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I am submitting herewith a thesis written by Martin Russell Arford entitled "Late Holocene Environmental History and Tephrostratigraphy in Northwestern Costa Rica: A 4000 Year Record from Lago Cote." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Sally P. Horn

Sally P. Horn, Major Professor

We have read this thesis
and recommend its acceptance:

Carol P. Harden

Carol P. Harden

Ken Orvis

Accepted for the Council:

Interim Vice Provost and
Dean of the Graduate School

LATE HOLOCENE ENVIRONMENTAL HISTORY AND TEPHROSTRATIGRAPHY IN NORTHWESTERN COSTA RICA: A 4000 YEAR RECORD FROM LAGO COTE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Martin Russell Arford

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DEDICATION

This thesis is dedicated in memory of my father,

Oliver M. Arford

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ABSTRACT

Paleoecological studies in the neotropics are revealing changes in past climate regimes and human use of the landscape that were previously unknown. Few paleoecology studies have been conducted in Costa Rica and, in most of these studies, strong evidence of prehistoric human impacts overwhelmed evidence of climate signals. Lago Cote, in the Cordillera de Tilarán, is the largest natural lake in Costa Rica (198 ha). Because of its size, Cote sediments reflect a more regional record of pollen and charcoal accumulation. The sediments also preserve tephra layers from past eruptions of nearby Arenal volcano. In this thesis, I present an environmental history and tephrostratigraphy based on pollen, charcoal, and tephra preserved in a 3.6 m sediment core from Lago Cote.

High amounts of grass charcoal and grass pollen from the lower part of the core indicate a drier climate regime with frequent landscape fires from ~4000 to 2600 cal. yr BP. Many or most of these fires were likely of human origin. The occurrence of a maize pollen grain in this zone documents agriculture at ~3900 cal. yr BP. After 2600 cal. yr BP, a dramatic decrease of grass pollen and charcoal reflects wetter conditions that limited landscape fires and agriculture. This climate change occurred simultaneously with an archaeological phase change documented in the nearby Arenal basin by the Proyecto Prehistórico Arenal. Small peaks in pollen of lower montane pollen taxa at the base of this zone may indicate forest regeneration.

Comparison of Cote tephra to an earlier tephrochronology at the nearby El Tajo site was not straightforward. Cote tephras, analyzed by X-ray fluorescence, show differences in mineral composition when compared to the more proximal El Tajo tephras,

and have lower levels of silicon dioxide than found at El Tajo. Because of major differences in tephra chemistries, visual comparison was a more effective way to compare tephra layers between the sites. Three tephra layers reported from El Tajo are not present in the Cote sediments, including the most recent Arenal eruption in 1968. Two tephra layers in the lower part of the Cote core are not part of the El Tajo tephrochronology, and represent earlier eruptions from Arenal or the nearby and older Chato volcano. In the Cote sediments, peaks in *Cecropia* pollen follow at least two tephra layers, most likely indicating vegetation regeneration following eruptions of Arenal volcano.

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CHAPTER 1

INTRODUCTION

The history of landscapes and vegetation in tropical Latin America has long interested geographers, ecologists, and anthropologists. While the specific history of most areas remains poorly understood, current research is revealing evidence of changing vegetation patterns in areas that were traditionally perceived to be pristine and stable for long periods. Some researchers have suggested that humans have altered the tropical landscape and vegetation in major ways. Denevan (1992) went so far as to state that there were no virgin tropical forests in 1492, while Brown and Lugo (1990) stated that 40% of current Latin American tropical forests have regrown following human clearing. Certainly, there was spatial and temporal variability in the manner and degree to which early inhabitants altered forests, and some areas must have been more disturbed than others. In the past few decades, paleoecologists and archaeologists have begun to explore the questions of where, and to what extent, indigenous peoples modified neotropical vegetation through burning, clearing, and agriculture. During this same period, evidence has come to light of significant Holocene shifts in climate within the American tropics.

Paleoecologists use pollen, spores, charcoal, diatoms, and other micro- and macrofossils from lake sediments, along with radiocarbon and other dating techniques, to help interpret the past. Pollen and charcoal records can reveal evidence of agriculture, fires, climate change, and responses to natural disturbances such as volcanic eruptions. When combined with archaeological evidence, paleoecological investigations can lead to a better understanding of interactions between prehistoric humans and their environment.

Many studies have documented prehistoric human influence on landscapes and fluctuations in climate in the Neotropics. These studies indicate, for example, that indigenous peoples may have created and/or maintained savannas in Colombia and Panama, and pine forests in Nicaragua (Denevan, 1992). The Maya were responsible for widespread land clearance in southern Mexico and adjacent northern Central America (Deevey *et al.*, 1979; Islebe *et al.*, 1996; Whitmore *et al.*, 1996; Dunning *et al.*, 1998). Some recent studies have shown significant changes in climate during this period of human alteration of the environment, while evidence of human impacts may mask paleoclimate signals in other studies. Research sites include areas of Mexico and the Yucatan Peninsula (Hodell *et al.*, 1995; Curtis *et al.*, 1996; Leyden *et al.* 1996, 1998; Whitmore *et al.*, 1996; Sluyter, 1997a; Goman and Byrne, 1998), Panama (Bush and Colinvaux, 1994; Behling, 2000), and South America (Colinvaux *et al.*, 1988; Liu and Colinvaux, 1988; Hansen and Rodbell, 1995; Colinvaux *et al.*, 1996; Piperno and Becker, 1996; Turcq *et al.*, 1998; Curtis *et al.*, 1999; Behling *et al.*, 2000; Bush *et al.*, 2000). Caribbean studies are fewer, but they also reveal evidence of past changes in climate and fire history (Hodell *et al.*, 1991; Burney, 1994; Kjellmark, 1996; Holmes, 1998; Higuera Gundy *et al.*, 1999; Horn *et al.*, 2000).

In Costa Rica, paleoecological studies completed in several areas reveal evidence of early human influence on the landscape. Charcoal and pollen in sediments show past fires and maize cultivation at the La Selva Biological Station (Kennedy, 1998; Kennedy and Horn, 1997; Horn and Kennedy, forthcoming), at Lagunas Bonilla and Bonillita (Northrop, 1994; Northrop and Horn, 1996) in the Central Atlantic watershed, and at Laguna Zoncho (Clement, 1999, Clement and Horn, forthcoming) in the southern Pacific region. In all of these studies, evidence of major human impact obscures what might potentially be evidence of climate change. However, records of changing fire occurrence in the high elevations (>3000 m) of Cerro Chirripó that were never settled by people may signal Holocene climate shifts (Horn, 1993; Horn and Sanford, 1992; League and Horn, 2000).

In this thesis, I evaluate evidence of human and natural disturbance and possible climate change preserved in a 3.6 m long lake sediment core from Lago Cote, located on the southern end of the Cordillera de Guanacaste in northwestern Costa Rica. This lake lies near the continental divide at an elevation of 650 m, about 28 km northwest of the recently (and prehistorically) active Arenal volcano. Lago Cote provides a good site for paleoecological research because the large lake size suggests that local pollen will not overwhelm the regional pollen signal (Jacobson and Bradshaw, 1981). Thus, pollen in the Cote sediment record should reflect any regional climate changes, as well as local human influences on the landscape. The local vegetation still contains large areas of intact mature forest (primary and/or late successional), and recently botanists have been collecting and documenting the flora surrounding the lake. Much of the larger area has been altered by human activity during historic times, including logging of forests and creation of pastureland. Archaeology studies were conducted during a large project, the Proyecto Prehisóric Arenal, in the mid- to later 1980s at the nearby Arenal Reservoir basin. This archaeology provides a prehistoric human context in which to interpret the evidence of fire and vegetation history preserved in the Cote lake sediments.

I focus here on what the pollen, charcoal, and tephra contained in the Cote core reveal about environmental history and human-environment interactions at the lake. I explore the role of fire, both natural and anthropogenic, as well as climate, as agents of change. In addition, I attempt to correlate tephra layers in the core to an established tephrochronology from Volcán Arenal, and use X-ray fluorescence analysis to aid in the comparison. Tephra layers can be valuable to paleoecological and archaeological studies because after being identified, dated, and correlated at several locations they can serve as chronostratigraphic markers at other locations (Borchardt *et al.*, 1972; Steen-McIntyre, 1981; Westgate and Gorton, 1981; Sarna-Wojcicki *et al.*, 1983; Einarsson, 1986; Stokes *et al.*, 1992; Froggatt, 1992). Several recent studies have included analyses of tephra layers in lake sediments as marker beds or to track the distribution of particular volcanic events (Child *et al.*, 1998; Newnham *et al.*, 1998; Whitlock *et al.*, 2000).

This thesis is the first paleoecological study in the Cordillera de Guanacaste. It addresses the following research questions: Is there any evidence of human disturbance in the Cote record and, if so, does it match with known archaeological information? Is there evidence of climate change that can be separated from any human signals? Does the charcoal record provide evidence of changes in the fire régime and, if so, is there any evidence to suggest how the fires originated (anthropogenic or natural)? Do the pollen profiles indicate any changes in local vegetation composition following tephra deposition? Is it possible to correlate the Cote tephra layers with an Arenal volcano tephrochronology developed at the El Tajo site, by Melson and others, and provide better chronological control for the Cote sediment record as well as more information on Arenal's eruptive history?

This thesis consists of seven chapters. In Chapter 2, I present the physical setting, including present climate, vegetation and land use, and the local archaeology. Chapter 3 describes the field and laboratory methods I used to study pollen, charcoal, and tephra contained in the lake sediments. In Chapter 4, I present the stratigraphic evaluation including chronology and tephra analysis, and discuss these results in order to provide appropriate background for the pollen and charcoal interpretation. Chapter 5 includes the results of my pollen and charcoal analysis, and in Chapter 6, I discuss the findings of the paleoecological record in the context of known local archaeology. Finally, in Chapter 7, I provide conclusions about the environmental history at Lago Cote and the significance of this study.

CHAPTER 2

ENVIRONMENTAL SETTING

Lago Cote (10° 35.0′ N, 84° 54.7′ W) is the largest natural lake in Costa Rica, with a surface area of 198 ha (Horn and Haberyan, 1993). The lake lies at an elevation of 650 m on the southern end of the Cordillera de Guanacaste, just north of the continental divide and the Cordillera de Tilarán in northwestern Costa Rica (Figure 2.1). In this chapter I describe the physical and cultural settings of the lake as a basis for later interpretation and discussion of the pollen and tephra sequences from the lake sediment record.

Physical Environment

Study Location

Lago Cote has a maximum depth of 11 m with a broad, flat bathymetry. Water is turbid with a shallow secchi depth of 1.6 m (Horn and Haberyan, 1993), and because of the windy conditions the lake may be unstratified for most of the year (Umaña *et al.*, 1999). The surrounding watershed seems small for a large lake, encompassing only about 16 km^2 (Figure 2.2), because Cote is located within a small mountainous basin. The small Río Pierna de la Laguna flows into Cote from the northwest (Figure 2.3), but the lake receives much of its water directly from abundant, almost daily rainfall, and likely through groundwater by way of highly porous soils on the surrounding slopes. Natural discharge would occur through the Río Cote to the northeast, but this flow has been

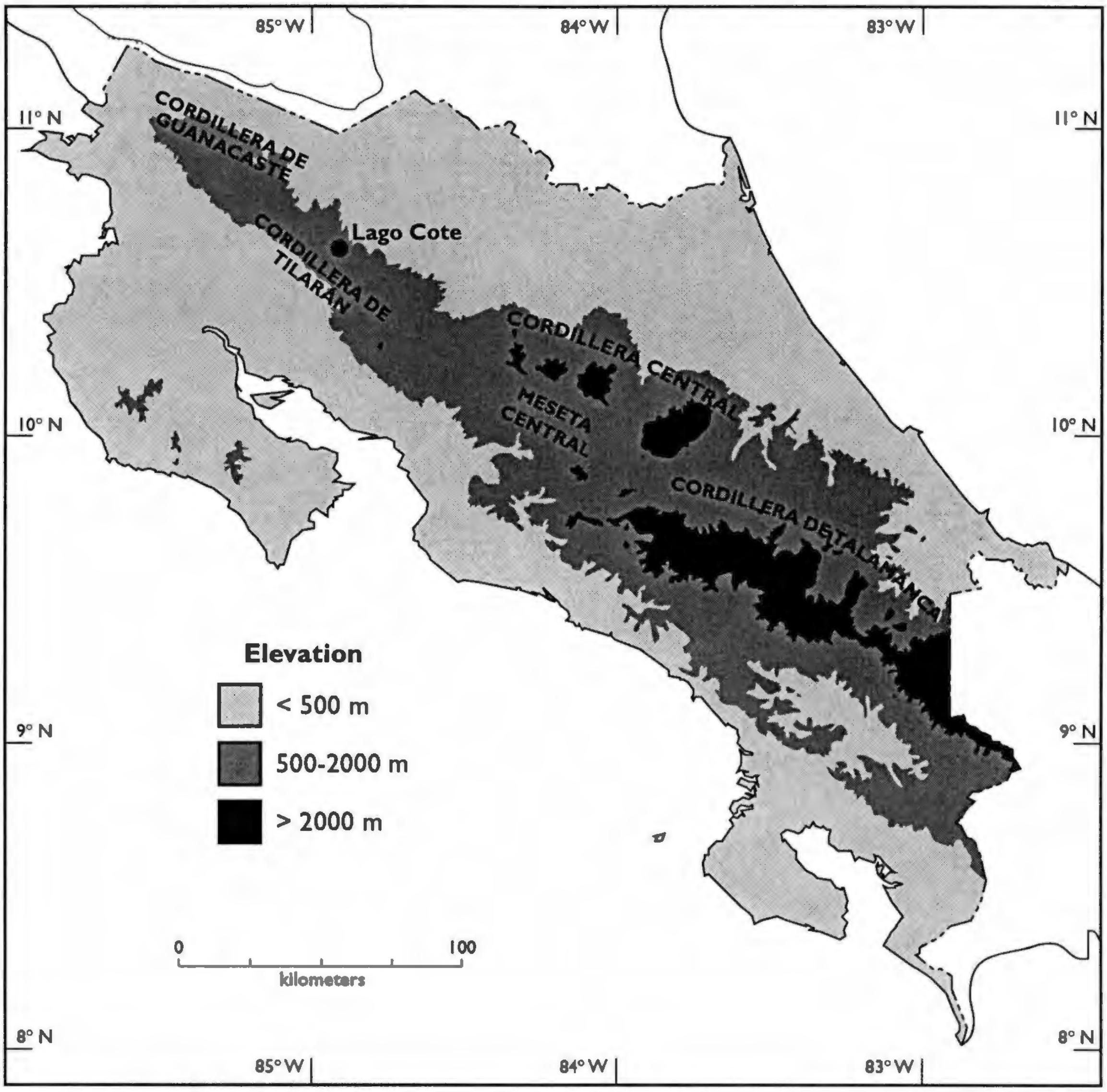


Figure 2.1 Location of Lago Cote in the Cordillera de Guanacaste, Northwestern Costa Rica.

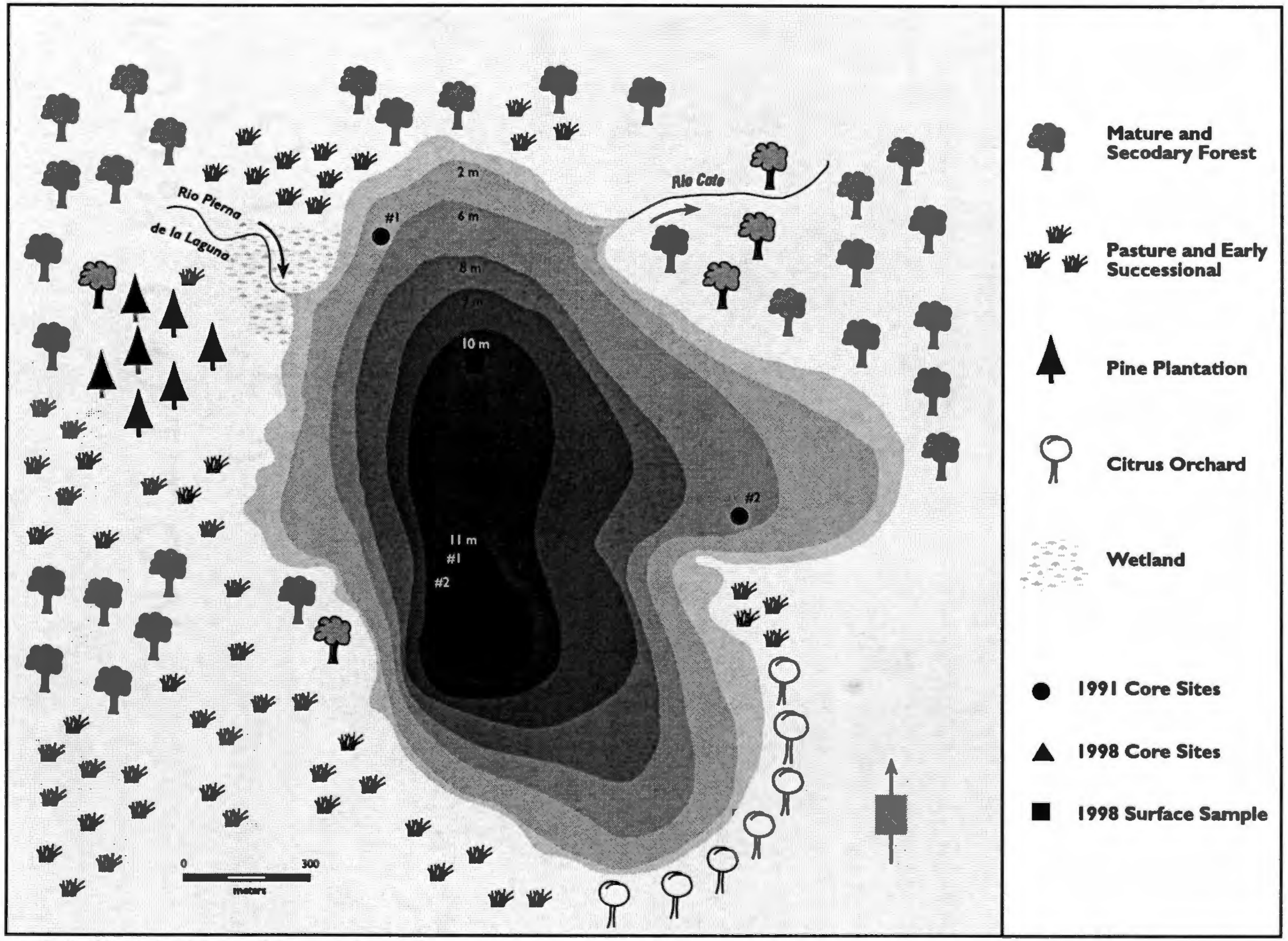


Figure 2.2 Sketch Map of Lago Cote Bathymetry, Core Sites, and Surrounding Vegetation.
Bathymetry from G. Umaña (unpublished data).

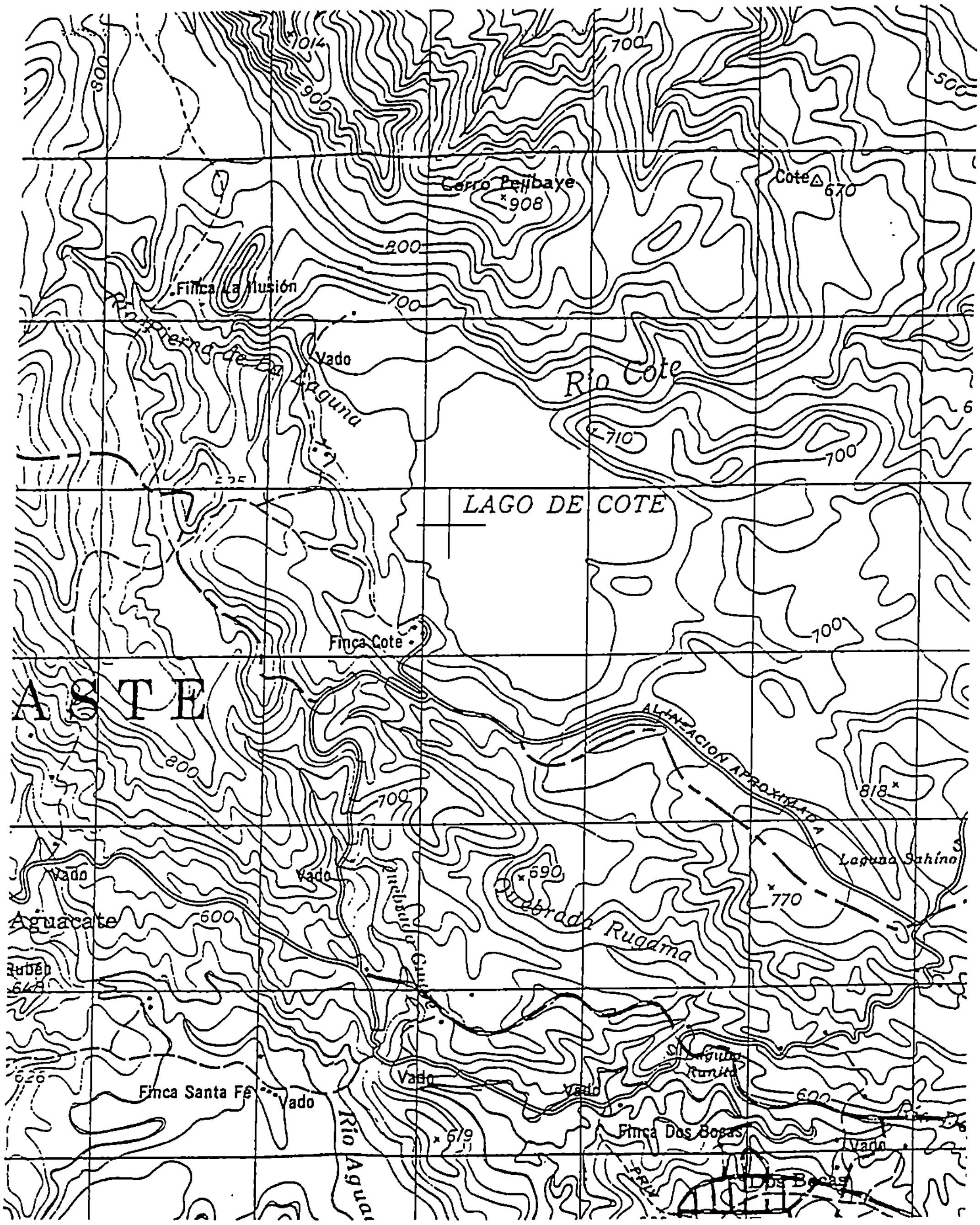


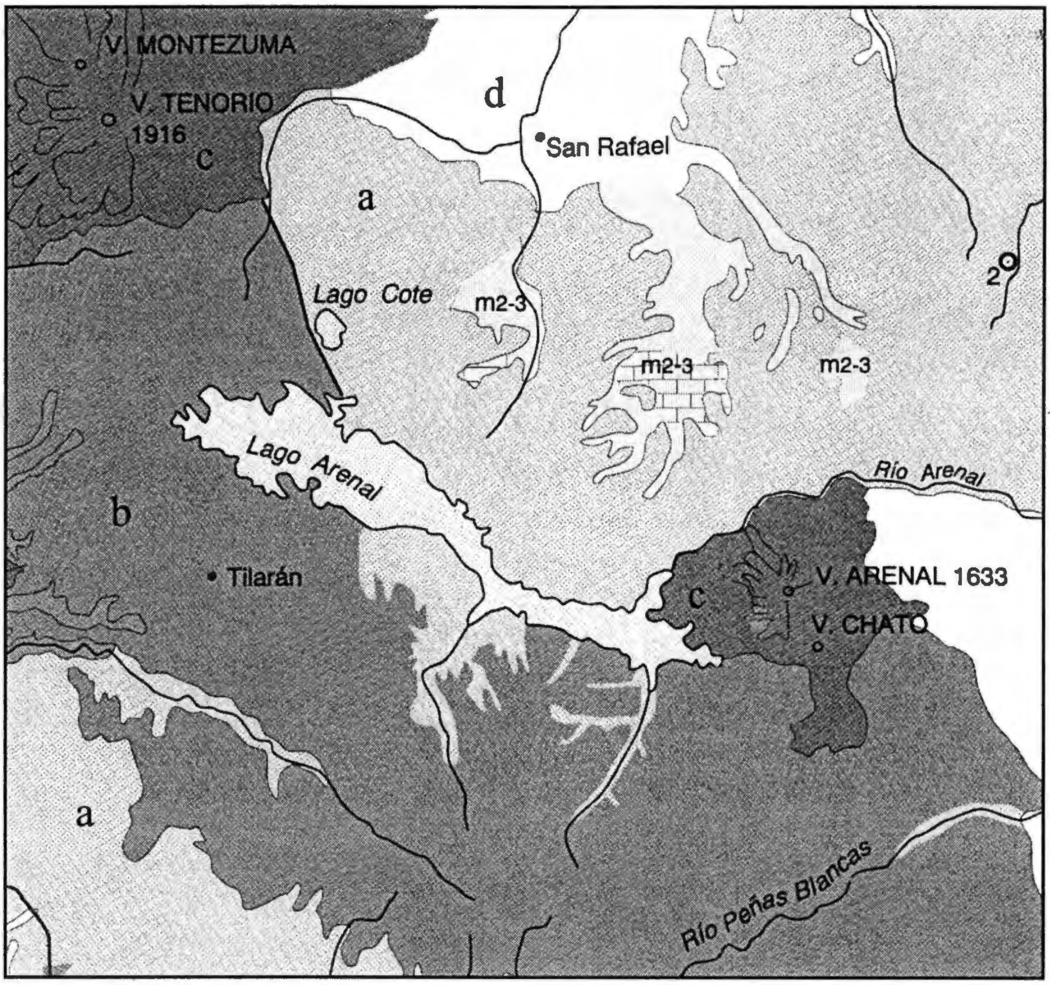
Figure 2.3 Topographic Map of the Lago Cote Vicinity.
From Arenal 1:50,000 map, Costa Rica Series, Instituto Geographico de Costa Rica, Revised 1965. Each grid square is I km^2

diverted to the south through a large pipe into Lago Arenal for hydroelectric power production.

Geologic Setting

Costa Rica formed through a complex series of rifts and collisions, sedimentation, and volcanism that was initiated when North and South America began rifting apart in the Mid-Jurassic. By the late Cretaceous the Pacific Plate was pushing the now-extinct Farallon Plate eastward where it was being subducted, and oceanic volcanism in the proto-Caribbean Ocean created the Panama Arc (Condie, 1989). The shallow proto-Caribbean Ocean continued to fill with volcanics and autochthonous detritus, while calcareous shelves developed in the area of Costa Rica (Tournon & Alvarado, 1997). The isthmus closed during the Pliocene, about 5 million years ago (mya). Tectonic activity created linear mountain ranges that trend NW to SE through Costa Rica, bisecting the Atlantic and Pacific coastal plains. The Cordillera de Talamanca in the south is orogenic, and was uplifted when the Cocos Ridge collided with the early Costa Rican land mass about 3.5 mya (Tournon and Alvarado, 1997). The Cordilleras de Guanacaste and Tilarán in the northwest and Cordillera Central are of more recent volcanic origin (Tournon and Alvarado, 1997), and include the active volcanoes Arenal, Poás, and Irazú (Alvarado, 1993).

