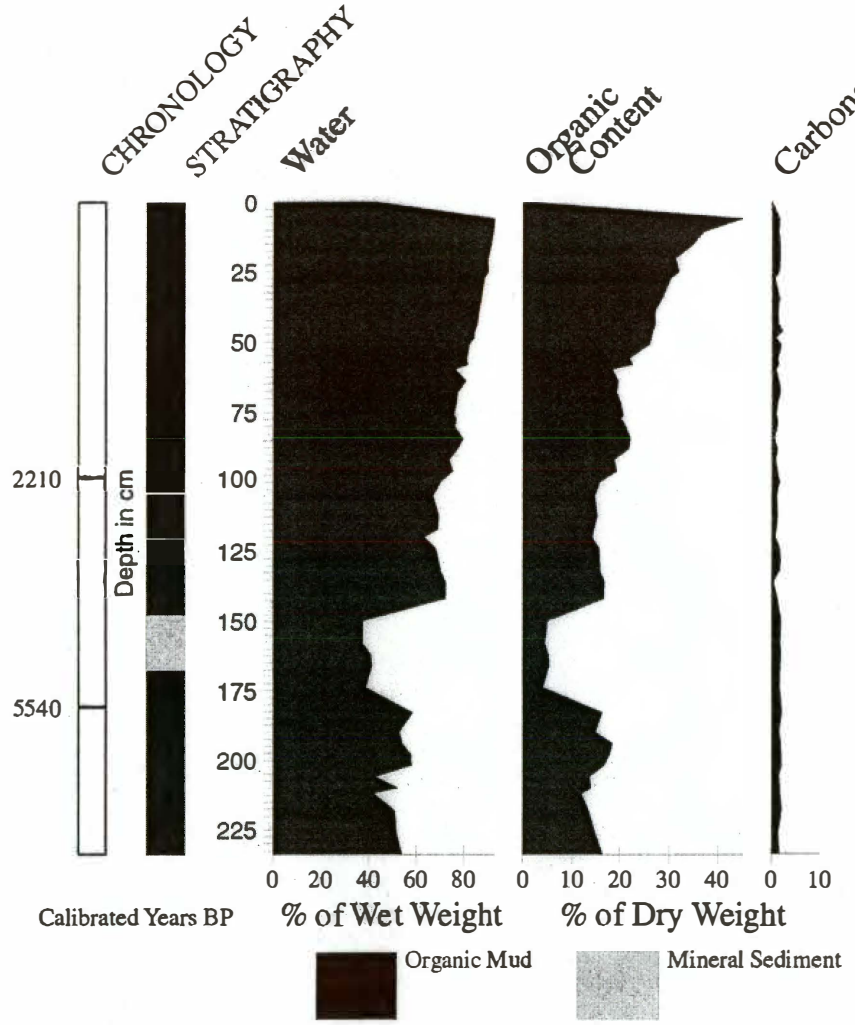


Figure 5.1: Laguna Yaguarú Sediment Diagram

^{14}C Dating

The three radiocarbon dates (Table 5.1) show a reversal within the lower unit, with the stratigraphically lower date ~600 calibrated years younger than a date 59 cm higher in the profile. Several factors make this lower date suspect. First, the sample came from a core tube that had 105 cm of material recovered from pushing the corer 100 cm. This suggests either the recovery of material collapsing in to the coring hole or higher sediments being sucked up into the bottom of the coring tube when the corer was being pulled up. Since the sample was taken only a few centimeters from the bottom of the coring tube, it seems likely that the material was sucked in from a higher (younger) level. This may have been a result of the corer creating a seal with the clay layer of the mineral unit while the corer was being pulled out, sucking in material out of sequence. The date comes from numerous macrofossils so a mixture of younger and older material may explain the age of the lower date.

^{210}Pb Dating

Figure 5.2 shows the ln of ^{210}Pb activity against depth for the upper 14 cm of the core. The sedimentation rate was calculated by first using linear regression to fit a line to the profile. In this case, the equation for the line is $Y = -0.13646X - 3.794$ with an $R^2 = 0.954$. I divided the slope of this line by the decay constant of ^{210}Pb, which is 0.031082833. This number was then divided by the slope, yielding a sedimentation rate of 0.23 cm/yr over these 7 data points (L. Cooper, pers. comm.). This suggests the uppermost 13 cm of the core spans approximately the past 57 years.

Table 5.1: Radiocarbon Determinations from macrofossils (predominantly charcoal) in the Laguna Yaguarú Sediment Core

Lab Number	Depth (cm)	$\delta^{13}C$ (‰)	Uncalibrated ^{14}C Age (^{14}C yr BP)	Calibrated Age Range (cal. yr BP) ± 2 σ	Area Under Probability Curve	Weighted Mean Calibration Age yr BP
β-192648	98	–26.1	2240 ± 40	2062–2088 2099–2332	0.039 0.961	2210
β-188889	181	–22.6	4880 ± 40	5339–5340 54672–5652	0.001 0.999	5540
β-182613	240	–12.6	4420 ± 40	4841–5048 5201–5211	0.991 0.009	4950

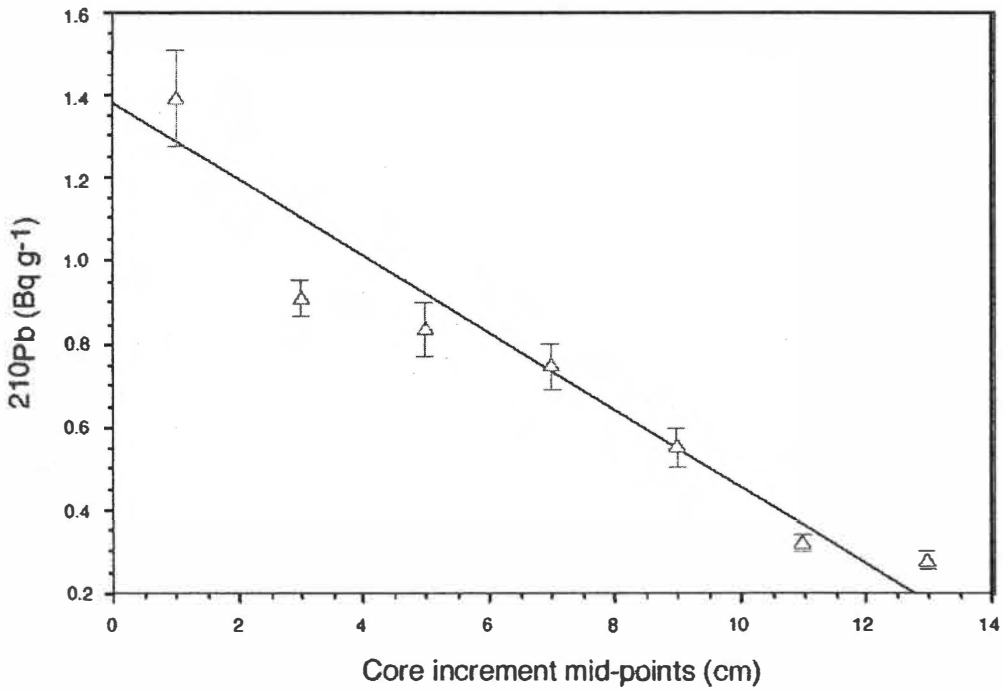


Figure 5.2: Laguna Yaguarú ^{210}Pb Depth Profile

Particle Size Data

Particle size analysis of 15 samples from the middle unit (152–171 cm depth) showed that all samples are dominated by fine particles, but there is a 7 cm distinct peak in the presence of larger particles (63–125 μm) centered on 165 cm depth (Figure 5.3).

