Environmental change in the west-central Mexican highlands over the last 1,000 years: evidence from lake sediments.

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Declaration

I have composed this thesis, which is the result of my own research. Where appropriate, the contribution of collaborating researchers has been stated clearly.

Date....31st...May...2000..........

Abstract

Palaeoenvironmental records are presented from two lakes in the volcanic uplands of west-central Mexico, which are believed to be relatively undisturbed: Lago de Zirahuén in Michoacán (19°26'N, 101°44'W) and Laguna de Juanacatlán in Jalisco (20°37'N, 104°44'W). The principal technique employed is diatom analysis, although the analysis of mineral magnetic susceptibility and metal content in the sediments provides important additional information. The chronological framework is provided by a combination of ^{210}Pb dating, AMS ^{14}C dating and tephrochronology. In order to interpret effectively the diatom record from the two sites, modern diatom samples were collected from a range of sites within the Trans-Mexican Volcanic Belt. These data were combined with results from previous investigations to produce a surface sediment diatom calibration dataset for Central Mexico. The development of diatom-based transfer functions from this dataset allows the numerical reconstruction of hydrochemical variables from diatom assemblages in sediment cores. The limitations of this approach are also discussed.

The record from Lago de Zirahuén extends back ca. 1,000 years. Tentative evidence is provided from the diatom record for a drier climate ca. 1,000 yrs. BP, although further work is required to confirm this. Increased soil erosion between ca. AD 1100 and AD 1550 likely relates to settlement by the Post-Classic Purépecha civilisation. This is followed by a period of catchment stability during the early Colonial Period, when the indigenous population declined steeply. The impact of Colonial development in the basin from the mid-18th century is clear, with increased soil erosion, distinct changes in the diatom flora and evidence of pollution from copper smelting. The record from Laguna de Juanacatlán is shorter, but covers at least the period since the arrival of Spanish settlers in Mexico in 1521. Evidence is provided of silver mining in the basin during the Colonial Period with associated catchment disturbance indicated by marked changes in the diatom assemblage. The most striking feature of the records from Lago de Zirahuén and Laguna de Juanacatlán, however, is the rapid and dramatic change in the diatom flora during the last 10-20 years as a result of changing land use.

The dominant signal in the palaeolimnological records is of human impact, rather than climate change. This was surprising, given that the two lakes are regarded as relatively undisturbed. The highly sensitive nature of these ecosystems must therefore be an important consideration in planning future land use management strategies.

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Glossary and Abbreviations

Lakes

Allochthonous:	Sediment that is transported to the site of deposition.
Autochthonous:	Sediment that is deposited *in-situ*.
Eutrophic:	Nutrient-rich water of high primary productivity.
Mesotrophic:	Water of intermediate nutrient levels.
Oligotrophic:	Nutrient-poor waters of low primary productivity.
Epilimnion:	The upper, warm, circulating layer in a thermally stratified lake.
Hypolimnion:	The lower, cooler, non-circulating layer in a thermally stratified lake.
Metalimnion:	The transition between the epilimnion and hypolimnion, where the thermocline (rate of temperature change with water depth) is greatest.

Diatom Ecology

Aerophilous:	Living in a sub-aerial habitat.
Periphytic:	Living attached to a substrate or submerged objects (sometimes used for diatoms found near the margin of a water body).
Epilithic:	Living attached to rock.
Epipelic:	Living on sediment.
Epiphytic:	Living attached to vegetation.
Planktonic:	Free-floating, living suspended in the water column.
Facultative Planktonic:	Usually associated with periphytic habitats, but is often found in the plankton.

Acidobiontic:	Occurring at pH < 7, optimum < 5.5.
Acidophilous:	Occurring at pH 7, optimum < 7.
Indifferent / Circumneutral:	Optimally occurring around pH 7.
Alkaliphilous:	Occurring at pH 7, optimum > 7.
Alkalibiontic:	Occurring only in alkaline water.

(after Hustedt, 1937-1938).

Abbreviations

AMS:	Accelerator Mass Spectrometry
BSEI:	Back-Scattered Electron Image
CCA:	Canonical Correspondence Analysis
DCA:	Detrended Correspondence Analysis
DO:	Dissolved Oxygen
DSCA:	Digital Sediment Colour Analysis
EC:	Electrical Conductivity
ENSO:	El-Niño Southern-Oscillation
ITCZ:	Inter-Tropical Convergence Zone
MGVF:	Michoacán-Guanajuato Volcanic Field
NAO:	North Atlantic Oscillation
PNA:	Pacific-North American pattern
RMSE:	Root Mean Squared Error
RMSEP:	Root Mean Squared Error of Prediction
SEM:	Scanning Electron Microscope
SLP:	Sea Level Pressure
SOI:	Southern Oscillation Index
STHPB:	Sub-Tropical High Pressure Belt
TMVB:	Trans-Mexican Volcanic Belt
WA:	Weighted Average

Chapter 1: Research context and rationale

1.1: Research Aims

The aim of this thesis is to provide a detailed reconstruction of environmental change in the central Mexican highlands over the Late Holocene. Evidence from the sediments of two lakes: Lago de Zirahuén, in Michoacán and Laguna de Juanacatlán in Jalisco, will be used to address the following specific objectives:

- To identify climatic changes during the Late Holocene.
- To examine the extent of human impact, away from major population centres, since the Post-Classic period.
- To assess the degree of coherence between the palaeoenvironmental evidence and that contained within historical records.

It is hoped that such high-resolution records will provide a clearer picture of the nature and timing of climatic changes since the Late Holocene in the central Mexican highlands. Furthermore, any evidence of human impact found in the records from these lakes will add to the debate surrounding the relative contributions of Pre- and Post-Hispanic settlers to the degradation of the central Mexican landscape. The rest of this introductory chapter sets the context for this research, focusing on the rationale behind the project. An outline of the thesis structure is also provided.

1.2: The Research Context

Large scale, generalised patterns of climate change, have been identified from the increasing number of palaeoclimatic records in tropical regions. These broad, millennial scale variations in climate since the Last Glacial Maximum can be largely explained by orbital forcing (Gasse and Van Campo, 1994; Leyden *et al.*, 1994; Cross *et al.*, 2000). Superimposed on this general trend, however, is evidence of rapid and abrupt climatic fluctuations, particularly during the Holocene (e.g., Street-Perrott and Perrott, 1990; Holmes *et al.*, 1998), which cannot be accounted for by orbital forcing alone. Increasing the temporal resolution of palaeoclimatic records, in order to understand more fully finer scale climatic variability, has now become a key focus of palaeoclimatic research.

The impact of dramatic fluctuations in tropical climate on human societies at scales of 10^1 – 10^2 years is clear. Between 1968 and 1988, severe drought devastated the Sahel region of Africa, causing widespread famine (Street-Perrott and Perrott, 1990). The wide-ranging impacts of the El Niño-Southern Oscillation phenomenon, which include drought, flooding, forest fires and associated economic issues, have been the focus of recent media and scientific attention. Given that over 75% of the world's population lives in a region directly affected by tropical climate variability (Thompson, 2000), the need for a greater understanding of climate change at time scales relevant to societies is therefore of the utmost importance.

A number of recent palaeoclimatic studies have indicated that climate change may have been responsible for the collapse of important cultures during the past (Hodell *et al.*, 1995; Curtis *et al.*, 1996; Binford *et al.*, 1997). An extreme dry phase centred around 1,000 yrs BP has been associated with the collapse of the Maya civilisation on the Yucatán Peninsula (Hodell *et al.*, 1995), whilst the Andean Tiwanaku civilisation may have succumbed to a prolonged drought between 900 and 600 yrs BP (Binford *et al.*, 1997). A direct causal link between climate change and cultural collapse has not been proven. Therefore, further high-resolution studies with good chronological control are required if the complex interactions between climate, humans and the environment are to be elucidated.

1.3: The Choice of Mexico

Mexico, straddling the boundary between tropical and temperate climatic regimes, is located in a region highly sensitive to changes in the general atmospheric circulation. Coupled with its long history of human occupation spanning several thousand years, this makes Mexico an ideal location to examine climate-environment-human interactions. Throughout the Colonial Period, between 1521 and the mid-19th century, meticulous written records were kept on all aspects of the country by Spanish settlers, including descriptions of climate, landscapes and human activities. This valuable source of information provides a second line of evidence to compare with that gained from lake sediments. The opportunity is therefore provided to assess the degree to which the historical and palaeoenvironmental records are in agreement.

Previous palaeoclimatic studies provide a general framework of climatic change since the Late Pleistocene in Mexico (e.g. Watts and Bradbury, 1982; Leyden *et al.*, 1994; Metcalfe *et al.*, 1997; Caballero and Ortega, 1998). Evidence is mounting that the Late Holocene in Mexico was extremely variable (Bridgwater *et al.*, 1999), with several prolonged arid phases, the most intense occurring between 1,500 and 900 yrs BP (Metcalfe *et al.*, 2000). Obtaining a clear picture of climatic fluctuations during this time period has, however, proved to be problematic. Chronological control is often poor and records are of insufficient resolution (Metcalfe, 1997). Furthermore, most records have been obtained from basins within the highlands of Central Mexico, which have been the foci for human settlement over the last 3,500 years. Therefore, the Late Holocene palaeoenvironmental record from lake sediments has often been highly disturbed or, as in the case of the Basin of Mexico, destroyed (Caballero, 1995).

Indeed, the relationship between humans and the environment since Pre-Hispanic times has become the subject of intense debate. The traditional view that Pre-Hispanic populations lived in harmony with their environment, causing minimal landscape degradation has been challenged by both archival and palaeoenvironmental studies (e.g. O'Hara *et al.*, 1993; Butzer and Butzer, 1997). It is now argued that Spanish settlers arriving after the Conquest encountered an already modified and degraded landscape (Denevan, 1992). This argument clearly challenges the view that a return to traditional land use practices would lead to a more sustainable use of natural resources (O'Hara *et al.*, 1993). This issue remains contentious, requiring further studies which compare the relative impacts of Pre- and Post-Hispanic settlers on the environment. In the absence of written records for the

Pre-Hispanic period, this can only be achieved through palaeoenvironmental reconstructions. Those records currently available do not have sufficient resolution or chronological control to pinpoint the exact timing of episodes of catchment disturbance which have been identified.

Whilst the main focus of this study is to identify climatic changes during the Late Holocene, the issue of human impact on the palaeoenvironmental record during this time period must also be considered. Any evidence of anthropogenic disturbance during the Late Holocene encountered in the records from Lago de Zirahuén and Laguna de Juanacatlán will add further information to the important debate over natural resource management in Mexico.

1.4: The Research Approach

Within the volcanic highlands of central Mexico are found numerous hydrologically closed lacustrine basins, which are ideal for palaeolimnological investigations. This study will focus on the palaeolimnological record from two lakes in the west-central highlands of Mexico: Lago de Zirahuén and Laguna de Juanacatlán. These sites have been carefully selected to ensure that continuous high-resolution records are likely to be obtained. Furthermore, it appears that these lake basins, unlike many others in the central highlands, have not been subjected to prolonged anthropogenic disturbance. It is therefore more likely that the sedimentary record has not been too disturbed and a reliable chronological framework can be established for the palaeoenvironmental record. The choice of field sites is discussed in more detail in Section 3.4.

The principal technique employed in this study is diatom analysis. This technique has been selected as the sensitivity of diatoms both to moisture availability and to anthropogenic disturbance is widely reported (e.g. Anderson *et al.*, 1995; Laird *et al.*, 1996; Battarbee, 2000). The development of a surface sediment diatom calibration dataset using new data collected during this study and existing material (Metcalfe, 1985, 1988; Caballero, 1995) will for the first time allow quantitative palaeoenvironmental reconstructions to be developed in this region. This allows for a more effective interpretation of diatom assemblages in core material. In order to achieve the objectives outlined above, it is necessary to construct a robust chronological framework for the sedimentary records. This will be based on a combination of ^{210}Pb dating, ^{14}C AMS dating and tephrochronology.

1.5: Thesis Outline

This thesis is organised into eight chapters. This chapter has provided a general context and explained briefly the rationale behind the study. Issues raised in this chapter are explored more fully in Chapters 2 and 3. In Chapter 2, the present day climate of Mexico is described in some detail. A review of the published literature on climatic variability in Mexico focuses on three main themes: interannual variability, evidence from historical records and evidence from the palaeoenvironmental record. Chapter 3 provides a detailed background to the study area: the Trans-Mexican Volcanic Belt. Not only is the nature of the physical environment described, but also the archaeological context and history of human settlement in the region. An understanding of both the physical and cultural factors that may influence environmental change is equally important. The two lake basins: Lago de Zirahuén in Michoacán and Laguna de Juanacatlán in Jalisco, are also introduced in Chapter 3, with a justification of their selection. A map of the states of Mexico is provided in Appendix 1 for reference.

In Chapter 4, the methodology and techniques used in this study are outlined. As the main technique employed in this study, particular attention is paid to diatom analysis and recent developments in its application in palaeoenvironmental research. An explanation of other palaeoenvironmental techniques used as supplementary evidence in this study, including mineral magnetic analysis and metals analysis, is provided. The application of chronological techniques (^{210}Pb dating, ^{14}C dating and tephrochronology) in this research is also discussed.

Chapter 5 focuses specifically on the modern aquatic environment. The results of a survey of lakes within the Trans-Mexican Volcanic Belt, focusing on modern diatom species distributions and their relationship to water chemistry variables, are presented. These results are then merged with previous surveys of diatom ecology to produce a surface sediment diatom calibration dataset for Central Mexico (Davies *et al.*, in press). This dataset allows quantitative palaeoenvironmental reconstructions, based on diatom assemblages in core material, to be made. In Chapters 6 and 7 the palaeolimnological records from Lago de Zirahuén (Ch. 6) and Laguna de Juanacatlán (Ch. 7) are presented. The results of diatom, magnetic and metal analysis from multiple cores taken from each lake are presented individually before providing an overall interpretation of environmental changes for each basin.

Chapter 8 draws together the three individual strands of the thesis: the modern diatom dataset; the palaeolimnological record from Lago de Zirahuén and the palaeolimnological record from Laguna de Juanacatlán. The advantages and limitations of the transfer function approach are discussed in the light of its application to the records from the two lakes. The issue of dating control in palaeoenvironmental studies is also explored. The palaeoenvironmental records from Lago de Zirahuén and Laguna de Juanacatlán are compared with each other to explore their degree of coherence. The palaeolimnological evidence presented in this study is then placed in a wider context by comparison with other published palaeoenvironmental records from Mexico and Central America. To conclude, the contribution of this study to the understanding of environmental change in Mesoamerica over the last 1,000 years is presented in relation to the original research objectives. Suggestions for future research priorities are also made as a result of the findings of this study.

Chapter 2: The Climate of Mexico, Past and Present

2.1: Introduction

This chapter focuses on the climate of Mexico, outlining firstly the principal circulation patterns that influence the present day climate. The nature of climatic variability across the country is discussed at a variety of different time scales, drawing on evidence from instrumental, historical and palaeoenvironmental records. This review of climate change studies in Mexico provides a justification and sets the context for the key research questions identified in the previous chapter.

2.2: Mexico: The Physical Environment

Mexico lies between ca. 14° and 32°N and 82° and 115°W, in the Northern Hemisphere tropics and sub-tropics. A wide variety of environments are encountered within this funnel-shaped country, from deserts in the north-west to the lush, tropical forests of the south. Whilst latitude is an important factor controlling the diversity of environments in Mexico, altitude is also highly significant, with more than half the country lying over 1,000 metres above sea level (Mosiño and García, 1974). The country has two major peninsulas: the long, narrow mountainous arm of Baja California in the north and the low-lying limestone platform of the Yucatán Peninsula in the south-east. Figure 2.1 highlights the principal topographic features of Mexico.

Two extensive mountain ranges follow the east and west coasts of Mexico. The Sierra Madre Oriental, runs parallel to the Gulf of Mexico coastline in a north-south orientation, whilst the Sierra Madre Occidental follows the Pacific coast in a north-west to south-east direction, reaching elevations of over 3,000m in places. These two ranges separate the coastal plains from Mexico's most distinctive topographic feature: the *Mesa Central* or Central Plateau. This huge plateau extends from north of the border with the USA to approximately 19°N, with an average elevation of 1,500m above sea level, increasing from north to south. A chain of volcanic mountains that dissect the country in an east-west direction defines the southern extremity of the Central Plateau. Known as the Trans-Mexican Volcanic Belt (TMVB) or Neo-Volcanic Axis (NVA), this mountainous region is primarily the product of Pliocene and Quaternary volcanism (Demant, 1978). Much of the terrain within the TMVB lies above 2,000m above sea level, containing the highest peaks in Mexico (Figure 2.1), including the Pico de Orizaba (5,699), Popocatapétl (5,452m), Iztaccihuatl (5,286m) and the Nevado de Toluca (4,575m). The physical characteristics of the TMVB are discussed in more detail in section 3.2. South of the TMVB, the Sierra Madre del Sur extends from the Pacific Coast across the Isthmus of Tehuantepec, where it becomes the Sierra Madre de Chiapas, continuing into the Guatemalan highlands.

2.3: The Present Day Climate of Mexico

Mexico is situated in a region highly sensitive to fluctuations in global circulation patterns that have occurred in the past (Metcalfe, 1987; Endfield and O'Hara, 1997). Mexico is influenced by three major components of the atmospheric circulation: the Northern Hemisphere Trade Winds, the Sub-Tropical High Pressure Belt (STHPB) and the Westerlies (Metcalfe *et al.*, 2000). The southern half of the country is largely dominated by the easterly Trade Winds, whilst further north, the Sub-Tropical High Pressure Belt brings generally drier conditions. In winter, north-west Mexico is visited by the mid-latitude Westerlies. The STHPB can be regarded as the boundary between the tropical atmospheric circulation of the Hadley Cell and the mid-latitude westerly circulation. Given that Mexico straddles the boundary between temperate and tropical climatic zones, it is reasonable to expect that fluctuations in the geographical extent of these circulation systems would be reflected in palaeoclimatic records from this region.

The Mexican climate is far more complex than the simple picture outlined above. The latitudinal position of the major circulation features varies between summer and winter, meaning that the Mexican climate is highly seasonal. Latitude is not the only major influence. The characteristic high relief of the country, which has been described above, is a major factor in determining local temperature and precipitation patterns (Mosiño and García, 1974; Cavazos and Hastenrath, 1990). Also important is the distribution of land and oceans. The interplay between these factors, which is discussed below, produces several distinct climatic features, notably a summer monsoon and a mid-summer drought, known as *La Canícula.*

2.3.1: The Seasonality of the Mexican Climate

Figure 2.2 is a schematic representation of the major features of the atmospheric circulation in Mexico in summer and winter. In winter, between November and April, the Inter Tropical Convergence Zone (ITCZ) is located close to the equator and the STHPB dominates the country, bringing dry and stable conditions. Occasionally, large masses of polar air, known as *nortes*, penetrate into eastern parts of Mexico, causing outbreaks of heavy rain (Mosiño and García, 1974). Westerly flows from mid-latitudes exert a considerable influence in the extreme north-west of the country, with depressions originating from the Pacific providing an important moisture source for this region. The north-west of Mexico is the only part of the country with a winter rainfall maximum. Mid-latitude westerlies can extend deep into Mexico during the winter months, sometimes as far south as 19°N. The high elevation of the land, as described in section 2.2, means that upper westerlies can be intercepted, producing cold conditions and snowfalls (Metcalfe *et al.*, 2000).

During the northern hemisphere summer, between May and October, the ITCZ is displaced northwards (Figure 2.2b), due to a reduction in the temperature gradient between the equator and the northern polar region. This northward migration is not as marked as over Africa (where it can approach 20°N), due to the lesser continentality of Central America (Nieuwolt, 1982). Unstable weather associated with the ITCZ is often experienced along the southern Pacific Coast of Mexico (Mosiño and García, 1974).

The two semi-permanent high-pressure cells which influence the Mexican climate, the Bermuda-Azores High and the East Pacific High, also experience a northward shift during the summer months. As the STHPB moves northwards in accordance with the ITCZ, a deep easterly flow, largely originating from the Gulf of Mexico and the Caribbean Sea, dominates much of the country, bringing heavy rainfall (Cavazos and Hastenrath, 1990; Dilley, 1996). Surges of moist air from the tropical eastern Pacific are channelled northwards through the Gulf of California, providing the major moisture source for north-west Mexico (Stensrud *et al.*, 1995). The terms 'Mexican Monsoon' (Douglas *et al.* 1993) and 'North American Monsoon' (Adams and Comrie, 1997) have been used to describe this seasonal reversal in wind direction. In this thesis, it will be referred to as the Mexican Monsoon, given that the area of greatest influence is north-west Mexico (Douglas *et al.*, 1993). This phenomenon is discussed in more detail in section 2.3.3.

A mid-summer drought, called *La Canícula*, is observed in eastern Mexico during July and August. A disruption to easterly flow across the country is caused by the development of an upper air trough over the Gulf of Mexico. Airflow is diverted northwards and blocks any tropical disturbances from entering the Gulf, temporarily halting an important precipitation source (Mosiño and García, 1974). During this time, moisture originating from the Pacific becomes increasingly important (Dilley, 1996). Drought conditions cease in September as tropical storms and hurricanes reach their maximum occurrence. These disturbances are discussed further in section 2.3.4.

2.3.2: The Effect of Orography

Aside from the effects of latitude, orography is the single most important factor determining local temperature and precipitation regimes (Mosiño and García, 1974). The principal topographic features of Mexico have been outlined in section 2.2. The presence of the numerous mountain ranges has a profound influence on the climate of Mexico.

At present, the Gulf of Mexico is the predominant moisture source for the country. The Sierra Madre Oriental intercepts these easterly air masses, causing most of the moisture to be released over the mountains themselves. This produces a marked precipitation gradient with considerably drier conditions in central and western parts, as only upper layers of the trade winds can flow over the Sierra. The existence of a high altitude plateau in Mexico is important in producing convective rainfall during the summer months. Surface temperatures at this altitude can become considerably greater than air temperatures at the same height over the Gulf of Mexico, due to a process known as the elevated heat source effect (Mosiño and García, 1974; Tucker, 1999). Incoming easterly waves from the Gulf are lifted when they encounter this elevated heat source, producing convective precipitation.

The Sierra Madre Occidental, in the west, forces the release of moisture from the Pacific as air masses are lifted. Moisture is carried onshore from the Pacific largely in the form of sea breezes, although tropical disturbances can also be important (section 2.3.4). These breezes are more important in the south-west of the country. The north-west is much more arid due to the proximity of the land to the cold California Current, which flows southwards along the Pacific coast, producing very stable conditions. The major moisture source here is in winter when the mid-latitude westerlies extend their influence southwards. Even then, precipitation is limited as the Sierra Madre Occidental deflects the westerly air masses southwards, causing them to flow parallel to the coast.

The orography of Mexico has a clear impact on the amount and distribution of precipitation. However, the mountainous terrain means that air temperatures are considerably lower than would be expected in a tropical region. The highest volcanoes in the TMVB, Pico de Orizaba, Popocatapétl and Iztaccihuatl, all over 5,000m, support permanent snow and ice fields.

2.3.3: The Mexican Monsoon

The summer monsoon circulation, which develops over central and northern Mexico, extending into the southern USA, has been described as "the most distinct regional scale convective weather phenomenon in North America" (Stensrud *et al.*, 1997). A monsoon circulation develops due to the combination of warm land surfaces and moisture supply from the nearby oceans (Adams and Comrie, 1997). The Mexican

Monsoon has two components: the seasonal reversal of trade winds which brings moisture from the Gulf of Mexico to the whole region, whilst west of the Sierra Madre Occidental, moisture surges originating in the Gulf of California bring rainfall to western Mexico and the south-west USA. The Mexican Monsoon has been the subject of numerous investigations. However, most have focused on the second component of the system, rather than on the larger scale monsoon that affects the whole of Mexico. Adams and Comrie (1997) provide a comprehensive review of the literature regarding this phenomenon. The key issues are briefly discussed here.