Costa Rica has a complex tectonic history and an extensive system of faults. Lago Cote lies within the Arenal Graben (Borgia, *et al.*, 1988), and there is a normal fault immediately to the west of the lake (Figure 2.4). The Quaternary Cote Formation outcrops near the lake, and consists of pyroclastic ash, tuffs, sands and lapilli (Castillo-



[a] Miocene–Pliocene Volcanics
[b] Early Quaternary Volcanics
[c] Quaternary Volcanics/Stratovolcanoes.
[d] Quaternary Alluvium

Figure 2.4 Geologic Map of the Lago Cote–Arenal Area.
From Tournon and Alvarado (1997). The Line to the West of Lago Cote is a Normal Fault.

Muñoz, 1983). The Lago Cote basin is either a tectonic feature or an old explosion crater (Alvarado, 1989; Horn and Haberyan, 1993); the presence of the normal fault along the western side of the lake makes a tectonic origin seem more likely.

Lago Cote is located along a northwest-southeast trending line of volcanoes, about 28 km northwest of Arenal volcano (Figure 2.5). A conical stratovolcano, Arenal reaches an elevation of over 1630 m at its peak, and its base covers an area of 4 km^2 (Mueller, 1994). An inactive sister volcano to the southwest, Chato, preceded Arenal in eruptive activity. Arenal was thought to be dormant until 1968 when a violent eruption killed nearly 100 people, destroyed two towns, and scattered pyroclastics as far as Tilarán (Figure 2.5) (Barquero, 1997). Since 1968 Arenal has remained the most active volcano in Costa Rica. Tephra from past Arenal eruptions has been deposited in the area of Lago Cote, and can be seen in soil profiles exposed in road cuts and by landslides.

The tephra sequence from Arenal volcano has been under study for many years as geologists reconstruct the history of Arenal's eruptions. Thick tephra sequences were exposed during the construction of the Arenal reservoir in the late 1970s and early 1980s, allowing the development of a detailed tephrostratigraphy. Examination of lapilli from these layers at the El Tajo site (Figure 2.5), 7 km due west of Arenal volcano, showed that the composition has alternated between basaltic andesite and dacite throughout the record (Melson and Saenz, 1973; Melson, 1982, 1984). Malavassi (1980) stated that Arenal tephra layers display greater compositional variations than corresponding volcanic rocks, and classifies the tephras as pyroxene basalts, pyroxene basaltic-andesites, a pyroxene hornblende andesite, and hornblend dacites. Sheets (1994a) provided dates for

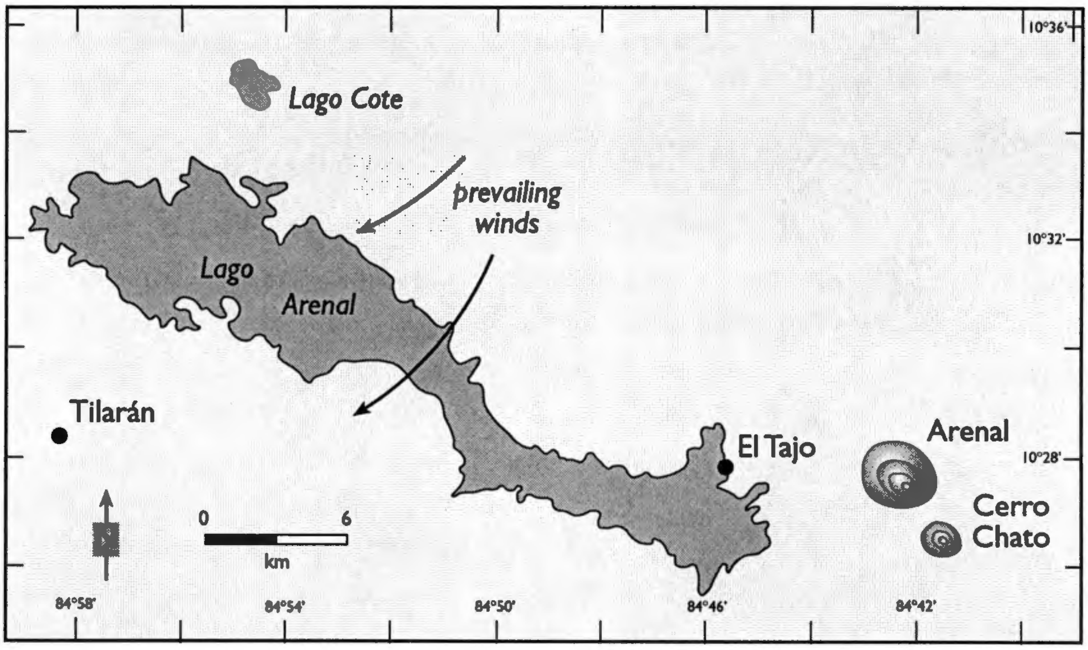


Figure 2.5 Map of Lago Cote and the Arenal Reservoir.
Adapted from Sheets (1994a)

some of the eruptions based on radiocarbon dating of charred plant material and archaeological evidence, while Melson (1982, 1994) dated tephra layers based on time calculations for soil formation between tephra horizons. Because there is a possibility that climate change and landscape modification by humans may have influenced the time for soil formation between volcanic deposits, the accuracy of Melson's dating technique has been questioned (Soto *et al.*, 1998).

The soils around Lago Arenal are andepts according to the USDA soil taxonomy (Vasquez, 1983). Vasquez (1983) described the regional soils as "soils developed from volcanic ash deposits, [in areas of] mountainous relief with slopes of 30-80%, dark, deep, rich in organic matter, medium-textured, moderately fertile, excessively drained." Local soil type varies with the timing and amount of tephra deposition, as well as with differences in slope.

Climate

The area around Lago Cote has many microclimates due to the rugged topography and local differences in aspect, slope, and exposure. Outside the Cote basin, areas to the south and west are dominated by Pacific air masses and have greater annual ranges in temperature and greater variation in monthly rainfall. The lake basin and areas to the east are under the influence of the Atlantic climate regime and show less seasonal variability. Most of the rainfall is orographic in origin, caused by the upslope movement of moist air from the Atlantic propelled across the divide by the Northeast Trade Winds. Monthly (seasonal) and annual rainfall around Lago Cote varies with elevation and aspect. Data from the Lago Cote meteorological station, on the southern edge of the lake at 670 m, show an average annual rainfall of 3875 mm from 1966 to 1989 (Figure 2.6) (Instituto Costarricense de Electricidad, unpublished data for station 069532). January through April is the driest period (Figure 2.7), but rainfall exceeds evapotranspiration rates in all months in the life zone that includes Lago Cote (Sheets, 1994a). A mid-year period of reduced rainfall, during the rainy season, is referred to as veranillo, or "little summer" (Coen, 1983). The abundant regional rainfall increases potential for soil erosion and leaching. According to Sheets (1994a), the Lago Arenal area is not recommended for agriculture because of high precipitation and cloud cover. Mean monthly temperatures near Lago Cote vary only slightly from 22° to 23° C, while the diurnal difference can be as much as 8° C (Sheets, 1994a).

Regional wind direction is dominated by the prevailing NE tradewinds, with local variations due to topography. At Lago Arenal, winds are from the northeast year round (Sheets, 1994a), with wind speeds greatest from November to April. Average annual wind speeds range from 15 km per hour in Tilarán, to 23 km per hour in the nearby Arenal drainage basin, where January winds are in excess of 30 km per hour (Sheets, 1994a). Because of the sustained wind speed and direction, trees in the region are windswept. A windmill farm for electricity generation has been developed along the continental divide to the west of Lago Arenal to take advantage of the constant and strong regional winds.

Present Vegetation and Land Use

The Holdridge life zone system classifies areas based on total precipitation and elevation. Although the life zone system is a climate classification, the life zones are named after vegetation "formations" or "biomes" (Hartshorn, 1983), and are expected to

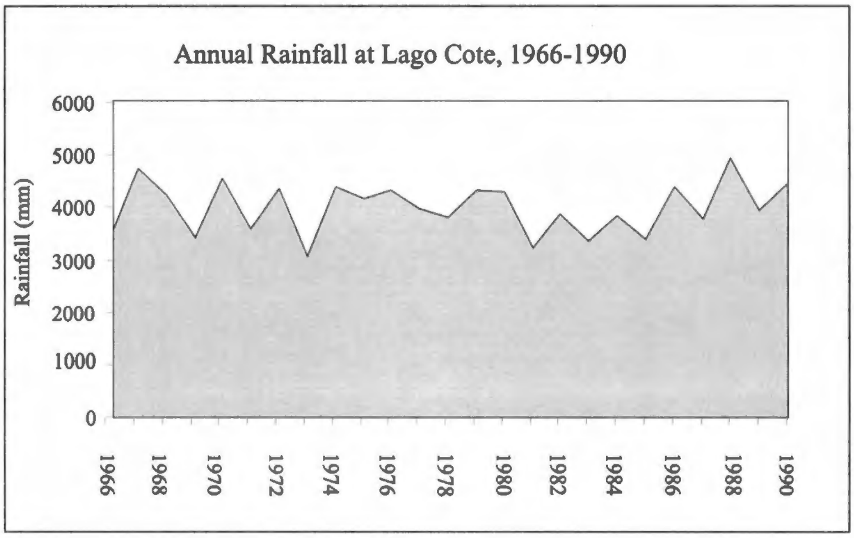


Figure 2.6 Annual Rainfall at Lago Cote from 1966 to 1990.

From Lago Cote Meteorological Station (#069532), Instituto Costarricense de Electricidad, unpublished data.

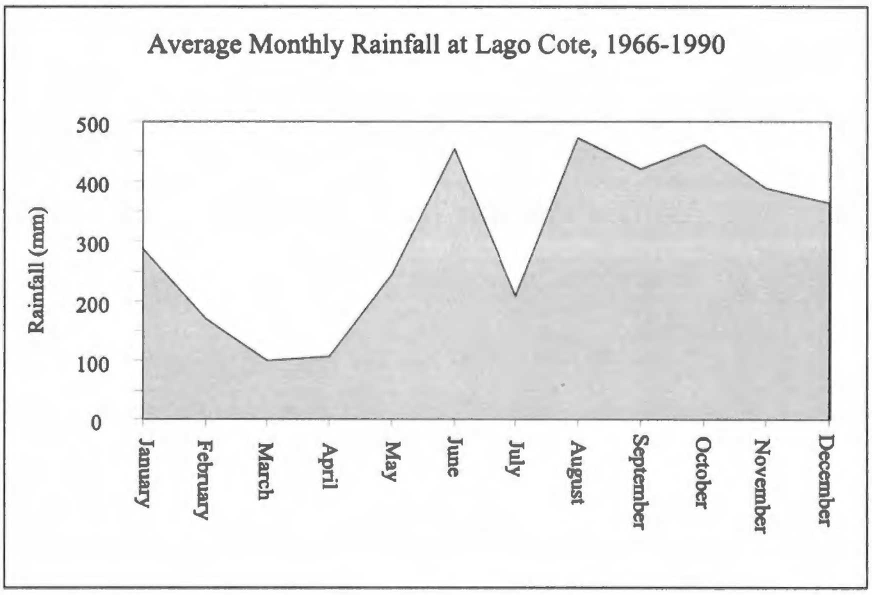


Figure 2.7 Average Monthly Rainfall at Lago Cote, 1966 to 1990.

From Lago Cote Meteorological Station (#069532), Instituto Costarricense de Electricidad, unpublished data.

show a close correlation with vegetation. Mature vegetation in each life zone is thought to have a particular and predictable physiognomy. Lago Cote falls within the tropical wet forest, (bmh-T) life zone (Sheets, 1994a) (Figure 2.8). To the northeast is premontane rain forest (bp-P) that receives higher annual rainfall, and to the south is a band of premontane wet forest (bmh-P) with lower annual rainfall. The lowest rainfall area occurs in the tropical moist forest (bh-T) that includes the town of Tilarán.

The vegetation around Lago Cote has been significantly altered in historical times by human activity. Remnant primary and secondary forests abut the lake on the east and northwest (Figure 2.2). North and north-northwest of the lake are large patches of even-aged pines from a former plantation. Now abandoned, the plantation is succeeding to tropical forest but the pines persist. Southeastern slopes are covered with citrus groves, while areas to the southwest and west are pastures and recently-abandoned pastures. On the southwest shore, the Río Pierna de la Laguna enters the lake through several channels in a large, flat, deltaic-wetland area where vegetation is dominated by shrubs. The outlet into the Río Cote is a narrow channel choked with rushes, and has been dammed to divert water away for hydroelectric power.

Areas north and west of the lake are privately owned and protected as part of an ecotourism business, the Lago Coter Eco-Lodge ("Coter" is an alternate spelling of Cote used by the Eco-Lodge). There is some small-scale farming, and cattle pastures, but many fields are in various stages of succession. Guides at the Eco-Lodge told me that these fields would remain ungrazed to allow for forest regeneration. The Eco-Lodge maintains several interpretive trails through the forests with raised walkways, crushed

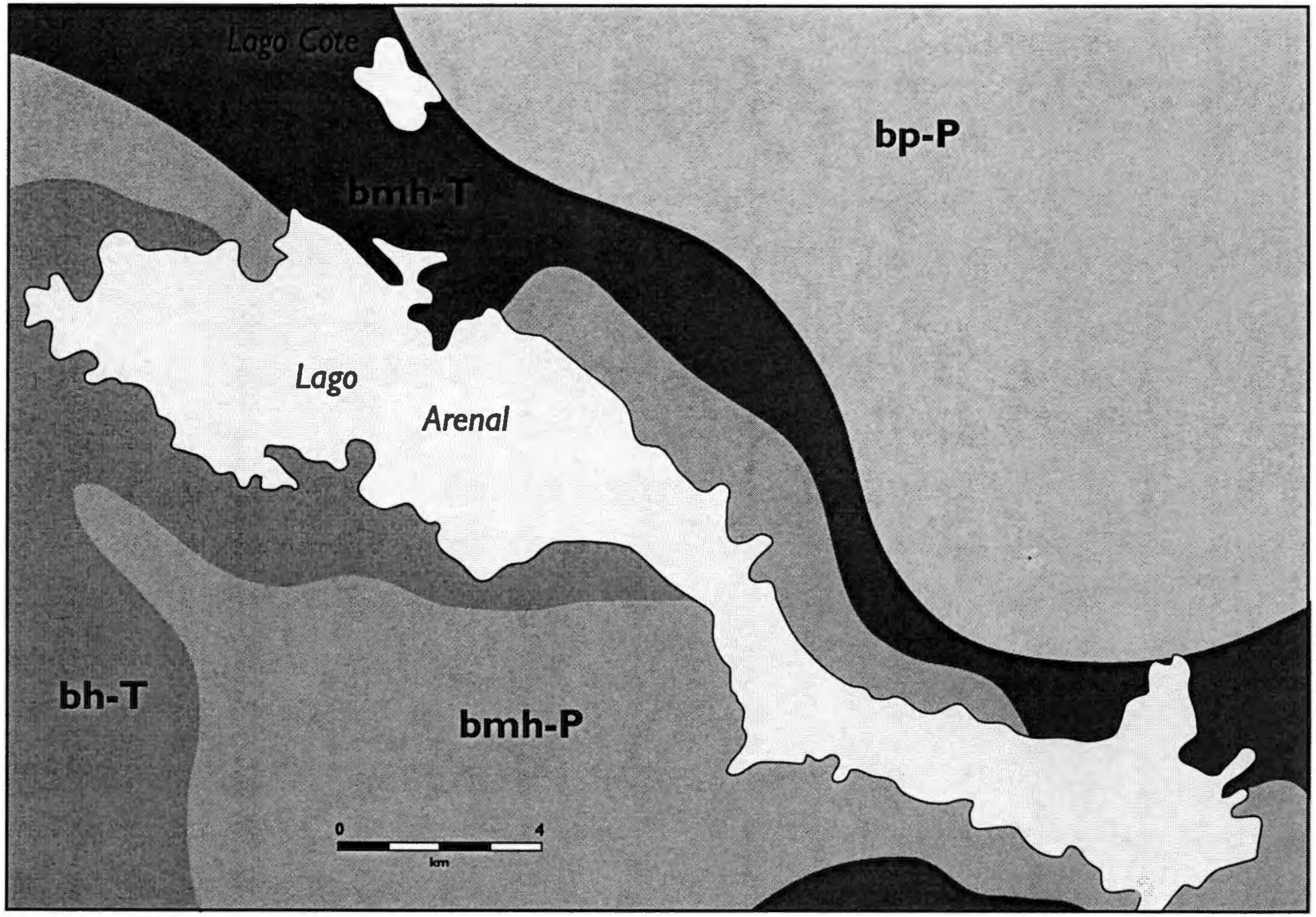


Figure 2.8. Holdridge Life Zone Classification for the Lago Cote–Arenal Area. Adapted from Sheets (1994a). bmh-T = tropical wet forest. bp-P = premontane rain forest. bmh-P = premontane wet forest. bh-T = tropical moist forest.

stone paths, and labeled plants. It provides many activities for tourists including horseback riding, guided rainforest hikes, a canopy tour, and water sports such as canoeing, kayaking, and fishing that take advantage of the lakeside location.

Former Eco-Lodge naturalist Gerardo Rivera documented much of the flora of the Cote area. I have included as Appendix B a list of taxa that he and others collected and deposited in an herbarium at the Eco-Lodge. The completeness of the botanical survey is not known, but the herbarium collection includes 476 species within 119 families representing Magnoliopsida (dicots), Liliopsida (monocots), Cycadophyta, Lycophyta, and Pteridophyta.

Human Interaction With The Landscape

Archaeological Context

The first humans had apparently arrived in Costa Rica from the North by about 10,000 BC, based on the presence of Paleo-Indian (Clovis-type) stone projection points in the Turrialba Valley (Snarskis, 1979; 1984). These earliest Costa Ricans presumably depended on many fruits, tubers, nuts, and seeds, in addition to hunting megafauna and other animals (Snarskis, 1984; Mora *et al.*, 1995). There are few archaeological sites to document human history over the next several millennia of the Archaic Period, but there were sedentary villages with permanent structures in the Arenal area by 3000 BC (4950 BP) (Sheets, 1994a) and in the southern Pacific and Central Highlands-Atlantic regions by at least 1000 BC (2950 BP) (Snarskis, 1984). Rapid population expansion occurred in many areas of Costa Rica from about 500 BC to 600 AD (~2450 BP to 1350 BP (Snarskis, 1981, 1984; Sheets, 1994b).

Costa Rica is divided into three archaeological regions of distinct material cultures: the Greater Nicoya Region, including the province of Guanacaste and the Nicoya Peninsula; the Central Region-Atlantic Watershed; and the Greater Diquís, including the southwest Pacific slope of Costa Rica (Stone, 1977; Snarskis, 1981; Mora *et al.*, 1995). Lago Cote is located along the border between the Greater Nicoya and Central Region-Atlantic Watershed regions. Most archaeological research in the Greater Nicoya region has been focused along the Pacific Coast and lowlands of Guanacaste, and not the highland area that includes Arenal and Lago Cote. Recently, four archaeological studies have been done in the Arenal area, led by Metcalf (1969, artifacts not analyzed), Murray (1974, unpublished survey), Aguilar (1977), and Sheets and collaborators (Sheets, 1994a). The latest, the Proyecto Prehistórico Arenal, was undertaken from 1984 to 1987 in the wetlands west of Arenal volcano. None of these studies included Lago Cote and the immediate vicinity. However, in early 2001 Maureen Sanchez, of the Laboratory of Archaeology at the University of Costa Rica, conducted a brief reconnaissance survey near the lake as part of a project funded by the National Geographic and directed by Sally Horn (S. Horn, personal communication).

Arenal Area Archaeology

The Proyecto Prehistórico Arenal was undertaken after the completion in 1980 of the Sangregado Dam, which flooded a former wetland to create the Arenal reservoir. Directed by Dr. Payson Sheets, the study had as its goal the evaluation of human interaction with the natural landscape near Arenal volcano, and included in-depth archaeological mapping and excavation as well as tephra studies and remote sensing. Most of the occupation sites were found in bmh-P and bh-T life zones (Figure 2.8), and included lithic artifacts dated from pre-Archaic times until the Conquest (Sheets, 1994c).

Five regional archaeological phases were identified in the Arenal Project (Table 2.1). The Fortuna Phase represents the time from 7000 BC (8950 BP) to the beginning of permanent structures and sedentary villages about 3000 BC (4950 BP). This phase roughly corresponds to the Archaic Period of Middle American archaeology (Sheets, 1994a). Sites from this period yielded cooking stones, and cutting edges that had been made using informal core-flake percussion (Sheets, 1994b). Because of an absence of archaeological evidence, little is known about the time period from 3000–2000 BC (4950–3950 BP), representing the change from the Fortuna (Archaic) to the Tronadoran (Formative) (Sheets, 1994b).

During the Tronadoran Phase, from 2000–500 BC (3950–2500 BP), there was an increase in sedentary villages and maize agriculture, although Arenal residents were apparently not as dependent on maize agriculture as were contemporaneous societies of Mesoamerica (Sheets, 1994b). Ceramics from the Tronadoran phase were elaborate and distinctive, and showed influences from the Atlantic Watershed of Costa Rica (La Montaña and Chaparrón phases), southern Mesoamerica, and northwestern South America (Hoopes and Chenault, 1994b). Burial sites were small rectangular pits within village sites.

Table 2.1 Chronology of the Arenal Archaeological Phases[1].

Years BC/AD	Arenal Phase[2]	SAR Period[3]	Years BP
AD 1500	TILARAN (Late Polychrome Period)	Late VI	450 BP
AD 1300	SILENCIO (Early/Middle Polychrome)	Early VI Late V Early V	650 BP
AD 600	late ARENAL (Zoned Bichrome Period) early	IV	1350 BP
500 BC	late TRONADORA (Middle Formative Period) early	III	2450 BP
2000 BC	? (Formative)	III	3950 BP
3000 BC ? 7000 BC	FORTUNA (Archaic Period)	III	4950 BP ? 8950 BP

[1] Adapted from Sheets (1994, 1984) and Hoopes (1984).
[2] Guanacaste Periods.
[3] School of American Research Periods, used as a standard for comparison to Arenal Periods.

Population densities were highest during the Arenal Phase, from 500 BC–AD 600 (2450–1350 BP), although they were not as high as in other regions of Costa Rica. There was little change in house construction or stone tool manufacturing, but metates became more elaborate, as if for ceremonial purposes (Chenault, 1994), and burial sites were moved onto ridges outside of the villages. Zoned Bichrome pottery was first found during this phase, and the culture showed strong ties with the Greater Nicoya culture (Hoopes and Chenault 1994a, b).

Fewer sites date to the succeeding Silencio Phase AD 600–1300 (1350–650 BP), a pattern that Sheets (1994b) interpreted to indicate a decline in population. However, there may have been larger villages in more strategic locations for better defense (Hoopes, 1994). Polychrome ceramics appeared and stone tools became more elaborate. Cemeteries moved farther from villages, and burials changed to include placing bodies in cists (stone slab boxes). Local culture again showed an affiliation with the Greater Nicoya region. Prehistoric footpaths, still visible on satellite images, linked villages to springs, stone sources and storage areas, and cemeteries (McKee and Sever, 1994; McKee *et al.*, 1994).

During the Tilarán Phase, AD 1300–1500 (650–450 BP), there was continued population decline and increasingly scattered settlements. Pottery was more simply ornamented and mostly monochromatic, and ceramic durability declined to the lowest quality found in the Arenal Project. According to Hoopes and Chenault (1994a), the cultural context changed to reflect a strong affiliation with peoples to the east and south of the Greater Nicoya region, in contrast to earlier times when the culture reflected a more autonomous development in a self-sufficient environment.

Prehistoric Agriculture and Land Use

Archaeological work in the Arenal area reveals that prehistoric inhabitants were more dependent on gathered foods than on widespread cultivation of maize and other crops (Sheets, 1994b). They had a lower population density than in many other areas of Costa Rica and Central America, and maintained independent, local methods of stone tool production with little influence from other regions (Sheets, 1994b; 1994c). Less dense populations here may have reflected the difficulty of living in an area of periodic volcanic activity, or the result of a climate regime that was unfavorable for the widespread agriculture necessary to support large groups of people (Sheets, 1994b).

The Arenal project did not include the recovery and analysis of sediment cores from the Arenal wetland or nearby lakes. However, plant remains and fossil pollen and phytoliths were collected in some of the archaeological excavations. Soil profiles (such as collected in archaeological excavations) need to be interpreted cautiously owing to the possibility of downward movement of pollen grains in soil layers (Horn *et al.*, 1998), which can result in assemblages of charcoal and pollen of different ages. Whether phytoliths are also affected by this problem seems uninvestigated.

The pollen, phytolith, and macrobotanical evidence from Arenal excavations do not provide detailed information on vegetation history but do suggest a long reliance on maize agriculture throughout all archaeological phases (Clary, 1994; Mahaney *et al.*, 1994; Piperno, 1994). However, analyses of carbon-13 to carbon-12 ratios in human bones from burial sites showed that less than 12% of the Silencio Phase diet came from C-4 plants such as maize (Bradley, 1994b). Many of the grinding stones and metates found in the Arenal project exhibited little wear and had more ornamented top surfaces than in other regions, perhaps indicating they were used more for ceremonial purposes than for the actual preparation of maize for food (Chenault, 1994; Sheets, 1994b).

Other crops grown by the Arenal residents included beans and avocado (Silencio and Tilarán Phases) and possibly squash (Clary, 1994; Mahaney *et al.*, 1994). Remains were found of gathered foods like *Bactris gasipaes* (pejibaye) and *Byrsonima crassifolia* (nance), and utilitarian plants such as *Crescentia alata*, used for containers (Clary, 1994; Mahaney *et al.*, 1994; Piperno, 1994). Phytoliths in excavations suggested moist, forested vegetation during the Tronadoran time period, but a large increase in grass phytoliths and decrease in phytoliths of tree taxa were thought to indicate forest clearance after 500 BC (2450 BP) during the Arenal and later phases (Piperno, 1994).

Volcanism and Prehistoric Settlements

From the Proyecto Prehistórico Arenal we know that the Arenal area had continuous low-density population from Archaic times until the Spanish arrival, with some individual villages exhibiting continual use from at least 2000 BC (3950 BP) until the Conquest (Sheets, 1994b). During this time period there were at least nine major eruptions of Arenal Volcano that deposited tephra over the occupied Arenal wetland, but there was little noticeable change in the archaeological record following eruptions (Sheets, 1994b). Other volcanically active areas in Latin America have experienced major changes in culture and settlement patterns following volcanic eruptions, such as near Barú volcano in Panama (Sheets, 1994b; Behling, 2000) and Ilopango volcano in El Salvador (Sheets, 1994b), where tephra layers delineate cultural boundaries or phase changes. However, no such boundaries are apparent in the Arenal region.