Pollen Results

Pollen preservation and concentration varied significantly through the core (Figure 5.4, Table 5.2). Pollen concentrations were low in the mineral sediment of the middle unit, in several cases too low for the sample to be counted (Table 5.2). In total, I counted 15,916 pollen grains. Less than 1.5 % of the total pollen was classified as indeterminate. Less than 1 % of the pollen was classified as unknown. I classified pollen grains into 33 different genera, families, or morphological groups. Approximately 88 % of all pollen was classified in the taxonomic groups Asteraceae, Cyperaceae, Poaceae, *Typha*, Urticales, *Celtis-type, Alchornea*, and Mimosoides (Fabaceae). Spore concentrations are generally low and tend to follow pollen concentrations. There are several sections of the core (especially 175–200 cm) with large intervals between levels due to low pollen concentration (Figure 5.4, Table 5.2). Although the highest and lowest stratigraphic units both have significant organic content, the latter has a lower pollen concentration. Based on changes in stratigraphy that corresponded to changes in pollen concentration and taxa distribution, I designated the sedimentary units as pollen zones 1–3.

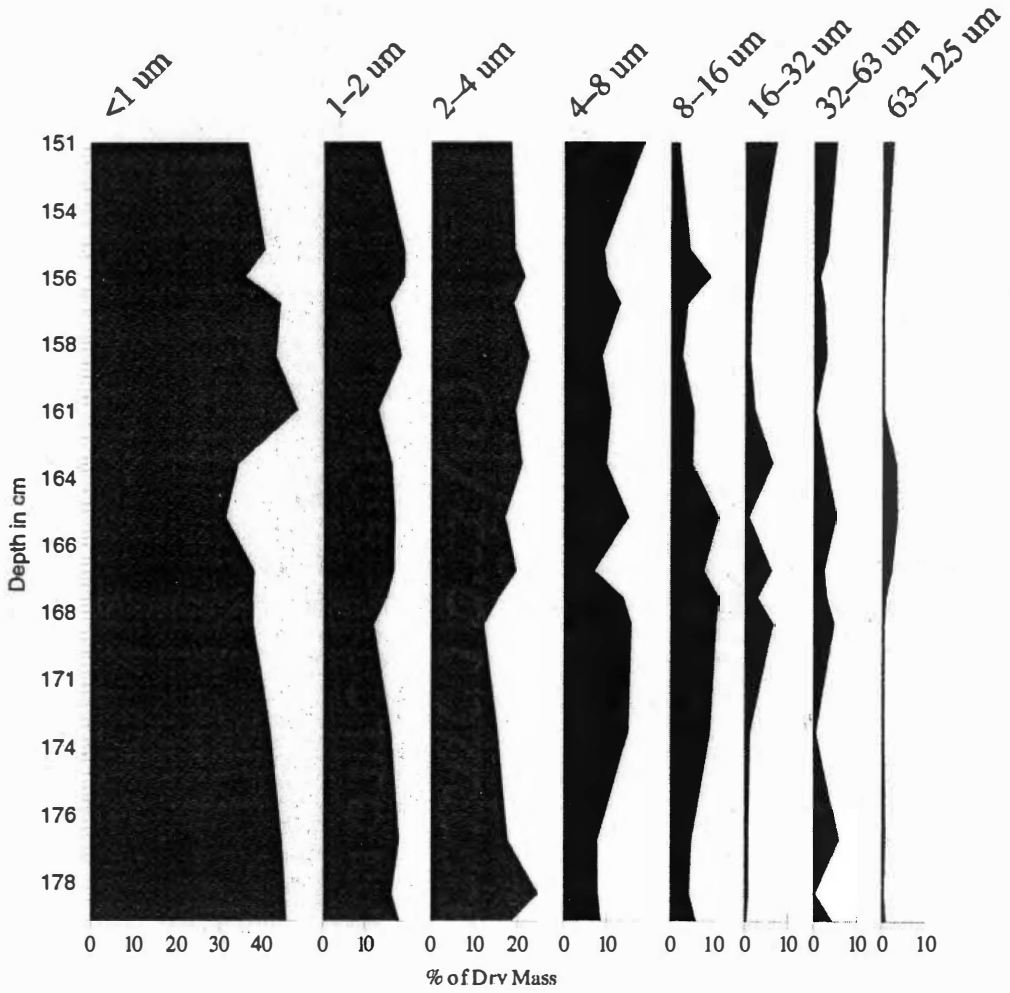


Figure 5.3: Laguna Yaguarú Particle Size Diagram, 151–180 cm Depth

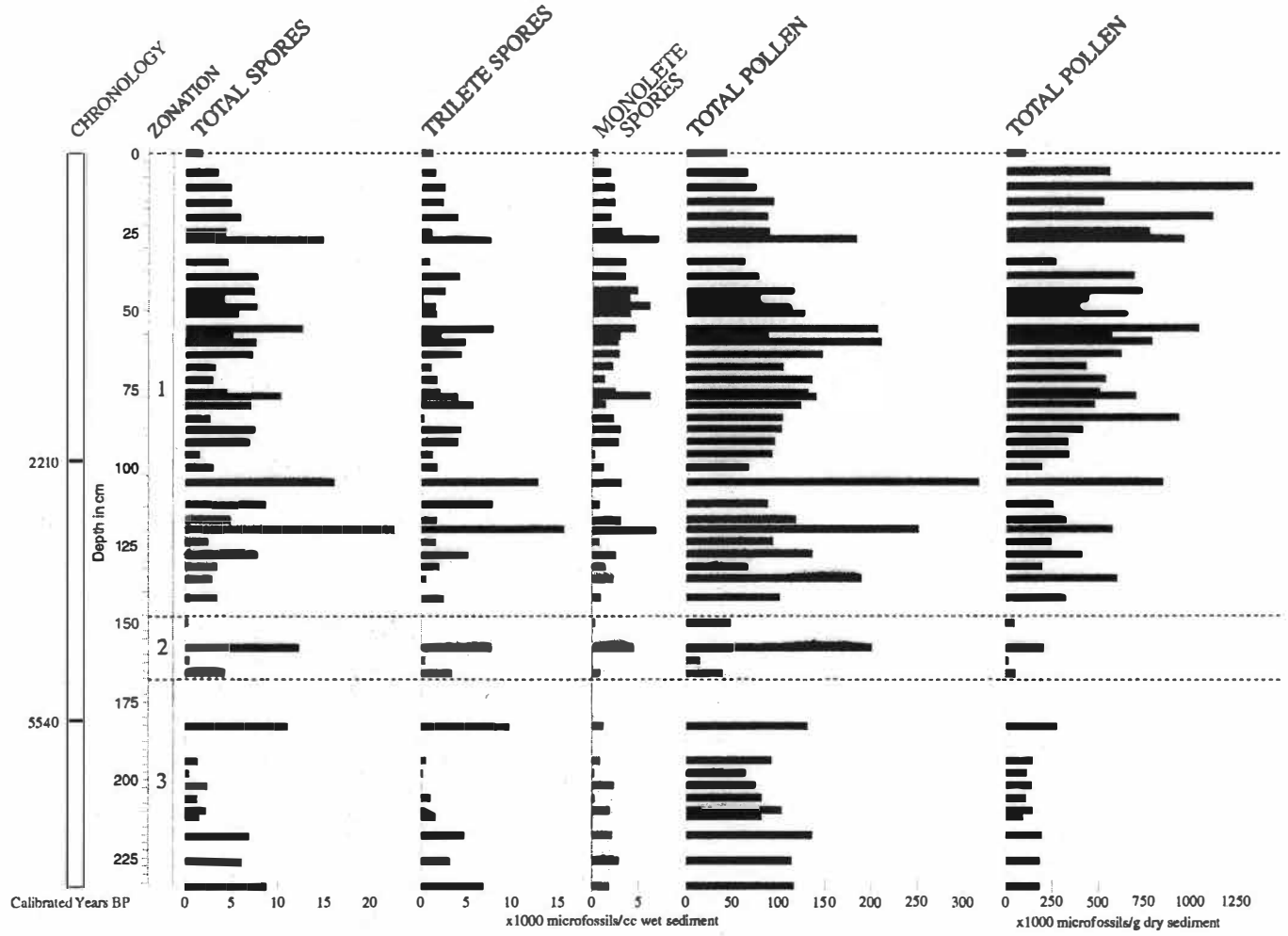


Figure 5.4: Laguna Yaguarú Total Pollen and Spore Concentrations Diagram

Table 5.2: Laguna Yaguarú Pollen Concentration (grains/cc wet sediment). Bold type indicates counts that were not completed due to low pollen concentration.