The Gulf of Mexico is the principal moisture source for the region (Sellers and Hill, 1974; Tang and Reiter, 1984). In north-west Mexico and south-west USA, however, air is unable to travel over the high altitude terrain without releasing its moisture (Douglas *et al.*, 1993). An alternative explanation for convective summer rainfall west of the Sierra Madre Occidental involves surges of moisture northwards along the Gulf of California (Hales, 1972; Stensrud *et al.*, 1997). Episodic low-level tropical disturbances at the mouth of the Gulf of California cause the development of atmospheric pressure gradients, forcing the moist air along the western slopes of the Sierra Madre Occidental into Arizona and New Mexico. Major surges appear to be related to the presence of a mid-latitude trough in the upper atmosphere, prior to the passage of an easterly wave at approximately the same longitude.

It is now generally agreed that at lower levels in the atmosphere, below 850 mb, the eastern tropical Pacific provides most of the summer moisture on the western side of the Sierra Madre Occidental and into the south-west USA. However, above 850 mb, most of the moisture arrives from the Gulf of Mexico (Higgins *et al.*, 1997). Unravelling the relative importance of these two moisture sources is problematic in the westernmost part of Mexico as mixing occurs over the Sierra Madre Occidental when low-level moist air from the Pacific is forced to rise (Adams and Comrie, 1997).

The strength and areal extent of the Mexican Monsoon can vary greatly from year to year. Given the complex nature of this circulation system, which incorporates synoptic-scale, and meso-scale features, and the paucity of long instrumental records, it is not surprising that the interannual variability of the Mexican Monsoon is poorly understood. The nature of climatic variability in Mexico is examined in detail later in this chapter in section 2.4.

2.3.4: Tropical Disturbances

Tropical disturbances are of great importance in determining precipitation patterns across Mexico. Easterly waves are relatively minor wave disturbances originating over the Caribbean, where the trade winds encounter lands masses which disrupt the flow of air (Nieuwolt, 1982). During the summer months a pattern of several rainy days between drier conditions, observed over much of Mexico, is consistent with a precipitation regime significantly influenced by wave motion. However, the considerable relief can break up these structures, preventing their influence over a wider area (Mosiño and García, 1974).

Tropical storms, or hurricanes, predominate in late summer, the greatest number occurring in September (Reyes and Mejía-Trejo, 1991), as progressive warming of ocean waters provides sufficient energy to induce storm formation. Hurricanes forming over the Atlantic Ocean and Gulf of Mexico frequently reach the east coast. Those originating in the eastern Pacific affect the Mexican mainland south of 25°N, but can also reach the southern portion of Baja California (Reyes and Mejía-Trejo, 1991). Storms developing in the eastern Pacific are associated with an open wave aloft, meaning that their influence can extend over the central highlands to bring heavy rains in late summer (Mosiño and García, 1974). Interannual variations in the number of tropical storms reaching Mexico have been related to the El-Niño Southern Oscillation. This is discussed in more detail in section 2.4.2

2.3.5: Temperature and Precipitation Patterns in Mexico

The major features of the Mexican climate, as outlined above, create a wide range of temperature and precipitation patterns across the country. In general, temperature varies less between seasons than precipitation, although distinct changes are observed.

In general, lowland areas of Mexico have an average temperature of approximately 20°C, whilst the highlands and northern part of the country experience greater diurnal variation (O'Brien and Liverman, 1996). During winter, due to the greater continentality in the northern half of the country, temperatures decrease from south to north. The *nortes* occasionally bring cold conditions to the east of the country, whilst the interception of upper westerlies at high altitudes can cause frosts (Perez, 1990). In summer, the reverse pattern is observed, with hotter temperatures in the north due to the heating of the central plateau.

All parts of Mexico, except the extreme north-west have a summer precipitation maximum, although distribution of rainfall is highly uneven. For example, 40 % of the country's total annual precipitation falls over just 7 % of the land in the south-east (O'Brien and Liverman, 1996). Precipitation is high along the southern Gulf coast, reaching 3,500 mm yr^{-1} in places, contrasting with values of between 500 and 1,200 mm yr^{-1} along the northern Gulf coast. Parts of the Sierra Madre de Chiapas experience annual precipitation of up to 4,000 mm. Moving northwards into the Central Plateau, conditions are drier. The southern portion of the Central Plateau receives between 600 and 1,000 mm of rainfall each year, with a precipitation maximum in July (García, 1965). The northern portion of the central plateau is much drier as it is situated within the STHPB and isolated from the major precipitation sources by high mountain ranges. Annual precipitation is less than 500 mm and often less than 300 mm. Baja California is very dry. Annual rainfall is generally below 300 mm, although it can be slightly higher in the mountains.

The information above provides a brief outline of the climatic regimes of Mexico. However, substantial variations in annual precipitation occur locally and interannual variability is high, particularly in regions of low rainfall (García, 1965; O'Brien and Liverman, 1996).

2.4: Climatic Variability in Mexico

Fluctuations in the climate of Mexico have been observed both on long (10^3) (Bradbury, 1989; Metcalfe *et al.*, 1997; Caballero *et al.*, 1999) and short (10^{1-2})

(Jauregui and Klaus, 1976; O'Hara and Metcalfe, 1995; Endfield and O'Hara, 1997) timescales. The nature and periodicity of climatic variability has become the focus of intense investigation during the last 15 years, as concern heightens about the impact of future climate change. Whilst such studies in Mexico are relatively few, compared with North America and Europe, a considerable amount of information on climatic fluctuations in Mexico is now available. Statistical analysis of instrumental records has been used to assess interannual variability, both in Mexico and across the North American tropics (e.g. Hastenrath, 1984; Ropelewski and Halpert, 1986; Rogers, 1988; Cavazos and Hastenrath, 1990). Proxy methods have also been employed to examine high-resolution climate variability in the region. These include dendroclimatology (e.g. Cleaveland *et al.*, 1992; Stahle and Cleaveland, 1993), laminated marine sediments (e.g. Biondi *et al.*, 1997; Schimmelman *et al.*, 1998) and annual coral growth bands (e.g. Carriquiry *et al.*, 1994; Slowey and Crowley, 1995). These studies have largely been driven by the need to understand the impact of the El-Niño Southern Oscillation (ENSO) on tropical and sub-tropical regions of North America. This phenomenon, regarded as the most important factor in global interannual climatic variability (Stahle and Cleaveland, 1993), is discussed in section 2.4.2. Historical records provide a valuable source for reconstructing climatic change. Mexico has extensive archives, with information extending as far back as AD 1400 (O'Hara and Metcalfe, 1995). Numerous such studies have been carried out in Mexico (Metcalfe, 1987; O'Hara, 1991, 1993; Florescano and Swan, 1995; Endfield, 1997), which are examined in section 2.4.3. A broader, long-term picture of climatic change in Mexico is provided by palaeoenvironmental investigations. These studies have largely focused on lake basins in the central Mexican highlands (e.g., Watts and Bradbury, 1982; Lozano-Garcia *et al.*, 1993; Metcalfe, 1995; Caballero and Ortega, 1998) and on the Yucatán Peninsula (e.g., Curtis *et al.*, 1996; Whitmore *et al.*, 1996). Palaeoenvironmental records of climate change in Mexico are the focus of section 2.4.4.

2.4.1: Interannual Variability

Interannual variability in tropical and sub-tropical regions can be attributed to an enhancement or reduction of the annual cycle (Hastenrath, 1984). In Mexico, this has been related to variations in the zonality of the atmospheric circulation. Jauregui and Klaus (1976) examined raínfall trends from 33 stations in north and central Mexico. They found that the behaviour of the upper westerlies in mid-latitudes influences the amount of precipitation falling in Mexico. During conditions of zonal flow, higher summer precipitation occurs due to a northerly extension of trade wind influence as the STHPB moves northwards. Meridional conditions are associated with drought in Mexico. An expanded ridge over western North America and the development of a closed anticyclonic cell, a westward extension of the Bermuda-Azores High, over the Mexican Plateau suppress the trade wind flow equatorward (Jauregui and Klaus, 1976). Tropical storms originating in the Atlantic have a more northerly trajectory during meridional flow, leading to fewer hurricanes reaching the Gulf coast (Jauregui, 1979). Increased precipitation may however be observed during winter along the Gulf coast as the meridional conditions allow more frequent penetration of *nortes* into the eastern part of the country (Jauregui and Klaus, 1976).

The Mexican Monsoon also experiences considerable interannual variability. Carleton *et al.*, (1990) found that wetter summers in Arizona are related to meridional flow and a more southerly displacement of the mid-tropospheric ridge, whilst relatively dry summers occur during zonal conditions, with the sub-tropical ridge located further north. Higgins *et al.*, (1998) examined the relationship between the monsoon and U.S. summer precipitation based on daily observed precipitation over a 32 year period. In accordance with Carleton *et al.*, (1990), they found that wet monsoons occur when the monsoon anticyclone is stronger than normal and shifted to the north-east. Dry monsoons are associated with a weaker anticyclone located south of its mean position. To date, however, there have been no studies that consider the impact of interannual variability of the monsoon system on the Mexican climate, as research has focused on the effects north of the border. If the mechanisms of this important climatic feature are to be fully understood, investigations need to be undertaken over the whole of the monsoon region.

Fluctuations in mid-latitude circulation patterns have a large influence on interannual climate variability in Mexico and neighbouring regions. Indeed, Malmgren *et al.*,

(1998) in their analysis of Puerto Rican climate trends, found a correlation between the North Atlantic Oscillation (NAO) and rainfall. The NAO is related to changes in the orientation of maximum moisture transport from the Atlantic across to Europe. A high NAO index is associated with a more south-west to north-east orientation of moisture transport across the Atlantic to Europe, compared with low or normal years. Analysis of data from five stations in Puerto Rico extending back to the beginning of the century, revealed that annual precipitation is lower during the high phase of the NAO (Malmgren *et al.*, 1998). There have been a number of recent studies concerning interannual climate variability in Mexico (Cavazos and Hastenrath, 1990; Cavazos, 1994; Pereyra *et al.*, 1994), although these have largely focused on the relationship to the El-Niño Southern Oscillation, a tropical phenomenon. No research has been carried out into the relationship between interannual precipitation variability in Mexico and mid-latitude circulation systems, such as the NAO and the Pacific-North American pattern (PNA). These oscillations both display decadal scale variability and are related to ENSO (Slowey and Crowley, 1995) although the exact nature of the teleconnnections is not clear. Such extra-tropical influences may be equally as important as ENSO events in determining climatic variability in Mexico and must be a priority for future research. The effect of ENSO events on climatic variability in Mexico is discussed below.

2.4.2: El Niño and the Mexican Climate

The El Niño Southern Oscillation (ENSO) phenomenon is the single most important factor affecting interannual climatic variability at a global scale (Diaz and Markgraf, 1992). Its often severe effects, such as extreme drought and flooding, have attracted the attention of the scientific community and the media alike in recent years. An exact definition of the phenomenon is problematic, given that the nature and duration of events has varied considerably through time (Diaz and Kiladis, 1992). ENSO events occur when sea level pressure (SLP) is lower than normal over the eastern equatorial Pacific whilst higher than normal SLP is observed over Australasia. A band of anomalously warm water develops across the central and eastern equatorial Pacific generating cloudiness and convection (Allan *et al.*, 1996), which typically brings flooding along the coast of Peru and Ecuador. This phase of the phenomenon is commonly known as El Niño, but is also referred to as the 'warm' or 'low' phase. In addition to flooding along western South America, El Niño events are also associated with drier conditions in the monsoon regions of Asia and Australasia, as the tropical rainfall regime experiences a major reorganisation (Diaz and Kiladis, 1992). Another important feature of ENSO is the La Niña phase (also referred to as 'cold' or 'high'). Essentially, this is an amplification of 'normal' conditions, with heavier than usual rainfall in monsoon regions and colder than normal sea surface temperatures over the eastern equatorial Pacific. There is considerable variability in the duration of ENSO events, which have a periodicity of between 3 and 7 years (Galindo, 1995). Recent analysis of instrumental and proxy records of ENSO events reveals a number of episodes of 'persistent' El Niño and La Niña conditions through time. The most recent, a protracted El Niño phase, occurred between 1990 and 1995 (Allan and D'Arrigo, 1999). The highly variable nature of ENSO events themselves, coupled with a variable response in different regions means that deciphering the exact impacts of this phenomenon is far from easy.

Published accounts of the impact of ENSO in Mexico have been relatively few (Galindo, 1995; Metcalfe *et al.*, 2000). A number of studies have explored the relationship between ENSO and large-scale precipitation variability in the circum-Caribbean region (Ropelewski and Halpert, 1986; Rogers, 1988; Kane, 1999). These are useful in providing a generalised picture of the effects of ENSO on the Mexican climate, although it is clear that Mexico displays a complex and variable response (Cavazos and Hastenrath, 1990). There are differences between the sub-tropical latitudes of the country, which are more heavily influenced by the upper westerlies and the southern, tropical latitudes, which are dominated by the location of the ITCZ. Furthermore, east-west differences may be as important as north-south differences as the Pacific and Atlantic oceans both respond differently to ENSO events.

In general, most of Mexico experiences increased winter precipitation during the El Niño (low) phase (Ropelewski and Halpert, 1986; Rogers, 1988; Kane, 1999) due to the intensification of mid-latitude westerly circulation (Ropelewski and Halpert, 1986; Cavazos and Hastenrath, 1990). In the summer, drier conditions prevail due to a southward displacement of the ITCZ (Rogers, 1988; Dilley, 1996). Higgins *et al.*, (1999), in their analysis of the variability of the Mexican Monsoon, found that dry monsoons in north-west and south-west Mexico are related to El Niño years and wet monsoons occur during the La Niña phase. ENSO events have a significant impact on tropical storm frequency in the region. During the El Niño phase, sea surface temperatures in the eastern Pacific are higher, leading to a greater frequency of tropical storms in late summer, whilst the number of perturbations over the Atlantic is diminished (Reyes and Mejía-Trejo, 1991). These general patterns of response are highly modified by features such as the penetration of *nortes*, which can have a considerable impact on precipitation levels in regions of relatively low rainfall. Such factors need to be taken into consideration when attempting any high-resolution climatic reconstructions.

Concerns about the possible increase in the frequency of extreme phases of ENSO due to the introduction of greenhouse gases into the atmosphere, has driven a concerted effort to investigate the variability of ENSO events in the past (Diaz and Markgraf, 1992). In the absence of long meteorological records, proxy methods are necessary to obtain palaeo-ENSO records. Mexico has been identified as a key region for developing ENSO chronologies using dendrochronology as it appears to show the most sensitive signal in North America (Cleaveland *et al.*, 1992). In northern Mexico, the El Niño phase brings moist and cool conditions to the region, which promotes above average tree ring widths the following year. The opposite relationship applies to La Niña episodes, but with less consistency (Stahle and Cleaveland, 1993). Tree ring chronologies extending back to 1699 from the northern Sierra Madre Occidental and the southern Great Plains of the USA were combined to produce a reconstruction of the Southern Oscillation Index (SOI). 56 extremes of winter SOI were identified between 1699 and 1965, although it is likely that a similar number remain undetected in the record (Stahle and Cleaveland, 1993). Data from these studies have since been incorporated into a global reconstruction of the SOI based on dendrochronological records from across ENSO sensitive regions (Stahle *et al.*, 1998). These reconstructions are valuable for comparison with other forms of proxy data, such as historical records and palaeolimnological records.

2.4.3: Historical Records of Climatic Variability

Following their arrival in Mexico in 1519 and throughout Colonial Period, the Spanish kept meticulous and detailed records covering all aspects of their new territory, including demographic patterns, economic and agricultural activities and environmental information. This wealth of information is now found in the country's many archives. The earliest historical sources containing environmental information are the pre-Hispanic *codices* and the *relaciones*, which were written shortly after the Conquest (O'Hara and Metcalfe, 1997). In the absence of long, reliable instrumental records (Jauregui, 1997), this vast array of historical documents provides the opportunity for reconstructing climatic fluctuations in Mexico (O'Hara and Metcalfe, 1995).

In a country where 85% of the land is classified as semi-arid, arid or very arid (O'Brien and Liverman, 1996), it can be of no surprise that water availability has been a major preoccupation of Mexican society through time. Abnormal weather conditions, such as drought or flooding, are therefore often referred to directly in historical documents (O'Hara and Metcalfe, 1997). They can also be elucidated indirectly through legal conflicts over access to water (Endfield and O'Hara, 1997). The strong link between agriculture and climate in Mexico was demonstrated by Florescano (1969). He inferred periods of low rainfall from information on crop yields and prices. Reconstructions of former lake levels from maps, descriptions and land disputes have also been successfully used as an indicator of changes in moisture availability (O'Hara, 1991, 1993; Endfield, 1997). However, drought and flooding are not the only indicators of climate change. Frost can have a severe impact on agricultural productivity and is often associated with meridional circulation patterns (Metcalfe, 1987). The variety of different sources used to reconstruct climate variability in Mexico has been synthesised in a number of papers (Metcalfe, 1987; O'Hara and Metcalfe, 1995, 1997). The following discussion provides an overview of the general climatic trends observed in the historical record. These are summarised in Figure 2.3.

The majority of documentary evidence for climatic change is found in the basins of Mexico, Toluca and Puebla and in the Bajío, historically, the most intensely populated areas of the country, with the earliest reliable records confined to the Basin of Mexico (Florescano and Swan, 1995). Drought episodes were recorded in the Basin of Mexico in 1052, 1064 and during the 12th century, although the intensity and duration of these events could not be determined (Florescano and Swan, 1995). Sanders *et al.*, (1979, cited in Metcalfe, 1987) suggest that prolonged drought during the 12th century was an important factor in the collapse of Tollán, the capital city of the Toltec empire. The *Relaciones originales de Chalco Amaquemecac* refer to drought in the southern part of the Basin of Mexico around 1287, 1328, 1332 and 1347 (Sánchez-Mora, 1980, cited in Florescano and Swan, 1995). It is thought that drought conditions in the north of the country prompted the southward migration of the *Azteca* or *Mixteca* who finally settled in the Basin of Mexico around 1345 (Metcalfe, 1987). The Aztecs built their capital, Tenochtitlán, on an island in one of the numerous lakes within the basin, apparently unaware of the potential threat of flooding. This led O'Hara and Metcalfe (1995) to conclude that a drier climate may have prevailed at the time the capital was established. The Aztec Period (AD 1345-1521) seems to have been dominated by generally wetter conditions in the Basin of Mexico (O'Hara and Metcalfe, 1995). Rising lake levels at Lago de Pátzcuaro in Michoacán, to the west, between 1380 and 1520 (O'Hara, 1991) indicate that this was indeed a regional phenomenon. Heavy rains, which flooded the capital regularly around 1382, were followed by a series of extremely wet summers during the 1440s, resulting in the construction of the Albarradón de Netzahualcóyotl dyke ca. 1450 to protect Tenochtitlán from inundation (Metcalfe, 1987). However, it appears that the Aztec civilisation was also affected by drought (O'Hara and Metcalfe, 1995). A number of sources, including the *Anales de Tlatelolco* and the *Crónica Mexicáyotl,* report a severe drought in the Basin of Mexico, lasting three to four years (Florescano and Swan, 1995: p. 168). In 1460 it was said to have "rained fire" in Tenochtitlán (Florescano and Swan, 1995: p. 52) due to the intensity of the sun. The *Códice Chimalpopoca* refers to a drought lasting two or four years around 1502. Harvests were so bad that maize had to be imported from elsewhere. The effects of the drought were so severe that the war between the Aztecs and the neighbouring

Tlaxcalans came to a brief halt (Sanchez-Mora, 1980, cited in Florescano and Swan, 1995).

A generally wetter climate continued to prevail following the arrival of the Spanish in 1519. Cortes encountered high lake levels in the Basin of Mexico during the Conquest (Metcalfe, 1987), whilst Lago de Pátzcuaro was at its highest level of the whole historical period in 1522 (O'Hara, 1993). A shift to drier conditions was experienced from the mid-16th century. Of the 12 droughts identified by Florescano and Swan (1995) in the 16th century, 9 occur after 1570. Butzer and Butzer (1993) report the desiccation of Lago de Cuitzeo in Guanajuato in 1543, whilst numerous sources indicate drought and frosts during the same year (Florescano and Swan, 1995: p. 173). The small water body of San Gregorio, an important resource for the townspeople of Pátzcuaro was drying up in 1550 (Endfield, 1997) and Lago de Pátzcuaro itself was at a low stand between 1560 and 1564, although this does not appear to have persisted (O'Hara, 1993). A return to wetter conditions was experienced during the late 1570s and 1580s, when maps indicate higher levels of Lago de Cuitzeo (Butzer and Butzer, 1993), although drought in Mexico City was recorded in 1576 and 1580 (Florescano and Swan, 1995: p. 173). The 1590s were very dry in Mexico, evident by the desiccation of Lago de Cuitzeo in 1591 (Butzer and Butzer, 1993) and records of severe droughts and frosts in the Basin of Mexico in 1594, 1597 and 1598 (Gibson, 1964, cited in Florescano and Swan, 1995). Tree ring records from the north of Mexico suggest dry conditions between 1590 and 1610 (O'Hara and Metcalfe, 1995), indicating that this was a regional climatic signal. Despite the severe droughts that appear to have afflicted Mexico at the end of the 16th century, Endfield (1997) found very little evidence of disputes over water in Michoacán. She argues that pressures on natural resources would have been low at this time, following the decimation of the indigenous population after the Conquest.

The 1590s were to signal the onset of a shift towards a drier climate in Mexico, which lasted until at least the 1820s (O'Hara and Metcalfe, 1995). The early part of the 17th century appears to have been marked by fluctuating conditions, with reports of rivers drying up around Lago de Pátzcuaro in 1605 and again in 1612, whilst

Mexico City was once again inundated in 1604 and 1607 (O'Hara and Metcalfe, 1995). In the mid-17th century, Zamora in Michoacán was plagued by a series of frosts and late rains bringing with them epidemics, harvest failures and crop pests in between 1630 and 1660 (Pastor and Frizzi, 1989, cited in Endfield, 1997). In 1644, according to Fray Diego de la Basalenque, Lago de Cuitzeo had again desiccated (Endfield, 1997). Drought conditions also dominated in the Basin of Mexico between 1640 and 1720, with particularly severe episodes in 1641, 1661, 1663 and 1692. A total of 29 droughts are reported across the state of Michoacán between 1661 and 1785 (Florescano and Swan, 1995). The spatial extent of these reported droughts indicates a regional scale climatic shift from the generally wetter conditions of the Aztec and immediately post-Colonial periods. The combination of drought and frosts often reported implies a more meridional circulation pattern in the upper westerlies (Metcalfe, 1987).

Drought conditions intensified during the 18th century, with 50 droughts identified in Mexico between 1701 and 1821, compared with 25 between 1600 and 1699 (Florescano and Swan, 1995). Between 1700 and 1736, no less than 36 disputes over water resources were documented in the basins of Pátzcuaro and Cuitzeo (Endfield, 1997). It is likely that increases in population and monopolisation of resources by powerful groups and individuals served to exacerbate water shortages (Endfield and O'Hara, 1997). There is evidence for falling lake levels at Lago de Pátzcuaro during the early 1700s (O'Hara, 1993). By the mid-18th century, however, water levels were rising again as evident from records of land disputes (Endfield, 1997). In the Basin of Mexico there is no evidence for adverse weather conditions during the mid-1700s (O'Hara and Metcalfe, 1995). The latter part of the 17th century was to see a return to drier conditions, with a shortening of the rainy season from July to November to August to October in the Basin of Mexico (Swan, 1981). Whilst the level of Lago de Pátzcuaro was relatively high until the early 1780s, reports of lake bed being exposed in 1791 and 1793 suggest a marked decline in water level (O'Hara, 1993; Endfield, 1997). "The year of great hunger", as it has now become known, occurred between 1785 and 1786 (O'Hara and Metcalfe, 1997), when maize prices rose dramatically due to a devastating combination of severe drought and frosts. Repercussions were felt in all economic sectors, with many factories forced to reduce production (Florescano and Swan, 1995). Further drought between 1807 and 1810 exacerbated agricultural and economic problems, playing a significant part in the political unrest and eventual revolution in 1810 (Florescano and Swan, 1995). It has been suggested that the prolonged drought conditions between the mid-18th and early 19th centuries were a tropical manifestation of the Little Ice Age (Swan, 1981; Endfield and O'Hara, 1997). Endfield and O'Hara (1997) coined the term "The Little Drought Age". Whilst it is clear that there was significant climatic drying in Mexico during this period, some caution should be adopted before relating it to any global mechanisms. Further work needs to be done on this issue before a causal link can be established.