Archaeological evidence shows that settlements may have temporarily spread out into local river valleys, where the tephra layer was thinner, following an eruption around AD 900 (1050 BP), but they remained in the Arenal vicinity. Sheets (1994b) suggested that the stability of the Arenal civilizations through active volcanic episodes may be a function of the lower population density and less dependency on a few staple crops, making the inhabitants more able to cope with environmental stressors.

CHAPTER 3

METHODS

Sally Horn and students and faculty from the University of Costa Rica and the University of Tennessee first recovered cores from Lago Cote in 1991, with support from a UT Professional Development grant to Horn. The team recovered cores from near the northwest and east shores of the lake (Figure 2.2) but with a lightweight Livingston-type corer that could get no deeper in the sediments than 1.6 m. With funding from the National Geographic Society, Sally Horn, Lisa Kennedy and I recovered longer cores from the deeper part of the lake in 1998. In this chapter I describe the recovery of the 1998 cores and the methods used to analyze the tephra, pollen, and charcoal contained in the core sediments.

Field Methods

In March 1998, Sally Horn, Lisa Kennedy, and I collected two parallel sediment cores from the deepest part of Lago Cote (Figure 2.2) while working from an anchored platform in 10.9 m of water. Using a plastic tube corer (PTC), which consists of a piece of 5 cm diameter PVC pipe fitted with a rubber piston, we recovered 22 cm of softer upper sediments. We extruded and sampled the PTC sediments in 2 cm increments in the field, placing the samples in plastic bags for return to the lab at the University of Tennessee. We used a Colinvaux-Vohnout locking piston corer, which samples sediments in aluminum tubes in one meter sections, to recover cores of deeper sediments from two sites in Lago Cote about 20 m apart. The total length of the profile recovered was 2.7 m at core site 1 and 3.8 m at core site 2. High winds during the coring process moved the platform before we reached the bottom of the sediments and, because of time constraints, we were unable to continue coring. The depth of the unrecovered sediments is unknown. Cores were sealed in the aluminum collecting tubes and returned to the University of Tennessee where they were stored at 6° C. During the 1998 coring expedition, we used a YSI Model 55 handheld dissolved oxygen and temperature meter to measure the temperature and dissolved oxygen of the water column at 0.5 m intervals.

Laboratory Methods

Sediments, Stratigraphy, Pollen, and Charcoal

We opened the aluminum tubes lengthwise in the lab using a specially designed router and sliced the cores lengthwise into two equal parts, one for sampling and one for archival purposes. We photographed the core halves immediately, and measured and described the stratigraphy in terms of sediment texture and Munsell color. I sampled the cores for pollen and charcoal analysis and loss-on-ignition (LOI) at approximately 16 cm intervals, with depths adjusted slightly so that samples were not taken directly from tephra layers. I used volumes of 0.5 cm^3 sample for LOI and 0.25 cm^3 for pollen processing. LOI samples were placed in preweighed crucibles, weighed, dried for a minimum of eight hours at 100° C, and reweighed to determine water content. Loss-on-ignition was done by igniting the sample at 550° C for 1 hour, and then at 1000° C for one hour, to estimate organic and carbonate content respectively (Dean, 1974). I processed samples for pollen analysis using standard palynological techniques (HCl, HF, KOH, acetolysis, safranin stain; Berglund, 1986; Appendix A). I added one tablet of *Lycopodium* spores (13,500 spores per tablet) to each sample to allow calculation of pollen concentrations (Stockmarr, 1971). I used silicone oil as a mounting medium and prepared two microscope slides for analysis from each of 25 sample depths.

I scanned all slides in entirety at low magnification (100x) using a Leitz Laborlux microscope to determine the presence or absence of maize pollen, pine pollen, and microscopic charcoal. For charcoal, I additionally noted whether fragments were present (at least one fragment observed) or abundant (multiple fragments in any given view). I then made standard pollen counts for each level at 400x magnification to a total of at least 300 pollen grains excluding indeterminate pollen grains and fern spores. I determined that counting 300 grains was adequate after plotting a curve relating pollen taxonomic richness to number of grains counted (Figure 3.1).

I identified pollen to the lowest possible taxonomic level by comparison to pollen reference samples of vouchered plant collections from Costa Rica and other neotropical areas, and to published pollen keys and descriptions (Heusser, 1971; Markgraf and D'Antoni, 1978; Hooghiemstra, 1984; Horn, 1986; Moore *et al.*, 1991; Roubik and Moreno, 1991). I followed the taxonomy used by the Instituto Nacional de Bioversidad (INBio), Costa Rica (http://www.inbio.ac.cr/bims/PLANTAE.html), in their Manual de Plantas de Costa Rica, because their plant list included all pollen taxa from Lago Cote.

Some pollen types I grouped together because their similar morphologies made separation difficult or impossible, including Melastomataceae/Combretaceae,

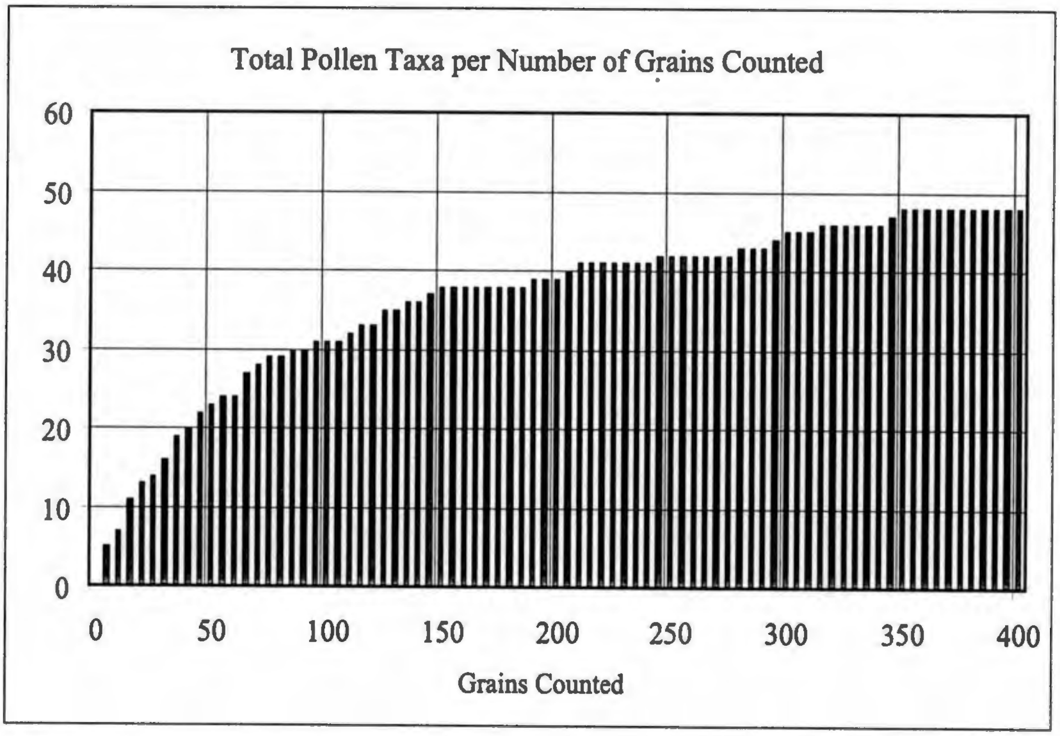


Figure 3.1 Pollen Taxonomic Richness Compared to Number of Pollen Grains Counted. Fern spores and indeterminate grains are excluded.

Sapotaceae/Meliaceae, and the order Urticales. Pollen from the Urticales order, including the families Cecropiaceae, Moraceae, Ulmaceae, and Urticaceae, are small, mostly wind-dispersed grains with exines that are psilate or scabrate. Pollen of *Ulmus* is distinctive, but many Urticales-types cannot be separated because of overlapping morphologies. I distinguished *Cecropia*, *Dorstenia*, *Trema*-type, *Celtis*-type, and *Ficus*, and classified others according to pore number (diporate, triporate, 4-porate, polyporate, or undifferentiated pore number). I only included in the *Ficus* category grains that were lozenge-shaped and diporate (Horn and Ramirez, 1990).

I separated maize pollen grains from other grass grains based on the maximum dimension of the grain; this is the most accurate method of determining maize according to Sluyter (1997b). Grains over 60 μm in diameter were classified as maize. Whitehead and Langham (1965) use an overlap range of 46-87 μm between maize and other *Zea* species, like teosinte. Maize grains overlap in size with pollen of teosinte (up to 90 μm, Ludlow-Wiechers *et al.*, 1983), however, teosinte is not known to have grown in Costa Rica. Other methods of distinguishing maize based on exine sculpturing (Tsukada and Rowley, 1964) or spinules (Eubanks, 1997) may not be effective at discriminating between these species (Fearn and Liu, 1997; Sluyter, 1997b).

I classified pollen grains as indeterminates according to the following factors that rendered them unidentifiable: exine corrosion, exine degradation, mechanical damage, or concealment by detritus or authigenic minerals (Delcourt and Delcourt, 1980). Following Northrop (1994), I used only a single and most apparent type of deterioration for indeterminate classification, and did not use categories for combined types of deterioration.

Grains I could not identify I classified as "unknown." I assigned each unknown morphotype a number, and drew and described each morphology. I recorded the microscope slide coordinates for representative grains, and kept track of the occurrences of each unknown type by sampling level. Many of the unknown pollen grains were small (<15 μm), tricolporate reticulate grains that I found hard to differentiate, a problem previously noted (Horn, 1986; Roubik and Moreno, 1991; Kennedy, 1998). I also encountered numerous small tricolporate, but not reticulate, grains that were difficult to key out, each morphotype occurring rarely.

I classified fern spores by morphology (monolete and trilete) and exine characteristics (psilate, scabrate, verrucate, coarsely verrucate, echinate, striate, rugulate, bacculate, and clavate).

I counted all charcoal fragments I observed during pollen-count transects and classified charcoal according to three size classes by the longest dimension: greater than 50 μm, 25 to 50 μm, and 5 to 24 μm. I counted only black, opaque, angular fragments, and only those larger than 5 μm. I plotted the pollen, spores, and charcoal data using a modified version of CalPalyn (Bauer *et al.*, 1991). I later reexamined microscope slides from near the base of the core to systematically evaluate charcoal morphology. I examined 200 charcoal fragments at 400x from the levels with high amounts of charcoal (355 to 298 cm), and counted only black, opaque fragments greater than 25 μm in one dimension. I categorized pieces as (1) "grass" or other herbaceous monocots, or (2) "other" (dicot leaves, wood, unable to classify) by looking for grass-like cuticle structures, including stomata, and cell margin shapes (Suman, 1983; Mworia-Maitima, 1997; Wooller *et al.*, 2000). When cuticle structures or stomata were absent or inconclusive, I compared the length to width ratio of particles after Umbanhower and McGrath (1998), and used a conservative ratio of 2.5 or greater to indicate grass.

Radiocarbon Determinations

To determine the chronology of the sediment core, I sent eight samples of charcoal and bulk sediment to Beta Analytic Inc. for Accelerated Mass Spectrometry (AMS) radiocarbon dating. I obtained the charcoal samples by sieving sediment from the core, and collecting individual charcoal fragments under low power magnification with fine tweezers.

Tephra Analysis

To allow comparison of the tephra layers from the Lago Cote cores to published studies of Arenal tephras (Melson, 1982; 1994), I analyzed tephra chemistries using X-ray fluorescence (XRF) facilities in the Department of Geological Sciences at the University of Tennessee, under guidance from Dr. Otto C. Kopp. X-ray fluorescence provides a fast and efficient method for identifying chemistries from bulk tephra (Cormie *et al.*, 1981; Froggatt, 1992), and provides better resolution than electron microprobe analysis when the goal is to distinguish between tephra layers of similar compositions (Sarna-Wojcicki *et al.*, 1983).

I removed about 30 cm^3 of tephra from each of ten layers in the cores, varying the sample size according to tephra thickness with the goal of obtaining a dry mass of approximately 10 g for each layer. Tephra samples were washed through stacked sieves with mesh sizes of 500 μm, 250 μm, and 125 μm, and flushed with distilled water. I wanted to compare the largest ash-sized particles from the Cote layers to the lapilli-sized tephra from the El Tajo site studied by Melson (1982) in hopes of minimizing size fractionation differences at our more distal location. Therefore, I separated the seven largest tephra samples into two size fractions in order to use grains larger than 500 μm (Table 3.1). For tephra layer CT4 (see Results) I split the sample at 250 μm to have enough mass in each size class for XRF. Two tephra layers, CT8 and 9 (see results), were too small to divide, so the entire sample was used. The resulting 18 samples (Table 3.1) were placed in labeled petri dishes, photographed, oven dried at 105°C to remove any water, and weighed. I placed each tephra sample into a mill (shatterbox), grinding each for 6 minutes until it was reduced to homogenous powder. From each powdered sample, I placed approximately 3 g into a cylindrical die, then added about 5 g of boric acid crystals. I compressed each sample in a hydraulic press at 10,000 psi (5 tons) for 30 seconds, then at 30,000 psi (15 tons) for one minute, yielding boric acid-backed pellets suitable for XRF analysis.

Dr. Kopp and I then placed 18 Cote tephra samples, 5 U.S. Geological Survey (U.S.G.S.) standards, and a normalization standard (NORM5) into an EG&G ORTEC (TEFA III) X-ray Fluorescence Analyzer for an automated analysis using IGROCK protocol. Cote tephra mineralogies were expected to fall within the range of basalt to dacite, based on the results of Melson (1982) from the El Tajo site. Five U.S.G.S. standards (BIR1, DNC1, STM1, AGV1, and BCR1A, see Appendix D) were included in the XRF analysis as controls based on the expected ranges.

Table 3.1 Tephra Samples Used for X-Ray Fluorescence Analysis.
Samples were taken from the Lago Cote 1998 II Sediment Core.

Sample ID[1]	Size ID[2]	Size Range (μm)	Dry Weight (g)
CT1	A	<2000 – >500	6.04
	B	<500 – >125	4.14
CT2	A	<2000 – >500	9.59
	B	<500 – >125	3.49
CT3	A	<2000 – >500	3.51
	B	<500 – >125	8.38
CT4[3]	A	<2000 – >500	4.23
	B	<500 – >125	7.70
CT4′	A	<2000 – >250	3.28
	B	<250 – >63	7.31
CT5	A	<2000 – >500	3.36
	B	<500 – >125	5.80
CT6	A	<2000 – >500	3.06
	B	<500 – >125	6.08
CT7	A	<2000 – >500	7.54
	B	<500 – >125	6.19
CT8[4]		<250 – >63	3.48
CT9[4]		<500 – >125	9.00

[1] Samples are listed in numerical order from the top to of the core to the bottom
[2] Samples were split in order to use the largest size fraction for comparison to the tephrochronology developed at El Tajo site by Melson (1982).
[3] CT4 and CT4′ were treated as part of the same eruptive sequence.
[4] Samples were too small to split into two size fractions.

I examined samples from each tephra layer under a low-power microscope, and visually compared tephras between sediment cores taken from Lago Cote in 1991 and 1998. Following XRF analysis, I recalculated the total iron, reported by IGROCK as Fe_2O_3, to FeO in order to match the reporting format used by Melson (1982) for the El Tajo tephra analysis. I used the following equations to convert the iron:

$$\frac{2(\text{molecular wt. FeO})}{(\text{molecular wt. } Fe_2O_3)} = f \qquad \text{and} \qquad (\%\ \text{wt. } Fe_2O_3)\ (f) = (\%\ \text{wt. FeO})$$

I attempted to use Discriminate Function Analysis (Stokes *et al.*, 1992) to correlate the tephras between the two sites. Discriminate Function Analysis (DFA) is a less subjective way to analyze tephras, but this technique may or may not work to discriminate layers from the same volcanic source (Stokes *et al.*, 1992).

CHAPTER 4

SEDIMENTS, RADIOCARBON DATES, AND TEPHROSTRATIGRAPHY

In our coring at Lago Cote in March 1998 we used the hammering feature of the Colinvaux-Vohnout corer to break through several tephra layers, ultimately recovering cores that were 1.2 m and 2 m longer than the 1991 cores. In this chapter I present and discuss the results of the radiocarbon determinations carried out on macroscopic charcoal and bulk sediment from the Còte cores, and my analyses of sediment and tephra stratigraphy. The information on sediments, chronology, and tephrostratigraphy sets the stage for the next two chapters of the thesis in which I present and discuss the results of the pollen and charcoal analyses.

Sediment Stratigraphy

Core Description

The sediment cores from Lago Cote consist of fined-grained copropel with ten interspersed tephra layers of mostly ash-sized particles, all displaying discrete horizontal contacts. Sediment color varies only slightly from black to very dark gray or very dark brown (Munsell 10YR 4/1 to 2/1, 5Y 3/1, and 2.5YR 2.5/0) (Figure 4.1). Organic material consists mostly of zooplankton fecal pellets and fine particulate organic matter, with an complete absence of coarse organic particles. Organic content estimated from LOI varies from 11.6% to 26.7% on a dry mass basis, except for the sample at 160 cm,

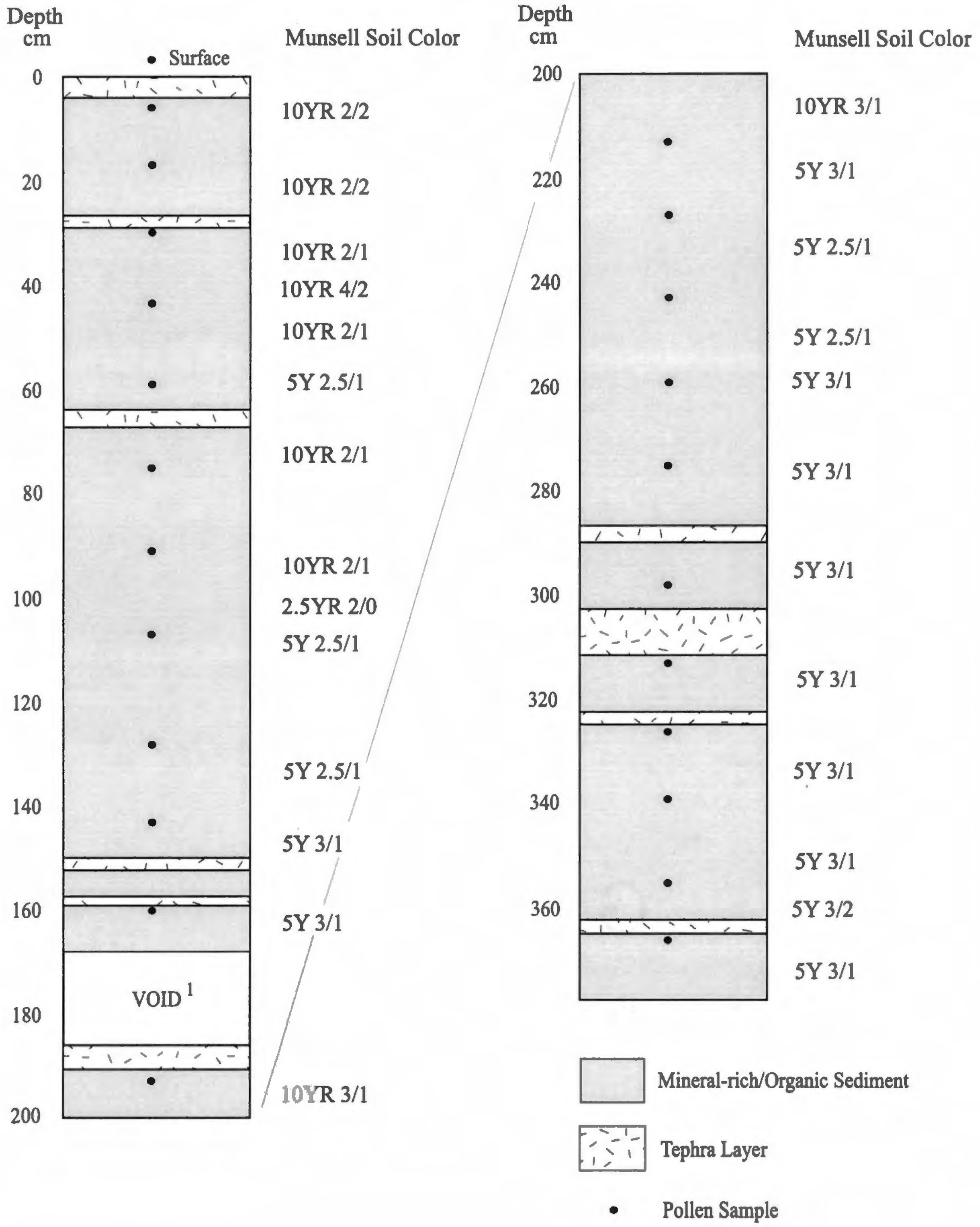


Figure 4.1 Lago Cote Stratigraphic Column From Core Site 1998 II.

[1] Comparison of the void interval to the core from site 1998 I reveals soft sediment with a Munsell color 10YR 3/1.

which is much less organic due to abundant tephra particles (Figure 4.2). Samples from 59 and 30 cm also show slightly lower organic content due to the presence of mineral tephra. Carbonate percent ranges from 0.3 to 1.0 (Figure 4.2). Bulk density remains nearly constant at about 1.15 g/cc, except for the surface sample that is uncompacted and contains more water. There is no evidence of soil or bedrock in the base of the core, consistent with our appraisal during coring that we did not reach the bottom of the deposit.

Lake Stratification and Sediment Mixing

Figure 4.3 graphs the temperature-oxygen profile of Lago Cote from our 1998 measurements. Umaña *et al.* (1999) reported that the lake is isothermal most of the year due to high winds, and Haberyan *et al.* (1995) reported that Lago Cote was unstratified during sampling in 1991. In March 1998 the lake also showed isothermal conditions, but revealed a clinograde oxygen distribution with negligible oxygen levels below 10 meters (Figure 4.3). This type of oxygen distribution is characteristic of stratified eutrophic lakes (Cole, 1994), but Lago Cote is not reported as being eutrophic (Horn and Haberyan, 1993; Haberyan *et al.*, 1997). In the absence of a thermocline, low oxygen levels in lake bottoms may be due to inflow of oxygen-depleted groundwater (A. Stewart, personal communication) and, since Lago Cote receives most water from rainfall and groundwater, this could explain the low levels of oxygen in its benthic waters. It is doubtful that bioturbation occurs in most of the bottom sediments at Lago Cote because of the low benthic oxygen levels. Few organisms can survive at 10 to 15% of oxygen saturation (Wetzel, 1983); and it is unlikely that bioturbation occurs in these conditions because there is insufficient oxygen for most benthic organisms (Larsen *and* MacDonald, 1993).

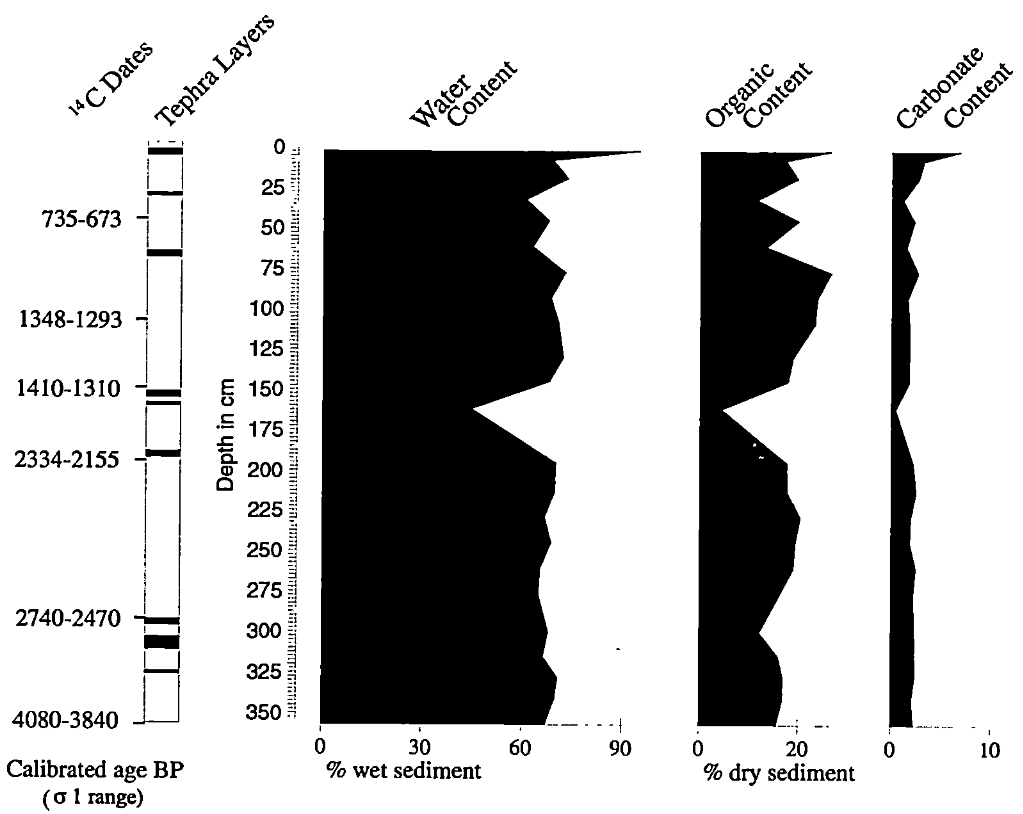


Figure 4.2 Lago Cote Sediment Diagram.

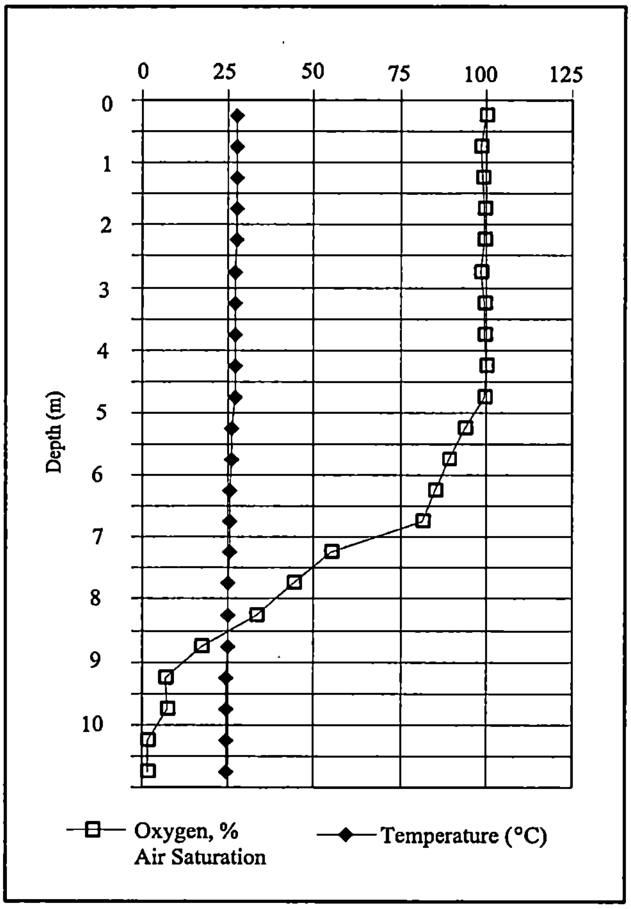


Figure 4.3 Temperature and Oxygen Profiles at Lago Cote.
Measured at Coring Site on March 9, 1988

The March 1998 oxygen profile also suggests that wave action does not reach the deep benthic sediments, making it less likely that vertical mixing occurs. However, the data in Figure 4.3 represent only one point in time, and do not reflect any seasonal or annual variations in stratification that may occur. It remains likely that sediment reworking occurs along the shoreline due to constant wave action, and this could lead to resuspension and minor redeposition of older sediments across the lake bottom.