Level	Concentration
0.0	43820
5.9	66434
10.7	75771
15.5	94104
20.2	87604
25.0	89842
27.4	183824
34.5	63664
39.2	78503
44.0	117421
46.4	79965
48.8	113993
51.1	128540
56.0	206678
58.3	89573
60.0	210752
64.0	147265
68.0	105287
72.0	136067
76.0	132155
77.3	140668
80.0	124486
84.4	104206
88.0	103145
92.0	95638
96.0	92951
100.0	68251
105.0	316743

Level	Concentration
112.0	87830
117.0	118244
120.0	251267
124.0	93482
128.0	136067
132.0	67337
136.0	189537
142.0	101171
150.0	48541
154.0	**<331**
158.0	**3375**
162.0	15215
166.0	39390
170.0	**11193**
174.0	**<1739**
178.0	**<556**
183.0	130927
190.0	**1739**
194.0	92091
198.0	64697
202.0	75921
206.0	81326
210.0	103200
212.0	81629
218.0	136067
226.0	113876
234.0	116779
244.0	**<604**

Pollen and Stable Carbon Isotope Diagrams

Pollen, charcoal, and stable isotope data are presented on the same graph to allow for comparison different proxies (Figure 5.5). The most noticeable changes in the record include a dramatic decline in *Typha* between zones 3 and 1, a peak in Cyperaceae pollen at the top of zone 2, and increasing Urticales percentages throughout zone 1 (Figure 5.6).

Charcoal

Figure 5.7 presents a detailed breakdown of the charcoal particles in the sediment. The larger fragments of charcoal (>125 μm) represent less the 1 % of the total charcoal with particles in the 125–50 μm size class making up the remaining 99 %. Charcoal concentrations, like pollen concentrations, show intermediate values in zone 3, low values in zone 2, and high values in zone 1. Charcoal: pollen ratios are higher in zones 2 and 3 than in zone 1.

Stable Carbon Isotopes

Stable carbon isotope compositions range from –19 to –25 ‰ in zone 1, –21 to –24 ‰ in zone 2, and –22 to –24 ‰ in zone 3 (Appendix B). The stable isotope compositions are generally uniform in zone 3, but exhibit variability in zone 2 and show a strong upcore trend of decreasing isotope values in zone 1 (Figure 5.5 and 5.6).