There are few archival records pertaining to the early 19th century, largely due to the political upheaval at the time (O'Hara, 1993). It does appear, though, that conditions remained generally dry following the War of Independence in 1821. Padillas and Rodríguez (1980, cited in Florescano and Swan, 1980) report 10 regional and national scale droughts in the Mexican Republic between 1822 and the close of the century, the most severe occurring in 1868, 1877-78, 1891 and 1892. Low lake levels are also inferred at Lago de Pátzcuaro from the mid-19th century, although a dramatic rise in level documented in the late 1800s may well be associated with a major earthquake (O'Hara, 1993).

Instrumental records began in Mexico in the 1870s (O'Hara and Metcalfe, 1995). Analysis of the longest records from the country by Jauregui (1997) shows that the country was indeed affected by widespread and severe drought between 1892 and 1896. A number of winter storms bringing hail, snow and rain to Mexico City were also observed between 1878 and 1895, suggesting cold polar outbreaks (Jauregui, 1997). Summer droughts accompanied by cold winters at the end of the 19th century and into the beginning of this century are again suggestive of meridional circulation. A positive index of the winter phase of the Pacific North American pattern (PNA), indicative of meridional conditions, has been observed during this period in coral records from the Gulf of Mexico (Slowey and Crowley. 1995). Again, drought conditions led to political unrest, culminating in the Mexican Revolution in 1911 (Metcalfe and O'Hara, 1995). Extremely severe droughts were recorded in Mexico during the 1920s, late 1950s and 1960s (Florescano and Swan, 1995). However, instrumental records do not show these events clearly. This may be due to a mismatch between the areas affected and the location of meteorological stations (Jauregui, 1997). Most of these droughts appear to have affected only northern parts of the country (Florescano and Swan, 1995). Since the late 1960s, average rainfall in Mexico City has been increasing, as evident in the record form the observatory of the Servicio Meteorologico Nacional at Tacubaya (Jauregui, 1997). However, a decrease in annual rainfall has been observed in instrumental records from Michoacán between 1970 and 1986 (Antaramian and Múzquiz, 1997).

It seems that the wider the spatial coverage of information, the more complex the picture of climatic fluctuations in Mexico becomes. As discussed in sections 2.4.1 and 2.4.2, different parts of the country respond in different ways to changes in atmospheric circulation. Difficulties in identifying clear patterns are compounded by the imprint left behind by features of the global climate such as the interdecadal scale NAO and PNA and the interannual variability of ENSO events. Whilst a relatively simple picture of wetter conditions between 1340 and 1590, shifting to a drier climate between 1590 and 1820 emerges from historical sources, short lived departures from the general trends occurred during these periods. It may be that the records are over-simplified due to the lack of data. With increasing coverage during the 20th century, it certainly does appear that identifying general climatic trends is somewhat problematic.

2.4.4: Palaeoenvironmental Records of Climatic Change in Mexico

Climatic fluctuations observed in the historical and instrumental records discussed above, are superimposed on much broader shifts in circulation patterns, evident in palaeoenvironmental records spanning the late Quaternary. As Metcalfe *et al.*, (2000) provide a synthesis of climatic records covering this period, including diatom, pollen and stable isotope records, only a brief summary is provided here. All dates mentioned are uncalibrated ^{14}C ages, unless otherwise stated. More detailed discussion of the nature of changes during the last 2,000 years follows, as this corresponds to the time scale of this study.

During the Last Glacial Maximum, around 18,000 yr. BP, rainfall patterns over Mexico were very different from the present day situation described above (Figure 2.4). The summer monsoon regime appears to have collapsed (Metcalfe *et al.*, 2000), with drier conditions in central Mexico and on the Yucatán Peninsula. However, northern and western parts of the country experienced much wetter and cooler conditions, as southward displaced mid-latitude westerlies brought increased winter precipitation from the Pacific (Bradbury, 1997a). The nature of the Pleistocene-Holocene transition in Mexico is not clear. Records from northern Mexico suggest a persistence of wetter than present conditions until at least 9,000 yr. BP, although whether this was due to summer or winter precipitation is disputed (see Spaulding and Graumlich, 1986; Van Devender *et al.*, 1990 and discussion in Metcalfe *et al.*, 2000). The few records from the Yucatán and those from central Mexico indicate generally dry, but fluctuating, conditions during the early Holocene. It was only after 9,000 yr. BP that the summer monsoon precipitation regime was established. A relatively wet mid-Holocene was interrupted by a marked dry phase c. 5,000 yr. BP in the central highlands, which does not appear to have affected the Yucatán Peninsula. The present day climate of the northern deserts was established by approximately 4,000 yr. BP. The late Holocene was marked by a number of climatic fluctuations, evident in lake records in the central highlands and the Yucatán (e.g. Metcalfe and Hales, 1994; Curtis *et al.*, 1996; Bridgwater *et al.*, 1999). The most dramatic of these was an intense dry phase, which is dated between 1500 and 900 yr. BP (O'Hara *et al.*, 1994), which has been related to the demise of the Classic Mayan civilisation (Hodell *et al.*, 1995). The nature and timing of climatic fluctuations over the last two millennia, as evident in the palaeoenvironmental record, will now be examined more closely. A location map of sites mentioned in the text is provided in Figure 2.5.

Attempts to investigate climatic variability during the last 2,000 years in Mexico have been relatively few. Archaeological investigations provided the first insights into the nature of changes over this period (e.g. Sanders *et al.*, 1979). Palaeolimnological studies have been concentrated in the closed lacustrine basins of the TMVB (Metcalfe *et al.*, 1991; Lozano-García *et al.*, 1993; O'Hara *et al.*, 1993; Metcalfe and Hales, 1994) and on the Yucatan Peninsula (Leyden *et al.*, 1994; Hodell *et al.*, 1995; Whitmore *et al.*, 1996). However, obtaining a clear late Holocene climatic signal from these records has proved to be problematic for two principal reasons: the effect of human impacts and poor chronological control (Metcalfe, 1997). Evidence in lake sediments of human activity extends back as far as 6,500 years (Sluyter, 1997). The Basin of Mexico has been the subject of intensive palaeoenvironmental investigations (Bradbury, 1971, 1989; Lozano-García *et al.*, 1993; Caballero, 1995, 1997; Caballero and Ortega, 1998). However, a combination of desiccation and deflation during dry intervals and considerable modification of the lake bed mean that there is no evidence for the last 3,000 years in these records (Caballero, 1995; Caballero and Ortega, 1998). Evidence of extensive soil erosion, since 3,500 ^{14}C yr. BP, has been found in the sediments of Lago de Pátzcuaro, Michoacán (Street-Perrott *et al.*, 1989; O'Hara *et al.*, 1993), whilst other records indicate considerable human impact over the last 1-2,000 years (Metcalfe and Hales, 1994; O'Hara *et al.*, 1994; Whitmore *et al.*, 1996). Developing reliable chronologies is thwarted by extensive erosion in these catchments, where the inwashing of old carbon may produce artificially old ^{14}C dates (Metcalfe, 1997) and lead to reversals in a sequence of dates (Metcalfe, 1992). In areas of carbonate geology, such as the Yucatán, the problems of ^{14}C dating are confounded by hard water error. Recent studies have been able to correct for this, but rely on the occurrence of terrestrial matter in the sediments which can be AMS dated (e.g. Curtis *et al.*, 1996). Metcalfe (1997) argues that more reliable chronologies could be obtained through the use of tephrochronology and ^{210}Pb methods. The application of these techniques in this study is discussed in Section 4.9.

Despite the problems discussed above, there is compelling evidence for significant climatic change around 1,000 years BP in the highlands of central Mexico. Desiccation of Lago de Chiconahuapan, in the Upper Lerma Basin, occurred between 1400 and 900 yr. BP (Metcalfe *et al.*, 1991). A decline of 4-5m at Lago de Pátzcuaro in Michoacán and evidence of catchment stability between c. 1,200 and 850 yr. BP are indicative of much drier conditions (O'Hara, 1991; O'Hara *et al.*, 1993). The presence of reed mats and the diatom assemblage in core material from nearby Laguna Zacapu around 1,000 yr. BP also support this conclusion (Metcalfe, 1992; 1995). Evidence of prolonged drought is also found in sediment cores from La Piscina de Yuriria (Metcalfe and Hales, 1994), Lago de Zempoala and Lago de Quila (Almeida-Leñero *et al.*, 1998). This arid phase was first identified on the Yucatán at Lago de Chichancanab, where enriched $\delta^{18}O$ in carbonate fossils and high sulphur content of sediments was found between 1,300 and 1,100 ^{14}C yr. BP. (AD 800-1,100). Hodell *et al.*, (1995) suggested a causal link between this dry interval and the collapse of the Maya civilisation, which occurred between AD 750 and 900. Evidence for aridity is also found at Punta Laguna between 1,785 and 930 ^{14}C yr. BP, with particularly intense episodes around 1,171, 1,019 and 943 ^{14}C yr. BP (AD 862, 986 and 1051 respectively) (Curtis *et al.*, 1996). Although wetter conditions have generally prevailed at this site for the last c. 1,000 years, a dry episode around AD 1,391 has also been identified (Curtis *et al.*, 1996). The identification of an aridity signal between c. 1,500 and 900 yr. BP across central and south-east Mexico clearly points towards at least a regional scale climatic fluctuation.

Palaeoenvironmental research in Mexico has generally focused on identifying broad scale, long term climatic variations. There is a clear need to focus on obtaining records of finer resolution that may shed light on climatic changes during the most recent past. That is one of the principal aims of this thesis. The following chapter introduces the study area, the Trans-Mexican Volcanic Belt of Central Mexico, in detail, outlining the reasons for its selection in light of the identified research objectives.

Chapter 3: Background to the Study Area

3.1: Introduction: The Choice of Central Mexico

The volcanic highlands of Central Mexico have been chosen as the focus of this palaeolimnological study for a number of reasons:

- The Trans-Mexican Volcanic Belt represents a 'hinge zone' between those parts of Mexico which are dominated by the STHPB and the Trade Winds. It is therefore, more likely to be sensitive to the more subtle shifts in circulation patterns that have occurred over the Late Holocene.
- Within the TMVB, numerous closed lacustrine basins are to be found, which are ideal for palaeolimnological investigations. These basins are more likely to contain continuous sediment records than those in the drier, northern parts of the country.
- Since the pre-Hispanic period, the central Mexican highlands have been the most densely populated part of the country. Rich in archaeological and historical information, this region provides an unparalleled opportunity for the examination of human-environment interactions.
- There exists a significant amount of information from previous palaeolimnological investigations and archival research in Central Mexico, which can be compared with the results from this study.

This chapter provides an introduction to the physical and cultural setting of the Trans-Mexican Volcanic Belt. The geology, hydrology and climate of the TMVB are described in detail in Section 3.2. The TMVB has a long history of human occupation, which is discussed in Section 3.3. Particular focus is placed on the debate surrounding the nature and extent of human impact on the environment since settlement began. At the end of the chapter, selection of suitable sites for palaeolimnological work is discussed. The choice of the two field sites, Lago de

Zirahuén in Michoacán and Laguna de Juanacatlán in Jalisco, is discussed in the light of the research objectives identified in Chapter 1.

3.2: The Trans-Mexican Volcanic Belt: Physical Environment

The TMVB cuts across Mexico in roughly an E-W orientation between 18 and 22°N. These volcanic highlands link the Sierra Madre Occidental and the Sierra Madre Oriental, forming the southernmost limit of the Central Plateau (see Section 2.1 and Figure 2.1). Located along this axis are numerous endorrheic lacustrine basins of tectonic and volcanic origin, which are of particular interest for the purposes of this study. The geological evolution of the TMVB has greatly influenced the present day climatic and hydrological characteristics. These principal features are discussed in this section.

3.2.1: Geology

The TMVB is an active continental volcanic arc, formed in response to the subduction of the Cocos Plate (Righter *et al.*, 1995). Unlike other such arcs, it does not run parallel to the subduction zone, the Middle American Trench, but makes an angle of approximately 15° to it (Hasenaka and Carmichael, 1985). The western portion of the TMVB appears to be associated with subduction of the Rivera Plate beneath the North American Plate at a higher angle of 45° (Righter *et al.*, 1995). The major features discussed here are illustrated in Figure 3.1. Whilst its boundary with the folded Mesozoic rocks of the Sierra Madre Oriental is well defined, the distinction between the Sierra Madre Occidental and the TMVB is less clear. The Sierra Madre Occidental, oriented NNW-SSE, is dominated by andesitic volcanic rocks of Eocene-early Miocene age. The TMVB, on the other hand, is oriented in a predominantly E-W direction, principally of basaltic to intermediate composition. The timing of the onset of TMVB activity has been disputed, with suggestions ranging from the late Oligocene to the Quaternary (Ferrari *et al.*, 1994). It is clear, however, that much of the volcanic terrain seen today is due to Pliocene and Quaternary activity. The numerous tectonic and volcanic processes that have formed the TMVB have created four distinct regions. These are described below.

The Western Sector

A combination of continental rifting and subduction of the Rivera plate influence the volcanic activity in the westernmost portion of the TMVB (Righter *et al.*, 1995). Basin and Range type extension in this sector since the middle Miocene has led to the development of three major rift systems: the Tepic-Zacoalco rift (NW-SE orientation), the Colima rift (N-S) and the Chapala graben (E-W), shown in Figure 3.2. The intersection of these fault zones lies approximately 50 km to the south of Guadalajara. The extinct Nevado de Colima and the active stratovolcano, Volcán de Colima, mark the southern edge of the Colima rift (Carmichael *et al.*, 1996). The Volcán de Colima is historically the most active in Mexico. The Tepic-Zacoalco and Colima rifts form the boundaries of the Jalisco Block, which is composed of Cretaceous rhyolite and ash flow tuff. Within it are found the Pliocene-Quaternary volcanic centres of the Mascota Volcanic Field and Los Volcanes (Carmichael *et al.*, 1996), illustrated in Figure 3.2. This region is discussed in more detail in Chapter 7. Historical evidence of a large earthquake in 1568 to the southwest of Guadalajara suggests that active deformation is still occurring in the Jalisco Block (Suarêz *et al.*, 1994). Strong earthquakes have occurred at the Jalisco Block – Rivera plate boundary this century in 1932 and 1995, measuring 8.2 and 7.9 on the Richter Scale respectively (Carmichael *et al.*, 1996).

The Michoacán-Guanajuato Volcanic Field

The Michoacán-Guanajuato Volcanic Field (MGVF) represents one of the most concentrated areas of monogenetic volcanic activity in the world, covering an area of approximately 40,000 km^2, in southern Guanajuato and northern Michoacán (Figure 3.2). The MGVF contains over 1,000 late Quaternary volcanic centres (Hasenaka and Carmichael, 1985), cinder cones making up 90 % of the total, with small numbers of lava domes, lava cones, lava flows and maars. Over 300 medium-sized volcanoes are also found, mainly shield volcanoes, whilst large composite volcanoes, such as Cerro Tancítaro and Cerro Paracho in the western part of the field, are rare (Hasenaka and Carmichael, 1985). The youngest volcanoes in the MGVF are Volcán Jorullo, which erupted between 1750 and 1774, and Volcán Paricutín (1943-1952). It is likely that tephra from these volcanoes was deposited in lake sediments in Michoacán, providing a clear and precise chronological marker. The intense volcanic activity in this region since the late Quaternary has undoubtedly had a major impact on hydrology. Maar lakes have been created, such as those in the Valle de Santiago of southern Guanajuato, whilst others, such as Lago de Zirahuén, have been formed by the damming of rivers by lava flows.

Toluca-Puebla Region

The Humboldt Line, an extension of the Chapala-Tula fault zone begins to the west of the Toluca Basin, continuing in an east-west direction. The large stratovolcanoes of the Nevado de Toluca, Popocatepétl, Iztaccihuatl and La Malinche occur at points where this fault line crosses older NW-SE oriented fault zones (Johnson and Harrison, 1989). This region contains three major basins from west to east: the Toluca Basin, the Basin of Mexico and the Puebla Basin. The three principal basins in this region have all contained lakes during the late Pleistocene (Metcalfe *et al.*, 1991; Caballero and Ortega, 1998) although their extent today is greatly diminished, or in the case of the Puebla Basin, they have completely disappeared.

The Oriental Basin

The chain of volcanic peaks, which include the Cofre de Perote and the Pico de Orizaba, at 5,750 m the highest peak in Central America, defines the eastern limit of the TMVB. This N-S oriented chain marks the edge of a graben in which the Oriental Basin is located. Several late Quaternary maars erupted from the main basin floor. Some of these contain lakes, such as Alchichica, Preciosa, Quechulac and Atexcac, whilst others are dry (e.g. Jalapasquillo). Remnants of the Mesozoic calcareous basement rock are visible in the southern part of the basin.

3.2.2: Climate

The present day climate of Mexico, as a whole, has been discussed in Section 2.3. Here, the focus is on the climatic regime of the TMVB. Like most of Mexico, the TMVB is characterised by wet summers and dry winters. According to the Köppen classification, this region is of 'C' type: humid-temperate (García, 1973). The average annual temperature across the TMVB is approximately 15°C, although there are large local variations related to altitude. Annual precipitation across the TMVB varies from approximately 1,000 mm yr^{-1}, in southern parts to approximately 500 mm yr^{-1} in the north, although as with temperature, these values are subject to modification due to the effects of orography.

The TMVB has traditionally been split into two altitudinal zones: the *Tierra Fría* and the *Tierra Templada*. The former includes all land above 2,000 m a. s. l., whilst the latter comprises terrain between 1,000 and 2,000 m a. s. l. As the name suggests, temperatures are lower in the *Tierra Fría*, frosts commonly occurring during the winter months. Permanent snow and ice are found on the highest mountains (>5,000 m a. s. l.). The incidence of winter frosts decreases on descending into the *Tierra Templada* and is also lower along the semi-arid northern fringes of the TMVB. Average annual temperatures vary greatly, even within these zones. For example, mean annual temperature on the Nevado de Toluca (c. 4,140 m a. s. l.) is 4°C (Caballero, 1995), whilst in the Toluca Basin (c. 2,575 m a. s. l.) it is around 12.5°C (Metcalfe, 1985). In the *Tierra Templada*, temperatures range between 18.1°C and 21.9°C. Across the TMVB, the coldest month is usually January, whilst the warmest month is either April or May, signalling the onset of the rainy season approximately one month later.

The TMVB is characterised by strong precipitation gradients. In general, the southern slopes of the TMVB are wetter as these are on the windward side. Average annual rainfall can reach up to 1,500 mm yr^{-1} along the southern fringes and higher terrain of the TMVB. Moving northwards towards the Central Plateau, precipitation decreases due to the increased continentality. Average annual precipitation figures for weather stations in the state of Michoacán illustrate this well. Uruapan, on the southward facing slopes receives 1,683 mm yr^{-1}. At Zirahuén (c. 2,075 m a. s. l.) in the sierra, average rainfall is approximately 1,182 mm yr^{-1}, whilst Morelia (c. 1,941 m a. s. l.) further north, receives approximately 745mm yr^{-1} (Data obtained from *Sistema de Informacion Climática de Michoacán*, Antaramian and Múzquiz, 1997). On the southern fringes of the Central Plateau, around the Valle de Santiago in Guanajuato, precipitation is around 700 mm yr^{-1}. The sub-humid to semi-arid transition zone between the TMVB and the Central Plateau experiences higher interannual variability than the more humid-temperate zones. However, not only is there a north-south precipitation gradient, but also a difference between eastern and western sectors of the TMVB. The Oriental Basin experiences a rain shadow effect caused by the presence of the Sierra Madre Oriental. Average annual precipitation here is less than 400 mm yr^{-1}, even though, at approximately 2,400 m a. s. l., the basin is at a relatively high altitude. Highlands in the western sector of the TMVB, on the other hand, receive larger amounts of rainfall. For example, the average annual total at Mascota in Jalisco is approximately 1,025 mm yr^{-1} (IMTA, 1996). In this western region, precipitation is augmented by the occurrence of tropical storms in the Pacific during late summer. During winter, *nortes* can bring rainfall to eastern and central parts of the TMVB, but these are usually restricted to the Gulf coastal plains and the eastern slopes of the Sierra Madre Oriental. As would be expected, potential evaporation varies across the TMVB. In the east, the Oriental basin experiences a moisture deficit of 100-200 mm yr^{-1}. The Basin of Mexico has a negative water balance, with many parts of the basin experiencing a deficit of around 1,000 mm yr^{-1} (Caballero, 1995). Southward facing slopes and areas of higher elevation tend to have a positive water balance.

The considerable variations in temperature, precipitation and evaporation across the TMVB, along with the geological processes that have shaped the topography, play an important role in the hydrological regime. This is examined in detail in the following section.

3.2.3: Hydrology

Within the TMVB are three major drainage basins: 1) the Lerma-Chapala-Santiago river system, which drains into the Pacific Ocean, 2) the Basin of Mexico and 3) the Oriental Basin, the latter two being endorrheic. To the south, the Balsas river basin runs almost parallel to the TMVB, draining its southern slopes into the Pacific Ocean. On the northern fringe of the TMVB, the Bajío, a large volcanic basin with many small internally draining basins (Butzer and Butzer, 1997), stretches from Lago de Cuitzeo in the south, up to the northern border of the state of Guanajuato. In addition to these major features, a large number of lakes of tectonic and volcanic origin are found in grabens, maars, calderas and valleys dammed by lava flows. Figure 3.3 illustrates the location of the basins and rivers discussed in this section.

East of the Basin of Mexico, the Oriental Basin covers an area of approximately 500 km^2. Diatomite deposits provide evidence of large lakes in this basin in the past, although all that exist today are a number of ephemeral streams and two playa systems. The playa of El Salado has been dry for a number of years and is now used for agriculture, whilst Totolcingo has dried out in the last decade and is also likely to be given over to cultivation (Alcocer and Escobar, 1996). Six crater lakes are found in the Oriental Basin: Alchichica, Preciosa, Quechulac, Atexcac, Aljojuca and Tequitlapa. Their depth ranges from 64 m (Alchichica) to 2.5 m (Tequitlapa), although excessive abstraction of groundwater is causing a reduction in water level (Alcocer and Escobar, 1990).

The Basin of Mexico is naturally an endorrheic system, however, artificial drainage has been occurring for the past 400 years. A series of canals and tunnels which have been under construction since the early 1900s now drain the basin (Alcocer and Williams, 1996). Prior to these modifications, a number of lakes, at times interconnected, occupied the basin floor. The major sub-basins are, from north to south: Tecocomulco, Zumpango, Xaltocan, San Cristobal, Texcoco, Xochimilco and Chalco. Today, only remnants of the former lakes remain in Texcoco, Chalco, Tecocomulco and Zumpango. The sub-basin of Xochimilco is dissected by a number of irrigation canals, which formerly sustained areas of intensive cultivation known as *chinampas*.

The source of the Río Lerma is in the southern part of the Toluca Basin. Although drainage in this basin is at present exorrheic, it is believed to have been hydrologically closed for periods during the Holocene (Metcalfe *et al.*, 1991). The Lerma drains into the largest lake in Mexico, Lago de Chapala, which occupies the graben along the Chapala rift zone. The Río Santiago flows from the west of Lago de Chapala, draining into the Pacific.