Radiocarbon Dates and Sedimentation

Radiocarbon analysis of the Lago Cote sediment core yields an approximate age of ~4000 years based on calibrated ^{14}C dates; results of all ^{14}C are presented in Table 4.1. Two dates were obtained from the lower 80 cm of the core on charcoal fragments smaller than 125 μm, while bulk sediments were used for an additional six dates. The paucity of charcoal for dating above 187 cm depth made bulk sediments the only option for dating. I calculated an average of the possible calibrated ages for each sample, and used this average when discussing calibrated radiocarbon dates throughout this thesis.

There are some potential problems associated with the use of bulk sediments for radiocarbon dating, including the old carbon effect that results when the ^{14}C content of deposited sediments is less than the contemporaneous atmospheric ^{14}C. Types of old carbon problems include the reservoir effect, hard-water effect, and sediment contamination. The reservoir effect occurs whenever carbon from a source in disequilibrium with ^{14}C in the atmosphere is incorporated into living tissues and causes dating errors (Stuiver and Polach, 1977; Olssen, 1986). This can occur when submergent vegetation recycles older carbon from within the lake basin and does not exchange

Table 4.1 Radiocarbon Determinations on Material from Lago Cote Sediment Profile.

Lab Number	Depth (cm)	Material Dated	$\delta^{13}C$	Uncalibrated ^{14}C Age (^{14}C yr BP)	Calibrated Ages (cal yr BP)	Calibrated Age Range (cal. yr BP) $\pm 1\sigma$	Calibrated Age Range (cal. yr BP) $\pm 2\sigma$
β-140778	10	Bulk Sediment	-28.8	800 ± 40	694	735 - 673	787 - 665
β-136022	42-44	Bulk Sediment	-29.5	730 ± 40	668	683 - 656	727 - 570
β-140779	105-107	Bulk Sediment	-29.1	1430 ± 40	1310	1348 - 1293	1407 -1285
β-137968	147-150	Bulk Sediment	-28.8	1490 ± 50	1350	1410 - 1310	1520 - 1290
β-136023	192-195	Bulk Sediment	-30.3	2240 ± 40	2309, 2222, 2209	2334-2155	2345 – 2128
β-134419	288-294	Bulk Sediment	-28.9	2730 ± 50	2840, 2830, 2790	2870 - 2780	2950 - 2750
β-134418	288-294	Charcoal	-23.8	2510 ± 50	2710, 2630, 2620, 2560, 2550	2740 - 2470	2750 - 2360
β-130736	353-359	Charcoal	-23.5	3630 ± 70	3960, 3950, 3930	4080 - 3840	4150 - 3720

Analyses were performed by Beta Analytic Laboratory. Errors estimate 68% (1σ) and 99% (2σ) probability. Radiocarbon ages were calibrated using version 4.3 of the CALIB program (Stuiver and Reimer, 1993) and the dataset of Stuiver *et al.* (1998). Sedimentation rates were calculated based on the calibrated ages. For the radiocarbon dates that calibrate to more than one calendar age, we used the average of the youngest and oldest calendar ages.

carbon dioxide readily with the atmosphere. Hard water effects occur in lakes with high amounts of dissolved carbonate that is deficient in ^{14}C, such as in areas with carbonate bedrock (Olssen, 1986) or volcanically active areas (Olsson, 1979; MacDonald *et al.*, 1991a). Contamination of lake sediments can occur when older deposits, detritus, or soils have been reworked and incorporated (MacDonald *et al.*, 1991a; Larsen and MacDonald, 1993).

To test for old carbon effects, or other dating problems with bulk samples, I dated two samples from the same level of the core. One consisted of charcoal (β-134418) and one of bulk sediment (β-134419) from opposite halves of the same core section at the same interval (288-294 cm, Table 4.1). The mean bulk date is 200 years older than the charcoal dates, suggesting a slight old carbon effect at least at this level. If the organics in the bulk date came from submergent aquatics there would be potential for the reservoir effect. To test this hypothesis, I looked at $\delta^{13}C$ values of the samples (Table 4.1).

Common submergent plants have a $\delta^{13}C$ range of –12‰ to –20‰, while the range for emergent aquatics, C_3 terrestrial plants, and planktonic algae is –30‰ to –24‰ (Aravena *et al.*, 1992). In the Cote bulk sediments, $\delta^{13}C$ values are in the emergent/terrestrial/planktonic range (Table 4.1), indicating that the reservoir effect is less likely. The lake morphometry supports this assumption, because most of the benthic region of Lago Cote has a water depth below the photic zone, leaving a restricted littoral region for emergent and submergent aquatic plants. Organic material is most likely derived from the pelagic zone by primary producers (plankton), and plant detritus from emergent and terrestrial plant material that is blown or falls into the lake. Therefore, it is unlikely that the 300 year difference between the bulk sediment radiocarbon date and the charcoal date are due to a reservoir effect created by submergent/emergent aquatics that are in disequilibrium with atmospheric carbon.

The charcoal that was used for dating the lowest two samples was mostly charred grass (see Chapter 5), and many/most tropical grasses are C_4 plants. C_4 plants are relatively high in ^{13}C, about –13‰ (Winkler, 1994) to –14‰ (Mohr and Schopfer, 1995), while C_3 plants are typically more enriched in ^{12}C with levels around –18‰ (Winkler, 1994; Falkowski and Raven, 1997). The $\delta^{13}C$ values from the charcoal dates (Table 4.1) are more enriched in $\delta^{13}C$ than bulk samples, an expected result if burned fragments of C_4 grass were included in the charcoal sampled. It is important to use caution when interpreting the Cote $\delta^{13}C$ values, though, because the referenced values are from temperate studies.

Low organic content of the sediments (Figure 4.2) and the incorporation of mostly terrestrial plant material, according to $\delta^{13}C$ values, indicates that the lake had lower productivity throughout the sediment record, except for the uppermost (modern) sample that has greater organic content. Because of the high percentage of inorganic material in the sediment samples, nearly 80%, it seems likely that the age difference between the two radiocarbon samples is due to contamination by older organic and/or inorganic material that has been deposited within the sediment. I cannot rule out hard water effects, but a modern sample of water chemistry from Lago Cote did not indicate high levels of dissolved calcium carbonate (10.71 mg/L) (Horn and Haberyan, 1993). Volcanic eruptions can add CO_2 that doesn't contain ^{14}C (Olssen, 1986; MacDonald, *et al.*, 1991a), causing dates to appear older. It is unknown whether active carbon dioxide venting occurred near Lago Cote, but that cannot be ruled out due to the close proximity to Arenal volcano.

Another possible complication for comparing the charcoal and bulk sediment dates is that bulk samples contained 6 cm of material averaged together in order to obtain enough charcoal for AMS dating. Whatever old carbon effects or other differences exist between the bulk and charcoal material may be slight when compared to the large range of age of the composite sample itself. Stream erosion and littoral wave action may have redeposited older sediments and charcoal in the deeper parts of the lake, affecting the dates, also.

The two uppermost dates (694 cal. yr BP, β-140778 and 668 cal. yr BP, β136022) overlap, indicating near synchronous deposition. This is unlikely, given the dates are separated by 32-34 cm of sediments. This apparent reversal in the top two dates is most likely a consequence of the imprecision of radiocarbon dating. Dates at 105-107 cm and 147-150 cm are unexpectedly close in age (1310 and 1352 cal. yr BP, respectively), given that they are nearly 50 cm apart. Even with a few dating irregularities, the general trend of the dates makes sense when plotted against core depth (Figure 4.4). Each date represents a range, potentially with some error, but the overall pattern is acceptable.

Calculated sedimentation rates vary from 0.05 to 0.99 cm/yr (Figure 4.4), but the slowest rate may be an artifact of the apparently anomalous young date at 147-150 cm. There is little change in sediment color, density, or organic/inorganic content to explain the changes in sedimentation rates. I would expect that as sedimentation rates vary, so would the organic/inorganic content ratio. For example, if there had been more land clearing and/or fires, then higher erosion rates would show as increased inorganic

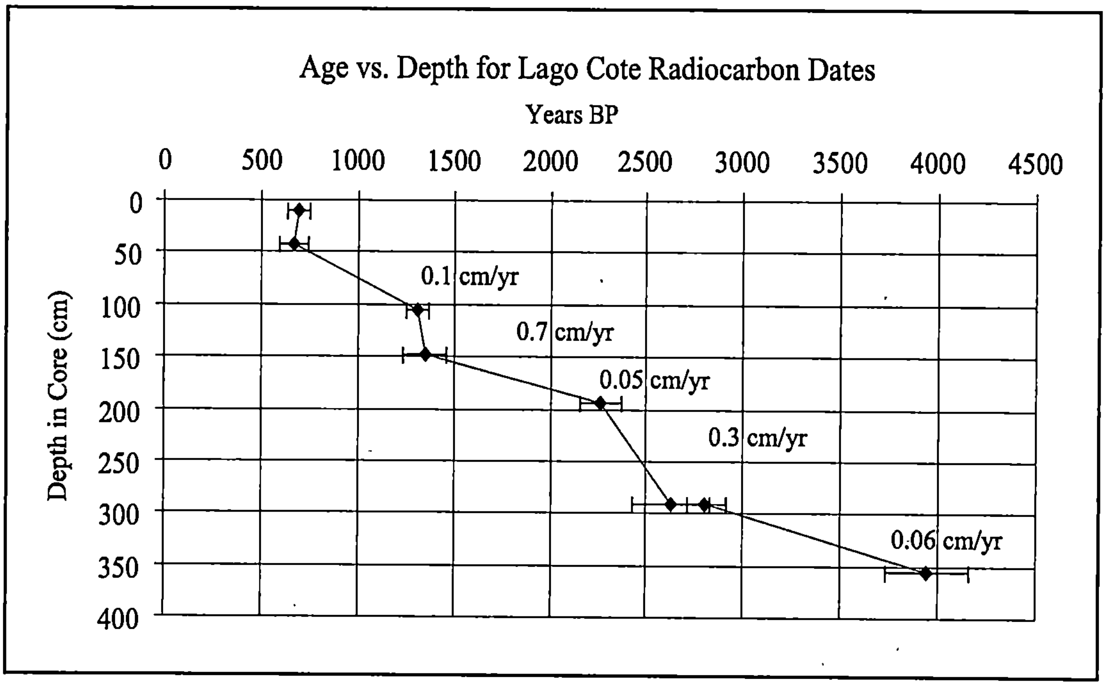


Figure 4.4 Lago Cote Radiocarbon Dates Plotted Against Depth.
Sedimentation rates between each dated interval are indicated (calculated from Table 4.1. Bars indicate 2σ range. Samples at ~290 cm, 1 charcoal and 1 bulk sediment, have overlapping ranges.

content, but this is not evident. In addition, the two intervals with slowest sedimentation (366-288 cm and 195-147 cm; Table 4.1) also have more tephra layers that would have been deposited quickly. These tephra-containing intervals are followed by sediment intervals that have faster sedimentation and fewer tephra layers (Table 4.1, Figure 4.4).

Tephrostratigraphy

X-Ray Fluorescence

In Table 4.2 I present the results of the X-ray fluorescence analysis for the nine most abundant mineral oxides. The largest size fraction of each sample is reported here to more closely match the lapilli-sized particles evaluated by Melson (1982). "Ash" refers to pyroclastics smaller than 2 mm, the size of most particles in Lago Cote tephra layers, while lapilli refers to pyroclastics from 2 to 64 mm in size (Wright *et al.*, 1981; Bates and Jackson, 1984). Table 4.3 reports the results of the recalculation of iron from Fe_2O_3 to FeO for comparison to the El Tajo EMPA data. Weight percent Al_2O_3 is slightly out of range of the standards; higher than we expected based on the El Tajo chemistries (Melson, 1982). Complete data for analysis of tephra samples, as well as standards, are listed in Appendix D.

Comparison of Cote and El Tajo Tephras

I compare the mineralogies from Lago Cote and the El Tajo section (Melson, 1982) by plotting the weight percent of each major mineral oxide against the weight percent of silicon dioxide in order to show differentiation (Figures 4.5 and 4.6). This comparison shows that tephras from these two locations represent two distinct but

Table 4.2 Results of X-ray Fluorescence Analysis of Lago Cote Tephra Samples.
Weight percent of each mineral oxide is reported for each tephra layer analyzed from Cote Core 1998 II.

	CT1 wt-/%	CT2 wt-%	CT3 wt-%	CT4 wt-%	CT5 wt-%	CT6 wt-%	CT7 wt-%	CT8 wt-%	CT9 wt-%
Na_2O	3.28	3.07	2.70	2.95	3.15	3.11	2.35	2.34	2.57
MgO	2.96	3.06	5.52	3.95	3.52	4.01	4.86	4.93	4.62
Al_2O_3	19.96	19.91	21.17	22.04	19.39	19.25	22.07	20.03	21.23
SiO_2	54.06	54.21	50.38	51.35	55.09	54.42	49.08	51.83	51.87
P_2O_5	0.13	0.13	0.08	0.09	0.16	0.15	0.11	0.11	0.10
K_2O	0.52	0.49	0.03	0.42	0.54	0.50	0.41	0.45	0.38
CaO	8.35	8.52	10.61	10.61	8.39	8.74	10.92	9.63	9.74
MnO	0.21	0.25	0.15	0.15	0.20	0.19	0.15	0.19	0.18
TiO_2	0.54	0.54	0.49	0.55	0.52	0.56	0.60	0.64	0.56
V	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.02
Cr[1]	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Fe_2O_3	8.85	9.05	8.53	8.15	8.41	8.46	9.07	9.94	9.29
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr	0.07	0.07	0.07	0.06	0.07	0.06	0.06	0.06	0.06
Y	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zr	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Nb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total[2]	98.95	99.31	99.76	100.36	99.47	99.47	99.70	100.18	100.61

[1]Cr – Not done (n.d.), below range.
[2]Total Precision at $3\sigma \pm 3\%$

Table 4.3 Weight Percent Fe_2O_3 in Lago Cote Tephras (from XRF) Recalculated to FeO.

Cote Tephra Sample	Wt. % FE_2O_3[1]	Recalculated to Wt. % FeO[2]
CT1	8.85	7.96
CT2	9.05	8.14
CT3	8.53	7.68
CT4	8.15	7.33
CT5	8.41	7.57
CT6	8.46	7.61
CT7	9.07	8.16
CT8	9.94	8.94
CT9	9.29	8.36

[1] Results from X-ray Fluorescence Analysis.

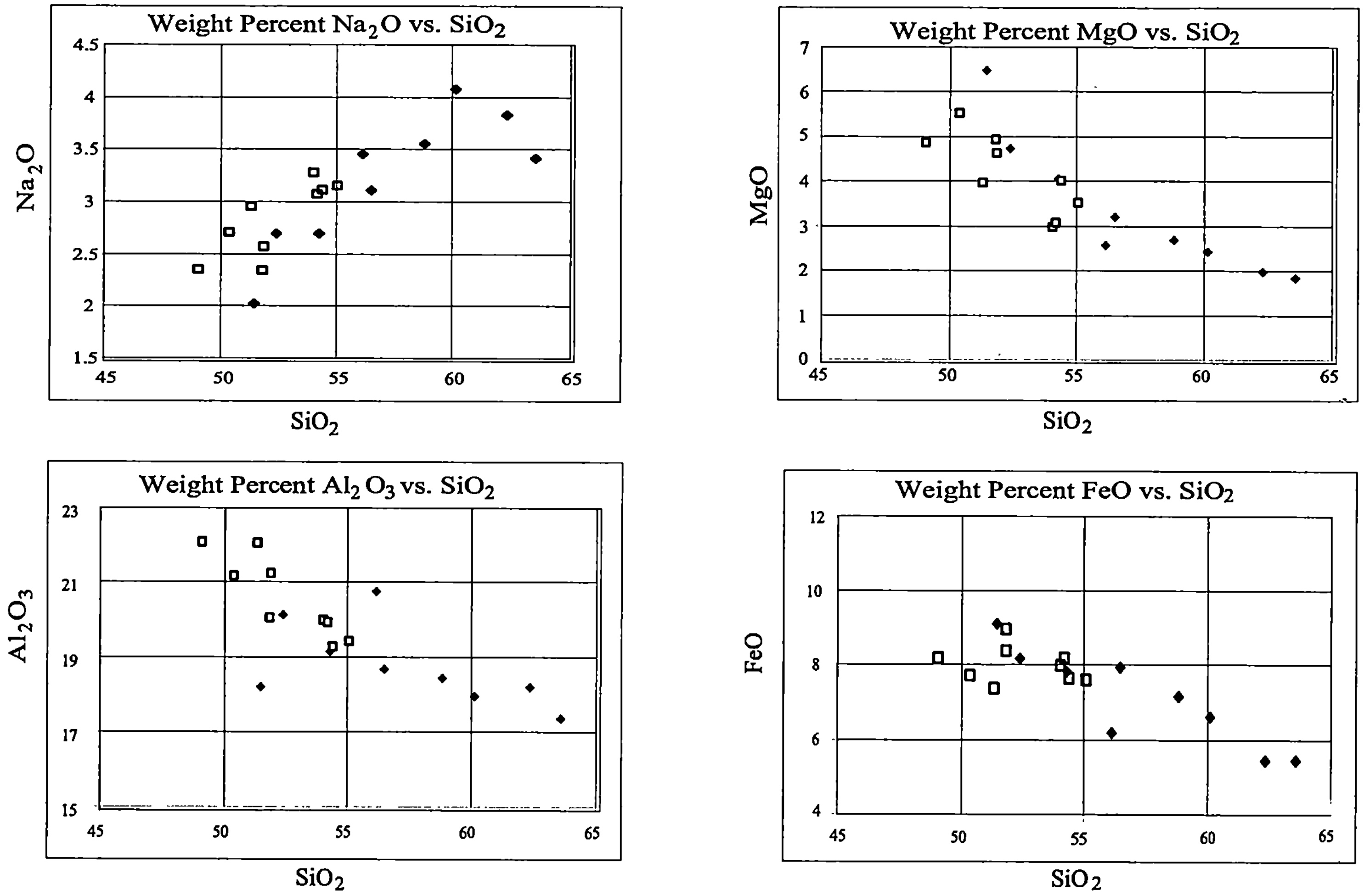


Figure 4.5 Scatterplot Comparison of Mineral Oxide Weight Percent from Lago Cote and El Tajo Tephra Samples. Cote samples (CT) are shown as open squares, El Tajo as closed diamonds.

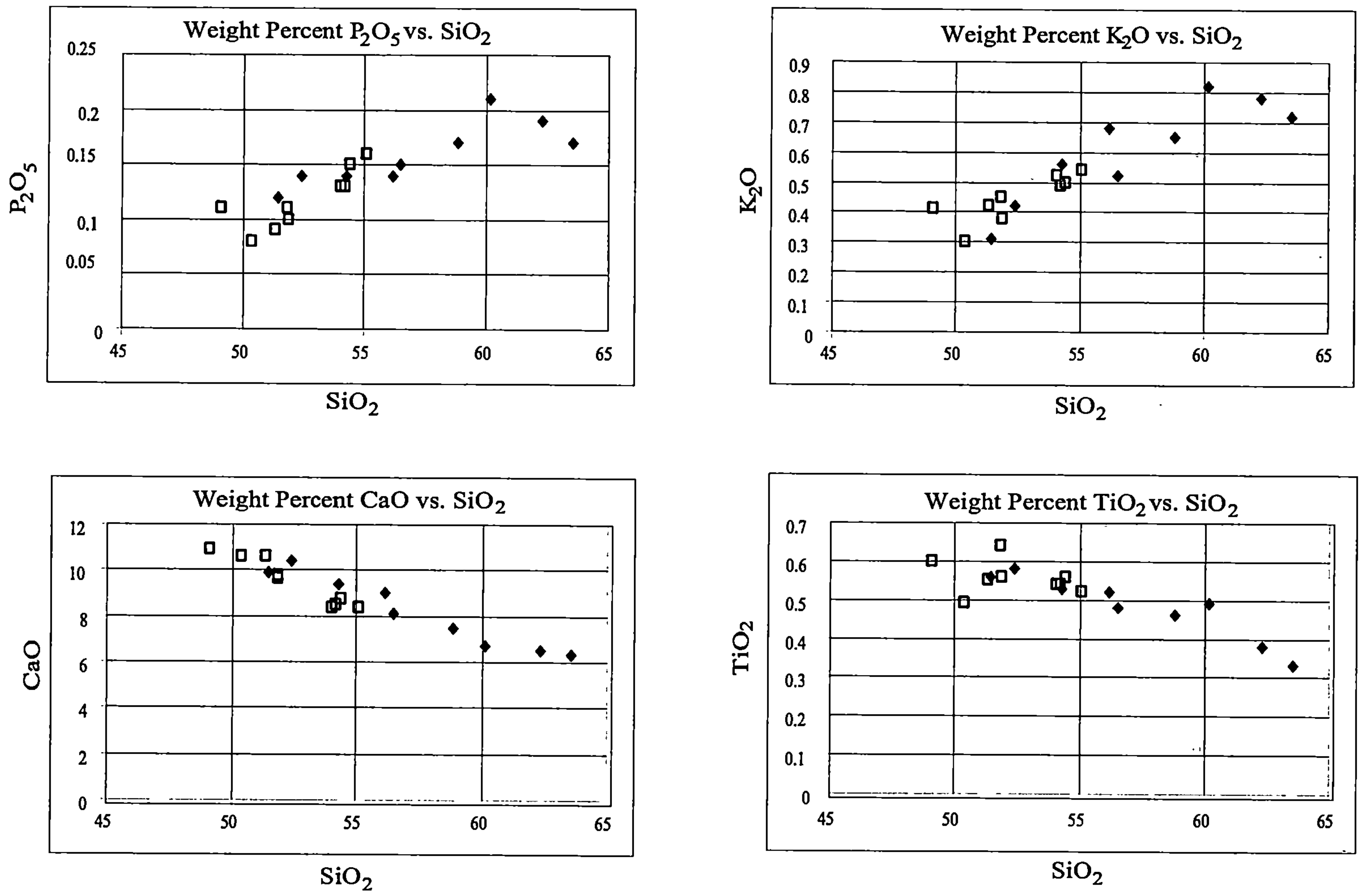
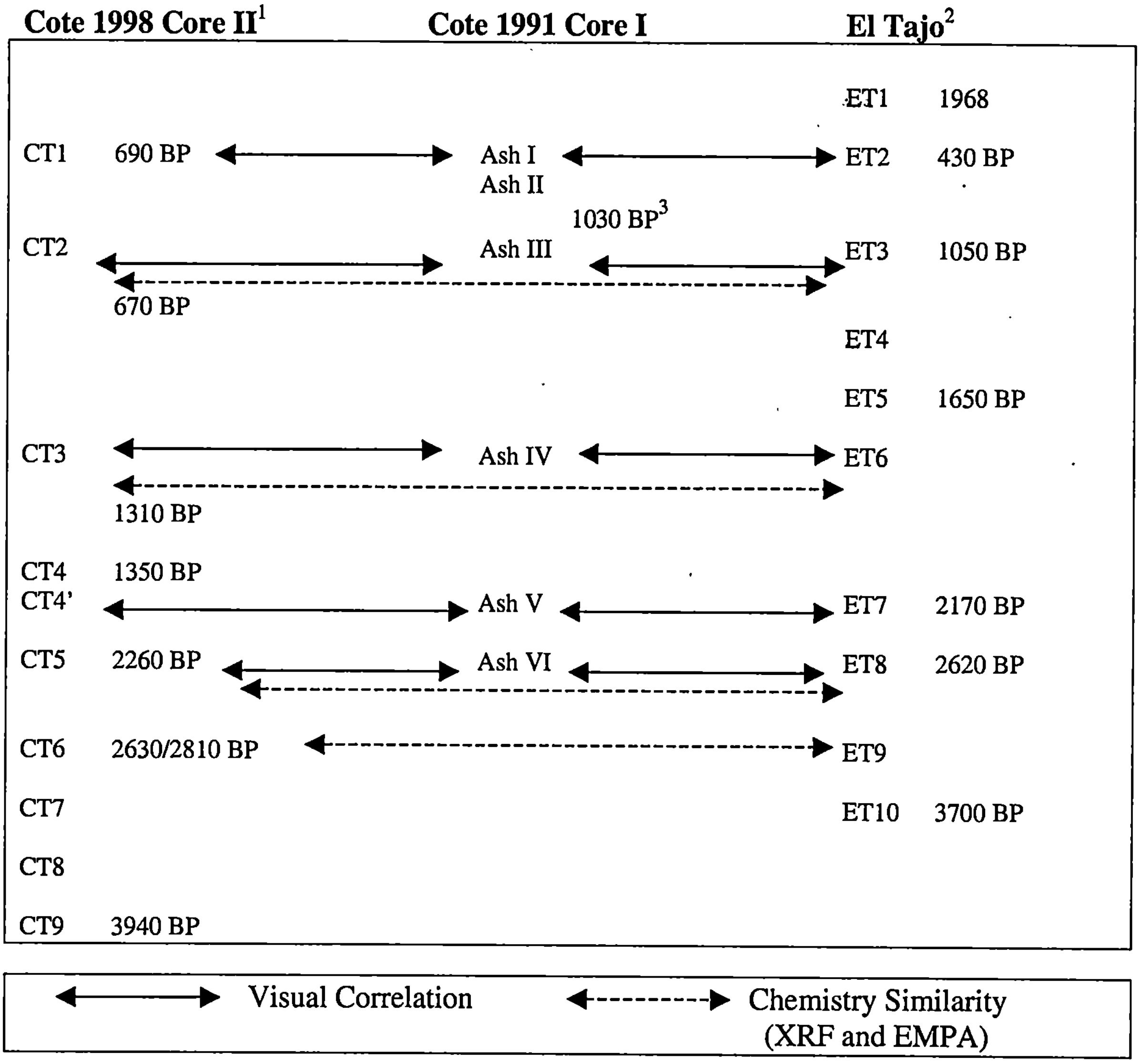


Figure 4.5 (continued)

lower than in El Tajo tephras (ET) reported by Melson (1982). It is expected that tephra compositions become more enriched in silica at more distal locations because of aeolian fractionation (Fisher and Schmincke, 1984) as the lighter minerals are dispersed farther downwind (Cox *et al.*, 1979) than the heavier, more mafic particles (Fisher and Schmincke, 1984). Why this is not the case with the Arenal deposits is unclear.