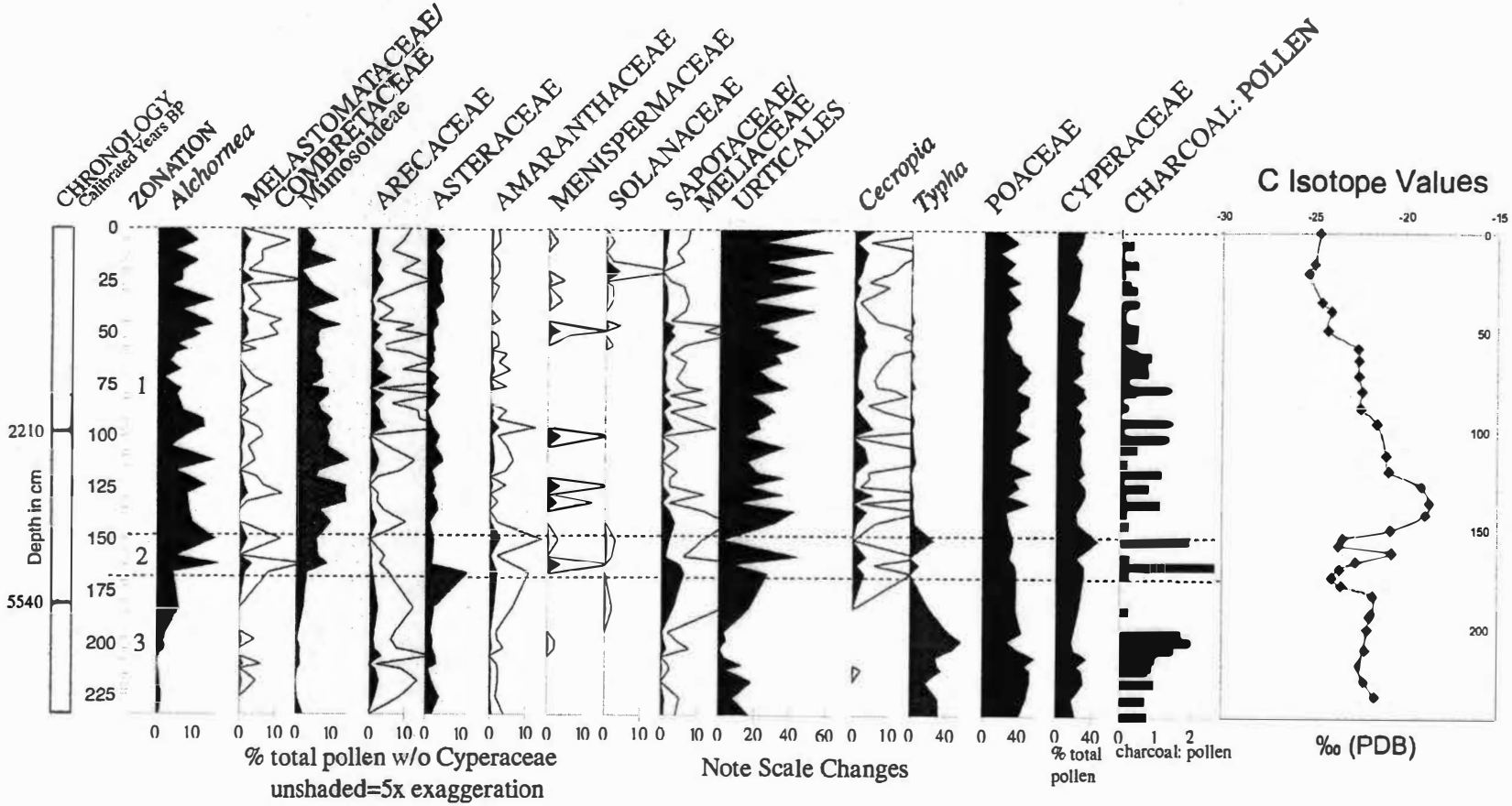


Figure 5.5: Laguna Yaguarú Pollen and Stable Carbon Isotope Diagram

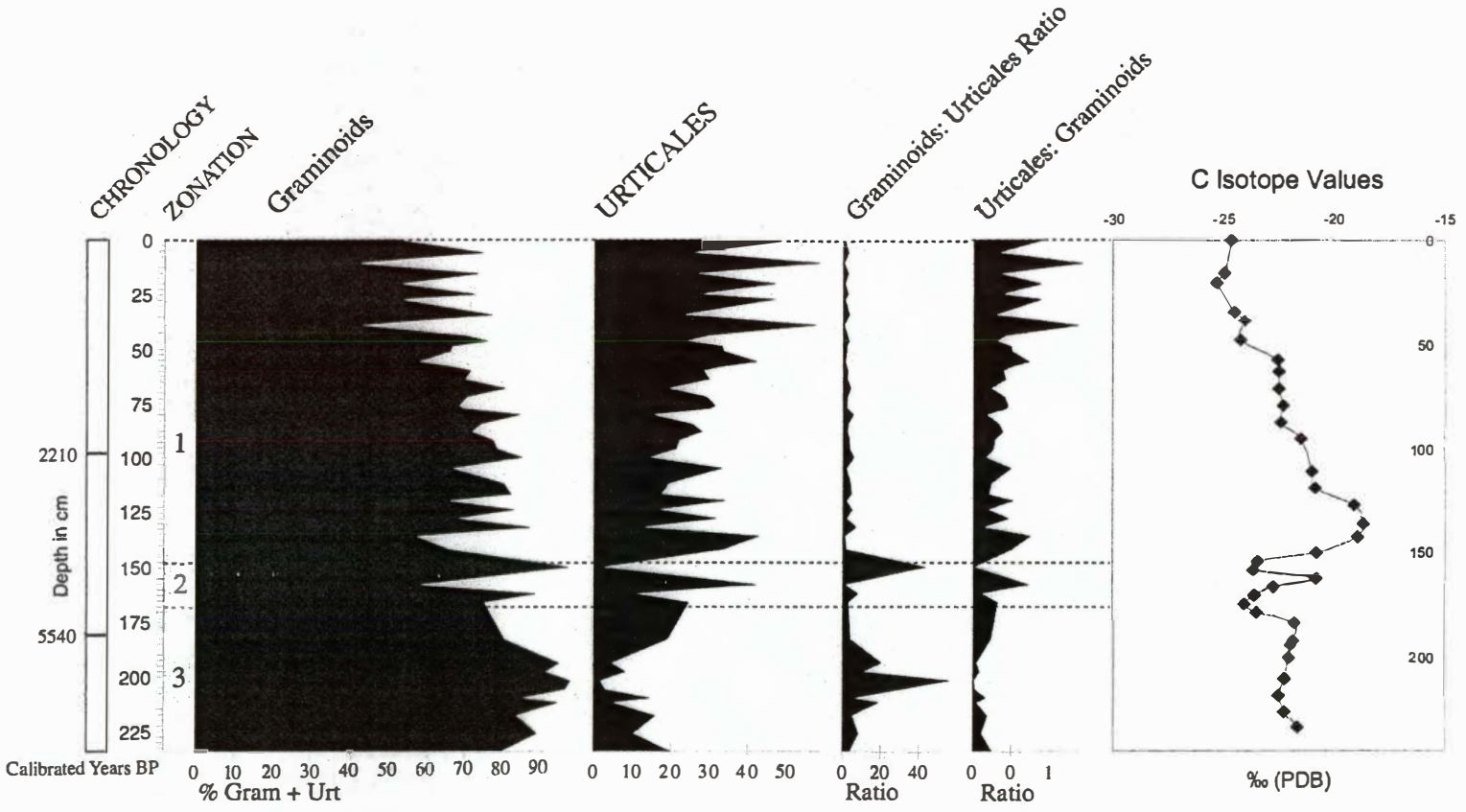


Figure 5.6: Laguna Yaguarú Graminoids, Urticales, and Stable Carbon Isotope Diagram

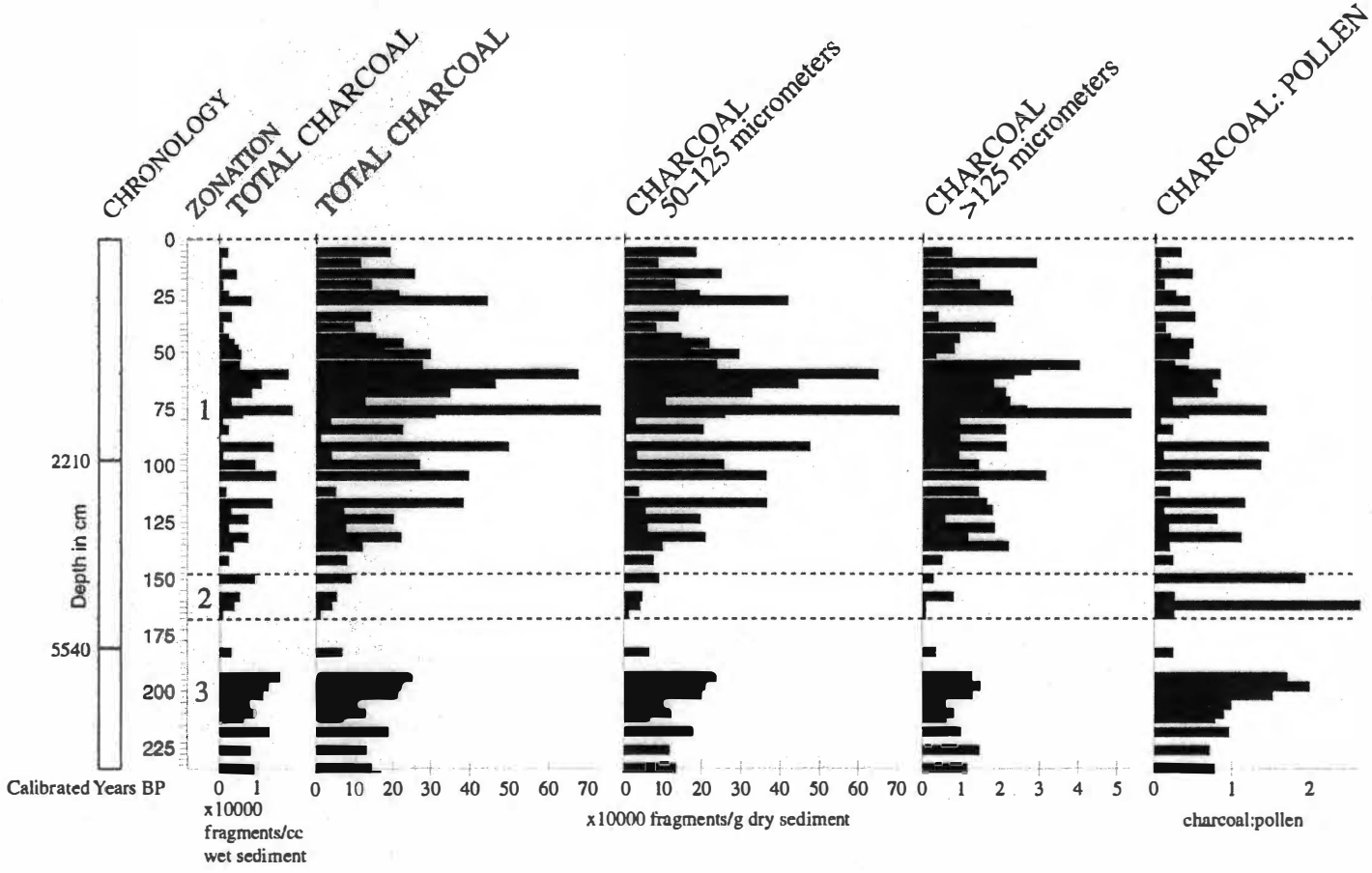


Figure 5.7: Laguna Yaguarú Charcoal Diagram

Chapter 6

Discussion

I begin this section with an examination of factors controlling the pollen and stable carbon isotope record. Then, because the sediment record of Laguna Yaguarú is so strongly controlled by the stratigraphy, I examine of each of the three sedimentary units/pollen zones. I then describe the actual environmental conditions at Laguna Yaguarú indicated by the analyses and offer hypotheses that could explain the environmental changes chronicled in the sediment record. Finally, I place the Yaguarú paleoenvironmental record in the context of other work done in highland Bolivia and the greater Amazon Basin.