A number of closed lacustrine basins are found in the state of Michoacán. Lago de Cuitzeo (1,820 m a. s. l.) represents the state border with Guanajuato. Occupying a graben along the Humboldt Line, it is the second largest lake in Mexico. Although it has been deeper in the past, artificial drainage, groundwater abstraction and climatic changes have lowered the level of the lake, allowing a highway to be constructed, which crosses the basin floor from north to south. To the west of the causeway, the lake is often completely dry. There are also frequent historical references to its desiccation (see Section 2.4.3). Other important lakes in Michoacán are Lago de Pátzcuaro (2,035m a. s. l.) and Lago de Zirahuén (2,075m a. s. l.). The geographical location, altitudinal gradation and the common occurrence of fish species between these basins, led De Buen (1943) to suggest that these lakes were all once connected. He argued that they were formerly part of a tributary of the Lerma, which then became isolated by successive periods of volcanic activity. De Buen (1943) proposed a model of youth, maturity and old age for these three lakes, with Zirahuén being the youngest and Cuitzeo the oldest. This issue is still the subject of debate amongst limnologists in Mexico (Bernal-Brooks, 1998). The hydrology and limnology of the Zirahuén basin are explored in chapter 6.

Aside from Lago Chapala, the western sector of the TMVB also contains a number of lacustrine basins. A large playa system is located within the Colima-Zacoalco rift zone. Shallow lakes within this system include Lago de Sayula, Lago de Zacoalco, Lago de Zapotitlan and Lago de Atotonilco. Exposure of Tertiary diatomite deposits in the hills above Atotonilco point towards a greatly expanded lacustrine system in this area in the past. Crater lakes are found on the northern margin of the Jalisco Block in Nayarit, including Santa Maria del Oro. Other lakes of volcanic origin occur in the highlands, such as the Laguna de Juanacatlán, a lava-dammed lake. Chapter 7 focuses in detail on this lake.

As this brief examination of the hydrological characteristics of the TMVB has shown, human impacts in this region have been substantial, leading to significant modifications of the natural environment. The following section focuses on the history of settlement in the central Mexican highlands, examining in particular human-environment interactions.

3.3: Human Influences in the Trans-Mexican Volcanic Belt

The TMVB has been the focus of human settlement in Mexico since the prehistoric period. Attracted by the temperate climate, abundant lacustrine resources and fertile volcanic and alluvial soils, early settlements were focused around the numerous lake basins, eventually transforming into highly organised and politically complex civilisations. This pattern of settlement has continued to the present, with Mexico City, the capital and home to over 20 million people, sprawling across the Basin of Mexico. This section examines human settlement along the TMVB, focusing on two distinct periods: the Prehistoric Period and the Colonial Period. A key element of this discussion is the relationship between settlers and their environment, in terms of resource exploitation. These relationships continue to be the subject of debate amongst researchers (Denevan, 1992; Butzer and Butzer, 1993).

3.3.1: Archaeology

Possibly the earliest evidence of humans in the TMVB was found at Tepexpan in the Basin of Mexico, although these apparently Pleistocene remains were never dated (Bradbury, 1989). Figure 3.4 illustrates the location of archaeological sites referred to in this section. More reliable evidence was found at Tlapacoya, a hill adjacent to the Chalco sub-basin in the Basin of Mexico. Here, a number of hearths and lithic tools yielded dates of between ca. 24,000 and 21,700 yr. BP (Mirambell, 1967, cited in Caballero, 1995). The first evidence of sedentary agriculture was found in three different locations: the Valle de Oaxaca in south-west Mexico; Tehuacán, 150km SE of Mexico City and in Tamaulipas in the north-east. The apparent cultivation of a maize-like plant near Mitla, Oaxaca was dated to between 8,860 ± 180 yr. BP and 10,700 ± 350 yr. BP (Schoenwetter, 1974, cited in Metcalfe, 1985). Recent genetic research has shown that maize was domesticated from Balsas *Teosinte* in southwestern Mexico (Wang *et al.*, 1999). Maize cobs from caves near Tehuacán were originally dated between 7,000 and 5,400 yr. BP. More recent AMS dates on early forms of *Zea mays*, the domesticated form, from Tehuacán, however, revealed an age of 4,700 ^{14}C yr. BP, suggesting a later date of domestication in this region than had been previously thought (Long *et al.*, 1989). The earliest records of sedentary agriculture in the Basin of Mexico come from Zohapilco and Tlapacoya in the southern part of the Basin of Mexico. Here, grinding tools and wild maize were found in a cultural horizon dating to around 7,000 yr. BP (Niederberger, 1979).

Mexican prehistory is divided into three periods: the Pre-Classic (2,500 BC – AD 300: 4,450 – 1,650 BP), the Classic (AD 300 – 900: 1,650 – 1,050 BP) and the Post-Classic (AD 900 – 1520: 1,050 – 450 BP) (Table 3.1). Domestication of wild plants and technological innovations associated with sedentary agriculture, such as irrigation, were to provide the basis for the rise of the important Mesoamerican civilisations, beginning in the late Pre-Classic. The first of these groups were the Olmecs, who established themselves on the coastal plains around the Gulf of Mexico in Veracruz.

It is during the Pre-Classic, around 3,600 yr. BP, that clear evidence of sedentary maize agriculture in the lacustrine basins of the TMVB emerges (Metcalfe *et al.*, 1994). *Zea mays* (domesticated maize) is found in the pollen record from Lago de Pátzcuaro at approximately 3,500 yr. BP (Watts and Bradbury, 1982). It is also encountered in small amounts at La Piscina de Yuriria (Metcalfe *et al.*, 1994), and in Hoya San Nicholas de Parangueo (Brown, 1984) around this time. By the late Pre-Classic, palaeoenvironmental records indicate that human activity was beginning to have a detrimental impact on the surrounding environment. Sediments from the Basin of Mexico suggest sustained human impact since at least 3,000 yr. BP. Around 2,000 yr. BP, the major development of Cuicuilco in the south of the Basin of Mexico, with its distinctive round pyramids, reached its peak. Following the eruption of Xitle volcano, which destroyed Cuicuilco in 2,030 ± 60 yr. BP (Del Pozzo *et al.*, 1997), the urban centre of Teotihuacán became established in the north-east of the basin. At its peak, during the Classic Period, the population of this city exceeded 100,000. Irrigation systems were developed to support cultivation. By 1,350 yr. BP, this great city lay in ruins, its demise occurring over a relatively short period of ca. 100 years. It has been postulated that unsustainable use of resources, such as excessive use of wood for ceramic production and drought conditions led to the political upheaval, which ended in the destruction of the city (Manzanilla, 1997).

Little is known about Pre-Classic and Classic cultures in the western central highlands. The first important cultural group is that known as El Opeño, who rose to prominence in Michoacán around 3,500 yr. BP. Straddling the boundary between Jalisco and Nayarit, a number of potentially important archaeological sites pertaining to the Classic Period have been found. This area of Mexico has been little studied compared to other areas in the TMVB such as the Basin of Mexico and Michoacán. However, evidence uncovered by Weigand and co-workers points towards significant cultural development in this region. The most important site, close to Teuchitlán (ca. 40 km west of Guadalajara), was discovered in the early 1970s and is believed to have been occupied by a number of different groups between 2,300 yr. BP and 1,250 yr. BP. (Soto de Arechavaleta, 1994). The early Classic Chupícuaro culture was centred around the Cuitzeo Basin, but its influence also extended northwards into the Bajío.

Evidence of accelerated erosion, contemporaneous with the late Pre-Classic to early Classic Period between 2,500 and 1,200 yr. BP, has been identified around Lago de Pátzcuaro in Michoacán (O'Hara *et al.*, 1993). Such environmental degradation must have been caused by a population of considerable size. A rise in soil related elements and sediment accumulation also occurred at La Piscina de Yuriria during the Classic Period, from approximately 2,500 yr. BP to 1,000 yr. BP (Metcalfe *et al.*, 1994). This may be related to the activities of the Chupícuaro culture. There is evidence for sustained environmental degradation at other sites along the TMVB, including the Zacapu Basin (Metcalfe, 1992; Arnauld *et al.*, 1997) and Hoya San Nicholas de Parangueo (Brown, 1992), although chronological control of individual episodes is problematic.

It is clear that the environmental impact of late Pre-Classic and Classic cultures in the central Mexican highlands must have been significant. Indeed, other Mesoamerican civilisations of this time are also believed to have caused substantial environmental degradation. It has been suggested that one of the key elements in the collapse of the Classic Maya civilisation of the Yucatán Peninsula was the over-exploitation of natural resources. Competition for resources, exacerbated by prolonged drought eventually leading to their demise (Hodell *et al.*, 1995).

Cultural development during the late Classic and early Post-Classic periods along the TMVB is reasonably well understood. It was during this period that the most famous of Mesoamerican civilisations, the Aztecs, rose to prominence. The Aztecs were one of a number of nomadic groups, collectively known as Chichimecs, from northern Mexico who were driven southwards towards the TMVB during the 12th century due to drought and civil unrest. After finally settling in the Basin of Mexico early in the 14th century, the Aztecs chose to build their capital, Tenochtitlán, on an island in the middle of Lake Texcoco around 1345 (Coe, 1994). They quickly became the sophisticated warriors, for which they are renowned, whilst acting as mercenaries under the rule of the Tepenacs of Atzcapotzalco. In 1428, the Aztecs overthrew their rulers and began to establish their empire. Their strength was increased by the formation of a triple alliance between the cities of Tenochtitlán, Texcoco and Tlacopan under the command of the emperor Moctezuma. At the height of the empire, it is estimated that up to 10 million people fell under Aztec rule, the capital of Tenochtitlán having a population of around 100,000 (Reddish, 1996). A population of this size must have had a substantial impact on the natural environment. The Aztecs made extensive modifications to the lacustrine environment surrounding their capital, creating a series of causeways by which to reach the island. As mentioned in section 2.4.3, numerous banks, levées and dykes were constructed during the mid-1400s to alleviate flooding (Alcocer and Williams, 1996). The Aztecs practised intensive agriculture in the form of *chinampas* or 'floating gardens'. These were created by piling up lake mud and vegetation to form garden plots, leaving behind channels where the material had been excavated (Reddish, 1996). Willow trees planted along the edges secured these fertile plots, which provided goods to sell in the marketplace or to present as tributes to the numerous deities. Remnants of these *chinampas* can still be seen today in the southern basin of Xochimilco. By the time the Spanish arrived in 1519, this empire of warriors had taken control of much of Mesoamerica (Figure 3.5). However, to the west of the Aztec empire had emerged another important highland civilisation which was never to succumb to Aztec domination.

The Purépecha, or Tarascan, civilisation which came to dominate over the present state of Michoacán during the Post-Classic was borne of similar origins to the Aztecs. According to the *Relación de Michoacán,* this group of Chichimecs from northern Mexico first arrived in the Basin of Zacapu under the leadership of Ticátame (Schöndube, 1996). No fixed seat of power was developed until the Purépecha moved into the basin of Pátzcuaro during the first half of the 14th century, headed by Taríacuari. Their first capital was established on the same site of the present day town of Pátzcuaro, although on Taríacuari's death, the power base was divided between three localities: Pátzcuaro, Ihuatzio and Tzintzuntzan (Schöndube, 1996). With a geographical spread of power, the Purépecha were able to expand their empire to encompass the whole of present day Michoacán and parts of Jalisco and Guanajuato (Figure 3.5). When the Spanish arrived in Michoacán in 1522, the power base had reverted back to one single entity, that of Tzintzuntzan. Like the Aztecs and earlier Classic civilisations, religion formed an important part of daily life for the Purépecha. They revered a number of deities, the most important being that of Curiacueri, the fire god. Huge bonfires were kept alight in his honour around the major ceremonial centres known as *yácatas* (Endfield, 1997). The finest example of these impressive structures is at Tzintzuntzan (Figure 3.6), although they occurred elsewhere in the empire. The Purépecha were a highly sophisticated society, which developed extensive trade links. Their superior skills in metallurgy would have afforded them many opportunities for exchange of goods. Gold and silver were used to produce ornaments, whilst copper was used to make weaponry and practical objects (West, 1948). Mines located near La Huacana and Sinagua appear to have been the most important sources of copper (Warren, 1968).

The level of environmental impact of the Purépecha civilisation has remained a contentious issue. The idea persists that use of natural resources was in relative harmony with the ecosystem (Caballero, 1982). With a population of over 41,000 in the Basin of Pátzcuaro alone (Pollard and Gorenstein, 1980), there must have been at least some level of environmental degradation. Indeed, evidence in lake sediments from Pátzcuaro suggests substantial erosion rates during the Post-Classic (O'Hara *et al.*, 1993). A similar record of disturbance is observed in the Zacapu Basin (Metcalfe, 1992). Deforestation would have taken place in order to clear land for agriculture, for ceremonial bonfires and for metal smelting, although Caballero (1982) suggests that the impacts of resource exploitation were tempered by the adoption of conservation practices, such as multiple use of resources. It is clear, however, that when Hernán Cortés and his army arrived in the central Mexican highlands, they encountered a substantially modified environment (Whitmore and Turner, 1992). The nature and impacts of post-Conquest settlement are explored in the following section.

3.3.2: The Colonial Period

Hernán Cortés and his men first arrived in the Basin of Mexico in 1519. Following the seizure of Tenochtitlán, the heartland of the Aztec civilisation, in 1521, the Spaniards were able to extend their dominance across Mexico. By 1530, the central highlands had succumbed to Spanish rule. Whitmore and Turner (1992) identified three major factors in early Colonial rule that bore consequences for the environment: indigenous depopulation, the introduction of foreign technologies and biota and the reorganisation of land use and management practices.

The decimation of the indigenous population in Mexico during the 16th century is well documented. However, many aspects of this issue are disputed, including the size of the original population, the manner of its decline and the relative contribution of different factors (Whitmore, 1991). Using a number of different sources, Borah and Cook (1994) calculated that in 1532, the Mexican population stood at 16.8 million. By 1605, it had fallen to just 1,075,000. Others argue that such catastrophic changes were simply not possible (see Whitmore, 1991 for discussion). The principal cause of 16th century depopulation is believed to be the spread of epidemics. The Spanish brought with them many diseases and infections to which the Mexicans simply had no immunity (Borah and Cook, 1994). However, other causes such as the effects of war and slavery are also thought to have been important. Whitmore (1991) carried out a computer simulation of population collapse in the Basin of Mexico. This model suggested a population loss of almost 90 % during the first century of Spanish rule, occurring in a step-like manner, primarily due to a series of epidemics.

During the 16th century, while the indigenous population was in decline, the Spanish set about restructuring and reorganising the political and economic framework of Mexico. Major settlements focused on the heartland of indigenous populations, with most of the major towns and cities of today established on former Indian settlements. The Church also played an important role in the development of a series of settlement policies, designed in part to convert the indigenous population to Christianity (Endfield, 1997). Land deemed to be suitable for mineral exploitation was given over to the Crown. With regard to agricultural land, a land granting system was set in place through the awarding of *mercedes*. This system led to the transferral of land to Spanish hands as *mercedes* were awarded to the highest bidder. Indigenous farmers simply could not compete with the wealthier Spanish settlers. Spanish settlers brought with them agricultural practices new to Mexico. As well as introducing the plough, they also bought with them numerous exotic plant species and cattle.

In their analysis of archival records from the Mexican Bajío, Butzer and Butzer (1997) discovered that significant landscape degradation did not appear to have occurred during the earlier Colonial period. The destructive consequences of new land use methods did not emerge until the mid-18th century, with evidence of soil erosion. By then, the population had recovered and was increasing rapidly, the system of government was more organised and technological advancements had been made. Butzer and Butzer (1997) argue that the most severe degradation was not experienced until well after 1830, with significant changes in hydrology due to deforestation and exploitation of groundwater. A similar pattern was observed by Endfield (1997), who used archival evidence to examine the impact of Colonial rule on landscapes within the Cuitzeo, Pátzcuaro and Zirahuén basins. During the 18th century, references in archival material to landscape degradation, such as gullying and deforestation, increase (Endfield and O'Hara, 1999). Around the same time, disputes related to land ownership and access to water also increased significantly. As discussed in section 2.4.3, this may have been related to prolonged drought, but increased competition for resources amongst a growing population must also have been important (Endfield and O'Hara, 1997). Endfield's (1997) investigation of documents pertaining to the Zirahuén basin is examined in more depth in Section 6.3. Not only did increased urbanisation and more sophisticated methods of agriculture lead to environmental degradation during the later Colonial period, but so too did the exploitation of mineral resources. The mining of precious metals such as gold, silver and platinum occurred, particularly in north-west Mexico, but also in Jalisco in the western sector of the TMVB (Rodriguéz, 1995). Also important were the copper mines of Michoacán, which were expansions of existing pre-Hispanic mines. Associated with these activities were smelting operations, which also caused significant environmental impacts (West, 1948). Changes in land use, industrialisation and urbanisation during the Colonial period and following Independence in 1821 have reshaped the landscape of the central Mexican highlands significantly, with large-scale modifications to the environment continuing today.

3.3.3: Exploring 'The Pristine Myth'

The impact of Spanish colonialism on the environment is a hotly contested issue. On the one hand, there is the belief that the Spanish encountered a pristine environment, as Whitmore and Turner (1992, p. 419) point out:

> "An idealised Amerindian experience of using nature in a benign way is contrasted with a European penchant for controlling or raping nature for profit."

Denevan (1992) challenged this traditional concept in his article "The Pristine Myth". Indeed, it is becoming increasingly clear, as has been discussed in section 3.3.1, that pre-Hispanic populations had a considerable impact on their natural surroundings. Archival evidence from the Mexican Bajío points towards considerable deforestation around Lago de Cuitzeo by the Purépecha (Butzer and Butzer, 1997). Examination of agricultural landscapes in the eastern sector of the TMVB highlights substantial modifications such as *chinampas* and the construction of dykes (Whitmore and Turner, 1992). Whilst descriptions of the landscape in archive material can shed light on the nature of the environment, it is only from the palaeoenvironmental record that a clearer picture of the extent of environmental degradation can be gleaned. O'Hara *et al.*, (1993) argue that accelerated erosion rates due to deforestation during both the early Classic and the Post-Classic periods were at least as high as those following the Conquest. However, to date, there are no palaeolimnological records in Mexico, which have good chronological control over the last 1,000 years. Whilst there is evidence of substantial deleterious environmental impacts, there is no hard proof as to who was to blame. With improved chronologies, which allow correlation with archival evidence, palaeolimnological records can make an important contribution to this ongoing debate.

3.4: Choice of Study Sites

It is clear from the discussion in Chapters 2 and 3 that there is a distinct lack of palaeolimnological records in Mexico, which focus in detail over the last 1,000 years. Although cores have been obtained which cover this time period, chronological control has been poor, meaning that certain key research questions have not been adequately addressed. These are:

- What climatic changes have occurred in Mexico during the last millennium?
- What were the relative impacts of pre-Hispanic and post-Conquest populations on the environment?
- Can evidence of climatic change and human impact in archival documents be linked to palaeolimnological records?

In order to be able to explore these issues, lake basins with certain characteristics must be chosen. These are:

- Lakes must be deep enough to preserve a continuous sediment record over this time period.
- Sedimentation rates must be fast enough to preserve a decadal scale record.
- Human disturbance should not have been so severe that the sediment record is disturbed.

Two lakes within the TMVB that fulfil these criteria are Lago de Zirahuén in Michoacán and Laguna de Juanacatlán in Jalisco (Figure 3.3). The Zirahuén Basin is located close to the heartland of the pre-Hispanic Purépecha empire, although archival evidence suggests that significant human impact did not occur until around 300 years ago (Endfield, 1997). A palaeolimnological study can explore this hypothesis. This site has three advantages. Firstly, there is a large amount of limnological information, which will aid interpretation of the palaeo-record. Secondly, archival information on land use and environmental change in the basin is available (Endfield, 1997), which can be compared with the palaeolimnological evidence. Finally, the lake is within the region affected by tephra fallout from eruptions of Volcán Jorullo (1759-1774) and Volcán Paricutín (1943-1952). Tephra layers from these eruptions may be valuable chronological markers in sediment cores. This is discussed further in section 6.2.1. The palaeolimnological record of Lago de Zirahuén is presented in Chapter 6. Laguna de Juanacatlán lies in a remote part of the Sierra de Mascota in Jalisco. Currently, there are no settlements in the basin, which means that the sediment record from this lake should not be greatly influenced by anthropogenic catchment disturbance. An earlier investigation at this site (Byrne and Metcalfe, unpubl.) revealed finely laminated sediments. This suggests that this lake will provide an undisturbed sequence of high-resolution climate changes. Results of palaeolimnological investigations at Laguna de Juanacatlán are presented in chapter 7. These two lakes both have relatively small catchment areas and appear to have suffered relatively little anthropogenic disturbance compared with the large basins within the TMVB, such as Lago de Pátzcuaro and the Basin of Mexico. They were both formed during the late Pleistocene as a result of volcanic activity blocking river channels. The similarities between these sites invite comparison between the nature of the palaeolimnological records. The following chapter outlines the research approach and methods used in this study.

Chapter 4: Research Approach and Methodology

4.1: Introduction

In this chapter, the palaeolimnological approach to environmental reconstruction is discussed, with a particular focus on diatom analysis, the principal proxy method employed in this study. A description of the techniques used during the course of this research is provided, which is split into five sections: field sampling; laboratory methods; chronological control; microscope work and data analysis.

4.2: The Palaeolimnological Approach

Changes in the physical, chemical and biological characteristics of the aquatic environment are reflected in the nature of the sediment that is deposited at the bottom of a lake. Such changes may be induced by a variety of factors. At a regional or global scale, lakes are sensitive to climatic fluctuations (Battarbee, 2000). The lacustrine environment also responds rapidly to basin-specific changes, such as anthropogenic disturbance or the alteration of the hydrological regime through tectonic activity. The analysis of lake sediments is therefore an ideal tool for reconstructing past environmental change.

Evidence from lake sediments has provided historical records of the impact of human activities on aquatic ecosystems, which is particularly valuable as very few lakes have long-term limnological monitoring programmes. Palaeolimnological evidence of impacts such as deforestation, cultural eutrophication and acidification is playing an increasingly important role in the management of the aquatic environment (e.g. Battarbee and Renberg, 1990; Bennion and Appleby, 1999).

Lakes in closed basins are particularly sensitive to climatic fluctuations (Street-Perrott and Harrison, 1985; Fritz *et al.*, 1993; Gasse *et* al., 1997). Variations in effective moisture (i.e. the balance between precipitation and evaporation) are reflected in changes in ionic strength and composition of lake waters through dilution and evaporative concentration (Eugster and Hardie, 1978; Fritz *et al.*, 1999). The sensitivity of a particular basin to changes in the precipitation – evaporation (P-E) ratio depends on the importance of groundwater in the system. Lakes with significant groundwater inflows and outflows do not usually exhibit major changes in water chemistry, whilst those which have negligible groundwater outflow respond rapidly to changes in P-E ratios (Fritz *et al.*, 1999). Sediment cores from closed basins therefore provide excellent opportunities for the reconstruction of past water chemistries (De Deckker & Forester, 1988). These records can then be used to infer periods of increased or decreased effective moisture, providing information on climatic variability through time.

A number of sedimentological and palaeoecological proxy methods can be employed in order to reconstruct both natural and anthropogenic environmental changes. Diatom analysis is one of the most powerful of these, and is widely used (Fritz *et al.* 1993; Gasse *et al.*, 1995; Gasse *et al.*, 1997). This technique is discussed in detail below.

4.2.1: Diatoms as Palaeoenvironmental Indices

Diatoms are unicellular, microscopic algae. They are found in almost any location where water is available, often forming a significant component of primary productivity in aquatic ecosystems. Diatoms possess several characteristics that make them excellent palaeoenvironmental indicators. Firstly, many taxa have narrow and well-defined ecological requirements, making them highly sensitive to fluctuations in water chemistry and nutrient availability. Secondly, they respond rapidly to environmental change due to their short cell cycle. Thirdly, they are abundant and form diverse communities in almost all aquatic habitats. Finally, their siliceous cell wall is readily preserved in the sedimentary record and can be identified to at least species level (Moser *et al.*, 1996).