In Figure 4.6 I compare the tephra layers from the 1998 and 1991 cores to the El Tajo tephrochronology developed by Melson (1982). I aligned the data based on (1) visual identification of tephra layers in the Cote 1991 core by Melson (V. Kier, unpublished data), and (2) my visual comparison of tephras between the 1991 and 1998 cores. V. Kier provided the Cote 1991 cores to Melson for tephra identification as part of her thesis project to look at fossil diatoms in the 1991 cores (Kier, in progress). Melson determined that some tephra layers were missing from the Cote 1991 core, including the1968 eruption of Arenal and layers corresponding to the El Tajo 4 and El Tajo 5 tephras. I found the same tephra layers missing from the 1998 core. I also treated tephra layers CT4 and CT4' as the same event, because they were indistinguishable at low-power magnification and were separated by only 3 cm. There may have been a small hiatus between eruptions that was recorded in the lake sediments but not distinguishable in the El Tajo soil profile. Borgia *et al.* (1988) also suggested that Melson's (1982) El Tajo 4 and 5 layers may represent the same unit.

Figure 4.7 compares the weight percents of each mineral oxide for each tephra layer at Cote and El Tajo, following the alignment from Figure 4.6. There are significant differences between the weight percents of mineral oxides at the two locations in two



[1] Visual comparison of Cote 91 and Cote 98 cores by Arford. Dates for Cote 98 were calibrated using Calib 4.3 (Stuiver and Reimer, 1993) and the dataset of Stuiver *et al.* (1998).
[2] Visual Comparison of Cote 91 Cores to El Tajo by Melson, 1995. Dates Melson compiled from the results of radiocarbon dating of charcoal, or were estimated from time for soil accumulation and mineral degradation. They are uncalibrated ages.
[3] Uncalibrated date

Figure 4.6 Comparison of Tephras from Cote 1991 and 1998 Cores to El Tajo Chronology.

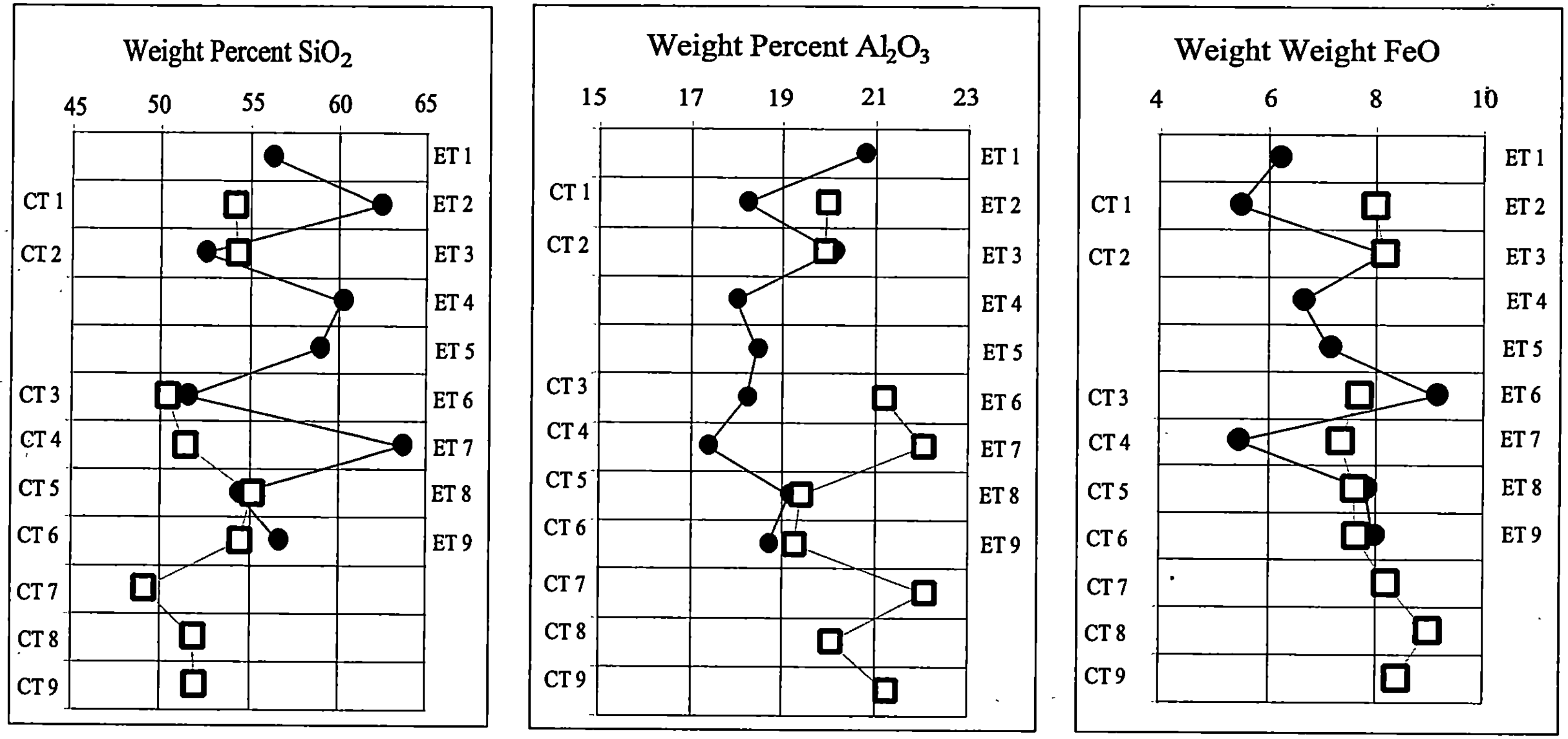


Figure 4.7 Line Graph Comparison of Mineral Oxide Weight Percents from Lago Cote and El Tajo Tephras. Cote tephra layers (CT) are shown as open squares, El Tajo (ET) as solid circles. Samples are aligned based on visual comparison of tephra layers.

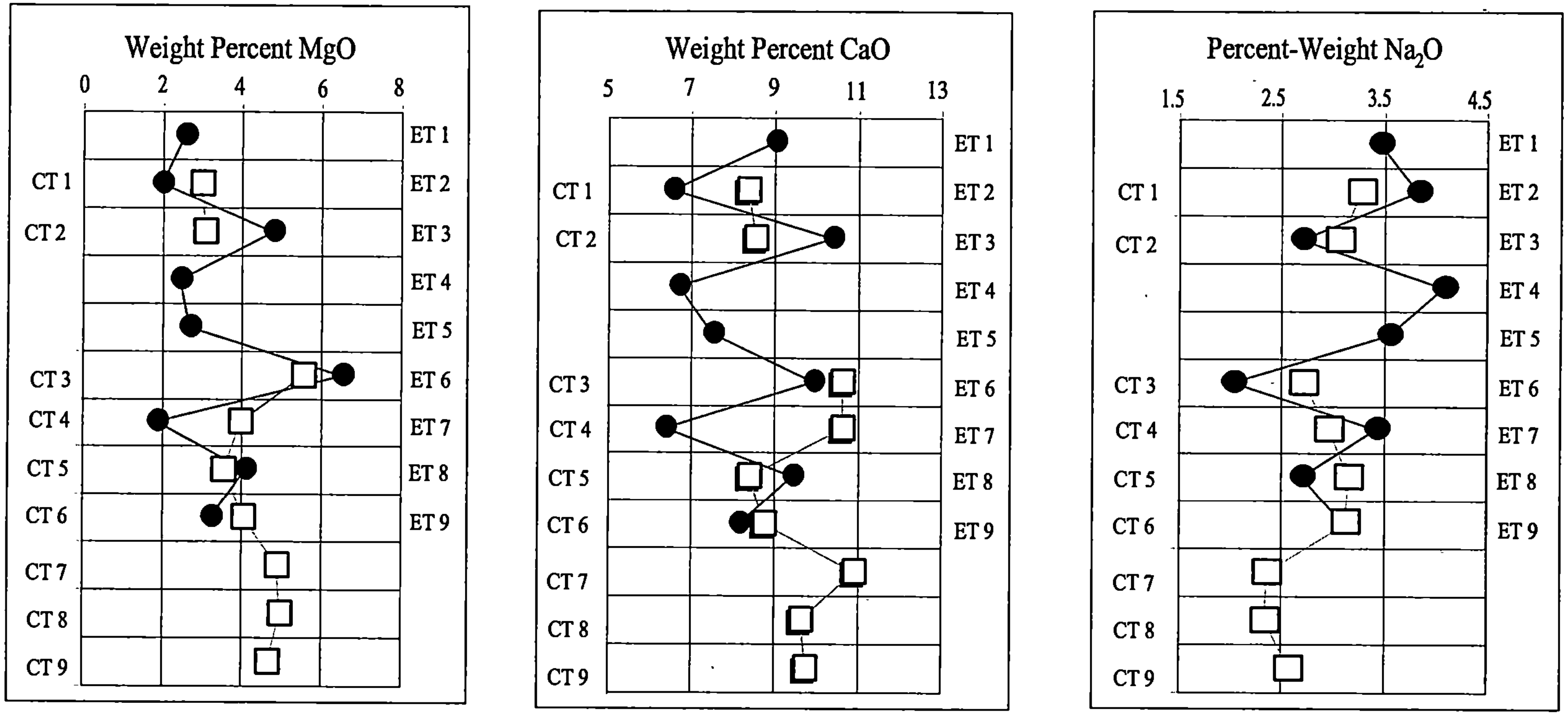


Figure 4.7 (continued)

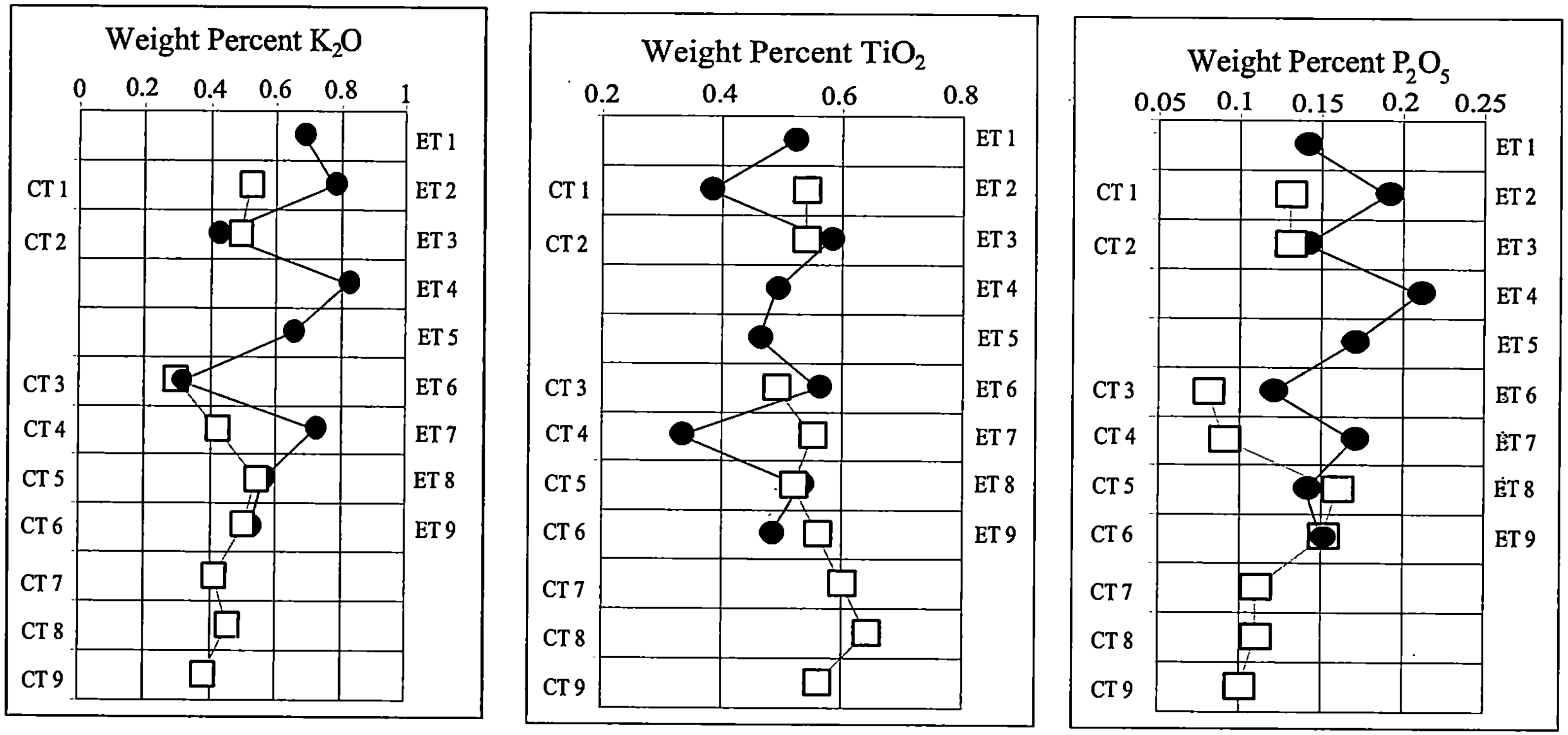


Figure 4.7 (continued)

ways. First, when comparing any single layer of Cote to El Tajo tephras there are very different weight percents of many mineral oxides. Second, there is no consistent pattern to the changes of mineral oxides between the sites so that iron, for example, is not consistently higher at one of the sites. This makes interpretation difficult. However, there are three or four layers that seem to correspond well between Cote and the El Tajo sections, for most mineral oxides: CT2 and ET3, CT3 and ET6, CT5 and ET8, and perhaps CT6 and ET9 (Figure 4.7). The first three of these paired layers are the same ones that match up according to visual examination (Figure 4.6), and this reinforces the idea that three Arenal eruptions, 1968, ET4, and ET5, are recorded at El Tajo but not in the more distal Cote sediments. Tephra layer ET7 should match CT4, but for most mineral oxides these two layers exhibit dissimilar chemistry trends (Figure 4.7).

Figure 4.7 provides another view of the apparent anomalous silica depletion in the Cote tephras with respect to El Tajo. When aligned by the best comparison of the XRF results and visual examination, some samples (CT3, CT6, CT8, CT9) are nearly identical to the corresponding ET values. This shows that silica values at Cote remain more consistent throughout the eruptive sequence, and do not display the cyclic alternations described by Melson (1973, 1982) in the El Tajo samples.

The two oldest tephras at Cote, CT8 and CT9, appear not to be reported from El Tajo. Because their chemistries are similar to the other tephras at Cote, they are most likely either earlier eruptions of Arenal or represent eruptions from the older Cerro Chato volcano that flanks Arenal to the southeast. These layers may not have been exposed at El Tajo during dam construction because the road cut was not deep enough. It is also possible that erosion at El Tajo accounts for the extra tephra layers at Cote. Borgia *et al.*

(1988) found that ET1 is currently mostly eroded near El Tajo, and suggested that older eruptions similar in magnitude to ET1 may have not been recorded at El Tajo. Cote tephra CT8 is less than 2 cm thick, and may have been preserved in lake sediments while it was eroded away at El Tajo.

Dating differences between the sites could be an artifact of how dates were derived between Cote and El Tajo. Melson (1982, 1984, 1994) based his dates on time for soil formation and mineral degradation between eruptions, although ET 2 and ET 7/8 dates are based on charred tree remains and archaeological evidence. Other factors, such as climate change and human use of the landscape, may have influenced the rate of soil formation (Soto *et al.*, 1998), rendering this dating technique somewhat less than ideal. The Cote date is based on ^{14}C and, admittedly, there is some room for error or contamination. Therefore, resolving the issue of "extra" tephra layers CT8 and CT9 may not be possible with the present data.

Statistical Results

Discriminate function analysis (DFA) (Stokes *et al.* 1992) could not be used to correlate the two tephra sequences at this time, because I did not have access to information from the El Tajo data set, such as standard deviation, that is necessary for DFA calculation.

Reasons for Differing Chemistries

Differences in both sampling and processing techniques may have exaggerated observed differences in chemistry between the Cote and El Tajo tephras. I sampled each entire Cote tephra layer, from 0.5 cm to a few centimeters in thickness, to make the pellets for XRF analysis, while Melson (1982) fused several selected lapilli from within each thicker layer at El Tajo for electron microprobe analysis (EMPA). Perhaps there were compositional changes in the tephra between the base and the top of layers that were "averaged" in the composite bulk samples I used, but were more apparent when selected lapilli were used from within the tephra layers at El Tajo. It is common for magma composition to change during a period of eruptive activity due to vertical zonation within the magma chamber (Fisher and Schmincke, 1984). Melson and Saenz (1973) found that within the 1968 to 1973 Arenal eruptive cycle there were differences in chemistry through time. In addition, they found that chronological changes in silica content from the AD 1500 eruption ranged from 53.6% to 59.3% (Melson and Saenz, 1973).

A difference in laboratory methods may also have caused differences in results. Our Cote XRF analysis reported all iron as Fe_2O_3, but the El Tajo EMPA reported all iron as FeO. Because EMPA recalculates cations as mineral oxides there is no way to correct for cation balancing, and how much iron is FeO or Fe_2O_3. A small difference in how iron is calculated between EMPA and XRF will change other calculations. I recalculated the Fe_2O_3 in the Cote tephras to FeO (Table 4.3), but this method only compared the total iron to El Tajo data (Melson, 1982) and not the difference between FeO and Fe_2O_3. This difference between techniques may help to explain the apparent depletion of SiO_2 and other mineral oxide differences in the Cote tephras (M. Bennett, personal communication).

Differences in preservation conditions between Lago Cote and El Tajo may be important. At El Tajo the tephra layers examined were within a soil profile, while the Cote tephras examined were deposited in lake sediments. The El Tajo soil would have higher oxygen levels than the anoxic sediments at Lago Cote, and this may have affected preservation, weathering, and authigenic mineral production over time, amplifying mineral differences between the two sites.

Finally, aeolian fractionation may have led to some mineral differences between the Cote and El Tajo studies. Properties of glass and primary phenocrysts can be better indicators over long distances than bulk tephra but, at the least, bulk analysis can provide local information about the tephras (Westgate and Gorton, 1981). Most mineral species remain present throughout the tephra fallout zone, and correlation can still be successful even over long distances from the source (Westgate and Gorton, 1981). However, there may be two dispersion gradients complicating the comparison of Cote and El Tajo tephra chemistries; density-dispersion and size-dispersion (K. Orvis, personal communication). Perhaps the heaviest lapilli have fallen out closer to Arenal volcano, with deposition of lighter, SiO_2 enriched lapilli at the El Tajo site, ~7 km from the volcano. For ash-sized particles, perhaps the heavier particles were settling out in an area that included Lago Cote, while lighter (SiO_2 enriched) ash particles have been deposited within more distal reaches of the tephra apron. Even if fractionation has complicated the correlation of CT and ET tephras, our X-ray fluorescence analysis documents the local geochemical parameters of the Cote tephras.

Tephra layers in lacustrine sediments can be useful to paleoecologists. After being identified and correlated at several locations, tephra layers can serve as chronostratigraphic markers at other locations. My attempt to correlate tephra layers from Lago Cote sediment cores to the tephrochronology developed at the El Tajo site produced mixed results. Visual comparison to previously identified tephra layers was the simplest and most effective method. Chemical comparison of Cote and El Tajo tephras reinforced the visual determinations, but was a marginally effective method by itself. Statistical correlations were inconclusive because the data sets may have inherent differences due to aeolian fractionation, different sampling and laboratory techniques, and different preservation processes between the two study locations. My analysis using X-ray fluorescence produced valid results, yielding data on the local chemistry of Arenal tephras at Lago Cote that may prove useful in later studies of the volcanic and archaeological history of this region.

CHAPTER 5

RESULTS OF POLLEN AND CHARCOAL ANALYSIS

In this chapter I present the results of my analyses of pollen, spores, and microscopic charcoal in the Lago Cote sediment cores. The most important results are summarized in five pollen and charcoal diagrams and one table included here. Information on rare pollen types in included in Appendix C.

Pollen Results

Pollen Preservation and Diversity

Pollen was well preserved in all 25 samples. However, I was unable to identify some grains in every sample because they were damaged or hidden. Of 8857 pollen grains I tallied, I classified 11.3% as indeterminates. Indeterminate percentages in individual samples ranged from 7% to 18%. Indeterminate pollen grains were most commonly mechanically damaged and/or degraded. Grains obscured by detritus or authigenic minerals were less frequently encountered, and corroded grains were rarely encountered.

I classified 7852 pollen grains into 84 taxonomic groups representing 55 families, 42 genera, and several species. Appendix C presents a complete list of identified taxa and their frequencies of occurrence. Most of the pollen taxa occurred rarely. Sixty taxonomic groups, combined, were represented only by 10% of total pollen, and each of these taxa occurred as less than 1% of the pollen record.

I counted pollen in 25 levels, but later realized that two samples could be affected by contamination with younger sediment introduced at the top and bottom of core tubes during the coring process. Contamination can occur when reintroducing the piston corer into the same hole, because a few centimeters of younger sediment may fill up the void between the bottom of the piston and the bottom of the core shoe. This younger sediment will be pushed to the top of the core tube during sediment collection. Contamination of the bottom few centimeters of a core tube may happen when pulling the piston corer up through younger lake sediments due to suction. I excluded the suspect levels (113 cm and 366 cm) from the pollen diagrams because they were very close to the end of a core tube and exhibited subtle color and/or textural differences. I used the remaining 23 sample levels to make the pollen diagrams.

Pollen Diagrams

Figure 5.1 shows pollen and spore concentrations in the Cote samples. Pollen concentrations ranged from 8.14 x 10^4 to 2.19 x 10^5 grains/cm^3 wet sediment, except in the watery surface sample which had a lower pollen concentration (4.06 x 10^4 grains/cm^3 wet sediment). Concentrations of total spores, monolete spores, and trilete spores are similar, and are comparable to the overall trends in total pollen concentration. Total pollen and spore concentration roughly follows the percent of organic material except at levels 223 and 243 cm, where pollen concentrations peak, and level 128, where pollen concentration decreases, while organic percent remains nearly constant in all three levels (Figure 4.2). The overall pollen concentration values are similar to those found by other

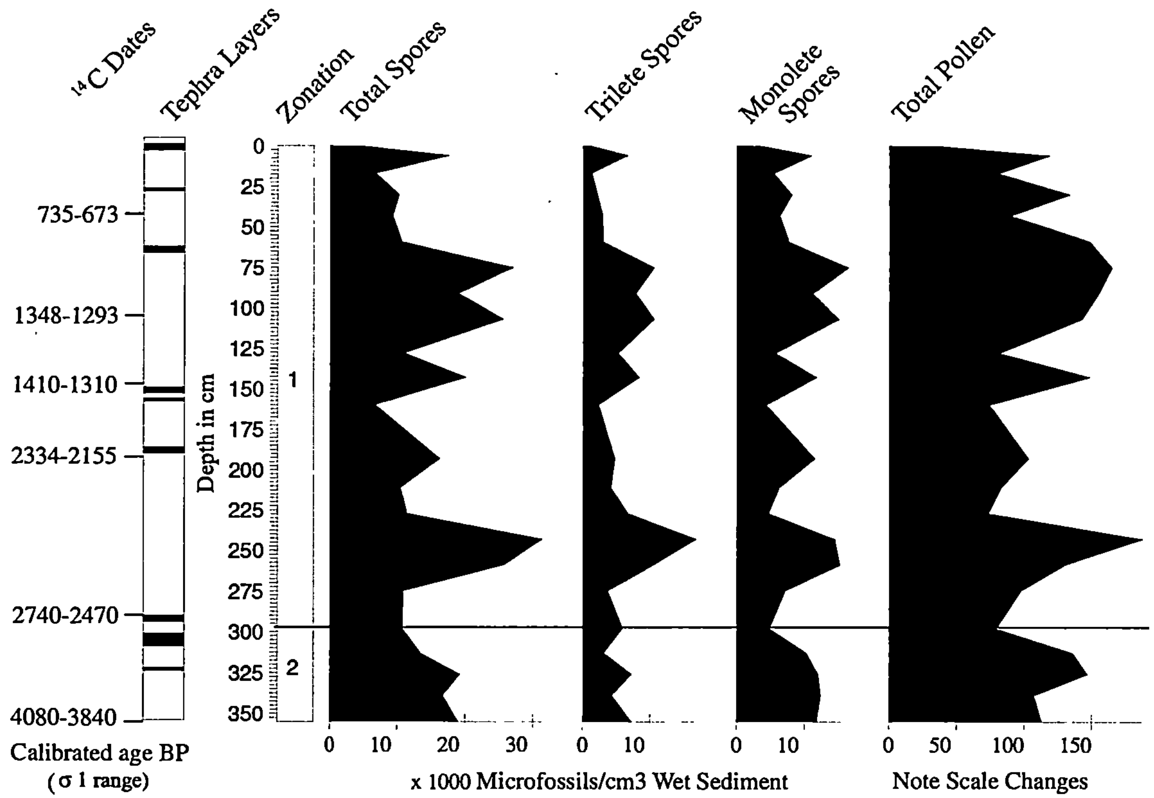


Figure 5.1 Lago Cote Pollen and Spore Concentration Diagram.

researchers studying lake sediments at lowland sites in Cost Rica (Northrop, 1994; Clement, 1999).

Frequently occurring pollen taxa and charcoal:pollen ratios are shown in summary diagram Figure 5.2. Figure 5.3 shows pollen from several arboreal taxa associated with montane and premontane habitats. Disturbance indicators, including arboreal and non-arboreal taxa, are illustrated in Figure 5.4. Charcoal concentration by size classes is illustrated in Figure 5.5. All diagrams show two zones that I designated based on the changing pollen and charcoal abundances. Zone 2 (355-298 cm) includes the lowest six samples, and is distinguished by high amounts of charcoal and grass pollen. Zone 1 (298 cm to surface) is characterized by a sharp decrease in charcoal and grass pollen, and exhibits peaks of *Myrica*, *Hedyosmum*, and *Myrsine* near the bottom of the zone. Most other pollen taxa in Zone 1 show few changes in percentage.

I found a high diversity of unknown pollen types that represent 2.6% of total pollen grains counted with a range of 0.6 % to 4.8% between sample levels. I categorized 77 distinct morphotypes, the most common types being tricolporate reticulate grains (44% of unknowns) and other tricolporate grains (19% of unknowns).

Six of the twelve most abundant pollen taxa are in the order Urticales, and together represented 42% of all the overall pollen counted, with a range of 29% to 59%. *Cecropia*, often used as a disturbance indicator, is the most abundant pollen type in every level, representing 15.2% of overall pollen and ranging from 7% to 28%. Other diporate Urticales (11%) is the next most frequently observed type, and is abundant in every sample. Other common Urticales include *Trema*-type (4%), *Celtis*-type (2.6%) and other triporate grains (3.7%).