Factors that Affect Pollen Data

Pollen diversity in the Yaguarú record is low compared to the species richness reported by Killen et al. (1998). Several factors may contribute to the lower pollen diversity in the Yaguarú record. First, the lake is fringed by swampy areas that may act to filter out pollen that would otherwise wash into the lake. Second, the lake has a surface area of ~250 ha. Studies suggest that the size of the effective pollen source area of lakes in temperate North America is proportional to the area of the lakes (Jacobson and Bradshaw, 1981; Jackson, 1990). This is especially true of lakes in temperate North America where a majority of tree species are gymnosperms (Davis et al., 1991). Tropical lakes like Laguna Yaguarú may not follow this pattern because a large majority of tropical species are entomophilious (Bush, 2002). In a tropical environment like Laguna

Yaguarú, the lake's large size creates a filter that anemophilious taxa can overcome more easily than entomophilious taxa. This can lead to the over-representation of anemophilious taxa in the pollen record. In flat bottomed lakes, like Laguna Yaguarú, with no sediment focusing to move the pollen to the center of the lake (Lehman, 1975), this over-representation may be greater.

Interpretation of Stable Carbon Isotope Record

Based on botanical studies in the region, terrestrial inputs from closed canopy forests should be almost exclusively C3 carbon and savanna-like open areas mostly C4 carbon (Killeen and Hinz, 1992; Killeen et al., 1998). Autochthonous inputs from algae and other sources have a range of values (Ficken et al., 1998). Diagenetic processes on sediment after deposition can also have strong effects, but do not seem to be a large factor in the Laguna Yaguarú record. I have taken care to interpret the carbon isotope record in conjunction with the core's stratigraphic and pollen record to identify any diagenetically-driven isotope excursions. Shifts in Yaguarú carbon isotope values are less pronounced than found by Lane et al. (2004) at two small lakes in Costa Rica. This may be a function of the lake's size and fringing wetlands, which could filter the allochthonous carbon, and preserve a higher proportion of autochthonous isotopic signatures of a shift between C3 and C4 vegetation. It is also possible that the changes in C3-C4 dominance at Laguna Yaguarú were not as severe or as sudden as those caused by human land use at the sites studied by Lane et al. (2004).

Stable Carbon Isotope Mixing Model

Mixing models such as those developed by Phillips and Gregg (2001) use measured isotope values and known values of environments to predict the importance of two isotopic sources, in this case C3 and C4 vegetation. Figure 6.1 shows the results of using this mixing model on the Laguna Yaguarú stable carbon isotope record. C3 vegetation was assigned a value of –27 ‰ and C4 vegetation a value of –12 ‰. Mixing models are useful because they allow be quantification of C3-C4 dominance in the watershed that is generally not possible with pollen. C3 importance ranges from 47–89 % in the record, indicating a significant shift between forest and savanna. This model is only an estimate since it does not take into account algae and other inputs.

Fire History

The charcoal record from Laguna Yaguarú indicates that fires have been part of the local ecosystem since the lake's formation and that their frequency/intensity has likely varied over the past 5000+ years. Because of the coarse chronological control on the record, I have not attempted to calculate charcoal influx. However, the charcoal: pollen ratio (Figure 5.7) may provide an indication of possible changes in charcoal influx over time, if we assume pollen influx to be approximately constant (perhaps a good assumption within zone 1). Under modern conditions, human-set fires are common and burn almost annually during the dry season (Killeen et al., 1998). Since the charcoal particles deposited in the lake were filtered by many of the mechanisms explained above, their concentration may be affected by more than just fire frequency and intensity.

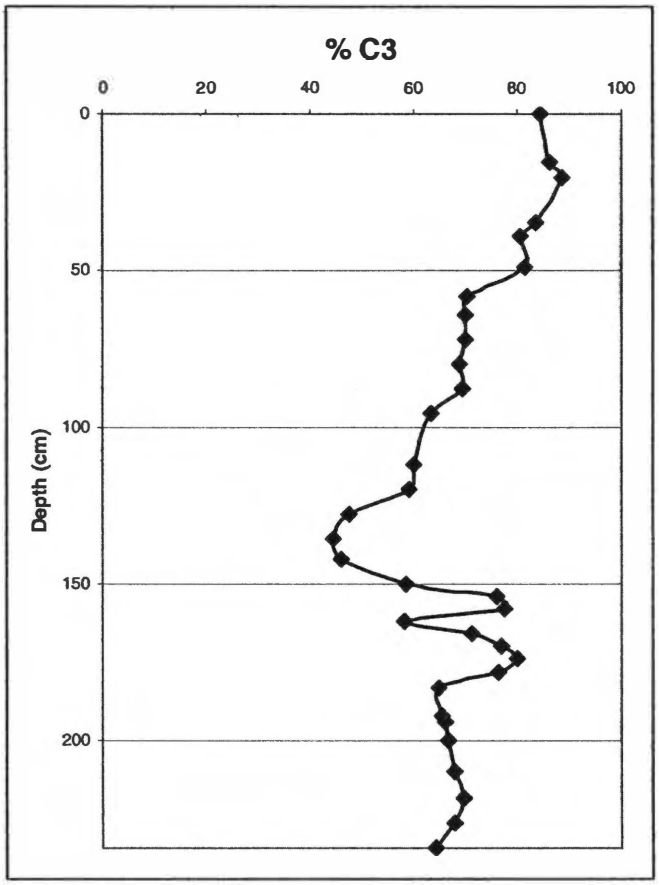


Figure 6.1: Two Component Mixing Model Based on Stable Carbon Isotope Ratios at Laguna Yaguarú.

Humans may have contributed to changes in fire activity (Northrop and Horn, 1996; Horn and Kennedy, 2001), though no archaeological or palynogical evidence of agricultural activities exists at Laguna Yaguarú.

Zone 3

The lower boundary of zone 3 is marked by the transition from mineral sand to organic sediment. Organic content fluctuates slightly around 15 % throughout the entire zone. Pollen, spore, and charcoal concentrations are relatively low when compared to zone 1. Stable carbon isotope values vary little and average –22 ‰. Pollen preservation was often poor in zone 3, so there are some significant gaps in my pollen counts. Low pollen concentrations led to only one sample being counted in the upper 20 cm of the zone. There is no visible stratigraphic change in the core corresponding to this low pollen interval.

Zone 3 has a distinctive pollen signature. *Typha* pollen makes up well over one-third of the total pollen when Cyperaceae grains are excluded. This is in contrast to zones 1 and 2, where *Typha* nearly disappears from the pollen record. Poaceae pollen, though steady throughout the record, is highest in zone 3. Urticales pollen is less important in zone 3 than in the other zones. Charcoal concentrations are higher than in zone 2, but lower than zone 1. Charcoal: pollen ratios, however, are similar to ratios in zone 1. Both size classes of charcoal fragments follow a similar pattern throughout the zone. Stable carbon isotope values indicate an environment with little shift in its dominant photosynthetic pathway. Values indicate a mixed ecosystem with a significant component (35 %) from C4 vegetation. A portion of the signal may represent

autochthonous inputs, but bulk isotope analysis cannot distinguish between the terrestrial and aquatic carbon (Huang et al., 2001; Ficken et al., 2002).

Zone 2

Zone 2 consists entirely of a mineral facies dominated by clay-sized particles, with a very low organic content. With the exception of the sample from 158 cm, pollen and charcoal were present in extremely low concentration (often too low to be counted). The charcoal counts show the lowest values in the core, except for a small spike in particles >125 μm at 158 cm. The extremely low organic content and lack of pollen in zone 2 suggests that this layer of mineral material was deposited by an event unlike normal sedimentation processes at Laguna Yaguarú. The carbon isotope values also fluctuate significantly in zone 2, perhaps indicating a variety of environments contributing carbon to the signal.