Whilst diatom analysis is an extremely valuable tool for reconstructing past environments, there are a number of potential problems which need to be taken into account. Firstly, diatom taxonomy and nomenclature are very complex, often leading to confusion (Van Landingham, 1967-1979). This makes the use of published ecological information problematic at times. Secondly, diatoms that are preserved in the sediments, may not be a true reflection of the living diatom assemblage. It is important to look for signs of dissolution and breakage of diatoms in samples, which may indicate that more fragile taxa are under-represented or even absent. Thirdly, fossil assemblages may contain diatoms that are not found in the present day environment, leading to problems with the accurate interpretation of data. The 'no analogue' situation can be helped by drawing on ecological data from other regions if it is available. If these limitations are taken into consideration it is almost always possible to draw meaningful conclusions from the palaeoecological record.

The potential of freshwater diatoms as palaeoecological indices was first recognised in the 1920s (Battarbee, 1986). For example, the ecological classification of diatoms according to their salinity preferences by Kolbe (1927) provided the basis for early studies of sea level change. Since then, the technique has been applied to a whole range of issues over both long and short time scales. Their sensitivity to changes in pH led them to become the cornerstone of investigations into the impact of acid deposition on the aquatic environment (Battarbee *et al.*, 1999). Diatom analysis has been extensively applied in eutrophication studies associated with catchment developments such as deforestation, settlement and agricultural activity (e.g. Bradbury, 1975; Anderson *et al.*, 1995; Bennion *et al.*, 1996).

Due to their sensitivity to changes in ionic strength and ionic composition, diatoms have become increasingly important in the development of palaeoclimatic records from closed lake basins. For example, a 200,000 year old diatom record from Owens Lake, California, has revealed major changes in water chemistry. A particularly arid phase between 70ka and 90ka BP is inferred from the abundance of saline diatom taxa (Bradbury, 1997b). Diatom records from Africa have also been used to infer changes in the intensity of monsoon circulation since the Last Glacial Maximum

(Gasse and Van Campo, 1994). Over shorter timescales and at finer resolution, fluctuations in the salinity of closed lake basins identified by changes in diatom assemblages have provided information on Holocene drought histories (Laird *et al.*, 1998).

4.2.2: Towards Numerical Palaeoenvironmental Reconstructions

The application of diatoms in palaeoenvironmental studies has increased rapidly over the last 20 years. Significant progress in diatom-based palaeoenvironmental reconstruction has been made during the last decade due to the development of quantitative methods (Birks, 1998). Clear correlations have been established between species composition and pH (e.g. Gasse and Tekaia, 1983; Birks *et al.*, 1990), salinity (e.g. Cumming and Smol, 1993), nutrient content (Bennion, 1994) and ionic composition (e.g. Gasse *et al.*, 1983; Fritz *et al.*, 1993). Modern calibration datasets have been established for a number of regions. Multivariate statistical methods, such as Canonical Correspondence Analysis (CCA) (ter Braak, 1986) are used to identify key environmental variables. Weighted averaging regression is then used to develop transfer functions for these variables, which can then be applied to palaeoenvironmental data. For example, a dataset of 282 modern diatom samples from Africa has been used to create transfer functions for conductivity, pH and ionic ratios (Gasse *et al.*, 1995). In the northern Great Plains region of North America, a salinity transfer function has been developed from a 66 lake dataset (Fritz, 1990; Fritz *et al.*, 1991). The transfer function approach means that palaeoenvironmental reconstructions are based on the overall species assemblage, rather than the occurrence of individual taxa.

Quantitative reconstructions are advantageous in that they provide an estimate of the magnitude of changes in a particular environmental variable within a lake. For example, application of the Great Plains salinity transfer function to a high resolution (sub-decadal) 2,300 year diatom record from Moon Lake, North Dakota indicated that the frequency and intensity of severe drought was greater prior to AD 1200 (Laird *et al.*, 1996). This information may not have come to light from a purely qualitative interpretation of the record.

To date, diatom-based transfer functions have not been developed in the American tropics. Indeed, there is very little ecological information on diatoms from this region at all. Haberyan *et al.*, (1997) report that cation concentration and related variables, such as hardness and pH have a significant influence on diatom species composition in a 25 lake dataset from Costa Rica. Servant-Vildary & Roux (1990) found that diatom assemblages from saline lakes in the Bolivian Altiplano were strongly linked to ionic composition. Such studies highlight the potential for quantitative diatom-based reconstructions in the tropical Americas.

4.3: Diatoms: Morphology, Biology and Ecology

Palaeoecology relies on the assumption that the ecological requirements of species were the same in the past as they are in the present. Correct interpretation of the palaeolimnological record therefore requires accurate taxonomic identification and a thorough understanding of the ecological preferences of individual species. This section provides an introduction to the morphology, biology and ecology of the diatoms. Previous work on diatom ecology in Mexico and its implications for the objectives of this study are also discussed.

4.3.1: The Morphology and Biology of Diatoms

Early microscopists recognised diatoms during the eighteenth century, the first known record was in 1703 (Round *et al.*, 1990). It was not until the following century, however, that serious work on the classification of diatom species began in earnest. Pioneering taxonomical works include Kützing (1833), Ehrenberg (1838), Smith (1853-1856) and Grunow (1860). Diatoms form the Class Bacillariophyceae, within the Division Heterokontophyta (Van den Hoek *et al.*, 1995). Some authors place the Bacillariophyceae within the Division Chrysophyta (e.g. Patrick and Reimer, 1966; Stoermer and Smol, 1999), although this is becoming less common.

Diatom cell size can range from as little as 3 μm to 2,000 μm, although most freshwater species are between 5 μm and 200 μm. Diatoms are distinguished by their ability to secrete a siliceous cell wall, the frustule, the morphology of which forms the basis of taxonomic identification. Figure 4.1 illustrates the main features of the diatom frustule. The frustule comprises two valves, which are linked together by a series of girdle bands. The epivalve and its girdle bands, collectively termed the epitheca, fit over the smaller hypotheca (Figure 1). Three main types of diatom pattern are distinguished: centric, araphid pennate and raphid pennate. Within these groups, the shape, size and ornamentation of the cell wall, particularly the valve, are diagnostic of each species. As indicated in Figure 4.1, centric diatoms possess radial valve symmetry, whilst pennate diatoms are bilaterally symmetric. Some pennate diatoms, such as *Eunotia* and *Epithemia* are symmetric across the width, whilst in others, such as *Gomphonema* and *Navicula*, the raphe represents the line of symmetry. Of the different types of valve ornamentation, perhaps the most important are the pores, or puncta. These can be arranged linearly to form striae, as in most pennate and some centric diatoms. Alternatively, they can be in concentric formation or in sectors.

Pennate diatoms are characterised by a longitudinal feature that usually runs down the centre of the valve. In araphid pennate diatoms, this is a silicified rib, clear of puncta and termed a pseudoraphe. Raphid pennate diatoms, however, have one or two longitudinal slits through the valve called the raphe. In most cases, two slits are observed, separated by a bridge of silica in the middle. This central area may be clear of pores or possess a distinctive pore arrangement. The central area, coupled with the nature of the raphe ends is important in taxonomic identification. In some genera, such as *Achnanthes* and *Cocconeis*, a raphe is present on the hypovalve whilst a pseudoraphe is found on the epivalve. These are known as monoraphid diatoms.

Within the diatom frustule are found the living components of the diatom, the protoplast. Diatoms, along with other eukaryotic algae are characterised by the presence in the cell of a nucleus. Other living parts included the plasmalemma, mitochondria and plastids. It is the latter which produce the golden-brown colour of living cells, due to the presence of carotenoid pigments (Round *et al.*, 1990).

The period between one cell division and the next is termed the cell cycle. In diatoms, this is short, a matter of hours or days). Reproduction is generally asexual, the epitheca being inherited from the mother cell, whilst the hypotheca is created by the daughter cell. Cell size decreases through time with this form of reproduction, only being restored through auxospore formation associated with sexual reproduction. As a result, any one species may have a considerable size range. Cells sometimes occur in colonies, being linked by siliceous structures such as spines (e.g. *Aulacoseira, Fragilaria*), through mucilage pads or stalks (e.g. *Asterionella, Nitzschia*) or through the development of mucilage tubes (e.g. some species of *Cymbella* and *Amphipleura*) (Round *et al.*, 1990).

4.3.2: The Ecology of Diatoms

There are numerous factors that may influence the diatom species composition of a particular lake. These include habitat, water depth, nutrient availability and water chemistry.

In general, centric diatoms are planktonic, free-floating in the water column, whilst pennate diatoms are benthic, either living attached to some form of substrate or motile, moving through or on sediment. Some centrics, however, such as *Melosira monoliformis* are found in benthic habitats, whilst some pennate diatoms, including the genus *Asterionella* and some *Nitzschia* species, live in the plankton (Round *et al.*, 1990). Benthic species are found in association with a variety of different substrates, including vegetation (epiphyton), rocks (epilithon), sand (episammon) and sediments (epipelon). Aerophilous species are found in subaerial habitats such as soils, marshes and bogs.

Diatoms are sensitive to a number of physical limnological characteristics. Water depth is a significant factor governing diatom distributions, as this has an effect on the amount and nature of benthic habitats available. As photosynthetic organisms, diatoms are restricted to the photic zone of aquatic environments. There are differences, however, in the light requirements of species. For example, a study of resource relationships between African planktonic diatoms revealed that *Melosira*

(=*Aulacoseira*) *ambigua* and *Melosira* (=*Aulacoseira*) *distans* have higher light requirements than *Melosira* (=*Aulacoseira*) *nyassensis* (Kilham *et al.*, 1986). The amount of light available is governed by the turbidity and colour of the water, which depends on factors such as the amount of suspended sediment present, the degree of mixing and productivity. All freshwater planktonic diatoms require turbulence to remain in suspension in the water column. The depth of vertical mixing in the water column can, however, play an important role in the abundance of heavily silicified diatoms of the genus *Melosira* (most common taxa are now placed in the genus *Aulacoseira*) which require a considerable amount of mixing to keep them buoyant (Lund, 1954).

The effect of temperature on diatom species composition is a contentious issue. Experimental work to assign temperature optima and tolerance ranges to species failed to reproduce consistent results in the natural environment (Moser *et al.*, 1996). A number of recent studies, however, have demonstrated a significant relationship between species composition and temperature (e.g. Vyermann and Sabbe, 1995; Pienitz *et al.*, 1995). A survey along an altitudinal transect of lakes in the Swiss Alps revealed a statistically significant correlation between diatom assemblages and surface water temperature (Lotter *et al.*, 1997). Although these recent findings are encouraging, the potential for inferring temperature change directly from diatoms is still in doubt. It is thought that other variables, such as habitat and chemistry may be strongly related to diatom species composition to allow the independent effects of temperature to be accurately assessed (Battarbee, 2000).

The availability of nutrients is an important factor governing the ecological distribution of diatoms. Relationships have been identified between the trophic status of different water bodies and their diatom species composition in different regions (e.g. Whitmore, 1989; Bennion, 1994). Given that diatoms secrete a siliceous cell wall, the availability of silica in the aquatic environment is clearly crucial to diatom production. Some heavily silicified species (e.g. *Aulacoseira*) are only abundant in lakes with high dissolved silica values (Kilham, 1971). Investigations into the role of silica and phosphorus in diatom distribution in African lakes indicated that planktonic *Synedra* species.had low phosphorus and high silica requirements, whilst *Stephanodiscus* species thrived in phosphorus enriched systems but had low silica requirements (Kilham *et al.*, 1986). Phosphorus is the limiting nutrient in most freshwater ecosystems, so its availability has a significant impact, not only on diatom species composition but on the whole ecosystem structure. Nutrient enrichment can not only lead to a change in species composition, it can also a significant increase in diatom productivity (Stoermer *et al.*, 1985). However, if nutrient enrichment is too great, silica depletion can occur and diatoms will be replaced by other algae as the dominant primary producers in the water column (Kilham, 1971; Stoermer *et al.*, 1985).

The chemical composition of lake waters can greatly influence the nature of the diatom flora present. Diatoms are sensitive to ionic strength (expressed as electrical conductivity or salinity), pH and ionic composition. A number of salinity classifications of diatom species have been produced (e.g. Kolbe 1927; Hustedt, 1953). However, these systems were based solely on chloride concentrations, ignoring the influence of other ions. Whilst these classifications are useful for studies of sea level change, they have limited applicability to studies of salinity fluctuations in a continental setting. Ecological classifications of diatoms, based on pH preferences, were also developed by Hustedt (1937-1938).

An increasing amount of information is available concerning the effects of ionic composition and ionic strength on diatom distributions (e.g. Gasse *et al.*, 1983; Gasse, 1986; Servant-Vildary & Roux, 1990). This work has largely been driven by the need for such ecological information in order to interpret palaeolimnological records accurately. Extensive research of African lakes has shown that species such as *Thalassiosira rudolfii* and *Navicula elkab* are most abundant in alkaline environments of sodium carbonate composition, whilst *Navicula ammophila* and *Amphora coffeaformis* dominate in concentrated sodium chloride systems. At the more dilute end of the spectrum, *Cyclotella stelligera* is common in calcium-sodium bicarbonate lakes (Gasse *et al.*, 1983; Gasse *et al.*, 1995).

4.3.3: Diatom Ecology in Mexico

There is relatively little information on the ecological distribution of diatoms in Mexico. Those studies, which have been undertaken, have largely been driven by the need for autoecological information in order to interpret the palaeoecological record (e.g. Bradbury, 1971, 1989; Metcalfe, 1985, 1988; Caballero, 1995, 1996). Closed-basin lakes in the highlands of central Mexico have been the subject of a number of diatom-based palaeolimnological studies (Bradbury, 1989; Metcalfe *et al.*, 1991; Metcalfe & Hales, 1994; Metcalfe, 1995; Caballero & Ortega, 1998; Caballero *et al.*, 1999). To date, interpretation of these records has been qualitative, based largely on ecological data from other regions, but also on the limited ecological information available on the ecology of diatoms in Mexico.

Dr. J. Platt Bradbury has an extensive collection of modern diatom samples and water chemistry data from numerous sites along the TMVB. These data, however, have never been fully published, the only information available being a qualitative classification of water chemistry and habitat preferences (Bradbury, 1989). Metcalfe (1985, 1988) used ordination techniques to examine species-environment relationships in a dataset of 67 samples from the central highlands, but found that habitat differences between the samples tended to mask the effects of water chemistry variations. Caballero (1995) used a CCA on a relatively small dataset of 9 different water bodies, largely within the Basin of Mexico. She found that ionic composition along a gradient between Ca-Mg-HCO_3 to Na-Cl water chemistries was the main factor determining the distribution of diatom species.

Surface sediment samples collected by Dr. Metcalfe and Dr. Caballero have already been merged into a single dataset. However, further sampling is required to increase both the environmental gradient covered and the size of the dataset before reliable transfer functions can be developed. The development of diatom-based transfer functions for central Mexican lakes is important for a number of reasons. It will allow quantitative interpretation of previous palaeolimnological studies and provide a basis for this study and for future investigations. The information can be used to test whether ecological requirements are comparable between regions by comparison with datasets from, for example, Africa or North America. If this is the case, then a long-term goal is to merge the Central Mexican dataset with those of other regions. This would increase the accuracy of transfer functions as the coverage of chemical gradients would be greater (Gasse *et al.*, 1995). It would also make it more likely that modern analogues for fossil data would be encountered (Gasse *et al.*, 1997).

The remainder of this chapter discusses the various methods employed in the collection and analysis of diatoms in both modern material and core samples. Additional techniques employed in this study to provide supplementary information to the diatom record are also described.

4.4: Field Sampling

A total of three field visits were made to Mexico. In March and April 1997, a total of eight weeks was spent collecting modern diatom and water chemistry samples that could be incorporated into the existing Central Mexican Diatom Dataset. Reconnaissance work was also carried out on several sites to determine their suitability for palaeolimnological work the following year. A further eight-week field season in February and March 1998 focused on obtaining sediment cores from Lago de Zirahuén and Laguna de Juanacatlán. A short visit was made to Laguna de Juanacatlán in September 1998 to carry out a limnological survey. During this visit, soil samples were collected from around the basins of Zirahuén and Juanacatlán for the analysis of magnetic properties that could be compared with those observed in the palaeoenvironmental records. Efforts were also made to acquire information on the history of land use within the Juanacatlán Basin as no studies had been carried out previously.

4.4.1: Limnological Measurements

Modern sampling during March and April 1997 focused on lake types that were perceived to be poorly represented in the Central Mexican Diatom Dataset and those which would expand its environmental gradient. A total of 17 different lakes were sampled along a transect from the state of Jalisco in the west to Puebla in the east. Water samples were collected from deep water where possible, although in certain circumstances only near shore samples could be obtained. Nineteen water samples from the 17 sites were collected for laboratory analysis. In each case, two 1 litre acid-washed polythene bottles were filled, one for analysis of cations, the other for anion measurements. A small amount of concentrated nitric acid was added to anion samples to preserve their composition. Water samples were kept refrigerated until laboratory analyses were carried out. At each site, water samples were taken for initial field analysis of chemical characteristics. Samples were filtered using Whatman 40 ashless filters, then analysed for total alkalinity (ppm $CaCO_3$), hardness (ppm $CaCO_3$), nitrate, chloride, phosphate and silica using La Motte field test kits. Field measurements were also made of secchi depth, electrical conductivity (E.C.) and pH. As the range of the conductivity meter used was found to be below that of some sites studied, it was necessary to rely on laboratory results. Evidence of human influence around the lakes was also noted.

In addition to the general limnological survey of central Mexican lakes, a more detailed study was carried out on Laguna de Juanacatlán, Jalisco. This site had been selected for palaeolimnological work and was known to have laminated sediments. There was, however, no published limnological data for this site, so information was required which might help to explain the existence of laminated sediments. A preliminary bathymetric survey was carried out using an echo sounder to record water depth along several transects of the lake. A hand held GPS was used to record the location of each depth measurement, although given the small distances between measurements, the positions recorded have proved to be unusable. A multi-parametric probe (Yellow Springs Instruments, Model 3800) was used to measure temperature, dissolved oxygen (DO), E.C., turbidity, pH, salinity and nitrates at different depths through the water column. A total of six depth profiles along a west - east transect of the lake were obtained.

Detailed limnological sampling was not carried out at Lago de Zirahuén as data was available from an extensive limnological monitoring programme which is being carried out by the Universidad Michoacana de San Nicholas de Hidalgo, Morelia, Mexico. It was therefore only necessary to record basic parameters.

4.4.2: Collection of Modern Diatom Samples

Modern diatom samples were collected from a variety of different aquatic habitats within the 17 lakes and from several streams. For the stream sites, only pH and E.C were measured. The principal aim was to obtain surface sediment samples from each of the lakes that could then be incorporated into the Central Mexican Diatom Dataset. Surface sediment samples are the most analagous to core samples, representing a broad average of the diatom assemblage of the lake as a whole. Sediment samples were collected from as great a water depth as possible using a grab. Plankton samples were obtained using 500ml bottles and diatom samples were also scraped from vegetation and rock surfaces. By sampling different habitats, it was hoped to provide information on the influence of habitat preferences as well as that of hydrochemical variables. Modern material was preserved in alcohol. Although the majority of sampling was undertaken in March and April 1997, some additional samples were collected in February, March and September 1998.

4.4.3: Core Sampling

Lake sediment cores were extracted from Lago de Zirahuén and Laguna de Juanacatlán using a micro-Kullenberg corer designed by Mr. G. Rooke of the School of Earth Sciences, University of Wales, Aberystwyth (Figure 4.2). This is a piston type corer designed specifically for use in deeper lakes (Kullenberg, 1947). This type of corer was chosen as undisturbed sediment-water interface cores can be retrieved, which is essential for any study of more recent environmental change.

Perspex tubes (75mm external diameter) of 1m or 2.5m in length were attached to the coring head. A piston was fitted at the bottom of the tube and attached to the trigger (Figure 4.2) by a steel wire running through the coring system. This steel wire was attached to a non-stretch rope, which was then used to lower the corer into the water. A separate weight attached to a rope just longer than the Perspex tube and a float were attached to the arm of the trigger. As the weight reached the sediment surface, the floats acted, releasing the trigger and allowing the weights on the corer to drive the Perspex tube into the sediment. As the tube moved into the sediment, the piston remained stationary, its final position being at the top of the tube. The vacuum created by the piston kept the sediment inside the tube as the corer was raised.

Immediately on emerging from the water, the tube was capped and sealed. Cores were kept upright for as long as possible to allow sediment in suspension at the sediment-water interface to settle out. Excess water was removed by siphoning. Flower-arranging sponge was then placed in the top of the tube to keep the sediment in place and to soak up any remaining water.

At each site, multiple cores were taken. This allowed an assessment of the degree of coherence of palaeolimnological records obtained from different parts of the lake. At Lago de Zirahuén, coring was carried out from a fibre glass boat. A total of 4 cores were obtained across the lake, 3 using 1m tubes and 1 using a 2.5m tube. A raft was constructed for coring at Laguna de Juanacatlán. At this site, 3 cores were obtained, 2 using 1m tubes and 1 using a 2.5m tube. An attempt was also made at this site to extract a longer core using a Livingstone corer although this failed. All cores were sealed and returned to Edinburgh by air freight, where they were kept in cold storage at 4°C.

4.4.4: Soil Sampling

Soil samples were taken from different points around the two lakes chosen for palaeolimnological study. As core material was to be analysed for magnetic susceptibility, it was important to ascertain whether there was any spatial variability in the magnetic signature of sediments around the catchments. This may give some indication as to the primary source material of the lake sediments (Dearing, 1994). Eleven samples were obtained from the Zirahuén Basin and 8 were taken from around Laguna de Juanacatlán. Samples were taken from a variety of different settings, including stream inputs, topsoil from land used for different agricultural purposes, exposed, highly weathered material and bedrock.

4.5: Laboratory Methods

4.5.1: Water Chemistry

It proved impossible to access facilities for water chemistry analysis in Mexico, so this work was contracted to Dra. Aurora Armienta of the analytical chemistry laboratory at the Instituto de Geofísica, UNAM, Mexico City. Water chemistry analyses were carried out using standard techniques (Armienta *et al.*, 1987; APHA, 1989). Due to financial constraints, not all samples collected could be analysed fully and so analyses had to be prioritised. Of the 19 samples collected, 15 were analysed for pH, E.C., major anions (CO_3^-, HCO_3^{2-}, SO_4^{2-} and Cl^-) and major cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+). All anion and cation data were originally measured in milligrams per litre (mg l^{-1}). These data were converted into milliequivalents (meq l^{-1}) using the conversion tables in Hem (1970) and are presented as such in this thesis. This allows comparison with the results of other studies (e.g. Metcalfe, 1985, 1988; Caballero, 1995).

4.5.2: Sediment Analysis

Stratigraphy

Before opening, all cores were x-rayed at the British Geological Survey, Edinburgh. This meant that a permanent record could be kept of the stratigraphy and that structures, which might not be visible to the naked eye, could be observed. X-raying of cores is also a quick and effective method of identifying microscopic tephra layers (Dugmore and Newton, 1992). Photographs were made from the x-ray negatives of particularly interesting sections of core material. Cores were then opened using a core-cutting device developed by Mr. G. Tulloch of the British Geological Survey, Edinburgh. Care was taken to ensure that the sediment was not penetrated during core cutting. The visual stratigraphy was described with the aid of a Munsell soil colour chart. Cores were also photographed.

On opening the 2.5m cores from both Laguna de Juanacatlán (JL/98) and Lago de Zirahuén (ZL/98), it was discovered that the stratigraphy of the lower parts of these cores had been disturbed and could not therefore be used for palaeoenvironmental work. However, with the aid of x-rays and the visible stratigraphy, it was possible to determine, through the preservation of horizontal layers, that the upper parts of each core had not been disturbed. The top 50cm of ZL/98 and the top 80cm of JL/98 were deemed to be reliable. It is likely that the disturbance observed in the lower parts of these cores was due to increasing pressure as the corer was driven into the sediment.