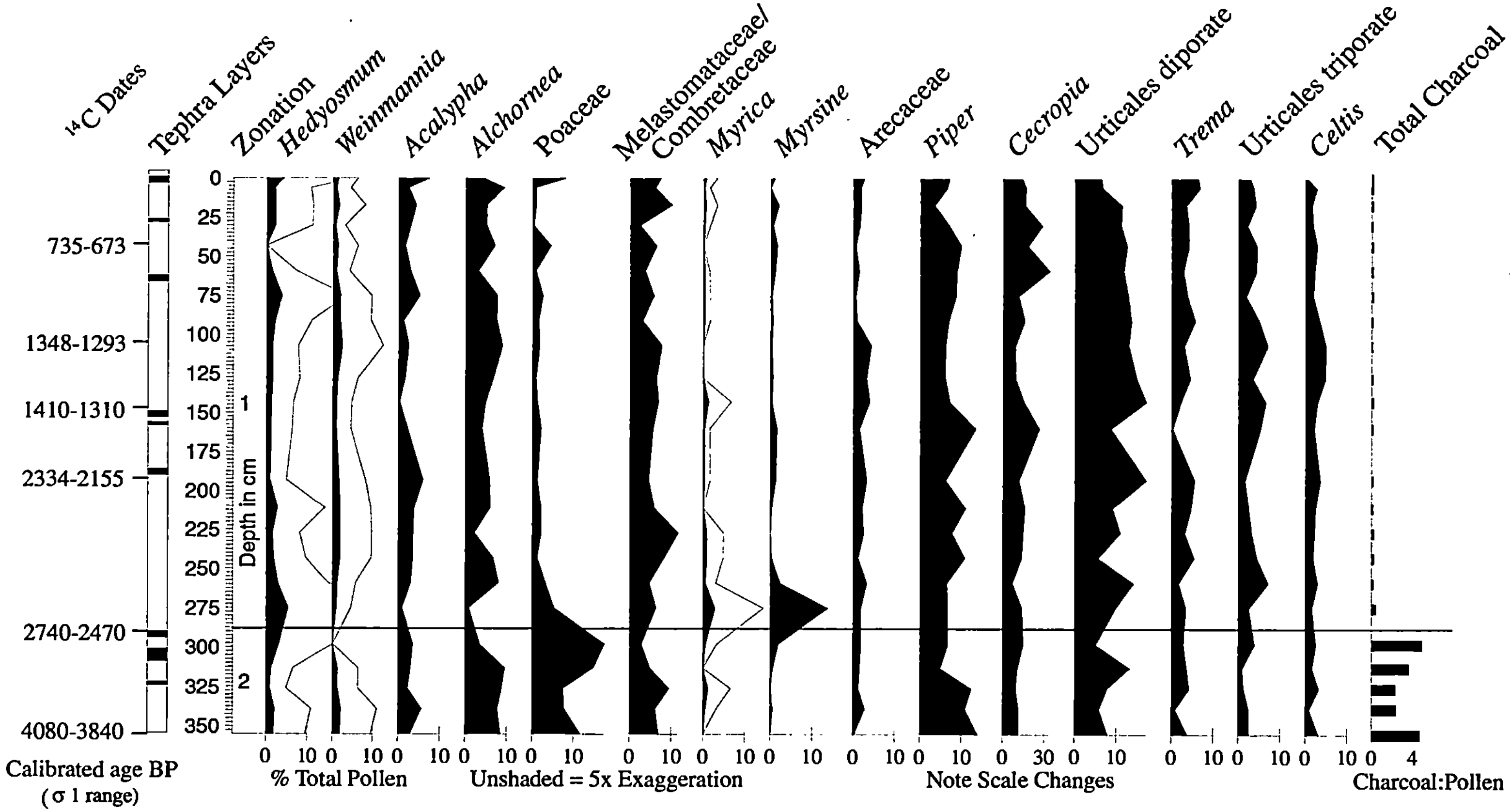


Figure 5.2 Lago Cote Summary Pollen Diagram.

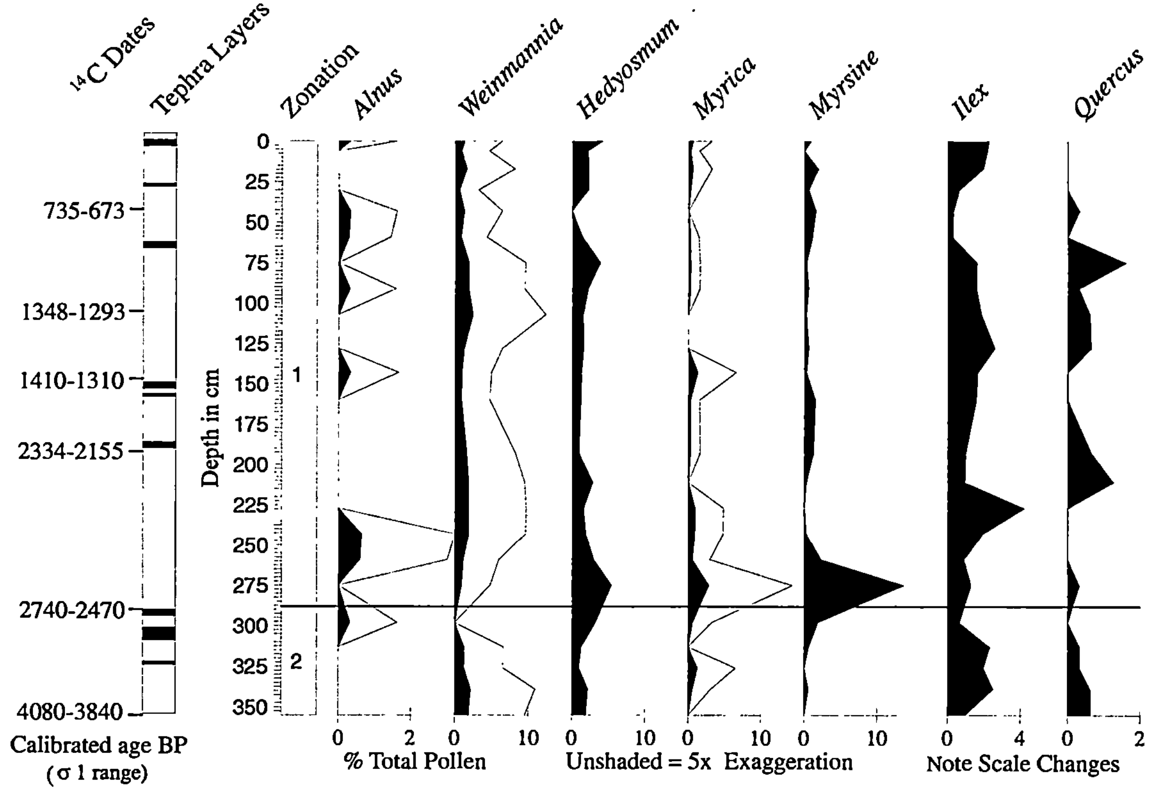


Figure 5.3 Lago Cote Montane/Premontane Pollen Taxa Diagram.

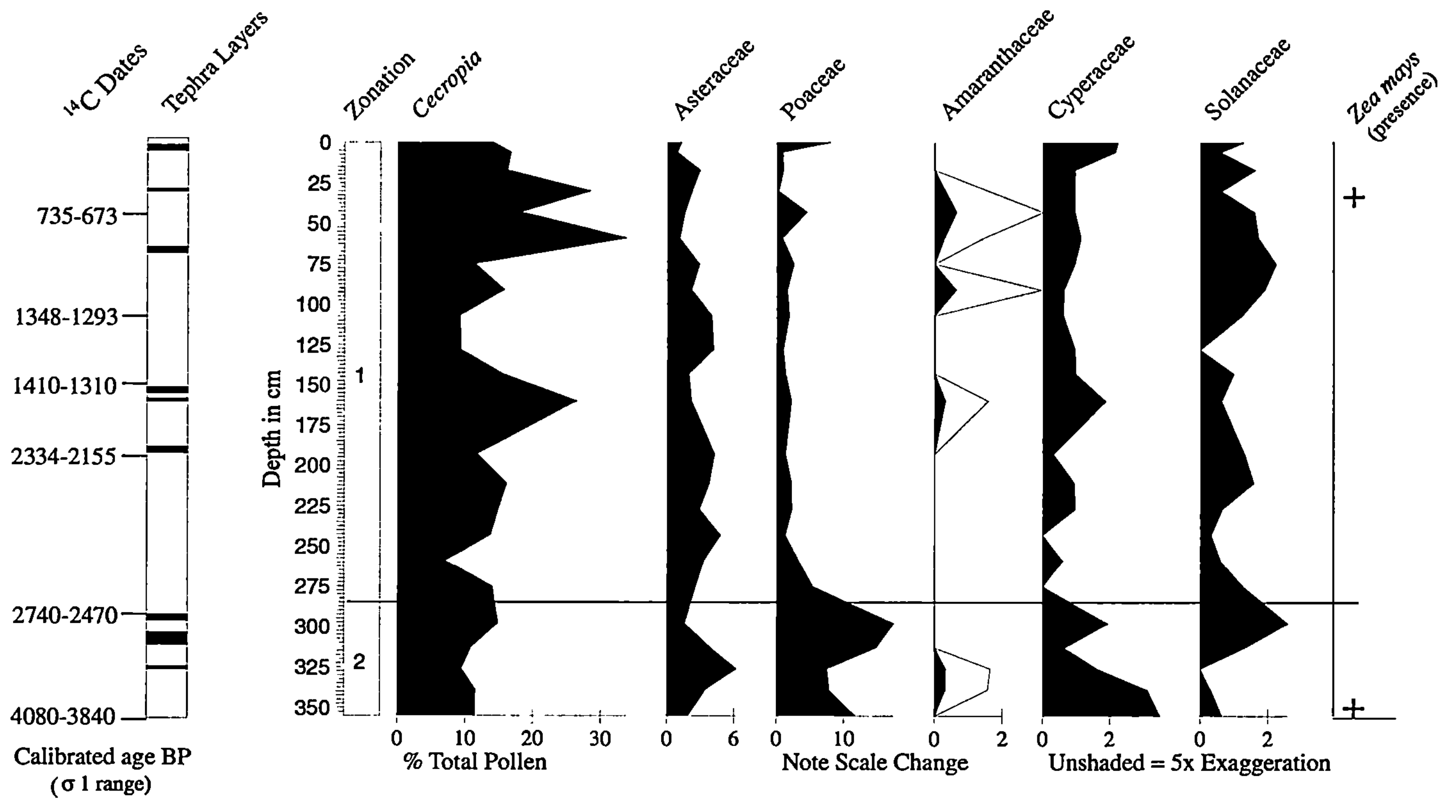


Figure 5.4 Lago Cote Disturbance Pollen Taxa Diagram.

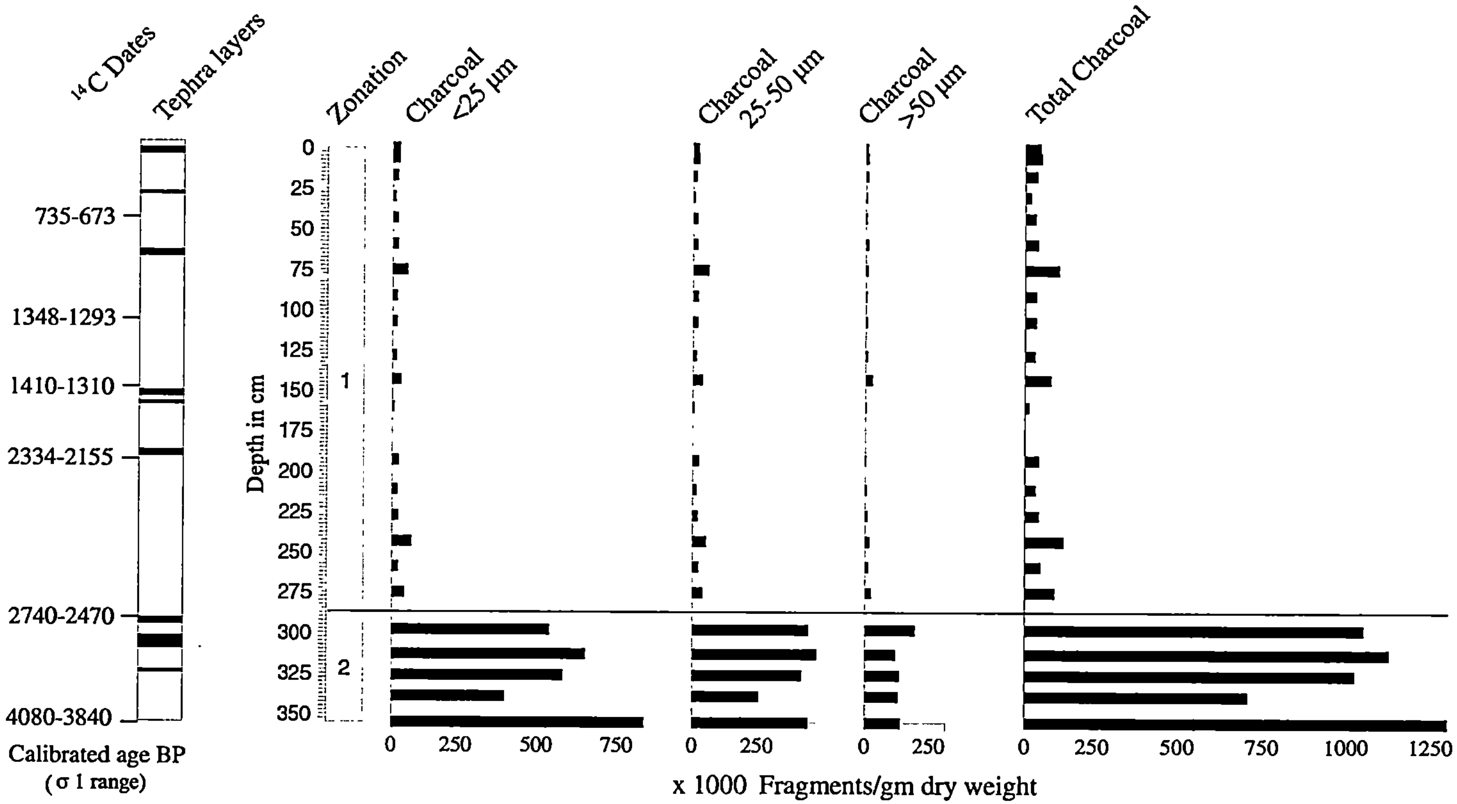


Figure 5.5 Lago Cote Charcoal Diagram.

Many other pollen taxa represent plants common from the Atlantic lowlands up to mid-elevations, including Piperaceae (8%), *Alchornea* (Euphorbiaceae, 6%), *Acalypha* (Euphorbiaceae, 3%), Melastomataceae/Combretaceae (6%), and Arecaceae (2%). In fact, 43 of 74 pollen taxonomic groups (excluding morphologic groups) currently grow around Lago Cote (Appendix C). It is difficult to separate out taxa that are lowland, because there are few taxa represented in the record that grow only at lower elevations.

Montane/Premontane taxa are also represented, including *Weinmannia* (Cunoniaceae, 1.5%), *Hedyosmum* (Chloranthaceae, 2%), *Myrica* (Myricaceae, 0.6%), and *Myrsine* (Myrsinaceae, 1.3%) (Figure 5.2). Three of these taxa, *Hedyosmum*, *Myrica*, and *Myrsine*, show a small peak near the bottom of Zone 1. Other Montane/Premontane taxa appeared occasionally, including *Alnus* (Betulaceae), *Quercus* (Fagaceae), *Fuschia* (Onagraceae), and *Podocarpus* (Podocarpaceae).

I identified several pollen types in addition to *Cecropia* that are considered to be disturbance indicators. These include Poaceae, which exhibits highest percentages in Zone 2 (Figure 5.4). The highest occurrence of Solanaceae pollen matches the highest peak of grass pollen at 298 cm (Zone 2). There are also small matching peaks of Asteraceae, Amaranthaceae, and Apiaceae at 91 cm, but these taxa only occur rarely.

Maize Pollen

I identified two maize pollen grains during low power (100x) scans of microscope slides; one at 30 cm depth (~700 cal. yr BP, Zone 3) and the other at 355 cm (3900 cal. yr BP, Zone 1) (Figure 5.4). The grain diameters were 75μm and 62.5 μm, respectively. I detected no maize pollen grains during standard pollen counts (400x).

Fern Spores

Fern spores represent 11.5% of total pollen and spores. Monolete spores comprise 62% of total spores, while trilete spores represent the remaining 38%. The most abundant spore sclerine types are monolete psilate (35%) and trilete verrucate (28%).

Charcoal Results

In low-power scans of the microscope slides I observed charcoal to be present in most sample levels. Figure 5.5 shows the changes in charcoal concentration throughout the core expressed on a dry weight basis. Charcoal is most abundant in Zone 2 and decreases dramatically at the Zone 2/1 boundary. Changes in charcoal abundance are proportional across size classes (>5-25 μm, 25-50 μm, and >50μm). Because pollen concentrations are similar at all levels, the total charcoal profile resembles the profile of charcoal:pollen ratios included in Figure 5.2.

Results of my systematic analysis of charcoal morphology from Zone 2 are reported in Table 5.1. At least 74% of all charcoal fragments evaluated from each of these levels appear to be from grass or other herbaceous monocot plants, with the remaining fragments ("other") representing wood charcoal, charcoal from herbaceous dicots, or charcoal of unknown origin.

Table 5.1 Lago Cote Charcoal Morphology from Pollen Zone 2[1]

Depth (cm)	n (>25 μm)	GRASS or MONOCOT (%)	*Other* (%)
298	207	77.8	22.2
313	214	74.8	25.2
326	221	74.2	24.8
339	232	75.9	24.1
355	249	77.9	22.1

[1]Charcoal was rare in Pollen Zone 1 and was not included in this analysis.

CHAPTER 6

DISCUSSION

Pollen and charcoal profiles from Lago Cote exhibit patterns that suggest changes in climate over the past 4000 years, and the presence of maize pollen confirms prehistoric agriculture near the lake. A sudden decrease in grass pollen and charcoal suggests a change to wetter conditions around 2600 cal. yr BP, which may have limited swidden agriculture, and correlates to an archaeological phase change. In the following sections I first discuss the significance of the lake size for interpreting the paleoecological data. I then interpret the pollen and charcoal records within the context of archaeological data from the nearby Arenal reservoir basin.

Pollen Source Area

Previous studies of lake and wetland sediments in Costa Rica have been conducted mainly at small lakes and wetlands, e.g., Lago Morrenas 1, 5.2 ha (Horn 1993); Lago Bonilla, 30.8 ha and Laguna Bonillita, 6 ha (Northrop and Horn, 1996); Cantarrana Swamp, 0.5 ha (Kennedy, 1998; Kennedy and Horn, 1997); Laguna Zoncho, 0.5 ha (Clement, 1999: Clement and Horn, forthcoming); La Chonta, 8.6 ha (Hooghiemstra *et al.*, 1992). These small sites with small surface areas probably have pollen records that reflect a relatively local (within 20 m of basin edge) and extra-local (20 to hundreds of meters) pollen source area, because local pollen influx would surpass deposition of regional pollen (Jacobson and Bradshaw, 1981). At many of these sites local human disturbance may have greatly influenced pollen and charcoal deposition, making it more difficult to recognize any signal of regional vegetation and climate change. Lago Cote, by contrast, has a surface area of nearly 200 ha and should receive a higher percent of pollen from a regional (of greater than several hundred meters, Jacobson and Bradshaw, 1981), or extra regional (thousands of meters) source. The pollen record at Lago Cote would not be overwhelmed by local pollen, like the smaller lakes and wetlands previously examined in Costa Rica. However, this model (Jacobson and Bradshaw, 1981) was developed in temperate areas and has not been tested in the tropics. In addition to its large size, Lago Cote may be predisposed to receive pollen from long-distance travel because of the windy environment in the region surrounding the lake. An example of long-distance transport is the presence of pine pollen in nearly every sample I examined.

Pine pollen is not only well-equipped for long distance transport due to the presence of air bladders, but it is also represented outside its geographic range because of abundant pollen production (Moore and Webb, 1978). Pine pollen has been found 300 km from the nearest pine forest (McAndrews and Wright, 1969). Annual pollen production from a 10-year old tree can reach 350 million pollen grains (Faegri *et al.*, 1989).

Pines are not native to Costa Rica, and other researchers have interpreted the presence of pine pollen in Costa Rican deposits as wind dispersal from Nicaragua. The southernmost limit of modern pines in Central America is in Nicaragua (Standley, 1937-1938), 200 km from Lago Cote (Clary, 1994). Three species of pine occur in Nicaragua: *Pinus caribaea* var. *hondurensis* on the eastern coastline and NE lowlands, and *Pinus* *oocarpa* and *Pinus pseudostrobus* in the NW highlands (Denevan, 1961; Farjon and Styles, 1997). Pine pollen was identified in terrestrial archaeological excavations during the Arenal Project (Clary, 1994), in the large and windy Arenal basin. Pine pollen has been found in lake sediment from small sites like Bonilla and Bonillita in the central Atlantic lowlands of Costa Rica (Northrop, 1998), but in much lower abundance than in the Lago Cote samples. This difference in pine occurrence, between larger (Cote) and smaller (Bonilla, Bonillita) sites may reflect the difference in pollen source area, as suggested by Jacobson and Bradshaw (1981).

Almost all of the most common pollen types from Lago Cote are small grains such as *Cecropia*, other Urticales, *Alchornea*, Poaceae, and Cyperaceae. These taxa are anemophilous (Bush, 1995), and are expected to occur frequently in the sediment record because they provide abundant pollen that is easily dispersed by wind. In general, most tropical trees are not wind pollinated, but the ones that are tend to be over-represented in tropical sediment records. However, a few common taxa from the Cote core, such as *Acalypha*, *Piper*, and Melastomataceae/Combretaceae, are insect pollinated. These entomophilous taxa are common plants growing around Lago Cote today (see Appendix B). Their abundance in the fossil record may be due to their flower morphologies, such as having more open smaller flowers and/or protruding stamens, and producing abundant pollen, as discussed by Bush (1995) and Kennedy (1998). It seems possible that small pollen grains from abundant small flowers, even insect pollinated types, could be wind transported in the Lago Cote area where wind speeds average 15 km/hr or more, sometimes exceeding 30 km/hr (Sheets, 1994a).

In interpreting the Cote pollen profiles it must be kept in mind that the potentially large pollen catchment area includes a diversity of vegetation zones along a gradient from mid-elevation montane forests down the Atlantic slopes towards, and maybe including, the lowland rain forests. Disturbance regimes may vary at different temporal and spatial scales across this large region, and include landslides, storms and windthrow, tectonic and volcanic activity, anthropogenic and natural fires, and forest clearance by humans. The lake sediments at Lago Cote may record the net pollen from an array of contemporaneous plant assemblages and disturbances, with each sample representing an average of the regional vegetation and disturbance processes.

Pollen Taxa

Pollen grains and spores in the Cote sediments represent great taxonomic diversity. Cote is located at 650 m elevation, but the regional catchment area includes several vegetation zones. Several of the most common taxa, such as *Cecropia* and other Urticales, *Alchornea*, *Acalypha*, Melastomataceae/Combretaceae, *Piper*, and Myrtaceae, are characteristic of modern pollen spectra from tropical wet forest (Rodgers and Horn, 1996). These plants are common from the Atlantic lowlands up through the forest surrounding Lago Cote. Montane/premontane taxa are also represented, such as *Hedyosmum*, *Myrica*, and *Myrsine* (Burger, 1977a,b; Standley, 1937-38; Haber *et al.*, 1996). Downcore changes in the abundances of some pollen types suggest large-scale changes in vegetation and disturbance regimes over the ~4000 cal. yr BP record.

Disturbance Taxa

Herbaceous taxa are commonly used as disturbance indicators, including Poaceae, Chenopodiaceae, Asteraceae, and Amaranthaceae (Brown, 1985; Leyden, 1987; Byrne and Horn, 1989, Northrop and Horn, 1996). Pollen from most herbaceous taxa in the Cote sediments is rare or occurs infrequently and is not useful for paleoenvironmental reconstruction. However, Poaceae is quite high in Zone 2, and shows an increase again during modern times (Figure 5.2). Increased percentages of *Cecropia* and *Trema* pollen also likely signal increased disturbance, based on the ecology of these genera (Standley, 1937-1938; Gentry, 1993; Bush and Colinvaux, 1994; Burger, 1977c). Many other taxa in the Urticales order are found in mature forests exclusively or in both mature and secondary forests (Burger, 1977c) so their pollen (e.g. in the Urticales diporate and triporate categories in Figure 5.2) does not provide a clear indication of disturbance.

Premontane/Montane Taxa

There is an increase in pollen of the premontane/montane plants *Hedyosmum*, *Myrica*, and *Myrsine* in the lower part of Zone 1 (~2600 cal. yr BP) (Figure 5.3). This could represent forest regrowth following disturbance, or it could indicate a change in vegetation owing to a change in climate. *Myrsine* is common from 1200-1600 m along pastures, edges, and secondary forest (Haber *et al.*, 1996). Most *Myrica* species occur above 1300 m, but *M. pubescens* can be present down to 800 m in seasonally dry evergreen montane forest (Burger, 1977b). *Hedyosmum* is a lower montane taxon and restricted to wet slopes, especially the Caribbean slopes of Costa Rica (Burger, 1977a).

Maize Pollen and Its Archaeological Significance

Maize pollen probably does not travel far from its plant source, with most grains falling to the ground within 60 m of the parent plant (Raynor *et al.*, 1972). Even in high-wind conditions, maize pollen may only travel up to 500 m from the plants (Purseglove, 1972). Its presence in lake sediments indicates maize cultivation near the lakeshore (Islebe *et al.*, 1996). The presence of maize pollen in the Cote sediments shows that the crop was cultivated near Lago Cote by prehistoric peoples at least around 700 and 3900 cal. yr BP (70 cm and 255 cm, Figure 5.4). The absence of maize pollen in other levels is not significant, though. Maize may have been in cultivation at other times, or continuously, even if maize pollen was not represented in other most samples. Since maize pollen does not travel far, and Lago Cote is very large, it would be unlikely to find maize grains at all. At nearby Lago Arenal, maize remains in archaeological context were interpreted to indicate continuous maize cultivation from the Tronadoran Phase (~4000 to 2500 BP) to the Tilarán Phase (650 to 450 BP), even though the crop was not considered to be a major food source (Sheets, 1994b).