The particle size data in Figure 5.3 suggest that all the material in zone 2 was laid down in a single event. The data suggest that fine material was laid down first, followed by a pulse of coarser material around 167 cm, and then by material that fined upwards until the upper limit of zone 2. I interpret this pattern as being a flood deposit from a single event. Due to the relatively small size of the particles involved and the sharp contact between the underlying organic layer and the flood deposit, it was probably a relatively low energy, backwater-type flow that created the deposit. The initial layer of fine sediment is likely the leading edge of the flood that spilled into the Yaguarú basin. This was followed by the peak of the flood and, with its higher energy, the pulse of larger-grained material. The upper 14 cm of the deposit represents the deposition of

these particles, fining upwards due to hydrological sorting processes as the flood waned. Other possible explanations for the layer include a landslide or a volcanic tephra deposit, but these possibilities are dismissed because of a lack of local relief and no documented eruption in the area, respectively. The presence of pollen in the layer is additional evidence against the layer being a tephra deposit.

The single event indicated by the particle size analysis is supported by the extremely low organic content and pollen and charcoal concentrations. The fluctuations in the carbon isotope record may be the result of the flood incorporating carbon from a myriad of sources that usually do not typically contribute carbon to Laguna Yaguarú. The radiocarbon date from immediately below the flood deposit dates this event to around 5500 BP. I will provide speculations on the origin of this flood later in this chapter. The large spike in Cyperaceae pollen at the top of the zone may represent the flood deposit being initially colonized by sedges.

Zone 1

Zone 1 has the highest organic content of all the zones as well as the highest pollen and charcoal concentrations. The pollen diagram is dominated by Poaceae, Cyperaceae, and Urticales. *Alchornea* and Mimosoideae are less important taxa. In contrast with zone 3, *Typha* is present only in minor levels. Charcoal: pollen rations reach their highest concentration in the middle of zone 1. The larger charcoal fragments also peak in this section, possibly indicating more local fire activity.

The stable carbon isotope values vary significantly through zone 1. At the bottom of the zone, immediately after the flood deposit of zone 2, the isotope values shift from

–25 ‰ to reach their most positive value (–19 ‰) in the entire core. From this peak, they increase to a value around –23 ‰ and then, at the 50 cm level, shift again to more negative values of –25 ‰. The more negative values correspond to an increase in forest pollen, indicating more forest and C3 vegetation near Laguna Yaguarú, as will be discussed below. Bulk isotope values do not distinguish between carbon sources, so a small portion these shifts may be the result of changes in the lake's algae production.

Environmental History of Laguna Yaguarú

The basin in which Laguna Yaguarú sits was initially a stream channel, as indicated by the 2 m of sand underlying the organic deposits. This channel eventually, through sediment aggregation or another process, became a low energy marsh. Organic matter began accumulating, marking the beginning of zone 3. During this time the basin was a marsh environment, dominated by *Typha.* Ficken et al. (1998) found *Typha* to have stable carbon isotope values that were solidly in the C3 range. The isotope values during zone 3 are intermediate. This may be the result of several factors. Algae may be contributing heavily to the organic content of the lake mud. The surrounding environment may have been dominated by C4 plants, perhaps grasses growing on seasonally dry hillslopes (Killeen and Hinz, 1992; Killeen and Hinz, 1992). Many species of sedges also utilize the C4 pathway, particularly those that grow in tropical environments (Ehleringer et al., 1997); these plants, if present, would have increased the isotope values. The sediments show no evidence of oxidation, suggesting that during this time Laguna Yaguarú did not dry seasonally. Perhaps there were areas of open water within the *Typha* swamp that supported floating mats of sedges that may have had a C4

component. It is also possible that there was sufficient current moving through the lake to transport heavier carbon from herbaceous plants on surrounding hillslopes, through the *Typha* (which would have acted as a filter and sediment catch), to the coring site at the center of the basin.

The *Typha* marsh persisted until around 5500 BP when the Yaguarú basin was most likely hit by a portion of a large flood. As discussed above, the sediment record indicates a single event was responsible for the deposition of the mineral layer that makes up zone 2. In addition to depositing the mineral layer, this flood also dammed the Yaguarú channel, closing the basin and creating an open water lake. Analysis of topographic maps and a digital elevation model (DEM) of the region suggest that the Rio Blanco is the most likely river to have experienced this major flood. Since the area around Yaguarú has so little relief this flood may have started far upstream and then traveled down the Rio Blanco valley and created a levee across the Yaguarú drainage. This drainage, now dammed, filled with water and began functioning as an open water lake. The low organic content and small particle size of the flood deposit within the lake basin itself may be the result of this material having to have washed over this dam. The Rio Blanco is not the only potential source for this flood; however, it is the most likely for several reasons. It has a drainage basin of sufficient size to generate such a flood. It also flows out of the hills near San Javier, some of the only relief in the region, making it a logical source area for the flood. The river to the east of Laguna Yaguarú, the Rio Zapaco, does not have a large drainage basin area and no likely source area for such a flood. The uppermost pollen sample from zone 2 shows an extremely high amount of Cyperaceae and *Typha* pollen. This may represent the colonization of the new material

deposited in the flood. Later, these taxa were replaced by others as succession proceeded.

In the ~5000 years since the flood, Laguna Yaguarú has functioned as an open-water lake. Productivity has been high, as evidenced by the high organic content, and there is no trace of the previous conditions, *Typha* swamp, in the pollen record. The pollen record throughout zone 1 represents a mixed environment of grasses, sedges, and forest taxa such as Urticales. This would suggest that the area around Laguna Yaguarú has been surrounded by some amount of forest for the last 5000 years. An increase in the percentage of Urticales at the expense of Poaceae and Cyperaceae in zone 1 may be an indication of an expansion of forest over the upper portion of zone 3 (Figure 5.6). Both the charcoal and stable carbon isotope records follow a similar pattern over this time period. Charcoal: pollen ratios are highest in the lower and middle of zone 3, suggesting frequent and nearby fires. These ratios then decrease around the time that Urticales pollen begins to increase. This may be explained by the tree-dominated ecosystem burning less often and less intensely. The stable carbon isotope values shift to lower values, indicating an increase in C3 photosynthesis, which is dominant in closed canopy tropical forests worldwide and in the Yaguarú region (Killeen and Hinz, 1992; Killeen et al., 1998).

Comparisons to Other Records

The Laguna Yaguarú pollen, charcoal, and stable carbon isotope records show several trends. Zones 3 and 2 reveal more about the lake environment itself, but zone 1, deposited when the lake was fully formed, offers a record of environmental change. The

general trend in this zone, shown by the three proxy indicators, is a gradual increase in forest at the expense of grasses and sedges, and a decrease in fires. This is likely explained by an increase in precipitation over the late Holocene. Records from all around the Amazon and the Amazon itself indicate a similar increase. Numerous highland records suggest wetter conditions during the late Holocene. Moister conditions began around 3000 BP in the Peruvian Andes (Hansen et al., 1994). A similar increase in moisture was documented in lakes in the Titicaca basin with neoglaciation beginning around the same time (Abbott et al., 1997; Abbott et al., 2003). Several studies from Lake Titicaca itself suggest an increase in lake level and regional rise in precipitation beginning around 4000 BP, with lake levels reaching modern levels around 2000 BP (Baker et al., 2001; Paduano et al., 2003; Tapia et al., 2003). This increase in moisture has also been correlated with archeological records of the rise of the Tiwanaku civilization on the shores of Lake Titicaca (Binford et al., 1997). The Sajama ice core has higher rates of deposition during this period as evaporation from the paleolakes increased (Thompson et al., 1998). On the northern fringe of the Amazon in the Colombian llanos, a rise in lake level is recorded around 3800 ^{14}C BP (Behling and Hooghiemstra, 1999). Pollen records indicate forest moving into savanna areas after 3000 ^{14}C BP in southern Brazil (Behling, 2002; Behling et al., 2004). Two carbon isotope records from soil profiles suggest a similar forest expansion in the same area around 4000 BP (Pessenda et al., 1998; Alexandre et al., 1999). Charcoal (Turcq et al., 1998), pollen, and sedimentological analysis (Behling and da Costa, 2000) show precipitation increases from several locations in the Amazon rainforest starting at 4000 BP. The Laguna Bella Vista and Laguna Chaplin records from sites ~350 km northeast