This problem has been observed with piston type corers and can result in the lateral displacement of sediment. The recommended 'safe length of sample' which can be achieved by piston corers in moderately deep lakes is approximately 1m (Aaby and Digerfeldt, 1986).

Laminated sediments preserved in the cores from Laguna de Juanacatlán were examined in more detail. Digital sediment colour analysis (DSCA) (Schaaf and Thurow, 1994, 1997) was carried out in order to obtain a grey-scale time series for cores JL/98 and JD/98. This work was undertaken at the Department of Geological Sciences, University College, London in conjunction with Dr. J. Thurow. Digital images were captured as 8-bit greyscale (resolution approximately 120 pixels/cm) using an OPTOSCAN imaging system (Figure 4.3). The image length was approximately 25cm, so 4 images were taken for each core. Digitised images were analysis using ERDAS IMAGINE software. This is described fully in Chapter 7.

Thin-sections of laminated sediment were analysed using back scattered electron imagery (BSEI) on a scanning electron microscope (Pike and Kemp, 1996; Dean *et al.*, 1999). This technique is particularly useful for identifying fine structures within laminated sediments. Sediment sections approximately 1cm × 1cm × 5cm were extracted for the preparation of thin sections. Thin section preparation was carried out by Mr. M. Hall (Department of Geology and Geophysics, University of Edinburgh) using a slightly modified procedure from that of Dean *et al.*, (1999). Following displacement of the water with acetone, samples were transferred to smaller containers, which were then filled with epoxy resin until the sample was covered. Further resin was added as it soaked into the sample. Once no more resin soaked into the sample, the sections were cured on a hotplate for several hours. Thin sections were then prepared and carbon coated. The thin sections were analysed in the Department of Geology and Geophysics, University of Edinburgh on a Philips XL30-CP scanning electron microscope (SEM) using backscattered electron imagery. Use was also made of a Link ISIS electron dispersive spectrometry (EDS) system for qualitative chemical analysis which was attached to the SEM.

Mineral Magnetic Properties

The magnetic susceptibility of lake sediment is a useful indicator of the degree of allochthonous inputs into the system. High levels of magnetic susceptibility suggest accelerated detrital mineral inputs (Thompson, 1984). The analysis of magnetic susceptibility, therefore, is an ideal tool for identifying periods of increased catchment erosion, which may be linked to human activity or climate. Downcore changes in the magnetic susceptibility of lakes sediments can also be used to correlate between cores (Dearing, 1986). All core and soil samples were analysed. Magnetic susceptibility samples were dried at 40°C, placed into $10cm^3$ pots and then weighed. Mass specific susceptibility (χ) was measured using a Bartington MS2B dual frequency sensor. Both low frequency and high frequency susceptibility measurements were taken. Samples where ultrafine magnetic minerals (c. 0.03μm) are present show lower values at high frequency, so the frequency dependence of the sample can be calculated. These are secondary minerals which have formed by burning or pedogenic processes and may help to identify anthropogenic influences (Dearing, 1994).

More detailed analysis of the magnetic properties of sediments from Lago de Zirahuén was carried out on cores AV/98 and ZD/98 as well as catchment soil samples. The author analysed samples from AV/98 with the help of Prof. R. Thompson (Department of Geology and Geophysics, University of Edinburgh), whilst Mr John Braisby (also Geology and Geophysics) analysed sediments from ZD/98. For both cores, saturation isothermal remanent magnetisation (SIRM) and anhysteretic remanent magnetisation (ARM) were analysed. These measurements provide an indication of the strength of the magnetic field required to change the magnetic properties of the material. Such information helps to differentiate between different sizes and types of magnetic minerals present in the sample (Thompson, 1986). Comparison of results from catchment soil samples and core sediments may help to identify sources of allochthonous inputs into the lake waters.

Metals Analysis

The concentration of heavy metals in the sediments from Lago de Zirahuén and Laguna de Juanacatlán was also analysed. The Zirahuén Basin has a known history of copper smelting at the town of Santa Clara del Cobre (West, 1948), whilst there are historical records of silver and gold mining in the hills around Laguna de Juanacatlán, centred around the town of Navidad (Rodríguez, 1995). It was thought that analysis of heavy metals would reveal whether these activities have had a significant impact within the catchments. Heavy metals (iron, lead, manganese, zinc, and copper) were analysed from cores AV/98 and ZD/98 from Lago de Zirahuén and from core JL/98 from Laguna de Juanacatlán. Samples were prepared by Mrs I. Anderson (Department of Geography, University of Edinburgh) following methods described in Bryant *et al.*, (1991). Analysis of heavy metals was carried out by Mrs. L. Eades (Department of Chemistry, University of Edinburgh) using a flame atomic absorption spectrophotometer (AAS).

4.5.3: Preparation of Diatom Samples

Initial preparation of modern plankton, vegetation, algae and stone samples was undertaken in the Laboratory of Aquatic Ecology, ENEP, Iztacala, Mexico City. Plankton samples were left to settle overnight and then decanted into 25ml glass vials. Vegetation, stone scrapings and algae were placed into beakers and boiled in 30% hydrogen peroxide (H_2O_2) to strip off attached diatom valves. Samples were cleaned in distilled water by centrifuging for 12 minutes at 1500 rpm, decanting and refilling with distilled water. This process was repeated 3 times. Cleaned samples were diluted in 50ml of distilled water, shaken and split between two 25ml glass vials for transportation back to Edinburgh. These samples were mounted onto slides in the same way as described for sediment samples below.

Surface sediment samples and core material were treated in the same way. Samples were dried overnight at 40°C, then 0.5g was weighed out for analysis, except for cores JI/98 and JD/98, where 0.2g was weighed out due to the very high diatom content of the sediments. Initially, samples were treated with 10ml of 10% hydrochloric acid (HCl) to remove any carbonate material present before boiling in

100 vols. H_2O_2 to oxidise any organic matter present, following Battarbee (1986). In cases where this treatment failed to remove organic matter effectively, approximately 10ml of concentrated nitric acid (HNO_3) was added to samples. It was found with many samples that treatment with H_2O_2 alone was simply not enough to clean the samples effectively. An alternative preparation method involving acid digestion was therefore used on core samples from Laguna de Juanacatlán. Diatom samples were heated in 50 ml of concentrated sulphuric acid (H_2SO_4). After 1-2 hours, a few drops of conc. HNO_3 were added to ensure that the sample had been completely oxidised. All diatom samples were placed in centrifuge tubes, filled with distilled water and then centrifuged for 12 minutes at 1500 rpm. This process was repeated 3 or 4 times until the acid had been neutralised. Clean samples were suspended in a final dilution of 30ml distilled water and stored in glass vials.

For all diatom suspensions, an aliquot of 450 μl was placed on a 19 mm diameter round coverslip using a Finipipette micropipette and left to dry overnight at room temperature. Coverslips were mounted on to slides using Naphrax resin. In most cases, further dilutions were required to obtain a countable sample. Also, ammonia was added to some samples to disperse clay minerals. Two or three slides were prepared for each sample.

4.6: Microscopy

Diatom slides were examined at 1000 × magnification under immersion oil using an Olympus BX50 transmitted light microscope. Diatoms were generally identified using bright field optics, but the phase contrast facility was particularly useful for observing finely striated specimens. For each sample, a minimum of 400 valves was counted, although in some samples where preservation was poor and diatom abundance was low, counts of only 300 were possible. Studies have shown that a count of at least 300 will provide a good representation of the diatom assemblage in the sample (Battarbee, 1986). A record was also made of the number of other siliceous microfossils present, including sponge spicules, chrysophyte cysts and *Mallomonas* scales. The presence and abundance of these can provide additional ecological information. Digital images of microfossils were captured using a JVC

KYF55B colour video camera and the Matrox Intellicam digital imaging system. Tagged image format (TIFF) files were stored in the ImageAxs database program.

Species that could not be identified easily under the light microscope were examined further using a Philips XL30-CP SEM in the Department of Geology and Geophysics, University of Edinburgh. Samples were diluted further and evaporated onto 13mm diameter coverslips. These were mounted onto SEM stubs using carbon coated adhesive then sputter coated with gold. The typical beam current was 60nA, whilst the gun current used was normally 20kV. Occasionally, the current was increased to 30kV to improve resolution of the image. A variety of magnifications have been used for SEM work, ranging from 1000 × up to 20,000 ×. Digital images were captured in TIFF format.

For core samples, an estimate was made of the concentration of diatoms per gram of dry sediment. This information can indicate changes in productivity or to the sediment influx into the basin (Battarbee, 1986). A traverse was made of the diameter of a coverslip and all diatoms in the field of view were counted. Given that a known dry weight of sediment was used and that the dilution of the sample was known, the number of valves per gram of dry sediment could be calculated.

4.6.1: Diatom Identification

Diatoms were identified with reference to a number of standard floras, principally those of Hustedt (1930-1966), Patrick and Reimer (1966, 1975), Germain (1981), Gasse (1980, 1986) and Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b). Valuable advice was given on the identification of certain species by Prof. D. Mann, Dr. H. Håkansson and Dr. J. P. Bradbury. Light microscope images of common diatoms and SEM images of problematic taxa are illustrated in Plates 1 to 32 in Volume II of this thesis.

4.7: Diatom Taxonomy

This section describes the taxonomic nomenclature used in this study. Light microscope photographs of all common taxa (>5% relative abundance) found during the course of this study are presented in the plates at the back of this thesis. A number of species were encountered in both modern samples and fossil material whose correct taxonomic identification was problematic. These species are discussed below.

4.7.1: *Aulacoseira*

A species of the genus *Aulacoseira* (formerly *Melosira*) was found to be abundant in core material from Lago de Zirahuén. Under the light microscope, it appeared to show affinities with both *A. italica* ssp. *subarctica* and *A. ambigua* (Plate 1, Figures 6-9). This taxon has been previously encountered by Metcalfe in core material from nearby Laguna Zacapu (Metcalfe, 1985: plate 17, figure 15-17). She identified it as *Melosira italica* (Hér.) Kütz. ssp. *subarctica* (O. Müller), although a question has remained over the identification of this species given its similarity to *A. ambigua.* Re-examination of material from Laguna Zacapu and comparison of light and SEM microscope photographs confirmed that the species in cores from these two lakes is indeed the same. Material from Lago de Zirahuén was sent to Dr. J. Platt Bradbury of the U.S.G.S., Colorado as he had also found the same species in core material from nearby Lago de Pátzcuaro (Bradbury, In Press). He suggested that this species encountered in these three lakes is *A. ambigua* var. *robusta* as described in Gasse (1980: Plate 7, Figures 3-7). The valve diameter of most specimens from Lago de Zirahuén is less than 10 μm, smaller than Gasse's description of 13-20 μm, although the example in Plate 1, Figure 6 does fit Gasse's description of *Aulacoseira ambigua* var. *robusta*. Samples from Lago de Zirahuén were sent to Dr. R. Crawford of the Alfred Wegener Institute, Germany. After a detailed investigation under the SEM, he concluded that various forms of *A. ambigua* were present (Plate 2, Figure 1). SEM analysis of broken valves revealed a hollow Ringleist (Plate 2, Figure 2), which is characteristic of *A. ambigua.* The external aperture of the rimoportula is large (Plate 2, Figure 2), there are no areolae on the valve face (Plate 3, Figure 1) and the Ringleist is deep (Plate 3, Figure 2). One interesting feature of these specimens is that the valves appear to be only forming separation spines (Plate 2, Figure 1). Round *et al.* (1990) state that *A. ambigua* only has linking valves. The formation of only separation spines in this variety may have an ecological explanation. The identified features all suggest that this taxon recorded in Lago de Zirahuén, Laguna Zacapu and Lago de Pátzcuaro is a variety of *A. ambigua*. As most of the specimens from Zirahuén do not fall precisely within Gasse's (1980) description of *A. ambigua* var. *robusta*, it is referred to in this thesis as of *A. ambigua* cf. var. *robusta*. Further taxonomic work is necessary.

Given the problem distinguishing this coarser form of *A. ambigua* from *A. italica* ssp. *subarctica* (also called *A. subarctica*; e.g. Krammer and Lange-Bertalot, 1991a), it is difficult to assign a particular ecological interpretation to the abundance of this taxon in core material. *Aulacoseira ambigua* cf. var. *robusta* may well have been misidentified in other localities, making it difficult to use published literature. This species has not been encountered in modern material from central Mexico, further confounding the problem of accurate ecological interpretation. The heavily silicified nature of this diatom, however suggests that, as with other species from the genus *Aulacoseira*, it is only likely to thrive in well-mixed, turbulent waters where it could remain suspended in the water column (Kilham, 1990).

4.7.2: Cyclotella

Cyclotella ocellata Pantocsek was very common in the most recent sediments from Lago de Zirahuén. Bernal-Brooks (1988) referred to *Cyclotella kuetzingiana* occurring at 99% relative abundance in modern plankton samples, although it is likely that this was misidentified and is indeed *C. ocellata*. The taxonomy of these two *Cyclotella* species and similar taxa has been the subject of a number of investigations (e.g. Håkansson, 1990, 1993; Teubner, 1995). *C. ocellata* Pantocsek was regarded by Cleve-Euler (1951) as a synonym of *C. kuetzingiana* var. *planetophora* Fricke, whilst Håkansson (in Krammer and Lange-Bertalot, 1991a) made *C. kuetzingiana* var. *planetophora* a synonym of *C. ocellata* (Håkansson, 1993).

Specimens encountered from surface sediment and core material from Lago de Zirahuén commonly had 3 distinct depressions in the valve centre, although some specimens had 4 or 5 (Plate 1, Figures 19-22). These appear to be the same taxon as that photographed by Håkansson from the original Pantocsek collection (Håkansson, 1990: Figures 11-17). SEM examination confirmed that specimens from Zirahuén do indeed conform to those specimens in Pantocsek's specimens from Lake Balaton, examined by Håkansson (1990, 1993). The example from Zirahuén (Plate 4, Figure 1) shows one valve face fultoportula and one rimoportula with no division of striae towards the mantle edge, which is consistent with Håkansson's (1993) description of the principal characteristics of *C. ocellata.* The name *Cyclotella ocellata* has therefore been used in this study.

Species from the stelligeroid group of the genus *Cyclotella* were common in core material from both Lago de Zirahuén and Laguna de Juanacatlán. In Lago de Zirahuén, specimens the encountered appeared to conform to descriptions of *C. stelligera* (Plate 1, Figure 14; Plate 4, Figure 2). In Laguna de Juanacatlán, however, in addition to *C. stelligera* (Plate 1, Figure 15-16), numerous very small specimens (5µm or less) were encountered where it was difficult to distinguish any detail under the light microscope (Plate 1, Figures 17-18). Examination under the SEM showed that there were at least two small types of stelligeroid taxa. Considerable confusion exists over the classification of the stelligeroid *Cyclotella* taxa due to their small size and the fact that they are often heterovalvate (Haworth and Hurley, 1986; Klee and Houk, 1996). Haworth and Hurley (1986) carried out a detailed SEM investigation of *Cyclotella stelligera* and related taxa (*C. pseudostelligera, C. stelligeroides, C. glomerata* and *C. woltereckii).* They concluded that it was impossible to separate these different types at the specific level on the basis of morphological characteristics, due to the presence of intermediate specimens. However, it was clear that morphological variations were related to different ecological conditions, so separate identification is useful. The following classification of this group of taxa was proposed: *Cyclotella stelligera* Cleve & Grunow, *C. stelligera* var. *glomerata* (Bachmann) Haworth & Hurley, *C. stelligera* var. *stelligeroides* (Hustedt) Haworth & Hurley, *C. stelligera* var. *pseudostelligera* (Hustedt) Haworth & Hurley and *C. stelligera* var. *pseudostelligera* forma *woltereckii* (Hustedt) Haworth & Hurley. SEM photographs of specimens from Juanacatlán were compared with those in Haworth and Hurley (1986). The most common of the small stelligeroid taxa was *C. stelligera* var. *glomerata* (Plate 5, Figure 1) which corresponds to Figure 6 of Haworth and Hurley (1986). Taxa resembling *C. stelligera* var. *pseudostelligera* (Plate 5, Figure 2: see Haworth and Hurley, 1986, Figure 15) and *C. stelligera* var. *pseudostelligera* forma *woltereckii* (Plate 5, Figure 3: see Haworth and Hurley, 1986, Figures 19-20) were also encountered. Given that more than one variety of these stelligeroid taxa was present whose identity could not be determined under the light microscope, these taxa have been referred to as "*Cyclotella* stelligeroid group", separately from *Cyclotella stelligera.*

4.7.3: Stephanodiscus

In the surface sediment sample from Lago de Cajititlán, a small species was found which belongs to the genus *Stephanodiscus*. Identification of *Stephanodiscus* to species level under the light microscope is often difficult and can even be problematic using an SEM (Håkansson and Kling, 1990). The specimens encountered were 4-12μm in diameter (Plate 6, Figures 5-8). Correct identification of this diatom was hampered by the scarcity of diatoms in the sample and poor preservation. SEM images of the internal view of two valves are illustrated in Plate 7, Figures 1-2. In this taxon, the marginal fultoportulae have two satellite pores and a further fultoportula with three satellite pores is placed close to the junction of the valve face and mantle. The specimen from Cajititlán is similar to *Stephanodiscus nipigonensis* Kling and Håkansson and *Stephanodiscus* cf. *minutulus* (Kütz.) Cleve & Möller described in Håkansson and Kling (1990), although the location of the eccentric valve face fultoportula in their examples is always closer to the centre of the valve. In the absence of a firm identification for this taxon, this is referred to as *Stephanodiscus* sp. 1.

Another small *Stephanodiscus* species was found in modern samples from Lago de Chapala (Plate 6: Figures 9-12; Plate 8: Figures 1-2). As with the specimens from Lago de Cajititlán, diatoms were sparse in the sample. This taxon was generally between 5 and 12 μm in diameter, although most specimens had a diameter of between 6 and 8 μm. This taxon is characterised by a loose pattern of areolae in the valve centre. The SEM image of the internal view of a valve in Plate 8, Figure 2 illustrates a single valve face fultoportula (a). This internal view shows a lack of ornamentation in the valve centre. This taxon has similarities with *Stephanodiscus oregonica* described in Håkansson (1986), which is referred to in Krammer and Lange-Bertalot (1991a) as *Stephanodiscus oregonicus.* Håkansson (1986) makes reference to the fact that the central area in this species is sometimes disorganised and has a single visible rimoportula. The specimens from Lago de Chapala also appear similar to the examples shown in Bradbury (In Press: Plate 1, Figures 6-8) found in core material from Lago de Pátzcuaro, Mexico. Further taxonomic work is required to determine whether the species from Lago de Chapala is indeed the same as that found in Pátzcuaro. This taxon has not been identified with any degree of certainty and is therefore referred to as *Stephanodiscus* sp. 2.

Dr Hannelore Håkansson examined the specimens from Lago de Cajititlán and Lago de Chapala under the light microscope. She was unable to identify these specimens to species level but provided some very useful information for comparison of these specimens with published literature.

4.7.4: Cyclostephanos

A species believed to be of the genus *Cyclostephanos* was found in significant numbers in the lower section of core ZD/98 from Lago de Zirahuén. It was found in association with *Aulacoseira ambigua* cf. var. *robusta* and *Aulacoseira granulata* var. *angustissima.* Light microscope images of this species (Plate 6, Figures 13-17) illustrate its range in size from 4 µm to around 10 µm. Most specimens encountered were between 6 and 8 µm in diameter. Analysis under the SEM revealed the possibility that there may actually be two species present in the material, which are impossible to distinguish under the light microscope. The first, illustrated in Plate 9 has two fascicles between each raised interfascicle. There appear to be spines on every interfascicle, although most specimens examined had lost most of their spines. Marginal fultoportulae with two satellite pores occur approximately every fourth interfascicle. A single valve face fultoportula occurs close to the centre of the valve (Plate 9, Figure 1). A smaller specimen is illustrated in Plate 10. It was not possible to split the two different types under the light microscope. This taxon has three fascicles between each interfascicle (Plate 10, Figure 1) and appears to have had spines on each interfascicle. Marginal fultoportulae with two satellite pores occur every five to six interfascicles (Plate 10, Figure 2). A single valve face fultoportula is found slightly offset from the centre of the valve (Plate 10, Figure 2). Most of the features of the species illustrated in Plate 9 and 10 are very similar, with only the number of fascicles between each interfascicle differing. It is possible that this difference may simply be a function of valve size and these species may be the same. Further taxonomic work is required to determine this. The specimens from Laguna Zirahuén appear very similar to a species found in Lago de Pátzcuaro by Bradbury (In Press: Plate 1, Figures 15-21), which he names *Cyclostephanos* cf. *tholiformis* Stoermer, Håkansson & Theriot. Stoermer *et al.*'s (1987) original description of this species indicates that a rimoportula occurs below every third or fourth spine, which is more often than in the specimens from Lago de Zirahuén. A similar species has also been found in core material from Laguna Zacapu, Mexico (Metcalfe, 1985). She recorded this as *Cyclostephanos* sp. (Metcalfe, 1985: Plate 20, Figures 14-16; Plates 22-23). Her specimens have two fascicles between each interfascicle and appear remarkably similar to the specimen from Lago de Zirahuén in Plate 9. The species found in Lago de Zirahuén is called *Cyclostephanos* sp. in this thesis.

The centric taxa discussed above have not been conclusively identified with reference to the published literature but appear to have been found in other central Mexican lakes. It is possible that they are new varieties or species. Further detailed taxonomic work is necessary to determine whether the species from the different lakes are indeed the same and secondly to provide full descriptions of any new species which may have been identified.

4.7.5: Fragilaria

The genus *Fragilaria* Lyngbye was revised by Williams and Round (1987), who investigated the fine structure of numerous species using electron microscopy. They separated 5 genera from *Fragilaria*: *Staurosira, Staurosirella, Pseudostaurosira, Punctastriata* and *Neofragilaria.* Many of the features of these genera can only be identified under the SEM, which has not been used routinely in this study. This is particularly problematic for the correct identification of such species such as *Fragilaria pinnata* which, according to the new classification, is part of the genus *Staurosirella*, although many specimens identified as *F. pinnata* may actually belong in the genus *Punctastriata* (Williams and Round, 1987). A number of specimens were examined which had been described as *Fragilaria pinnata* and it was found that both *Staurosirella* and *Punctastriata* forms were present. Given that all counting was undertaken using a light microscope, the decision was taken to adopt the old taxonomic classification for *Fragilaria.* SEM images of some of the small *Fragilaria* species encountered in this study are found in Plate 14.

A species of the genus *Fragilaria* was abundant in core sediments from Lago de Zirahuén. It was usually found in chains (Plate 11, Figure 3) and rarely occurred in valve view (Plate, 11, Figure 4), which made correct taxonomic identification difficult. This taxon is between 60 and 80 µm long and 1.5-2.5 µm wide. The valve sides are very straight and do not taper towards the end of the valve. The valve ends are distinctly capitate (Plate 12, Figure 1). The striae are alternate (18-20 in 10 µm) and poorly developed or absent in the central area. The central area is slightly constricted (Plate 12, Figure 2). The alternate striae arrangement and the presence of interlocking spines at the junction of the valve face and mantle (Plate 12, Figure 3) indicate that this specimen belongs in the genus *Fragilaria.* Identification to species level is more problematic. It appears to fall within the *Fragilaria capucina* group, but is too narrow and too finely striated to be considered as *Fragilaria capucina* Desmazières *sensu stricto* (see Krammer and Lange-Bertalot, 1991a). The specimens from Zirahuén are similar to the illustrations of *F. capucina* in Hustedt (1930-1966: Figure 659 a & b) although again they are more finely striated than in his description of the species. The taxonomy of the *Fragilaria capucina* complex is poorly defined, with a large number of synonyms and inconsistency between authors. No direct match could be found in the published literature could be found for the Zirahuén specimen. This taxon is therefore referred to as *Fragilaria* cf. *capucina.*

4.7.6: Synedra

Krammer and Lange-Bertalot (1991a) subsumed the genus *Synedra* within the genus *Fragilaria*. These genera have been retained separately for this study to avoid confusion and to allow proper comparison with descriptions of *Synedra* species in the published literature.