Modern climate conditions in the Arenal basin may not favor agriculture, especially seed crops, because of wet and windy conditions and low light levels (Sheets, 1994a,b). Because of cloud cover, full sunlight can be as low as 4.4 hours/day in parts of the Arenal-area (Sheets, 1994a). Sheets (1994b) suggested that early inhabitants depended more on hunting and gathering and less on wide-scale agriculture. In western Panama, Linares *et al.* (1975) determined that corn would grow best in mid and low areas of the Pacific Coast because of its requirements for light and relative dryness. These interpretations suggest that maize was probably not widely cultivated near Lago Cote at least since 2600 cal. yr BP (Zone 1). Before 2600 cal. yr BP (Zone 2) high amounts of charcoal and grass pollen, as well as a maize pollen grain, show that climate conditions at Cote were drier and more favorable for maize cultivation than more recent times.

Interpretation of Pollen and Charcoal Stratigraphy

Pollen percentages for most taxa represented in the Cote sediments do not change markedly from level to level. Instead, curves are relatively smooth or complacent. Given the large size of the lake, it is probably not appropriate to interpret the complacency of the curves as indicating only or primarily great stability of vegetation over this time. As mentioned, it is likely that Lago Cote receives pollen from a very large source area and that the pollen signal for any localized changes in vegetation may have been "drowned out" by pollen coming from many different vegetation associations across a gradient of environmental and disturbance conditions.

The abundance of microscopic charcoal in the Cote sediments does, however, indicate a major change in the record, and this change is matched by the percentages of one pollen type, Poaceae. The much greater amounts of charcoal, most of it grass charcoal, and Poaceae pollen in the lowest pollen Zone (Zone 2) is all the more striking when compared to the relative complacency of all other pollen percentage curves. The pollen and charcoal values in Zone 2 clearly signal very different vegetation and environmental conditions than do those of the preceding pollen Zone 1. I interpret this change to be the result of both natural climate variation and human activity. Specifically, I believe that Zone 2 (4000 to 2600 cal. yr BP) reflects a period of drier climate in and near Lago Cote, which resulted in greater land clearance and burning for agriculture, as indicated by the increase in grass/monocot charcoal. At the Zone 2/1 boundary, climate conditions became wetter and it was no longer easy to accomplish agricultural burning. Hence, charcoal and Poaceae pollen decline. This Zone 2/1 boundary corresponds to the timing of a shift in archaeological phases, from the Tronadoran to the Arenal phases. Peaks in premontane forest taxa early in Zone 1 may indicate forest regeneration following the change away from swidden agriculture. Poaceae pollen percentage increases again in the modern sample, reflecting modern forest clearance and the recent establishment of large pasture areas and plantations of pine and citrus trees.

The extent to which the changes between Zones 2 and 1 indicate changes in climate as well as human use of the landscape are discussed further in a later section of this thesis. First, though, I consider the degree to which the pollen data shows evidence of the impacts of volcanism, and what the charcoal record reveals about both fire and climate history.

Volcanism

There were nine volcanic eruptions recorded in the ~4000 year Cote sediment record. This is similar to the time interval and number of eruptions documented from the El Tajo sequence (Melson 1982, 1994). Sheets (1994b) determined that prehistoric populations in the Arenal area were small and not dependent on widespread agriculture, and that this lifestyle was a successful strategy in this volcanically active area. The pollen and charcoal record at Lago Cote does not reveal whether volcanism had an effect on local human populations. However, swidden agriculture and maize cultivation were occurring during times of active volcanism at 3900 cal. yr BP, and again at ~700 cal. yr BP, based on the occurrence of maize pollen grains. This is consistent with the Proyecto Arenal findings that maize was under continuous cultivation in the Arenal wetland (Sheets, 1994b). The sudden decrease of fires around Lago Cote at about 2600 cal. yr BP corresponds to an increase in population at the Arenal wetland, lower in elevation and closer to the volcano. Perhaps, following volcanic activity (CT 7-9), inhabitants of the Arenal area found a more suitable place for agriculture near Lago Cote where the tephra layers were much thinner. They may have returned to the Arenal wetland during times of less volcanic activity, such as after the eruption that deposited CT6 at about 2500 BP. There is one documented shift of settlement out from the Arenal basin into the Piedra River valley, just southwest of Lago Cote, about 1000 BP following volcanic deposition of El Tajo/Cote tephra layer 3 (Sheets, 1994b).

Cecropia pollen may indicate vegetation response to volcanic eruptions, as the tree may quickly colonize following volcanic disturbance. Vargas (1985) found *Cecropia peltata* growing in patches near the Arenal reservoir within a zone of pyroclastic gravels and sands that was deposited 17 years earlier by the 1968 eruption of Arenal. *Cecropia* in the Cote record shows increases at 30 and 59 cm, both samples at the top of tephra layers, and at 159 cm, about 5 cm above a tephra layer. Tephra layers at Cote were thin, and changes in *Cecropia* pollen may reflect vegetation disturbance closer to the volcano. Other changes in the Cote pollen record may not be evident simply because my sample spacing is too coarse to observe short-term vegetation changes. In addition, the large pollen source area would record regional influx that may overwhelm the local pollen signals.

Fire History

Microscopic charcoal is only abundant in Zone 2, in the lower 80 cm of the core, and macroscopic charcoal (>125 μm in maximum dimension) was rare in Zone 2 and almost absent in the Zone 1 samples. Researchers disagree over the interpretation of fire histories based on charcoal particle size. According to Clark (1988) and Clark and Royal (1995), small charcoal particles are more likely to be carried long distances than larger charcoal, such that larger particles (>50 μm) most likely represent local fires. Whitlock and Millspaugh (1996) suggest that macroscopic charcoal between 63 and 125 μm may be best for reconstructing local fires, and Millspaugh and Whitlock (1995) say that microscopic charcoal provides evidence about the regional importance of past fires. However, Pitkänen *et al.* (1999) and Ohlson and Tryterud (2000) demonstrated that abundant small charcoal could also represent low-intensity local fires at their Scandinavian boreal forest study sites. Even when local fires produce larger charcoal particles, they can be broken during transport, especially by water (Patterson *et al.*, 1987). Strong wave action at Lago Cote might be expected to break up large charcoal that landed on the surface or shores of the lake.

Other complicating factors for charcoal interpretation may be researcher-dependent. Charcoal viewed on pollen microscope slides may have become broken during processing procedures (Rhodes, 1998). It is possible that the pollen processing techniques I used to prepare the Cote samples could have contributed to the lack of large charcoal particles I saw on the microscope slides. However, Clark (1988) found that even though processing may cause a change in the size distribution, pollen processing caused little net change in the area or number of charcoal particles. It may be difficult to compare my charcoal results to other studies because charcoal records are affected by site-specific characteristics (Whitlock and Millspaugh, 1996). In addition, there are many differences in both sampling technique and methods of charcoal evaluation being used by paleoecologists (MacDonald *et al.*, 1991b; Clark and Royall, 1995; Clark and Hussey, 1996; Earle, *et al.*, 1996; Whitlock and Millspaugh, 1996). However, relative changes in charcoal abundance in the Cote record provide important information about changes in the fire regime over time.

The abundance of charcoal in the basal Zone of the Cote core indicates multiple fires from 4000 cal. yr BP to 2600 cal. yr BP in an area that is not climatically conducive to burning at present. That the charcoal is mostly grass or other monocotyledon charcoal (Table 5.1), and that it is associated with abundant grass pollen, suggests that the source for the charcoal was the burning of grassland and not forest. Human-set agricultural fires or escaped domestic fires likely account for much or all of the charcoal, although it is possible that some of it may represent natural fires in grassy areas created by people or drought.

Under modern conditions, large wildfires seem unlikely to occur in closed wet forest near Lago Cote. Even during the "dry" season, from January through April, rainfall exceeds potential evapotranspiration (Sheets, 1994a), with an average of 100 mm rainfall in the driest month (Figure 2.7). In the Amazon, studies have shown that wildfires are not likely under closed tropical evergreen forests, during modern wet conditions, because of high fuel moisture and high relative humidity (Uhl *et al.*, 1988; Uhl and Kauffman, 1990). However, if past climate conditions were drier, large fires may have been possible in the Cote catchment. Stott (2000) reports that tropical fires can occur in wet tropical climates during periodic droughts and El Niño/southern Oscillation events.

Forest clearance by humans can yield conditions conducive for forest fires, too. Studies have shown that second-growth forest in Amazonia is more easily burned after only eight to ten dry days than is mature forest, and that selectively logged forests can burn after five to six rainless days (Uhl and Kauffman, 1990). In the tropics, grasses and litter are the most combustible materials, and the main fuel in fires (Stott, 2000). Agricultural fires can lead to the growth of perennial and annual pyrophytic grasses that become dry and dormant, and this increases the fire potential for yet more natural or human fires (Mueller-Dombois and Goldammer, 2000). Secondary growth and grasses become more flammable after shorter dry seasons than mature and undisturbed forest (Koonce and González-Cabán, 1990). Other anthropogenic causes of increased fire potential include the cutting of vegetation that dries and becomes more flammable, and the creation of clearings that provide microclimates with lower relative humidity (Kauffman *et al.*, 1988; Uhl *et al.*, 1988; Uhl and Kauffman, 1990).

The high abundance of charcoal in Zone 2 indicates a significant amount of burning. It is likely, based on the importance of grass pollen and the occurrence of a maize pollen grain, that much of this burning was associated with agriculture, and the high Poaceae/monocot percentage may reflect agricultural weeds. This suggests the probable use of fire in the creation and/or maintenance of agricultural fields. The great reduction in fire, indicated by the sharp drop in charcoal values about 2600 cal. yr BP, occurred while human populations were increasing in the nearby Arenal region. At Lago Cote, local populations may have declined, but natural processes seem also to be involved: particularly a change to wetter climate.

Climate Change

Signals of prehistoric human disturbance are strong in most paleoecological records from the American tropics, and as a result, it is often difficult to extract from these records evidence of climate history. While it is now clear that the Holocene was a time of dramatic shifts in moisture in some areas of the American tropics, the difficulty of separating climate from human signals leaves interpretations quite tentative for most places – and regional patterns and mechanisms of change almost wholly unknown. The time period 3900-2500 BP was found to be drier at the Lake Darien site, Panama (Bush and Colinvaux, 1994), while several studies to the North, for example at Lake Chulchaca (Whitmore *et al.*, 1996) and Chichancanab (Hodell *et al.*, 1995), have revealed drier climate periods that overlap in time starting at about 3000 BP. Other studies in Costa Rica have suggested drier periods even later (Horn and Sanford, 1992; Northrop and Horn, 1996).

My interpretation of drier climates at Lago Cote during the Tronadoran archaeological phase is in agreement with some literature results but in conflict with others. The possible effects of changing climate cannot be separated from those of human activity in the Cote pollen and charcoal record. I suggest that it is the interplay that is responsible for the marked changes between Zones 2 and 1 of the diagram. A drier climate favored agricultural and other fires during the Tronadoran phase (Zone 2), while a wetter climate in the succeeding period (Zone 1) had a limiting effect on agriculture and fires on the landscape. Even a minor change in Caribbean/Pacific circulation could have caused significant changes in cloudiness boundaries, and changed the potential for agriculture as well as rainfall patterns.

Another important finding is the maize grain at 30 cm (~700 cal. yr BP) that occurs without an associated increase in charcoal. This suggests that while maize may have been in cultivation, fires were no more frequent than during the rest of Zone 1. If conditions were suitable for agricultural fires at this time, we would expect higher charcoal levels to occur with evidence of maize cultivation. This suggests it was just too wet for widespread agricultural fires.

Comparison to Arenal Archaeology

Charcoal and pollen data from Lago Cote suggest that fires, and probably swidden agriculture, were frequent from 4000 to 2600 cal. yr BP but declined dramatically after 2600 cal. yr BP due to climate change. It may be no coincidence that the climate transition (~2600 cal. yr BP) matches a cultural change that defines the end of the Tronadoran Archaeological Phase and the beginning of the Arenal Phase at 500 BC (2450 BP) in the Arenal basin (Sheets, 1994b). Climate change would have resulted in different agricultural and foraging strategies and may have influenced trade and cultural exchange outside the Arenal area.

My interpretation that Zone 2, which corresponds temporally to the Tronadoran archaeological phase, indicates a drier climate contradicts the interpretation of phytolith assemblages in archaeological excavations made for the Arenal project. Piperno (1994) found that soil phytoliths suggested moist forest vegetation in the Arenal wetlands during the Tronadoran Phase. A decline in tree taxa and a large increase in grass phytoliths during the succeeding Arenal Phase was interpreted as evidence that forest clearance beginning c. 2500 BP (Piperno, 1994). The apparent difference in interpretation between my charcoal and pollen record and Piperno's (1994) phytolith study could be an artifact of different fossil source areas and different paleohydrology within the source areas. During the Tronadoran Phase, drier conditions may have led to increased fires on drier slopes within the large charcoal catchment area of Lago Cote. Phytoliths from the Arenal Project, by contrast, reflect *in situ* vegetation growing within a wetland depression. In other words, the charcoal and phytoliths are recording vegetation at different spatial scales.

Another explanation for differences between the Cote and Arenal records could be that environmental conditions at Cote were drier than those at Arenal, as a result of local landscape differences affecting the local climatology. Sheets (1994a) reported a rainfall gradient in the greater Arenal area, with more precipitation at lower elevations and closer to the Arenal volcano (6000 mm/yr), less rainfall (3000 mm/yr) moving westward toward the continental divide, and only 1300 mm near Cañas moving farther westward from Tilarán. Sheets (1994a) also stated there is greater seasonality going westward, as well as decreasing rainfall. The same pattern in rainfall is reflected in the Holdridge life zone classification for the Arenal–Cote area (Figure 2.8) which indicates drier conditions as one moves westward. With even a small change toward more arid conditions, and a resulting shift eastward of the Holdridge zones, the local climate gradient could have produced drier conditions at Cote than at the Arenal basin, making Cote more favorable for agriculture at least until wetter conditions prevailed after 2600 cal. yr BP. After 2600 cal. yr BP, when climate conditions became wetter, there may have been abandonment of the already cleared forests at Lago Cote and a move into the Arenal basin where forest clearance began as suggested by Piperno's (1994) phytolith study.

It is also difficult to make direct comparisons between Lago Cote pollen and charcoal and the Arenal archaeology simply because the studies were so different. Several archaeological studies have been done at Arenal, but pollen and charcoal studies of lacustrine sediment have not been done. At Cote, I conducted pollen and charcoal studies but local archaeology remains poorly documented. Because of this, it is not easy to know how human populations changed near Lago Cote in the past. Populations may have persisted continuously around the lake, but evidence for widespread agriculture is not apparent in the pollen record. Instead, the basal high-charcoal zone indicates widespread fires, and maize grains indicate two moments when agriculture was occurring near Lago Cote. Since potential core sites in the ancient Arenal wetland were inundated when the reservoir was constructed, future archaeology studies at Lago Cote could be the key for understanding the links between the histories of the Arenal and Cote basins. This would also provide a larger context in which to interpret the pollen and charcoal evidence from the Cote sediments.

Human Occupation Times at Other Costa Rican Study Sites

Paleoecological studies in Costa Rica have provided new information about prehistoric settlement and land use that complements archaeological research in Costa Rica. At Lago Cote, two maize grains provide evidence for human occupation at 3900 cal. yr BP and 700 cal. yr BP. I attribute high charcoal levels and grass pollen in the entire Zone 2 (4000 to 2600 cal. yr BP) to agricultural burning, as well.

Other paleoecological studies in Costa Rica have yielded somewhat different results, presumably owing to the fact that early human settlement patterns varied greatly by region. At Laguna Zoncho, southwestern Costa·Rica, there is pollen evidence for 3000 years of maize cultivation, but perhaps human population levels declined after AD 1490 (460 BP) when amounts of maize pollen and microscopic charcoal decreased (Clement, 1999; Clement and Horn, forthcoming). In the Atlantic lowlands, the Cantarrana swamp record documents maize pollen from 1100 to 300 BP, although charcoal peaks occurred prior to 1100 BP suggesting human occupation may extend beyond the maize evidence (Kennedy and Horn, 1997; Kennedy, 1998). Macroscopic charcoal is present in about half of the sample levels older than 300 BP, suggesting periodic local and probably anthropogenic fires going back at least 3,000 years (Kennedy and Horn, 1997; Kennedy, 1998). The nearby Machita swamp preserves evidence of maize cultivation 2700 years ago (Horn and Kennedy, forthcoming). Analysis of Laguna Bonillita sediments revealed continuous maize cultivation and associated charcoal from 2560 BP, the basal date of the core (Northrop, 1994; Northrop and Horn, 1996). Hopefully, additional studies will extend knowledge of human occupation and land use back in time, but research has limited by the ages of available coring sites.

CHAPTER 7

CONCLUSIONS

The results of this study provide a first look at long-term vegetation history in the Cordillera de Guanacaste, Costa Rica. Pollen profiles indicate vegetation responses to natural and human disturbances, including fire and volcanism, over the past 4000 years. The presence of maize pollen in two levels is consistent with archaeological evidence that suggests continuous occupation and maize cultivation of the nearby Arenal basin for at least 7000 years. Another significant finding is the dramatic decrease in occurrence of grass pollen and microscopic charcoal about 2600 years ago. This charcoal provides compelling evidence of repeated prehistoric fire for at least 1500 years, followed by a dramatic change to a regime of infrequent burning that has continued to the present.

High amounts of grass charcoal within an interval of increased grass pollen and maize suggests that many or most fires were agricultural. The higher fire activity is probably related to a drier climate regime that was more conducive for burning. Around 2600 cal. yr BP conditions became wetter, and fire occurrence was substantially reduced. The decline in charcoal occurs at the same time as documented population increase at the nearby Arenal wetland, as well as elsewhere in Costa Rica and Central America. It thus supports the hypothesis that wetter environmental conditions limited landscape fires and swidden agriculture. In addition, an archaeological phase change was documented at the same time (Tronadoran to Arenal phases) in the Arenal basin, further suggesting the possibility of a direct link between environmental change and human activity. This trend has not been visible in many other studies in Costa Rica because local human disturbance around small lakes has masked evidence of possible climate change. Future archaeological studies at Lago Cote could help provide a better understanding of the local prehistoric human dynamics between Lago Arenal and Lago Cote basins.

Lago Cote has a large pollen source area, and changes in the pollen record reflect a mostly complacent history of wind-pollinated taxa common from the Atlantic lowlands to lower montane elevations. However, following the decrease in burning there is a brief period of lower montane forest regeneration. Modern pollen, from the sediment/water interface, shows an increase in grass pollen that probably reflects modern clearing for pastures and logging.

There is no pollen or stratigraphic evidence to indicate changes in human activity following the volcanic eruptions that deposited nine tephra layers in Lago Cote. Pollen results do show an increase in *Cecropia* pollen following two or possibly three Arenal eruptions, possibly associated with forest recolonization of land disturbed by the volcanic activity.

Correlation of Lago Cote tephra deposits to Melson's tephrostratigraphy at the El Tajo section has not been straightforward. Cote tephras, overall, have less silicon dioxide than at El Tajo, and other changes in mineral oxides vary greatly between the two sample sites. These results highlight the problem of aeolian fractionation that occurs at greater distances from the volcanic source, as well as the use of different sampling and analytical techniques. However, my analysis documents the local expression of Arenal tephra chemistries. Three levels do match well based on both chemical analysis and visual comparison. Two additional layers match by visual comparison; and one additional layer correlates well by chemical analysis. When compared to the El Tajo tephrochronology, it is apparent that three eruptions of Arenal are not recorded in the Cote sediments. However, there appear to be two older tephra layers at Cote that have not been described at El Tajo. They may predate the lowest layer in the El Tajo sequence, or may represent earlier eruptions of Cerro Chato, rather than Arenal, that were not preserved in the El Tajo exposure.

The pollen, charcoal, and tephra records from Lago Cote provide new information about prehistoric human activities and environmental change in Costa Rica. This record adds to the growing understanding that climate change and human and natural disturbance have created a dynamic vegetation history in the American tropics. Future tropical paleoecological projects would benefit from more studies of modern vegetation and pollen assemblages so that pollen records may be better interpreted in the context of modern analogs. Interpretations would also benefit from the availability of more information on the production and dispersion of pollen and charcoal in the tropics, since most models have been developed in temperate areas. Greater collaboration between archaeologists and paleoecologists can lead to better interpretation of sediment records, and in this way improve our understanding of the history of landscapes, vegetation, and human culture in tropical Latin America.

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APPENDICES

APPENDIX A

LAGO COTE SEDIMENT PROCESSING SCHEDULE

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LAGO COTE SEDIMENT PROCESSING SCHEDULE

I used the following schedule, PROC-JR2, to concentrate pollen within samples from the Lago Cote 1998 sediment cores. This processing schedule was developed by John C. Rodgers III and Dr. Sally Horn, following standard palynological techniques (Berglund, 1986). This procedure takes about 6 hours to complete a batch of six samples, and should be performed in a laboratory fume hood. We use an IEC tabletop centrifuge set to rotate at ~2500 RPM.

1. Place 0.5 cm^3 wet sediment in preweighed, 15 ml polypropylene centrifuge tubes and reweigh.
2. Add 1 tablet *Lycopodium* spores to each tube. (I used batch 307862, ~13,500 spores/tablet)
3. Add a few ml 10% HCl, and let reaction proceed; slowly fill tubes until there is about 10 ml in each tube. Stir well, and place in hot water bath for 3 minutes. Start beaker (250 ml) of distilled water heating on another 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, place in boiling bath for 10 minutes, stirring after 5 minutes. Remove from bath and stir again. Centrifuge 2 minutes and decant.

6. Wash four times with hot distilled water. Centrifuge for 2 minutes each time.

7. Fill tubes about ½ way with distilled water, stir, and pour through 125 μm 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.

8. Centrifuge down material in beaker by repeatedly pouring beaker contents into correct tube, centrifuge for 2 minutes, and decant.

9. Add 8 ml of 49-52% HF and stir, wearing gloves, goggles, and mask. Place tubes in boiling bath for 20 minutes, stirring after 10 minutes. Centrifuge for 2 minutes and decant.

10. Add 10 ml hot Alconox solution (2.5 cm^3 dissolved into 1000 ml distilled water). 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 that top of water comes close to top of tube. Stir, centrifuge for 2 minutes, and decant. Check top of tubes for oily residue after decanting. 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 silica is present repeat steps 9-11. Assuming that no samples need retreatment with HF, continue washing with hot distilled water as above for a total of 3 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 (for 6 tubes, 54 ml acetic anhydride and 6 ml 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.

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 sediment in tube.

19. Add 1 drop 1% safranin stain to each tube. Use vortex mixer for 10 seconds. Add distilled water to make 10 ml. Stir, centrifuge for 2 minutes, and decant.

20. Add a few ml tertiary-butyl alcohol (TBA), use vortex mixer for 20 seconds. Fill to 10 ml with TBA, stir, centrifuge 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 vials. Centrifuge down residue into vials and decant.

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

24. Place uncorked samples in a dust-free cabinet to let the residual TBA evaporate.

25. Stir again after 1 hour. Do not let the sample dry out.

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

APPENDIX B

PLANT TAXA AT LAGO COTE

APPENDIX B

PLANT TAXA AT LAGO COTE

This table includes a complete list of plant taxa included in the Lago Cote Eco-Lodge herbarium representing plants collected in the area surrounding the lake. This list was compiled from an herbarium list provided by Gerardo Rivera, March 1998, as well as taxa I observed in the herbarium collection in July 1998. The sendero (trail) column includes additional taxa from labels on plant specimens along the following trails at Lago Cote Eco-Lodge: Sendero Bromelias, Sendero Ilusion, Sendero Heliconias, and the Jardin de Palmas Nativas de Costa Rica.