of Laguna Yaguarú show an increase in forest taxa which is attributed to increased moisture circa 3000 BP. There is very good agreement between records from all these different environments and Laguna Yaguarú. Many authors attribute this increase in moisture to an increase in summer insolation over the southern hemisphere as a result of Milankovitch forcing. High summer insolation pulls the ITCZ farther south into the Amazon basin (Martin et al., 1997). This permits the moisture-laden Atlantic trades to reach farther south and west and to transport more moisture to the southern edges of the Amazon, as well as to the Andean highlands. Paleoenvironmental data from the region, including that from Laguna Yaguarú, record this ITCZ summer-location shift with the expansion of forest and rising lake levels. The timing of the initial increases in moisture varies with location. The central Amazon and the highland records are the first to gain precipitation from the ITCZ migration. As insolation increases, moisture reaches the southern edge of the Amazon basin. This may explain the ~1000 year lag between the precipitation increases in the central Amazon and highland records and the increase noticed at Laguna Yaguarú and other sites in lowland Bolivia.

Other Amazonian lake-sediment records show evidence of floods such as that experienced by Laguna Yaguarú (Colinvaux et al., 1985; Frost, 1988). As at Laguna Yaguarú, flooding changed Anañgucocha in Ecuador from a swamp to a lake. However, the sediment records indicate several key differences in these floods. Anañgucocha experienced a series of floods for 500 years. These floods were detected at four other sites and were presumably regional in scope (Colinvaux et al., 1985). The authors point at a regional wet period increasing flooding in several rivers coming off the Andes. The Yaguarú flood is different because the particle size analysis and lack of between-flood

layers suggest only a single event. The deposit does not appear in the other Bolivian lowland records (Mayle et al., 2000; Burbridge et al., 2004), suggesting it may be a more local event. Another fundamental difference is the type of fluvial environment. The Ecuadorian lakes are near the Andes and have the potential to be flooded by higher energy streams, while there is very little local relief near Laguna Yaguarú. This would also suggest a local event. The Ecuadorian records (Colinvaux et al., 1985; Colinvaux et al., 1988; Frost, 1988) and the Yaguarú record are examples of floods being important disturbance agents in lowland environments as well as factors in lake formation (Colinvaux, 1987).

The Laguna Yaguarú record had the potential to contribute more information to the controversy surrounding abnormally old radiocarbon dates in Amazonian sediments. Räsänen et al. (1991) compared radiocarbon dates on macrofossils and bulk sediments from sediment records in Peru and found that that the bulk dates were consistently much older than macrofossil dates on the same level. A similar dating anomaly has also been reported in Brazil (M. Bush, pers. comm. to S. Horn). All radiocarbon dates from Laguna Yaguarú were taken on macrofossil samples to avoid this problem. In contrast, Mayle et al. (2000) and Burbridge et al. (2004) relied almost exclusively on bulk sediment dates in their analysis of Bolivian lake sediments. Upon initiation of this study, it was thought potentially possible to correlate pollen changes in the Yaguarú record with those in the other Bolivian records, and in that way potentially test the validity of the Mayle et al. (2000) and Burbridge et al. (2004) chronologies. However, the pollen records are not easily matched and this was not possible. Bulk sediment from the Yaguarú core might later be dated using standard radiocarbon dating to test whether this

core also demonstrates the radiocarbon anomalies identified in Peru by Räsänen et al. (1991) and in Brazil by Bush (M. Bush, pers. comm. to S. Horn). However, such analyses would not necessarily increase understanding of the mechanism behind such anomalies, only help to determine how widespread the problem may be.

Chapter 7

Conclusions

The dry forest region of lowland Bolivia is important for paleoenvironmental research because it is located in a climatically controlled ecotone. The sediment record from Laguna Yaguarú proved sensitive to Holocene climate shifts. Its record of forest expansion over the last 3000 years fits well with nearby studies (Mayle et al., 2000; Burbridge et al., 2004) and corresponds to an increase in summer insolation (Martin et al., 1997). The paleoenvironmental record from Laguna Yaguarú was enhanced by the use of multiple proxies. The addition of stable carbon isotope analysis to pollen and charcoal analysis facilitated interpretation in a location where pollen, particularly Poaceae pollen, is hard to interpret (Bush, 2002).

The Laguna Yaguarú record is only the third lake record from lowland Bolivia. Like the records from Mayle et al. (2000) and Burbridge et al. (2004), Laguna Yaguarú shows an increase in forest, and presumably precipitation, over the past ~5000 years. As mentioned above, this is part of a regional signal seen around the Amazon. The sporadic records from the Amazon basin and adjoining Andean highlands show that the summer position of the ITCZ has slowly moved south since the mid-Holocene. More lake records, particularly from areas like Laguna Yaguarú that are sensitive to changes in precipitation, could potentially reveal the specifics of the ITCZ migration. Reconstructing the speed and path of this migration would significantly add to the current understanding of Amazon climate history. High resolution multiple proxy records, especially those including stable carbon isotope analysis, could determine the sensitivity to precipitation change (that is, the amount and timing of precipitation needed to support

forest) at specific locations within the Amazon basin. With aridity predicted to increase in the next century (Mayle and Beerling, 2004), a temporally and spatially explicit understanding of previous Amazon response to climate change would be particularly valuable in predicting the impacts of future global change in the basin.

The Yaguarú record also contains information about past hydraulic disturbance in the area. The stratigraphic and particle size evidence of a large flood event demonstrates that such events can occur even in areas of little relief. This is important in an ecological sense as floods can be important disturbance agents (Colinvaux et al., 1985), but also in a human sense as local inhabitants should be aware such events have precedent. More information could be learned about the flood by taking additional cores from Laguna Yaguarú. Comparing the thickness of the deposit and particle size data among several cores from different parts of the Laguna Yaguarú basin may make it possible to determine its source. A core closer to the shoreline, especially near where the flood entered in the lake, could provide more macrofossils for precise dating of the flood. The regional extent and impact of the flood could also be reconstructed. Nearby lakes, visible in satellite images, may also have sedimentary records of the flood, similar to that of Laguna Yaguarú. It is also possible that the channel that carried the flood contains deposits that could be radiocarbon dated. These data could then be combined to create a model of the flood using GIS technology.

Paleoenvironmental records, particularly multiple proxy records like that from Laguna Yaguarú, are valuable for many reasons. They provide land managers with long term information on the composition, environmental conditions, and location of the ecosystem they are trying to manage. The Laguna Yaguarú fire history, flood history,

and evidence of forest expansion may assist in the development of optimal management strategies. This is particularly important in an area as diverse and threatened as the Chiquitano region of lowland Bolivia (Killeen et al., 1998). Knowledge of past climate and resulting environments are also important to climate modelers. Information about past conditions in locations sensitive to climate change like Laguna Yaguarú can help in the testing of models. Such information also aids in predicting impacts of future climate change. This information has obvious benefits to land managers. The Laguna Yaguarú record is one of three paleoenvironmental records from lowland Bolivia. Records are more numerous across the Amazon basin, but are still few when compared with the enormous size of the Amazon region. More paleoenvironmental records are needed from throughout the region, but especially in seasonally dry forests and other marginal locations. Ecotone locations like the Chiquitano have been the most sensitive to climate change in the past and are more likely to be affected in the future (Mayle et al., 2004), making them important sites for paleoenvironmental research.