A number of species of the genus *Synedra* were found to be abundant in core sediments from Laguna de Juanacatlán. Particular difficulty was encountered in differentiating between *Synedra acus* Kütz., *Synedra delicatissima* W. Smith, *Synedra delicatissima* var. *angustissima* Grun. and *Synedra radians* Kütz. Hustedt (1930; p. 155) suggested that *S. delicatissima* and *S. radians* are actually varieties of *S. acus*. These species have been identified according to Patrick and Reimer (1966) who separated them at the species level. The most common of these species are illustrated in Plate 15. The characteristic valve end of these species is illustrated in Plate 17 (Figures 1 and 2), illustrating the apical pore field and single rimoportula.

Synedra tenera and *Synedra nana* were also identified at various levels in the core material from Juanacatlán. *Synedra tenera* does not usually have a defined central area (Patrick and Reimer, 1966) although SEM examination revealed a poorly developed central area with shortened striae (Plate 17, Figure 3). Specimens from Laguna de Juanacatlán were most similar in shape to those illustrated in Krammer and Lange-Bertalot (1991a: Plate 114, Figures 12-16). Those species identified as *Synedra nana* are those which were too fine to see individual striae under the light microscope (Plate 16, Figure 5).

4.7.7: Navicula

The genus *Navicula* has undergone considerable revision in recent years (see Round *et al.*, 1990). Round *et al.* (1990) suggested that the generic name *Navicula* should be reserved solely for the section *Lineolatae*, which includes species such as *Navicula radiosa* and *Navicula viridula*. Mann (in Round *et al.*, 1990) separated several new genera from *Navicula*, including *Cavinula*, *Fallacia*, *Luticola* and *Sellaphora*, as well as proposing new combinations under the generic name of *Lyrella*. Whilst these new generic classifications may be valuable, it was decided to adopt the traditional classification for the naviculoid diatoms. This is largely because previous modern diatom datasets from central Mexico with which this work is to be combined had used the traditional nomenclature. Furthermore, as most floras have not yet adopted the new system, it was felt more appropriate to continue with the previous classification system, particularly to avoid making any combinations that have not yet been validated in the published literature.

Two species of the genus *Navicula* were encountered in large quantities in a short section of core AV/98 from Lago de Zirahuén. The first (Plate 23, Figure 3; Plate 24, Figure 1) was between 12 and 20 μm long and 3-4 μm wide. It has slightly capitate valve ends and a bow-shaped central area with shortened striae. There are c. 20 striae in 10 μm. D. Mann (Royal Botanic Gardens, Edinburgh) examined SEM images and slides under the light microscope. He suggested that the closest match in the published literature was *Navicula absoluta* Hustedt. This species is referred to as *Navicula* cf. *absoluta*. The second species is more elliptical-linear (Plate 23, Figure 4; Plate 24, Figure 2). The Zirahuén specimens are between 8 and 16 μm long and 3-4 μm wide, with c. 20 striae in 10 μm, slightly radiating towards the valve end. This species was also examined by D. Mann. He suggested that it appears to be very similar to *Navicula seminulum* Grun., although the specimens from Lago de Zirahuén have only one row of pores in each stria, whilst *N. seminulum* has two. All other characteristics, however, are concordant with descriptions of *N. seminulum*. This species is therefore referred to as *Navicula* cf. *seminulum*.

4.8: Chronological Control

4.8.1: ^{210}Pb Dating

Radiometric dating of recent lake sediments is possible using the isotope ^{210}Pb (half-life: 22.3 yrs), a naturally occurring radionuclide in the ^{238}U (uranium) radioactive decay series. This technique is used to provide chronologies for the last 100-150 years (Olsson, 1986).

Radionuclides of the ^{238}U decay series are present in most minerals, resulting in a continuous flux of the inert gas ^{222}Rn (radon) into the atmosphere. This decays through a series of short-lived nuclides to ^{210}Pb, which then becomes associated with water droplets and particulate matter and washed out of the atmosphere onto the surfaces of lakes and oceans. ^{210}Pb can also be washed into the lake through in-wash from the catchment and produced *in situ* by the decay of ^{226}Ra in the water column. ^{210}Pb derived from these sources and subsequently incorporated into lake sediments is termed the **unsupported** component (Oldfield and Appleby, 1984). ^{210}Pb in radioactive equilibrium with longer-lived members of the decay chain is also supplied to the sediment in eroded material. This is termed the **supported** component. The total ^{210}Pb and ^{226}Ra activities can be readily measured using gamma spectroscopy. The supported component of the total ^{210}Pb concentrations can be estimated by measurement of the ^{226}Ra activity in the sample. This is then subtracted from the total ^{210}Pb activity to calculate the unsupported component. In a lake with a constant sedimentation rate and constant rate of supply of unsupported ^{210}Pb, the amount of unsupported ^{210}Pb will decay exponentially with increasing depth. Two models are used to derive ^{210}Pb chronologies for sediment cores: the constant initial concentration (C. I. C.) model and the constant rate of supply (C.R.S.) model. Both of these assume that no mixing occurs within the sediment and that there is no post-depositional mobility of ^{210}Pb (Oldfield and Appleby, 1984). The procedure for calculating ^{210}Pb ages for each model is included in Appendix 2.

Man-made radionuclides

As a result of nuclear weapons testing during the late 1950s and early 1960s, a number of artificial radionuclides were released into the atmosphere. The activity profiles of these radionuclides in sediment cores provides a further means of age estimation. ^{137}Cs (caesium), with a half-life of 30 years, reached its peak concentration in 1963 (Bonnett and Cambrey, 1991). A second peak in ^{137}Cs associated with fallout from the Chernobyl accident in 1986 has been identified in numerous European lakes (e.g. Bryant *et al.*, 1993; Eades *et al.*, 1998). This peak is not expected to be found in lake sediments in Mexico due to the distance from the source. If there is a peak in ^{137}Cs present, it is likely to be too small to detect.

Activities of ^{137}Cs are measured simultaneously with radionuclides used for ^{210}Pb dating, with profiles providing an independent means of validating the ^{210}Pb ages (Eades *et al.*, 1998). Whilst many ^{137}Cs profiles do exhibit a distinct peak which corresponds to the 1963 peak in weapons testing fallout, there is evidence that ^{137}Cs can be mobile in sediments, particularly in an organic-rich environment (Bryant *et al.*, 1993) and this should be taken into account when interpreting records. Very recently, it has been possible to detect small concentrations of the manmade radionuclide ^{241}Am (americium). This radionuclide was not produced in significant quantities through weapons testing, but its parent ^{241}Pu (plutonium) was released in large amounts. ^{241}Am is produced by the decay of ^{241}Pu (plutonium), which has a half-life of 14 years. Its activity has therefore been slowly increasing since 1963. Although detectable for the last 20 years using Compton suppressed systems, ^{241}Am has only recently become detectable using gamma spectroscopy.

The combination of dating through ^{210}Pb and manmade radionuclides is a powerful tool for developing reliable chronologies for recent environmental changes. Only one ^{210}Pb chronology has been developed in Mexico to the author's knowledge. This work was undertaken by A. R. Byrne (University of California at Berkeley) on a short core from Laguna de Juanacatlán (Byrne, unpubl. data). Results from this study will be compared with the data obtained by Byrne.

Preparation of Mexican core samples

Profiles were developed for ^{210}Pb and manmade radionuclides (^{137}Cs and ^{241}Am) were measured in cores AV/98 and JL/98. This work was undertaken at the Scottish Universities Environmental Research Centre at East Kilbride. Initial sample preparation was carried out by the author, whilst counting and calculation of results was carried out by Mrs A. Stewart and Dr. A. MacKenzie. For each core, contiguous 1cm slices of the uppermost 25cm were analysed. Samples were dried and ground to obtain an even geometry. As sample size was less than 5 grams, pellets could not be made and samples were counted in pots. Samples were weighed, placed in pots and then sealed with araldite to prevent radon from diffusing. Samples were then left for three weeks to attain radioactive equilibrium. The activity of the different radionuclides was measured by gamma spectroscopy. In order to determine the counting efficiency of the apparatus, a number of samples of known radionuclide concentrations were also measured for ^{210}Pb, ^{137}Cs, ^{222}Rn and ^{226}Ra. A correction factor could then be applied to the counts of the core samples. ^{210}Pb ages were calculated using both the C.I.C and C.R.S. models. An independent evaluation of the accuracy of the different models was made possible by comparison with the ^{137}Cs and ^{241}Am data. At Lago de Zirahuén, comparison of ^{210}Pb ages with historical tephra layers provided a further means of independent validation. Results are discussed in detail in Chapter 6 and Chapter 7.

4.8.2: Radiocarbon (^{14}C) Dating

As a high resolution of dating control was required, conventional radiocarbon dates were not suitable for this study. Radiocarbon dates were obtained through an allocation of 11 Accelerator Mass Spectrometry (AMS) ^{14}C dates provided by the Natural Environmental Research Council's Radiocarbon Steering Committee (Grant No. 742/0598). Bulk sediment samples of 1cm thickness were removed from the cores, taking care to avoid contamination by potentially younger material from around the edges of the cores. These were transferred into petri dishes and wrapped in foil to avoid prolonged exposure to light. Samples were prepared at the NERC Radiocarbon Laboratory at East Kilbride by Dr. C. Bryant and Dr. B. Miller. Samples were digested in 2M HCl (80°C, 10 hours), washed free of mineral acid using distilled water and dried in a vacuum oven. Each sample was homogenised and combusted to CO_2 in sealed quartz tubes. The CO_2 was then converted to graphite by Fe/Zn reduction. Graphite targets were then sent to either the University of Arizona AMS Facility (lab code AA) or the Lawrence Livermore National Laboratory Center for Accelerator Mass Spectrometry (lab code CAMS). ^{14}C dates were calibrated to calendar years BC/AD using the program CALIB Version 4.1 (Stuiver and Reimer, 1993). This calibration program produces a calendar age for the sample that represents the intercept on the radiocarbon calibration curve. The date obtained does not take into account the errors on the original radiocarbon date and so it is more appropriate to quote the age range at either the 1 or 2 sigma level, which are both also provided by the calibration program. For each date obtained in this study, the original radiocarbon date, the calibrated age (ie. the intercept) and the calibrated age range at the 2 sigma level are presented. When estimates of sedimentation rates are made, the calibrated age (intercept) is used and the reader is referred to the table of dates for an indication of the errors. This approach has been used in numerous palaeoenvironmental studies (e.g. Curtis *et al.*, 1996; Verschuren *et al.*, 2000).

4.8.3: Tephrochronology

The identification of layers of volcanic ash (tephra) in lake sediments is a useful tool both for core correlation and absolute dating. The major element composition of individual glass shards is unique to an individual eruption, thus acting as a fingerprint for a particular event. This technique has been applied successfully in volcanic regions such as Iceland (e.g. Dugmore *et al.*, 1992; Larsen *et al.*, 1999). However, until recently, no work had been carried out on glass shard geochemistry of tephras from Mexico. Recent work by Ortega and Newton (1998) and Newton and Metcalfe (1999) has shown that through geochemical analysis, tephra layers in sediment cores and sections can be ascribed to particular eruptions from stratovolcanoes and cinder cones within the TMVB. Given the location of the sites in this study, it was thought that tephras from Volcán Paricutín (1943-1952), Volcán Jorullo (1759-1774) and Volcán de Colima (numerous historical eruptions) might be encountered in lake sediments. The latter is an andesitic stratovolcano, whilst the others are basaltic cinder cones.

Possible tephra layers were identified by eye or through the identification of minerogenic bands in the x-rays. Samples were digested in concentrated H_2SO_4 and HNO_3 to remove organic matter, then centrifuged 4 or 5 times in distilled water (5 minutes at 3,000 rpm) to neutralise the acid, following the method described in Dugmore *et al.*, 1992. Preparation of thin sections and geochemical analysis of glass shards on a Cambridge Instruments Microscan Mk 5 electron microprobe (Department of Geology and Geophysics, University of Edinburgh) was carried out by Dr. A. Newton.

4.9: Data Analysis

The relationships between modern diatom distributions and hydrochemical variables were explored using two-way indicator species analysis (TWINSPAN; Hill, 1979), detrended correspondence analysis (DCA) and canonical correspondence analysis (CCA; ter Braak, 1986; 1987-1992). Surface sediment samples from this study were merged with existing data collected by Metcalfe (1985, 1988) and Caballero-Miranda (1995) to produce the central Mexican Diatom Dataset. Weighted-averaging (WA) regression and calibration with inverse deshrinking (Birks *et al.*, 1990; Birks, 1995) were used to develop transfer functions for a number of hydrochemical variables from the Central Mexican Diatom Dataset. The program CALIBRATE (Juggins and ter Braak, 1999) was used to perform WA calculations. Statistical analysis of the Central Mexican Diatom Dataset and the development of the transfer functions were largely carried out by Dr. Steve Juggins, Department of Geography, University of Newcastle. The author was responsible for the merging and checking of datasets and the harmonisation of taxonomy. The application of these multivariate statistical programs in this study is discussed in more detail in Chapter 5.

Percentage diatom diagrams for all sediment cores are presented using TILIA and TILIAGRAPH (Grimm, 1992). Taxa occurring at >2% relative abundance are illustrated. CONISS (Grimm, 1987), a stratigraphically constrained clustering program within TILIA, was used to identify diatom zones. Only taxa occurring at >2% relative abundance were included in this cluster analysis.

4.10: Summary

The approach and methods described in this chapter have been selected specifically to achieve the objectives outlined in Chapter 1. The palaeolimnological records from each of the two sites will be based on multiple cores to ensure that results are truly representative of basin-wide changes. A multi-proxy approach ensures that different lines of evidence can be used to construct a more complete picture of environmental change in Lago de Zirahuén and Laguna de Juanacatlán, although diatom analysis will form the major part of this study. The application of mineral magnetic susceptibility and metals analysis will provide important supplementary evidence. By using a combination of ^{210}Pb dating, ^{14}C dating and tephrochronology, it will be possible to construct a robust chronological framework for the palaeoenvironmental records from the two lakes.

In order to interpret effectively the diatom records from Lago de Zirahuén and Laguna de Juanacatlán, it was necessary understand the ecological distribution of diatoms in central Mexico. An ecological survey of modern diatoms in central Mexican lakes was carried out, the results of which have been combined with existing data to create a modern diatom calibration data set, which allows numerical reconstructions of past environments. The present day ecological distribution of diatoms in Central Mexico is the subject of the following chapter.

Chapter 5: Modern Limnology and Diatom Ecology

5.1: Introduction

This chapter focuses on the present day aquatic environment in the central Mexican highlands. The results of a limnological survey of a number of lakes across the TMVB are presented. The relationship between hydrochemical variables and diatom species composition in these lakes is then explored using multivariate statistical techniques. Results from this study are combined with those of Metcalfe (1985, 1988) and Caballero (1995) to form the Central Mexican Diatom Dataset. This merged dataset has been used to develop transfer functions (Davies *et al.*, in press), which allow quantitative reconstructions of key environmental variables.

5.2: Mexican Limnology: A Brief Overview.

Pioneering limnological research in Mexico was carried out by Fernando De Buen, who was head of the Limnological Research Station at Pátzcuaro, Michoacán between 1939 and 1944 (Alcocer *et al.*, 1993). His early work (De Buen, 1943, 1944) and that of others (e.g. Osorio-Tafall, 1946; Deevey, 1957) provides baseline data for comparison with more recent studies. Much of the limnological research on Mexican lakes has focused on reservoirs. Investigations of natural lakes have concentrated on lakes within the TMVB (e.g. Alvarado *et al.*, 1985; Bernal-Brooks, 1988; Chacón, 1989; Lugo *et al.*, 1993). Other studies of modern limnology in Mexico have been driven by the need for modern data with which to interpret palaeoecological records (e.g. Bradbury, 1971, 1989; Metcalfe, 1985, 1988; Caballero, 1995, 1996). The data available from these different investigations provide further information on sites selected for this study and in some cases, an assessment of change in water chemistry through time can be made.

5.3: Study Sites

Given that the goal is to combine water chemistry and diatom species data collected during this study with those of Metcalfe (1985, 1988) and Caballero (1995), site selection had to be considered carefully. Sites were chosen which would either increase the environmental gradient or which would fill perceived gaps within the existing dataset. Figure 5.1 illustrates the location of sites, including those sampled during this study and those previously sampled by Metcalfe (1985) and Caballero (1995) which form part of the Central Mexican Diatom Dataset. Sampling locations during the course of this study have concentrated on three areas of the TMVB: the state of Jalisco, the lakes of Michoacán and southern Guanajuato and the crater lakes of the Oriental Basin. The locations of the individual sampling sites are provided in Table 5.1, along with results of field analyses. A list of diatom samples collected is provided in Table 5.2. Given the incompleteness of the field data, the following discussion will focus largely on the results of laboratory analyses, which are presented in Table 5.3.

5.4: Water Analysis

The chemical composition of lake waters is governed principally by the surrounding geology. Chemical weathering of soils and bedrock by naturally acidic rainwater results in the accumulation of dissolved salts within surface run-off which, eventually reaches the lake. Groundwater flow may bring higher concentrations of dissolved salts into the lake, as there is more time to weather the surrounding bedrock. The types of salts present in a lake therefore depend on the chemical composition of the bedrock. The principal soluble minerals transported into lakes through weathering by surface or groundwater are bicarbonate, calcium, magnesium, sodium, potassium, silica, chloride and sulphate (Eugster and Hardie, 1978). Sulphate and chloride ions are also found in significant quantities in rainwater (Gasse *et al.*, 1983), but can also enter the lacustrine environment through the leaching of ancient evaporites (Risacher and Fritz, 1991).

Most lakes are chemically dilute as throughputs of surface and ground waters prevent the accumulation of dissolved salts. The chemical composition and concentration of basins where outflow is restricted or absent is, however, highly dependent on the hydrological balance. If evaporation exceeds precipitation, the volume of the lake is gradually reduced and the chemical composition changes in response to evaporative concentration. Eugster and Hardie (1978) developed a model to illustrate the three major pathways of brine evolution through evaporative concentration, which is reproduced in Figure 5.2. Alkaline-earth minerals (calcium and magnesium) are precipitated in the earlier stages of brine evolution, followed by the precipitation of silicate minerals and other salts. The initial composition of the lake water determines which of the pathways is followed. Lakes originally rich in bicarbonates but with low levels of calcium and magnesium follow pathway I, resulting in a Na-CO_3-Cl composition. Lakes with initially low bicarbonate levels, but high amounts of magnesium / calcium follow pathway II, leading to the development of Ca-Na-SO_4-Cl brines. The third pathway sees lakes with approximately equal amounts of bicarbonate and magnesium / calcium evolving into Na-Mg- CO_3-Cl brines. Previous studies have shown that lakes lying along the TMVB tend to follow pathway IIIA of Eugster and Hardie's (1978) model (Metcalfe, 1985, 1988: Caballero, 1995). It seems therefore appropriate to compare the results of the present study with this model.

Although the underlying lithology and the prevailing climate largely control the chemistry of lake waters, a number of other factors must be taken into consideration. These include the level of biological activity and the influence of man through inputs of industrial effluents and excess nutrients (Horne and Goldman, 1994). These factors must also be considered when interpreting water chemistry data.

5.4.1: Electrical Conductivity and pH

Both field and laboratory pH measurements (Tables 5.1 and 5.3 respectively) are available for all but 2 lakes sampled (Alberca and Pátzcuaro). Comparison of the two datasets shows that readings taken in the laboratory show consistently lower values than field measurements. This can be attributed to gaseous exchange following sample collection. Discussion of pH will be based around the field results (except for Alberca and Pátzcuaro, where field measurements are not available), as these are likely to be a truer reflection of the actual pH of the lake water. All sites sampled apart from Lagunilla de San Gregorio have a pH of above 7, with 9 sites falling between pH 8 and 9. The most concentrated lakes are La Piscina de Yuriria (10.18), Atotonilco (9.69), La Alberca (9.43), Alchichica (9.31) and Cuitzeo (9.02).

The laboratory measurements of E.C. are used in the discussion as field equipment failed on several occasions and two different types of field meter were used. The E.C. results show a wide range of values, from very dilute lakes such as Lagunilla de San Gregorio (E.C. 30 $\mu S\ cm^{-1}$) and Zirahuén (E.C. 119 $\mu S\ cm^{-1}$) to the highly concentrated systems of Atotonilco (E.C. 11,260 $\mu S\ cm^{-1}$) and Alchichica (E.C. 10,140 $\mu S\ cm^{-1}$).

5.4.2: Major Cation and Anion Composition of Central Mexican Lakes

Anion and cation composition data are available for 15 of the sites sampled along the TMVB (Table 5.3). These data are presented as milli-equivalents (meq l^{-1}) in order to allow a more effective comparison between different samples and to assist in assessing the ion balance (see section 4.6.1). The sampled lakes represent a wide range of ionic concentration. Lagunilla de San Gregorio has the lowest alkalinity at 0.24 meq l^{-1} (HCO_3^- and CO_3^{2-}), whilst Lago Atotonilco has the highest, at 78.05 meq l^{-1}. Chloride content also spans a large gradient, from negligible amounts (Lagunilla de San Gregorio: 0.03 meq l^{-1}; Lago de Zirahuén: 0.10 meq l^{-1}) to considerable concentrations, such as at Laguna Alchichica (84.63 meq l^{-1}). Of the cation data, sodium has the widest range of concentrations. Again, Lago de Zirahuén and Lagunilla de San Gregorio represent the most dilute end of the spectrum, whilst Lago Atotonilco (139.01 meq l^{-1}), Alchichica (103.31 meq l^{-1}) and La Piscina de Yuriria (95.79 meq l^{-1}) lie at the other extreme.

The relative proportions of anions and cations in the sampled lakes are illustrated in the ternary diagrams in Figure 5.3. Most of the lakes in this dataset are dominated by

HCO_3^- and CO_3^{2-} anions. HCO_3^- + CO_3^{2-} anions make up more than 85% of the total anion composition in Zirahuén, Juanacatlán and Potrerillo, whilst all other sample sites apart from Laguna Alchichica have values above 50%. Laguna Alchichica is composed mainly of Cl^- anions (approximately 60%). Lago de Cuitzeo, Lago Atotonilco, Laguna Preciosa and La Piscina de Yuriria occupy an intermediate position between this gradient from carbonate to chloride dominance. Lagunilla de San Gregorio and Lago de Chapala have the highest sulphate abundances (23% and 17% of total anion content respectively). High sulphate concentrations in Chapala relative to other anions may be the result of industrial contamination.

The cation composition of the sampled lakes shows a much greater variation than their anion composition. Potrerillo, Juanacatlán and Lagunilla de San Gregorio are dominated by Ca^{2+}, whilst Zirahuén has approximately equal amounts of Ca^{2+} and Mg^{2+}. Chapala and Preciosa are dominated by Mg^{2+} cations. All other lakes in the dataset are enriched in Na^+ + K^+, which make up more than 60 % of the total cations. Alberca, Cuitzeo, Atotonilco and La Piscina de Yuriria are almost exclusively dominated by these cations, which make up at least 90% of the total. The crater lakes sampled are all depleted in Ca^{2+}, which has been lost through evaporative concentration. These basins have very small drainage areas and no surface inflows. Figure 5.4a illustrates the calcium carbonate reefs deposited around the edge of Laguna Alchichica, which are produced by the precipitation of Ca^{2+} from spring water as it enters the concentrated lake. The high concentrations of Mg^{2+} in Preciosa are surprising given the relatively high electrical conductivity of the lake (2,090 $\mu S\ cm^{-1}$). These results, however, showed a remarkable degree of coherence with those obtained by Dr. J. P. Bradbury in 1973 from Preciosa (Bradbury, unpubl. data, cited in Metcalfe, 1985). Ca^{2+} depletion in Preciosa may also be partly due to the fact that Preciosa was sampled during a "whiting" event, when calcium carbonate is precipitated as the increased temperature of the epilimnion at the onset of summer leads to the saturation of $CaCO_3$. This turns the lake a distinctive turquoise colour, similar to that of glacial lakes with a high suspended sediment load (Figure 5.4b).