Taxa	Herbarium	Senderos
MAGNOLIOPHYTA/Magnoliopsida (Dicotyledones)		
ACANTHACEAE		
Aphelandra tridentata	x	
Justicia brenesii	x	
Justicia refractifolia	x	
Justicia sarapiquense	x	
Louteridium costarricense	x	
Mendocia retusa	x	
Razisea spicata	x	
Ruellia toduzii	x	
Thunbergia glandifolia (?)	x	
ACTINIDIACEAE		
Saurauia costarricense	x	
Saurauia yasicae	x	
AMARANTHACEAE		
Iresine diffusa	x	
ANNONACEAE		
Annona pittieri	x	
Cymbopetalum costaricense	x	
Guatteria amplifolia	x	
Guatteria costaricense	x	
Guatteria tonduzii	x	
Sapranthus viridoflorus	x	
Unonopsis costaricense	x	
Xylopia bocatorena	x	

Taxa	Herbarium	Senderos
APOCYNACEAE		
Prestonia portobellensis	x	
Rauwolfia aphlebia	x	
Stemmadenia alfari	x	
Tassidia obovata	x	
AQUIFOLIACEAE		
Ilex costarricensis	x	
ARALIACEAE		
Dendropanax arboreux	x	
Dendropanax gonatopodus	x	
Schefflera brenesii	x	
Schefflera rodriguesiana	x	
ARISTOLOCHIACEAE		
Aristolochia tonduzii	x	
ASTERACEAE		
Ageratina subcordata	x	
Ageratum conyzoides	x	
Baccharis trinervis	x	
Chaptalia nutans	x	
Jungia ferruginea	x	
Neurolaena lobata	x	
Vernonia argyropappa	x	
Vernonia patens	x	
BALSAMINACEAE		
Inpatiens balsamina	x	
BEGONIACEAE		
Begonia sp.	x	
BIGNONIACEAE		
Amphitecna sessilifolia	x	
Callichlamys latifolia	x	
Parmentiera varerii	x	
Tabebuia guayacan		x
BOMBACACEAE		
Ceiba pentandra		x
Hampea appendiculata		x

Taxa	Herbarium	Senderos
Pachira aquatica	x	
Quararibea costarricensis	x	
Spirotheca rosea	x	
BORAGINACEAE		
Bourreria costaricensis	x	
Cordia croatii	x	
Cordia cymosa		
Cordia megalantha	x	
Tournefortia bicolor	x	
BURSERACEAE		
Protium costaricense	x	
CAMPANULACEAE		
Burmeistera cyclostigmata	x	
Centropogon granulosus	x	
Hippobroma longiflora	x	
CAPPARIDACEAE		
Capparis discolor	x	
Podandrogyne sp.	x	
Podandrogyne decipiens	x	
CARICACEAE		
Jacaratia dollichaula	x	
CECROPIACEAE		
Cecropia insignis	x	
Cecropia obtusifolia	x	
Coussapoa glaberrima	x	
Coussapoa nymphaeifolia	x	
Pourouma bicolor	x	
CELASTRACEAE		
Maytenus segovianum	x	
Zinowiewia costaricensis		x
CHLORANTHACEAE		
Hedyosmum costaricense	x	
CHRYSOBALANACEAE		
Licanea triandria		x

Taxa	Herbarium	Senderos
CLETHRACEAE		
Clethra mexicana	x	
CLUSIACEAE		
Clusia amazonica	x	
Clusia minor	x	
Clusia palmana	x	
Clusia quadrangula	x	
Clusia stenophylla	x	
Clusia torresii	x	
Symphonia sp.		x
Symphonia globulifera	x	
Tovomitopsis glauca	x	
CONVULVULACEAE		
Ipomoea ramosissima	x	
Maripa nicaraguensis	x	
Merremia aegyptia	x	
CUCURBITACEAE		
Gurania sp.	x	
Gurania makoyana	x	
Gurania megistantha	x	
DILLENIACEAE		
Doliocarpus multiflorus	x	
EBENACEAE		
Diospyros sp.	x	
Diospyros sp. novum	x	
ELIOCARPACEAE		
Sloanea brachytepala	x	
Sloanea brenesii		x
Sloanea faginea	x	
Sloanea glabrata		x
Sloanea medusula	x	
Sloanea picapica	x	
ERICACEAE		
Cavendishia complectens	x	
Satyria warszewiczii	x	
Sphyrospermum buxifolium	x	

Taxa	Herbarium	Senderos
EUPHORBIACEAE		
Acalypha diversifolia	x	
Alchornia latifolia	x	
Croton brevicepsis	x	
Croton schniedeanus	x	
Dalechampia scendens	x	
Dalechampia spathulata	x	
Euphorbia sp.		x
Gymnanthes riparia		x
Hyeronima oblonga		x
Margaritaria nobilis	x	
Sapium laurifolium	x	
Sapium glandulosum		x
Sapium rigidifolium	x	
Tetrorchidium euryphyllum	x	
FABACEAE (Mimosoideae)		
Calliandra brenesii	x	
Inga coruscans		x
Inga exalata	x	
Inga goldmanii	x	
Inga mortoniana	x	
Inga oerstediana	x	
Inga punctata	x	
Inga sapinoides	x	
Mimosa pudica	x	
Pithecellobium costaricense	x	
Pithecellobium longifolium	x	
Pithecellobium palmatum	x	
Pithecellobium valerioi	x	
FABACEAE (Papilionoideae)		
Dussia cuscatlanica		x
Dussia macroprophyllata	x	
Erythrina gibbosa		x
Longocarpus oliganthus	x	
Machaerium biovulatum	x	
Machaerium seemannii	x	
Pterocarpus officinalis	x	
Swartzia simplex	x	

Taxa	Herbarium	Senderos
FLACOURTIACEAE		
Casearia coronata	x	
Hasseltia floribunda	x	
Lacistema aggregatum	x	
GENTIANACEAE		
Lisianthius skinneri	x	
GESNERIACEAE		
Alloplectus trichocalyx	x	
Besleria notabilis	x	
Capanea grandifolia	x	
Codonanthe sp.	x	
Columnea consanguinia	x	
Columnea lepidocaulis	x	
Columnea microphylla	x	
Columnea purpurata	x	
Drymonia conchocalyx	x	
Drymonia serrulata	x	
Drymonia submarginalis	x	
Drymonia turrialvae	x	
Drymonia warscewicziana	x	
Kohleria spicata	x	
Monopyle macrocarpa	x	
HERNANDIACEAE		
Hernandia didymantha	x	
Hernandia stenura		x
HIPPOCASTANACEAE		
Billia columbiana		x
ICACINACEAE		
Calatola costaricensis		x
LAMIACEAE		
Scutellaria costaricana	x	
LAURACEAE		
Cinnamomum chavarrianum	x	
Nectandra smithii	x	
Ocotea atirrensis	x	
Ocotea floribunda	x	

Taxa	Herbarium	Senderos
Ocotea meziana	x	
Ocotea valeriana	x	
Ocotea veraguensis		x
Persea americana	x	
LENTIBULARIACEAE		
Utricularia sp.	x	
LORANTHACEAE		
Psittacanthus schiedeanus	x	
Struthanthus costaricensis	x	
MAGNOLIACEAE		
Talauma gloriensis	x	
MALPIGHIACEAE		
Malpighia sp.	x	
Bunchosia cornifolia	x	
Tetrapteris donnell-smithii		
MALVACEAE		
Malvaviscus arboreus	x	
MARCGRAVIACEAE		
Marcgravia membranacea	x	
Norantea brenesii	x	
MELASTOMATACEAE		
Blakea anomala	x	
Blakea gracilis	x	
Blakea tuberculata	x	
Clidemia setosa	x	
Conostegia xalapensis	x	
Henrietta tuberculosa		x
Leandra sp.	x	
Miconia valeriana	x	
Ossaea brenesii	x	
Ossaea laxivenula	x	
Tibouchina longifolia	x	
MELIACEAE		
Guarea glabra	x	

Taxa	Herbarium	Senderos
Guarea rhopalocarpa		x
Ruagea glabra	x	
MENISPERMACEAE		
Cissampelos pareira	x	
MONIMIACEAE		
Mollinedia costaricensis	x	
Mollinedia pinchotiana	x	
Siparuna andina	x	
Siparuna pauciflora	x	
Siparuna tonduziana	x	
MORACEAE		
Dorstenia choconiana	x	
Ficus costaricana	x	
Ficus macbridei		x
Ficus werckleana	x	
Helicostylis tovarensis	x	
Maquira costaricana	x	
Naucleopsis caripensis	x	
Pseudolmedia mollii	x	
Sorocea trophoides	x	
Trophis racemosa	x	
MYRISTICACEAE		
Compsoneura sprucei	x	
Otoba novogranatensis		x
Virola guatamalensis		x
Virola koschnyi	x	
MYSRINACEAE		
Ardisia auriculata	x	
Ardisia calycosa	x	
Ardisia costaricensis	x	
Ardisia opegrapha	x	
Cybianthus schlimii	x	
Parathesis calophylla	x	
MYRTACEAE		
Eugenia coteriana	x	
Eugenia octopleura	x	
Eugenia oerstediana	x	

Taxa	Herbarium	Senderos
Eugenia truncata	x	
Marlieria mesoamericana	x	
Myrcia mollis	x	
Myrcia splendens		x
Myrciaria floribunda	x	
Myrciaria vexator		x
Pimenta dioica		x
Pimenta guatemalensis	x	
Plinia povedae		x
Plinia salticola	x	
NYCTAGINACEAE		
Neea latifolia	x	
OCHNACEAE		
Ouratea lucens	x	
Cespedesia macrophylla	x	
OLACACEAE		
Heisteria acuminata	x	
OLEACEAE		
Chionanthus dominguenses	x	
Chionanthus oblanceolatus	x	
ONAGRACEAE		
Ludwigia peruviana	x	
PAPAVERACEAE		
Bocconia frutescens	x	
PASSIFLORACEAE		
Passiflora ambigua	x	
Passiflora biflora	x	
Passiflora costaricensis	x	
Passiflora vitifolia	x	
PIPERACEAE		
Piper augustum	x	
Piper auritum	x	
Piper hispidum	x	
Piper imbricatum	x	
Piper umbellata	x	

Taxa	Herbarium	Senderos
POLYGALACEAE		
Monnina sylvatica	x	
POLYGONACEAE		
Coccoloba acuminata	x	
PROTEACEAE		
Panopsis suaveolens	x	
RHAMNACEAE		
Clematis dioica	x	
RHIZOPHORACEAE		
Cassipourea elliptica	x	
RUBIACEAE		
Chimarrhis latifolia		x
Chimarrhis parviflora	x	
Chione sylvicola	x	
Cosmibuena macrocarpa	x	
Cosmibuena valerii	x	
Coussarea austin smithii	x	
Coussarea talamancana	x	
Duroia costaricensis	x	
Elaeagia auriculata	x	
Elaeagia uxpanapensis		x
Faramea eurycarpa	x	
Faramea monofructus	x	
Faramea suerrensis	x	
Genipa americana	x	
Geophila cardifolia	x	
Gonzalagunia bracteosa	x	
Gonzalagunia ovatifolia	x	
Guettarda crispiflora	x	
Guettarda foliacea	x	
Hamelia patens	x	
Hillia maxonii	x	
Hillia triflora	x	
Hoffmannia longipetiolata	x	
Isertia laevis	x	
Pentagonia costaricensis	x	
Posoqueria grandiflora	x	
Posoqueria latifolia		x

Taxa	Herbarium	Senderos
Psychotria aggregata	x	
Psychotrai brachiata	x	
Psychotria chiapensis	x	
Psychotria elata	x	
Psychotria guadalupensis	x	
Psychotria gualipensis	x	
Psychotria insignis	x	
Psychotria jimenezii	x	
Psychotria luxurians	x	
Psychotria macrophylla	x	
Psychotria panamensis	x	
Psychotria pilosa	x	
Psychotria pittieri	x	
Psychotria polyphlebia	x	
Psychotria uliginosa	x	
Randia loniceroides	x	
Rondeletia brenesii	x	
Rudgea monofructus	x	
Rudgea reducticalyx	x	
Schradera costaricensis	x	
Spermacoce densiflora	x	
RUTACEAE		
Amyris brenesii	x	
Cecazyx macrophyllus	x	
Zanthoxylum junipernum	x	
Zanthoxylum panamense		x
SABIACEAE		
Meliosma brenesii	x	
Meliosma glabrata	x	
SAPINDACEAE		
Allophylus psilospermus		x
Cupania costaricensis	x	
Cupania marcophylla	x	
SAPOTACEAE		
Chrysophyllum hirsutum	x	
Pouteria congestifolia	x	
Pouteria sapota		x

Taxa	Herbarium	Senderos
SCROPHULARIACEAE		
Schlegelia parviflora	x	
Scoparia dulcis	x	
SIMAROUBACEAE		
Picramnia latifolia	x	
SOLANACEAE		
Cyphomandra hartwegii	x	
Markea leucantha	x	
Solanum evolvulifolium	x	
Solanum lancifolium	x	
Solanum umbellatum	x	
Witheringia solanacea	x	
STAPHYLEACEAE		
Turpinia occidentalis		x
STERCULIACEAE		
Theobroma simiarum		x
SYMPLOCACEAE		
Symplocos bradei		x
THEACEAE		
Freziera candicans	x	
THEOPHRASTACEAE		
Clavija costaricana	x	
THYMELEACEAE		
Daphnopsis americana	x	
Schoenobiblis sp.	x	
TICODENDRACEAE		
Ticodendron incognitum	x	
TILIACEAE		
Apeiba membranacea		x
Heliocarpus appendiculatus		x
Mortoniodendron costaricense	x	

Taxa	Herbarium	Senderos
ULMACEAE		
Trema micrantha	x	
URTICACEAE		
Myriocarpa longipes	x	
Pilea costaricensis	x	
Pilea diversissima	x	
Pilea ptericlada	x	
Urera baccifera	x	
Urera elata	x	
VERBENACEAEA		
Aegiphila costaricensis	x	
Aegiphila elata	x	
VIOLACEAE		
Gloeospermum diversipetalum	x	
Rinorea sp.		x
VISCACEAE		
Phoradendron piperoides	x	
VITACEAE		
Cissus sp.	x	
Cissus rhombifolia	x	
VOCHYSIACEAE		
Vochysia guatemalensis	x	
MAGNOLIOPHYTA/Liliopsida (Monocotyledones)		
ALISMATACEAE		
Sagittaria lancifolia	x	
ARACEAE		
Anthurium cosobrinium	x	
Anthurium cotobrusii	x	
Anthurium cuspidatum	x	
Anthurium fatoense	x	
Anthurium friedrichsthalii	x	

Taxa	Herbarium	Senderos
Anthurium michelii	x	
Anthurium pluricostatum	x	
Anthurium scandens	x	
Monstera costaricensis	x	
Philodendron anisotomum	x	
Philodendron pterotum	x	
Philodendron rugosum	x	
Philodendron verrucosum	x	
Xanthosoma robustum	x	
ARECACEAE		
Acrocomia aculeata	x	
Asterogyne martiana	x	
Astrocaryum alatum	x	
Bactris glandulosa	x	
Bactris gracilior	x	
Bactris grineensis	x	
Bactris groyumii	x	
Bactris hondurensis	x	
Calyptrogyne brachystachys	x	
Calyptrogyne condensata	x	
Calyptrogyne ghiesbreghtiana	x	
Chamaedorea costaricana	x	
Chamaedorea dammeriana	x	
Chamaedorea deckeriana	x	
Chamaedorea pinnatifrons	x	
Chamaedorea pumila	x	
Chamaedorea robertii	x	
Chamaedorea stenocarpa	x	
Chamaedorea tepejilote	x	
Chamaedorea undulatifolia	x	
Colpothrinax cookii	x	
Crysophila cookii	x	
Crysophila guagara	x	
Crysophila warscewiczii	x	
Euterpe macrospadix	x	
Euterpe precatoria	x	
Geonoma congesta	x	
Geonoma cuneata	x	
Geonoma ferruginea	x	
Geonoma gracilis	x	
Geonoma longevaginata	x	
Hyospathe elegans	x	

Taxa	Herbarium	Senderos
Iriartea deltoidea	x	
Pholidostachys pulchra	x	
Prestoea decurrens	x	
Reinhardtia simplex	x	
Sabal sp.	x	
Synechanthus sp.	x	
Synechanthus warscewiczianus	x	
BROMELIACEAE		
Guzmania nicaraguensis	x	
Guzmania plicatifolia	x	
Pitcairnia atrorubens	x	
Pitcairnia brittoniana	x	
CANNACEAE		
Canna indica	x	
COMMELINACEAE		
Commelina diffusa	x	
Tradescantia zanonia	x	
COSTACEAE		
Costus lasius	x	
Costus malortieanus	x	
Costus pulverulentus	x	
Costus scaber	x	
CYCLANTHACEAE		
Asplundia alata	x	
Asplundia longipetala	x	
Asplundia microphylla	x	
Aspundia utilis	x	
Carludovica drudei		
Carludovica palmata	x	
Chorigyne ensiformis	x	
Cyclanthus bipartitus	x	
HAEMODORACEAE		
Xiphidium coeruleum	x	
HELICONIACEAE		
Heliconia atropurpurea	x	

Taxa	Herbarium	Senderos
Heliconia irrasa	x	
Heliconia pendula	x	
Heliconia pogonantha	x	
Heliconia secunda	x	
MARANTACEAE		
Calathea crotalifera	x	
Calathea guzmanioides	x	
Calathea lasiostachya	x	
Calathea leucostachys	x	
Calathea macrosepala	x	
Calathea warscewiczii	x	
Hylaeanthe hoffmannii	x	
Thalia geniculata	x	
ORCHIDACEAE		
Elleanthus stolonifer	x	
Elleanthus hymenophorus	x	
Encyclia vespa	x	
Epidendrum sp.	x	
Epidendrum palmidium	x	
Epidendrum paniculatum	x	
Epidendrum platystigma	x	
Epidendrum radicans	x	
Habenaria monorrhiza	x	
Homalopetalum pumilio	x	
Lockhartia amoena	x	
Malaxix hastilabia	x	
Maxillaria angustisegmenta	x	
Oerstedella exasperata	x	
Oerstedella wallisii	x	
Pelexia funconia	x	
Pleurothallis sp.	x	
Sievekingia fimbricata	x	
Sobralia atropubenscens	x	
Sobralia leucoxantha	x	
Stelis sp.	x	
Stenorrynchos speciosum	x	
Systeloglossum acuminatum	x	
Vanilla planifolia		x

Taxa	Herbarium	Senderos
POACEAE		
Coix lacryma jobi	x	
ZINGIBERACEAE		
Renealmia cernua	x	
CYCADOPHYTA		
ZAMIACEAE		
Zamia skinneri		x
LYCOPHYTA		
LYCOPODIACEAE	x	
Huperzia sp.	x	
Lycopodium sp		
PTERIDOPHYTA		
ASPLENIACEAE		
Asplenium serra	x	
BLECHNACEAE		
Salpichlaena volubilis	x	
CYATHEACEAE		
Alsophila sp.		x
Cyathea pinnula	x	
DRIOPTERIDACEAE		
Olfersia cervina	x	
Stigmatopteris heterophlebia	x	
LOMARIOPSIDACEAE		
Bolbitis nicotianifolia	x	
Lomariopsis vestita	x	

Taxa	Herbarium	Senderos
MARATTIACEAE		
Danaea crispa	x	
Danaea nodosa	x	
POLYPODIACEAE		
Niphidium crassifolium	x	
PTERIDACEAE		
Adiantum tetraphyllum	x	
TECTARIACEAE		
Didymochlaena truncatula	x	
THELYPTERIDACEAE		
Thelypteris decussata	x	
Thelypteris ensiformis	x	
VITTARIACEAE		
Vittaria angustifolium	x	
WOODSIACEAE		
Diplazium ceratolepis	x	

APPENDIX C

POLLEN AND SPORE TAXONOMY AT LAGO COTE

APPENDIX C

POLLEN AND SPORE TAXONOMY AT LAGO COTE

This table includes all of the pollen and spore taxa/morphotypes I identified in the 1998 II sediment core from Lago Cote. Taxa listed as "type" match taxa within the family, but could not be separated from other taxa in the same group. Occurrence of each taxon is expressed as the percent of total pollen or total spores from all levels. This percent of counts data is included to show the rarity of most taxa.

Morphologic Group or Family	**Genus or other Classification**	**Total % of All Pollen**
GYMNOSPERMS		
PINACEAE		0.28
PODOCARPACEAE		0.03
ANGIOSPERMS		
AMARANTH/CHENOPOD		0.11
ANACARDIACEAE		0.33
ANACARDIACECE	*Spondias*-type	0.04
AQUIFOLIACEAE	*Ilex*	1.59
APIACEAE		0.13
APOCYNACEAE		0.05
ARACEAE		0.19
ARACEAE	*Anthurium*-type	0.05
ARECACEAE		2.01
ARECACEAE	*Iriartea*	0.09
ASTERACEAE	high-spine	0.50
ASTERACEAE	low-spine	0.23
BETULACEAE	*Alnus*	0.13
BEGONIACEAE		0.45
BOMBACACEAE		0.18
BURSERACEAE	*Protium*	0.04

Morphologic Group or Family	Genus or other Classification	Total % of All Pollen
BORAGINACEAE	*Cordia*	0.03
CECROPIACEAE	*Cecropia*	15.22
CLETHRACEAE	*Clethra*	0.52
CHLORANTHACEAE	*Hedyosmum*	2.06
CORNACEAE	*Cornus*	0.01
CUNONIACEAE	*Weinmannia*	1.45
CYPERACEAE		1.27
DIOSCORIACEAE	*Dioscoria*	0.01
ERICACEAE		0.19
EUPHORBIACEAE	*Acalypha*	3.06
EUPHORBIACEAE	*Alchornia*	6.33
EUPHORBIACEAE	*Croton*	0.01
EUPHORBIACEAE	*Chamaesyce*	0.01
FABACEAE	Mimosoidae	0.01
FABACEAE	Papilionoidae undif.	0.10
FABACEAE	Pap. *Erythrynia*-type	0.01
FABACEAE	Pap. *Andira*-type	0.23
FABACEAE	Pap. *Teramnus-type*	0.04
FAGACEAE	*Quercus*	0.32
LAMIACEAE		0.03
LAURACEAE		0.03
LECYTHIDIACEAE		0.01
LILIACEAE		0.01
LYTHRACEAE	*Adenaria*	0.01
MALPIGHIACEAE		0.14
MALPIGHIACEAE	*Heteropteris*-type	0.05
MALPIGHIACEAE	*Hiraea*-type	0.11
MALPIGHIACEAE	*Hampea*-type	0.01

Morphologic Group or Family	Genus or other Classification	Total % of All Pollen
MALPIGHIACEAE	*Byrsonima*	0.01
MALVACEAE		0.01
MELASTOM/COMBRET.		6.11
MORACEAE	*Dorstenia*	0.29
MORACEAE	*Ficus*	0.27
MYRICACEAE	*Myrica*	0.57
MYRISTICACEAE	*Virola*	0.29
MYRSINACEAE	*Myrsine*	1.32
MYRTACEAE		1.38
MYRTACEAE	*parasyncolporate*	1.68
ONAGRACEAE	*Fuschia*-type	0.01
PIPERACEAE	*Piper*	8.10
POACEAE		4.11
RUBIACEAE		0.01
RUBIACEAE	*Borreria*	0.01
RUTACEAE	*Zanthoxylum*	2.22
SAPOTACEAE/MELIACEAE		0.47
SAPINDACEAE		0.18
SCROPHULARIACEAE		0.17
SOLANACEAE		1.04
STAPHYLEACEAE	*Turpinia*-type	0.01
STERCULIACEAE		0.04
STERCULIACEAE	*Apeiba*-type	0.03
TILIACEAE	*Mortoniodendron*	0.45
THYMELAECEAE	*Daphnopsis*-type	0.11
URTICALES		3.96
URTICALES	diporate	11.05
URTICALES	*Trema*	3.96

Morphologic Group or Family	Genus or other Classification	Total % of All Pollen
URTICALES	triporate	3.73
URTICALES	*Celtis*	2.59
URTICALES	4-porate	0.78
URTICALES	polyporate	0.45
VERBENACEAE		0.29
VIOLACEAE	*Rinorea*	0.01
VOCHYSIACEAE		0.06

SPORES

Morphotype	Total % of All Spores
monolete psilate	35.03
monolete coarsely verrucate	9.00
monolete verrucate	3.52
monolete clavate	0.29
monolete scabrate	7.93
monolete echinate	5.38
monolete rugulate	0.29
monolete bacculate	0.10
trilete psilate	2.64
trilete coarsely verrucate	0.29
trilete verrucate	28.67
trilete scabrate	5.58
trilete echinate	0.49
trilete rugulate	0.10
trilete clavate	0.10
Hymenophyllaceae	0.10
native *Lycopodium*	0.20

APPENDIX D

REFERENCE DATA TABLES FOR X-RAY FLUORESCENCE ANALYSIS OF LAGO COTE TEPHRA LAYERS

APPENDIX D

REFERENCE DATA TABLES FOR X-RAY FLUORESCENCE ANALYSIS OF LAGO COTE TEPHRA LAYERS

This Appendix includes additional data tables pertaining to my X–ray fluorescence analysis of tephra layers in the Lago Cote sediments core (1998 II). Results and discussion of the XRF analysis are reported in Chapter 4.

D.1 Summary of El Tajo Tephra EMPA Results.[1]

.	ET1 Wt. %	ET2 Wt. %	ET3 Wt. %	ET4 Wt. %	ET5 Wt. %	ET6 Wt. %	ET7 Wt. %	ET8 Wt. %	ET9 Wt. %
Na_2O	3.45	3.83	2.69	4.08	3.55	2.02	3.41	2.69	3.11
MgO	2.56	1.99	4.74	2.43	2.68	6.48	1.85	4.06	3.2
Al_2O_3	20.75	18.18	20.11	17.95	18.43	18.18	17.34	19.13	18.67
SiO_2	56.15	62.32	52.4	60.14	58.83	51.44	63.57	54.29	56.5
P_2O_5	0.14	0.19	0.14	0.21	0.17	0.12	0.17	0.14	0.15
K_2O	0.68	0.78	0.42	0.82	0.65	0.31	0.72	0.56	0.52
CAO	8.98	6.52	10.38	6.68	7.5	9.89	6.35	9.4	8.12
TiO_2	0.52	0.38	0.58	0.49	0.46	0.56	0.33	0.53	0.48
MnO	n.d.[2]	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Fe_2O_3	6.19	5.45	8.14	6.62	7.13	9.09	5.44	7.79	7.94
sum	99.42	101.64	99.6	99.42	99.4	98.09	99.18	98.59	98.69

[1] Adapted from Melson (1982), electron microprobe analysis of tephra at El Tajo roadcut, ~7 km west of Arenal Volcano. Results are reported as weight percent of mineral oxides.
[2] Not done.

D.2 USGS Standards Used for XRF Analysis of Lago Cote Tephra.

BIR1 .... Basalt
DNC1 .... Diabase
STM1 .... Nepheline Syenite
AGV1 .... Andesite
BCR1A .... Basalt

D.3 Mineral Oxide Concentrations for USGS Standards used in IGROCK Protocol.

Mineral Oxide	IGROCK Ranges (Wt. %)	SEC	Cote Tephra Ranges (Wt. %)
Na_2O	0.01 – 8.27	0.42[2]	1.42 – 3.28
MgO	0.34 – 49.80	0.26	2.96 – 7.55
Al_2O_3	0.24 – 18.73	0.25	18.67 – 22.86[3]
SiO_2	38.86 – 73.15	0.52	47.38 – 55.09
P_2O_5	200 ppm – 0.49	0.0657	0.06 – 0.16
K_2O	100 ppm –5.53	0.05	0.03 – 0.54
CaO	0.15 –14.77	0.15	8.34 – 10.94
MnO	0.03 – 0.71	0.018	0.14 – 0.25
TiO_2	0.01 – 3.69	0.033	0.48 – 0.66
V	100 ppm – 0.05	0.005	0.01 – 0.16[3]
Cr	70 ppm – 2.20	0.008	0.02 – 550 ppm
Fe_2O_3	1.95 – 17.82	0.31	8.15 – 11.71
Ni	500 ppm – 0.23	0.003	100 ppm – 0.01
Rb	0.00 – 0.03	0.001	90 ppm – 150 ppm
Sr	0.00 – 0.45	0.002	0.05 – 0.07
Y	0.00 – 370 ppm	0.000	60 ppm – 140 ppm
Zr	0.00 – 1.10	0.002	0.01 – 0.02
Nb	20 ppm – 0.13	0.000	10 ppm – 40 ppm

[1] Standard Error of Calculation.
[2] Error due to counting statistics is 0.42.
[3] Exceeds the ranges of USGS standards used in IGROCK protocol. Standards were chosen based on the ranges reported from the El Tajo tephras by Melson (1982).

VITA

Martin Russell Arford was born in Johnstown, Pennsylvania on October 8, 1956. He graduated from United High School, Armagh, Pennsylvania in 1974. Martin was employed as a coal miner for three years, then entered the field of emergency medical services as a paramedic. Prior to becoming a full-time college student, Martin was manager of an ambulance service in Johnstown, Pennsylvania. He received his Bachelor of Science degree from Indiana University of Pennsylvania in 1997, graduating Magna cum Laude with double majors in geology and biology and a minor in geography. He spent a semester aboard the National Oceanic and Atmospheric Administration (NOAA) ship *Discoverer* in the equatorial Pacific Ocean collecting data for sea-surface carbon dioxide monitoring and for a study on the distribution of goose-neck barnacles. He also participated in field courses in Virginia (oceanography), Pennsylvania (aquatic ecology), Florida Keys and Bahamas (geology), Newfoundland (geology), and Costa Rica (development/planning). During these courses he developed strong interests in paleoecology and biogeography. Martin entered the graduate program in geography at the University of Tennessee in 1997 with a desire to study paleoecology and environmental history in Costa Rica.

While at the University of Tennessee, Knoxville, Martin has participated in field research in Costa Rica and the Dominican Republic funded by the National Geographic Society, The A.W. Mellon Foundation, and the National Science Foundation. In summer 1998, he attended a course on tropical ecology in Costa Rica sponsored by the Organization for Tropical Studies. He has served as a Teaching Assistant for introductory physical geography and is currently a Research Assistant on a project funded by a grant to his advisor, Sally P. Horn, from The A. W. Mellon Foundation. Martin received his Master of Science degree in August 2001. He has been accepted into the Ph.D. program in geography at the University of Tennessee, and will continue his research on environmental history in Costa Rica.