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Appendices

Appendix A

Pollen Processing Procedure

This processing schedule was developed by John Rodgers III and Sally Horn for use in processing tropical pollen samples prone to clumping. Within the Laboratory of Paleoenvironmental Research it is referred to as the JR-2 processing schedule.

1. Start water boiling on hot plate in hood (in glass saucepan) for the hot water bath. Get six vials that have been vacuumed free of dust, and label them. Refill chemical squirt bottles, and put away clean labware.

2. Add 1 lycopodium tablet (#710961 as of 07/27/01) to each tube. Keep track of procedure in the lab notebook.

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, and place in hot water bath for 3 minutes. Start beaker (250 ml) of distilled water heating on other hot plate. Remove from bath, centrifuge for 2 minutes, and decant.

4. Add hot distilled water, stir, centrifuge for 2 minutes and decant. Repeat for a total of two washes.

5. Add about 10 ml 5 % KOH, stir, remove stick, and place in boiling bath for 10 minutes, stirring after 5 minutes. Remove from bath and stir again. Centrifuge 2 minutes and decant.

6. Wash 4 times with HOT distilled water. Centrifuge for 2 minutes each time.

Fill tubes about 1/2 way with distilled water, stir, and pour through 125 um mesh screen, collecting liquid in a labeled beaker underneath. Wash out material remaining in test tube with more distilled water. Wash screen with a powerful jet of distilled water. Use the sieves that are not labeled reference.

8. Centrifuge down material in beaker by repeatedly pouring beaker-contents into correct tube, centrifuging for 2 minutes, and decanting.

9. Add 8 ml of 49–52 % HF and stir. Place tubes in boiling bath for 20 minutes, stirring after 10 minutes. Centrifuge 2 minutes and decant into waste receptacle.

10. Add 10 ml hot 5 % Alconox solution. Stir well and let sit for 5 minutes. Then centrifuge and decant.

11. Add more than 10 ml hot distilled water to each tube, so top of water comes close to top of tube. Stir, centrifuge for 2 minutes, and decant. Check top of tubes for an oily

residue after decanting the hot water. If present, remove carefully with a wadded up paper towel.

Also at this time, examine the tubes to see if they still contain silica. If so, repeat the HF treatment and return to step 11.

If not, continue washing with hot distilled water as above for a total of 3 water washes.

12. Add 10 ml of glacial acetic acid, stir, centrifuge for 2 minutes, and decant into waste receptacle.

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 sticks and place in boiling bath for 5 minutes. Stir after 2.5 minutes. Centrifuge for 2 minutes and decant into waste receptacle. Pour leftover acetolysis solution into the waste receptacle.

14. Add 10 ml glacial acetic acid, stir, centrifuge for 2 minutes and decant.

15. Wash with hot distilled water, centrifuge and decant.

16. Add 10 ml 5 % KOH, stir, remove sticks, and heat in vigorously boiling bath for 5 minutes. Stir after 2.5 minutes, then remove sticks. After 5 minutes is up, centrifuge for 2 minutes and decant.

17. Add 10 ml hot distilled water, centrifuge for 2 minutes, and decant for a total of 3 washes.

18. After decanting last water wash, use Vortex mixer for 20 seconds to mix residue in tube.

19. Add one drop Safranin stain to each tube. Use Vortex mixer for 10 seconds. Add distilled water to make 10 ml. Stir, centrifuge for 2 minutes, and decant.

20. Add a few ml TBA, use Vortex mixer for 20 seconds. Fill to 10 ml with TBA, stir, centrifuge for 2 minutes, and decant.

21. Add 10 ml TBA, stir, centrifuge 2 minutes 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 the precleaned and labeled glass vial. Make sure that you are transferring the correct sample into the corresponding vial. If need be, centrifuge down TBA midway through the transfer process. Make sure the centrifuge is balanced. Centrifuge down vials.

23. Add several drops of 2000 cs silicone oil to each vial (add more oil if there is a lot of sample). Stir with a clean toothpick.

24. Place uncorked samples in the dust free cabinet to let the TBA evaporate. Stir again after one hour, adding more silicone oil if necessary.

25. Check samples the following day; if there is no alcohol smell, cap the samples. If the alcohol smell persists, give them more time to evaporate.

Appendix B

Stable Carbon Isotope Data

Table B.1: Stable Isotope Compositions from Laguna Yaguarú

Sample code	Depth	$\delta^{13}C$	Date	Lab Code
PTC 0-2	0	–24.66	06/05/04	NA
PTC 10-12	15.5	–24.93	08/23/04	GR2-36-15
PTC 16-18	20.2	–25.28	06/05/04	NA
PTC 28-30	34.5	–24.52	08/23/04	GR2-36-7
PTC 32-34	39.2	–24.05	06/05/04	NA
PTC 40-42	48.8	–24.23	08/23/04	GR2-36-11
PTC 48-50	58.3	–22.56	06/05/04	NA
200-16	64	–22.49	06/05/04	NA
200-24	72	–22.49	12/03/05	GR2-42-9
200-32	80	–22.30	06/05/04	NA
200-40	88	–22.39	06/05/04	NA
200-48	96	–21.52	06/05/04	NA
200-64	112	–21.02	12/03/04	GR2-42-10
200-72	120	–20.86	12/03/04	GR2-42-14
200-80	128	–19.11	06/05/04	NA
200-88	136	–18.66	06/05/04	NA
200-96	142	–18.88	06/05/04	NA
300-12	150	–20.77	12/03/04	GR2-44-15
300-16	154	–23.38	12/03/04	GR2-44-12
300-20	158	–23.61	06/05/04	NA
300-24	162	–20.73	08/23/04	GR2-34-6
300-28	166	–22.69	12/03/04	GR2-44-16
300-32	170	–23.55	08/23/04	GR2-36-12
300-36	174	–23.98	08/23/04	GR2-36-13
300-40	178	–23.45	12/03/04	GR2-44-13
300-45	183	–21.74	06/05/04	NA
300-52	192	–21.81	12/03/04	GR2-44-17
300-56	194	–21.89	12/03/04	GR2-42-7
300-62	200	–22.02	08/23/04	GR2-36-14
300-72	210	–22.18	12/03/04	GR2-42-11
300-80	218	–22.46	06/05/04	NA
300-88	226	–22.20	12/03/04	GR2-44-18

Table B.1 (continued): Stable Isotope Compositions from Laguna Yaguarú

Sample code	Depth	$\delta^{13}C$	Date	Lab Code
300-96	234	–21.64	12/03/04	GR2-42-8
Sigma α Cell.	NA	–23.98	08/23/04	GR2-36-2
USGS 24	NA	–15.97	08/23/04	GR2-36-16
USGS 24	NA	–16.10	12/03/04	GR2-44-20
Sigma α Cell.	NA	–24.62	06/05/04	NA
USGS 24	NA	–16.71	06/05/04	NA

Vita

Zachary Paul Taylor was born on March 20, 1981 in Colorado Springs, CO. Growing up in Colorado Springs, he was active in many activities, including Boy Scouts, becoming an Eagle Scout in 1995. Zack graduated from the International Baccalaureate Program at William J. Palmer High School in Colorado Springs. He then earned a B.S. in Environmental Science from the University of Denver in 2003. He received his M.S. in Geography from the University of Tennessee, Knoxville in 2005.

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