Based on the anion and cation data, the lakes can be split into four different water chemistry types:

1. Calcium-magnesium carbonate-bicarbonate. This includes Lagunilla de San Gregorio, Potrerillo, Juanacatlán and Zirahuén. These lakes have an alkalinity of less than 1.5 meq l^{-1} ($HCO_3^- + CO_3^{2-}$). The pH is ranges from 6.57 to 8.78 and the E.C. from 30 to 158 $\mu S\ cm^{-1}$.
2. Magnesium carbonate-bicarbonate. This includes Preciosa, Quechulac and Chapala. Alkalinity is between 6 and 13 meq l^{-1} ($HCO_3^- + CO_3^{2-}$). pH ranges from 8.59 to 8.9 and E.C. from 840 to 2,090 $\mu S\ cm^{-1}$.
3. Sodium carbonate-bicarbonate. Lakes belonging to this category are Lago de Yuriria, La Piscina de Yuriria, Pátzcuaro, Alberca, Atotonilco, Cajititlán and Cuitzeo. Alkalinity ranges from 17 to 78 meq l^{-1} ($HCO_3^- + CO_3^{2-}$). pH is between 8.65 and 10.18, E.C. is between 756 and 11,260 $\mu S\ cm^{-1}$.
4. Sodium-chloride. Only one lake, Laguna Alchichica is included in this category (alkalinity = 41 meq l^{-1} ($HCO_3^- + CO_3^{2-}$). It has a pH of 9.31 and an E.C. of 10.140 $\mu S\ cm^{-1}$.

This range of water chemistry types represents increasing evaporative concentration through brine evolution. Calcium-magnesium carbonate-bicarbonate lakes of Group 1 are closest to the original composition of the inflow waters, whilst Laguna Alchichica represents the most highly evolved system. It is evident that geological factors are the most important control on the initial chemical composition of lake waters in the TMVB. Dilute waters, which have not been significantly altered through evaporative concentration, are rich in Ca^{2+} and Mg^{2+}. These cations are commonly leached from volcanic rocks such as the andesitic-basaltic and dacitic lavas, which form large parts of the TMVB. The progression from waters rich in Ca^{2+}, Mg^{2+} and HCO_3^- through to Na^+-CO_3^{2-}-Cl^- rich waters follows pathway IIIA of Eugster and Hardie's model (Figure 5.2), concordant with previous studies of central Mexican lakes (Metcalfe, 1985, 1988; Caballero, 1995). The crater lakes sampled are all at intermediate or latter stages of brine evolution, with Quechulac being the most dilute and Alchichica the most concentrated.

5.4.3: Nutrient Concentrations

Nitrate, phosphate (total reactive phosphate) and silica concentrations were analysed using field test kits for most but not all sites. Nitrate was undetectable in all samples analysed apart from Atotonilco (0.88 ppm), Chapala (0.35 ppm) and Arroyo el Puerto (0.308 ppm). All sites sampled showed detectable traces of phosphates apart from La Preciosa and Juanacatlán. The highest concentrations were observed in Chapala (5.72 ppm), Lago de Yuriria (>3.05 ppm), Atotonilco (>3.05) and Cuitzeo (3 ppm). Although these field measurements can only be regarded as a rough estimate of the biologically available phosphorus, they do suggest that these lakes are enriched in nutrients. Previous studies have indicated that both Chapala and Cuitzeo are eutrophic (Alvarado *et al.*, 1985; Guzmán, 1995).

Dissolved silica concentrations (expressed in ppm SiO_2) varied considerably from 0.16 ppm (Zirahuén) to over 40.3 ppm (La Piscina de Yuriria). Unfortunately, absolute values could not be determined for those sites with higher concentrations of dissolved silica as this involved numerous dilutions of sample and not enough reagents were available. However, it is clear that higher silica concentrations are present in shallow, turbid lakes (e.g. Cuitzeo, Chapala, Cajititlán, Atotonilco). Deevey (1957) and Metcalfe (1985) both observed the same relationship in central Mexican lakes. In general, these results corresponded well with those from previous studies. For example, SiO_2 results from Pátzcuaro are broadly similar with values of 8.44 ppm (this study), 11 ppm, 5 ppm (Metcalfe, 1985) and 7.8-16.3 ppm (Bridgwater, 1995). Two higher values of SiO_2 from Bridgwater's study were attributed to freshwater inputs to the lake. Bridgwater's (1995) SiO_2 analysis from Hoya la Alberca revealed a concentration of 8.44 ppm, whilst the result from this study is 3.68 ppm. Metcalfe (1985) found that, in general, volcanic crater lakes had higher SiO_2 concentrations. However, the sample from Alchichica analysed in this study only contained 0.75 ppm SiO_2. No other data were found with which to compare this result.

5.4.4: Transparency

The transparency of the lakes sampled was measured using a Secchi disk (Table 5.1). Although measurements are not available for all sites, some interesting patterns emerge. Laguna Alchichica (4 m) and Laguna Quechulac (6.2 m) have the greatest Secchi depths. These deep crater lakes (64m and 40 m respectively) are classed as oligo-mesotrophic lakes (Lugo *et al.*, 1993) and so a relatively high transparency is to be expected. The other Oriental crater lake, Preciosa has a lower secchi disk transparency of 1.2 m. The Secchi disk transparency at this site may have been affected by the "whiting" event, which was described in section 5.4.1 and is illustrated in Figure 5.4b. Juanacatlán and Zirahuén had similar Secchi depths of 1.8 m and 2 m respectively. There is no published limnological information for Juanacatlán; however comparison with previous studies at Lago de Zirahuén showed that there has been a significant decrease in the transparency of this lake in the last 15 years. Bernal-Brooks (1988) recorded a Secchi depth of 6m in March 1987, the same month in which measurements were taken for this study. Chacón (1989) also recorded a similar Secchi depth transparency of 6.4 m. The implications of this recent reduction in water quality are discussed in greater detail in Chapter 6. All other lakes measured had a Secchi disk transparency lower than 1m. These lakes, including Cuitzeo, Pátzcuaro, Atotonilco, Chapala and Cajititlán all appeared to be turbid, with a high level of suspended sediment. Lower transparency is characteristic of eutrophic lakes due to increased biological productivity (Horne and Goldman, 1994).

5.4.5: Discussion

Even though full water chemistry analyses are available for only 15 sites in this study, this relatively small dataset incorporates a wide range of ionic composition and concentration. In order to explore the relationship between the different hydrochemical variables in more detail, a series of correlations were carried out. Firstly, E.C., which is a measure of ionic strength was plotted against pH and alkalinity ($HCO_3^- + CO_3^{2-}$ meq l^{-1}). As pH is measured on a logarithmic scale, E.C. values were log-transformed when plotting against pH to maintain consistency. A strong positive relationship exists between E.C. and pH ($r^2 = 0.7624$) and alkalinity ($r^2 = 0.8672$), both significant at the 0.01 level (Figure 5.5). Alkalinity can be expected to increase with evaporative concentration where calcite precipitation occurs early in the brine evolution process (Risacher and Fritz, 1991). Alchichica clearly has a lower alkalinity than expected for its E.C. of 10,140 $\mu S\ cm^{-1}$. This lower alkalinity is due to the replacement of $HCO_3^- + CO_3^{2-}$ with Cl^- as the dominant anion.

Na^+ was correlated with the other major anions and cations. As this is a conservative cation and does not tend to be precipitated out, it was thought to be the most appropriate variable to use as a basis for comparison with other ions (Metcalfe, 1985). No statistically significant relationship was found between Na^+ and Ca^{2+} ($r^2 = 0.1672$) and Na^+ and Mg^{2+} ($r^2 = 0.1005$). Positive correlations were found, however, for Na^+ v. Cl^- ($r^2 = 0.6886$), Na^+ v. K^+ ($r^2 = 0.5719$), Na^+ v. $HCO_3^- + CO_3^{2-}$ ($r^2 = 0.7719$) and Na^+ v. SO_4^{2-} ($r^2 = 0.8898$). These relationships are illustrated in Figure 5.6. The correlations between Na^+ and Cl^-, $HCO_3^- + CO_3^{2-}$ and SO_4^{2-} are all significant at the 0.01 level, whilst Na^+ v. K^+ is significant at the 0.05 level. One important point to note with these four correlations is that whilst the dilute lakes with lower ionic concentrations are quite tightly clustered, the few concentrated sites in the dataset are more widely spread. Further data from more concentrated systems would be required to determine the most appropriate location of the trendlines.

The correlation between Na^+ and Cl^- indicates that Laguna Alchichica has high Cl^- concentrations relative to Na^+ (Figure 5.6a) which is due to the dominance of Cl^- over $HCO_3^- + CO_3^{2-}$ at this site. Concentrations of K^+ show considerable variability between the more concentrated systems. Cuitzeo is clearly depleted in K^+ relative to Na^+, whilst concentrations of K^+ in Alberca are high relative to Na^+ content (Figure 5.6b). Alberca also has a high alkalinity ($HCO_3^- + CO_3^{2-}$) relative to Na^+ (Figure 5.6c). The strongest correlation appears to be between Na^+ and SO_4^{2-} (Figure 5.6d) although Cuitzeo contains relatively less SO_4^{2-} than would be expected from its Na^+

content. This is not consistent with Metcalfe's (1985) water analysis, where her Cuitzeo sample was one of the most SO_4^{2-} rich. Comparison between results from different studies is discussed in more detail below.

Given that data are available from previous studies for a number of central Mexican lakes, it is useful to compare the results of water analyses in order to examine whether the chemical composition of the lakes has changed significantly. It was decided to compare measurements from Zirahuén, Pátzcuaro and Cuitzeo. These three closed-basin lakes are at different stages of brine evolution, with Zirahuén being the most dilute and Cuitzeo the most chemically concentrated. These lakes are thought to have been part of a tributary system of the Rio Lerma before being isolated due to volcanic activity (De Buen, 1943). Major anion and cation data from this study were compared with results obtained by Metcalfe in 1982 (Metcalfe, 1985) and Bradbury in 1973 (Bradbury, unpubl. data, cited in Metcalfe, 1985). Results are shown in Figure 5.7. Bradbury did not measure SO_4^{2-} at Pátzcuaro, therefore SO_4^{2-} concentration is calculated from the balance between anions and cations.

The ternary diagrams illustrate that whilst the cation composition of the three lakes shows little variation, there is a considerable discrepancy in the anion data for the different lakes. Metcalfe's analysis of Zirahuén recorded 16.7% SO_4^{2-} and no Cl^-, whilst the results from this study and that of Bradbury are almost identical, with approximately 90% HCO_3^- + CO_3^{2-} and approximately 10% Cl^-. The anion results from this study for Pátzcuaro compare well with those of Metcalfe, whilst Bradbury's sample contains more SO_4^{2-}. This may be due to the fact that this figure was calculated rather than measured directly. The largest spread of anion data is observed for Lago de Cuitzeo. Metcalfe's sample has the highest concentration of Cl^-, whilst the sample from this study and Bradbury's both contained approximately 30% Cl^-. Bradbury's sample, however, contained a significantly higher proportion of SO_4^{2-} than the sample from this study. The differences in the results may have a climatic explanation. Metcalfe's sample was obtained when the lake was almost dry, and therefore at its most concentrated. The sample from this study was obtained when lake level was higher. Considerable variation may also be expected in the water chemistry of this large, hydrologically complex lake, depending on where the sample is taken from. The western side of the lake tends to be more concentrated than the east (Alvarado *et al.*, 1985). It appears, from this simple comparison between different datasets, that anion composition is more variable than cation composition, which has changed little in the three lakes over the last 25 years. This may be due to the fact that anions are more sensitive to the effects of evaporative concentration than cations. However, the possibility that the choice of sampling site within a basin may play an important role should not be ignored. It is interesting to note the large difference between the Cuitzeo anion data from this study and that of Metcalfe. The return to a less concentrated chemical composition, also highlighted by E.C. measurements (Metcalfe - off scale, this study - 3,400 $\mu S\ cm^{-1}$), highlights the sensitivity of large, shallow, closed basin lakes to changes in the hydrological balance.

5.4.6: Summary

To summarize, a clear evolutionary trend can be identified in this dataset of central Mexican lakes. Classifications for pH, conductivity and alkalinity follow those described in Gasse *et al.* (1983). Group 1 lakes (calcium-magnesium bicarbonate-carbonate) have a low E.C., between 30 and 158 $\mu S\ cm^{-1}$, an alkalinity <1.5 $meq\ l^{-1}$ and a circum-neutral to medium pH (6.57-8.78). Group 2 lakes (magnesium carbonate-bicarbonate) are more evolved, being depleted in Ca^{2+} and enriched in Mg^{2+}. They are of medium E.C. (840-2,090 $\mu S\ cm^{-1}$), medium alkalinity (6-13 $meq\ l^{-1}$) and medium pH (8.59-8.9). The third group, consisting of sodium carbonate-bicarbonate systems has a wide range of E.C., from 756 to 11,260 $\mu S\ cm^{-1}$, medium to high alkalinity (17-78 $meq\ l^{-1}$) and medium to very high pH (8.65-10.18). Group 4 includes only one lake: Alchichica. This sodium-chloride lake has a high E.C. (10,140 $\mu S\ cm^{-1}$), medium alkalinity (41 $meq\ l^{-1}$) and a high pH (9.31). Clearly further data are required from sodium chloride lakes to evaluate how representative this site is of this lake type.

Although the initial chemical composition of lakes in the TMVB relates to the surrounding geology, the evolutionary trend in chemical composition identified in this dataset can be considered in terms of a climatic gradient. Those sites (see Figure 5.1) in the northern sector of the study area, towards the Central Plateau (e.g. la Piscina de Yuriria, Lago de Yuriria, Cuitzeo, La Alberca) and in the east (Alchichica, Preciosa, Quechulac) are all at intermediate or later stages of chemical evolution. The northern and eastern parts of the TMVB receive considerably less rainfall than the more humid southern and western portions of the TMVB. For example, the average annual precipitation in the Oriental Basin, in the north-east, is less than 400 mm yr^{-1}, whilst in the highlands of Michoacán in the west, annual precipitation is over 1,000 mm yr^{-1} (see section 3.2.2). Lakes sampled in these western and southern areas tended to be more dilute (e.g. Lagunilla de San Gregorio, Potrerillo, Juanacatlán, Zirahuén). The exception is Atotonilco, which is believed to be geologically older than the other basins sampled.

The water chemistry data presented in this section will now be considered in the context of diatom species distributions, discussed below.

5.5: Diatom Analysis and Classification

A total of 64 diatom samples were obtained from 19 different sites across the central Mexican highlands (Table 5.2). 44 samples yielded full diatom counts. A list of the 220 diatom taxa encountered in modern samples during this study is provided in Appendix 3. The results of the species counts are presented in Appendix 4. Each species was assigned a code in order to run the database through statistical packages. The coding system, DIATCODE, developed by the Environmental Change Research Centre at University College London was adopted. This checklist forms part of the AMPHORA database is found at http://www.geog.ucl.ac.uk/~pmalipha/amphora.

As Laguna de Juanacatlán and Lago de Zirahuén are the focus of palaeolimnological work, more detailed modern diatom sampling was carried out at these two sites. At Laguna de Juanacatlán, this included both wet and dry season sampling.

Unfortunately, the four wet season samples from Laguna de Juanacatlán, which were all aquatic vegetation samples, did not yield any counts. The continuing limnological monitoring programme carried out by the Universidad Michoacana de San Nicholas de Hidalgo at Lago de Zirahuén meant that surface sediment samples were available from a number of monitoring stations around the lake in addition to those sampled by the author. For two sites, paired wet and dry season samples were available. Sample locations are illustrated in Figure 5.8. The author is grateful to Lic. Juan Manuel Corona-García for providing access to this material.

Multivariate statistical techniques are a valuable aid to the effective interpretation of large environmental datasets. The modern diatom samples collected during this study have been analysed using two techniques: clustering and ordination. The clustering programme TWINSPAN (Hill, 1979) was used to classify samples and species, whilst CANOCO (ter Braak, 1987-1992) was selected for the ordination of the data. The ordination technique is described in more detail in Section 5.6. The surface sediment sample from Lago Atotonilco was removed from the database used for statistical analyses as it is thought that most of the diatoms encountered in this sample originate from Tertiary diatomite deposits within the catchment and do not reflect current environmental conditions (Bradbury, pers. comm.).

TWINSPAN (Two-Way-Indicator-Species-Analysis) is one of the most widely used clustering programmes in community ecology (van Tongeren, 1995). It is based on the idea that a group of sites can be characterized by a group of differential species (i.e. those species that prevail in one side of a dichotomy) (Jongman *et al.*, 1995). This hierarchical clustering technique essentially involves the repeated dichotomization of samples, then species. The data are then presented in a two-way table that expresses species synecological relations as succinctly as possible (Hill, 1979). The first step in the process is the ordination of the samples using correspondence analysis. From this, a crude dichotomy is made, whereby the samples are split into two groups: negative (left-hand) and positive (right-hand). A refined ordination is carried out based on the identification of differential species, which have particular preferences for either the negative or positive side of the dichotomy. The outcome of the refined ordination determines the exact location of the dichotomy. Finally an indicator ordination using discriminant functions based on the most highly preferential species is carried out to check the dichotomy suggested by the refined ordination. The two-way ordered table is presented so that species occurring in samples on the negative side of the dichotomy lie on the left-hand side of the table, whilst those preferring sites on the positive side lie on the right-hand side of the table.

The final database used for TWINSPAN classification consisted of 43 samples and 220 species. Pseudospecies levels were set at 0%, 2%, 5%, 10%, 25% and 50%, representing 7 categories of abundance (1 = 0-2%, 2 = 2-5%, 3 = 5-10%, 4 = 10-25%, 5 = 25-50%, 6 = 50-75%, 7 = >75%). Category 1, representing the rarest taxa, was down-weighted to half the weight of the other variables. The TWINSPAN programme was also run using different pseudospecies settings. The outcome did not change significantly, suggesting that the results obtained are reliable and not an artifact of the statistical parameters used. The full TWINSPAN table for all 220 species is provided in Appendix 5. Results of the analysis are summarized in sections 5.5.1 and 5.5.2.

5.5.1: TWINSPAN Classification of Samples

The TWINSPAN classification of samples is summarized in Figure 5.9. The first division created two groups: the *1 group (positive) includes all Zirahuén samples and two Juanacatlán samples, the *0 group (negative) includes all other samples. The indicator species for group *1 is *Cymbella cymbiformis* (0-2% abundance). Classification of Juanacatlán samples was clearly problematic at this level as J/AW/97 (13) and J/BVEG (14) were borderline negatives and J/AE/98 (12) and JUA/SED1 (16) were misclassified positives. This means that whilst the overall assemblages of J/AE/98 and JUA/SED1 placed them in the positive group, the indicator species score would place them in the negative category. These two samples were separated at the second division to form group *11, with the Zirahuén samples forming group *10. The indicator species for group *10 is *Cyclotella ocellata* (0-2% abundance). The *10 group was split further into 5 separate groups (*1000, *1001, *1010, *10110, *10111). It is interesting to note that the *100 groups (*1000 and *1001) represent samples taken by the author and the *101 groups correspond to those obtained by UMSNH. Samples taken for this study were taken on the lake margins, whilst the UMSNH samples were collected from a variety of different locations in deeper water. As would be expected, those samples from the lake margins, including vegetation samples (AV/BVEG1, AV/BVEG2, AVB/VEG3) and surface sediments (ZIR/SED1, ZIR/SED2) had a more diverse diatom flora, with a greater proportion of benthic and epiphytic taxa such as *Cymbella microcephala* and *Brachysira neoexilis*. ZIR/59A is separated from the other UMSNH samples at division 4 (*1010). This sample is from a separate sub-basin of the lake, Agua Verde and contained a more diverse flora than those from the deeper water sites in the main basin. It is interesting to note that there appears to be no seasonal signal evident in the assemblages from the surface sediment samples. There is no consistency in the separation of wet season (A) and dry season (B) samples at the fifth division. The lack of seasonal difference may be due to the fact that samples were obtained by UMSNH with a grab, rather than using a sediment trap. The samples obtained, therefore, may represent the average diatom composition over several years rather than one season. However, it is significant that sediment samples from different points around the basin have a very similar flora. This suggests that core samples are likely to be a true reflection of the diatom assemblage of the lake as a whole, with the exception of marginal areas.

The negative group (*0) was divided into two distinct groups at the second dichotomy. The *00 group includes samples from the most chemically concentrated sites (e.g. La Piscina de Yuriria, Alchichica and Cuitzeo) and also those which appeared to be at an intermediate stage of brine evolution (Pátzcuaro, Chapala, Cajititlán, Lago de Yuriria, Preciosa). Indicator species for this group are *Gomphonema subclavatum* var. *mexicanum* (0-2% abundance) and *Nitzschia romana* (0-2% abundance). In contrast, the *01 group consists of the more dilute systems

(Potrerillo, Juanacatlán, Yerbabuena). Laguna Quechulac is also included in this group due to the occurrence of *Fragilaria crotonensis* in small amounts in samples QUEC/VEG, QUEC/SED and QUEC/REE. This species is dominant in samples from Juanacatlán. Also included in this group are the stone scrapings from the Arroyo del Atajo (RDA/STO) and Rio de la Palma (RDP/STO). In addition to *Fragilaria crotonensis, Navicula cryptocephala* (0-2% abundance) is also an indicator species for this group. The surface sediment sample from la Piscina de Yuriria forms group *000. This sample was separated from the other chemically concentrated sites (Alchichica and Cuitzeo) based on the occurrence of *Anomoeoneis sphaerophora* var. *sculpta* (0-2% abundance). Samples from Alchichica (ALC/REEF, ALCH/SED) were placed into group *0010, whilst all other samples from the *00 group formed the *0011 category. This division was based on the indicator species *Rhopalodia gibberula* var. *vanheurckii* (coarse variety) (0-2% abundance) and *Nitzschia romana* (5-10% abundance) for the *0010 group. Essentially, the *0011 group contains samples from lakes which are at an intermediate stage of brine evolution. The fifth division separates Preciosa samples and the surface sediment sample from Chapala (group *00111) from the rest of group *0011. The remaining samples are clearly closely related, only separated at the sixth division. It is interesting to note that group *001100 contains only vegetation samples (CHAP/HYA, LY/MACR, PATZ/VEG), whilst three of the four samples in group *001101 are surface sediments (CAJI/SED, LYUR/SED, PATZ/SED). This division therefore, may be reflecting habitat differences.

The samples from more dilute waters which form the *01 group are split into 5 groups (*01000, *010010, *010011, *0101 and *011). The samples from Lagunilla de San Gregorio and Potrerillo were placed into group *011 at the third dichotomy (indicator species = *Gomphonema gracile* 0-2% abundance). Samples from Laguna Quechulac and the reed sample from Juanacatlán were separated at the fourth division into group *0101. The indicator species for this group is *Achnanthes minutissima* (10-25% abundance). The two samples from Yerbabuena form group *01000. These samples are dominated by *Fragilaria pinnata* var. *lancettula*, although the indicator species is *Amphora veneta* (0-2% abundance). The two stone scrapings from river samples (RDA/STO and RDP/STO) form group *010010 whilst the four samples from Juanacatlán make up group *010011 (J/AE/97, J/AW/97, J/BVEG, JUA/SED2).

To summarize the environmental significance of the sample classification, samples from Zirahuén are the most distinct from the others in the dataset. Following this principal dichotomy, samples from lakes with medium to high conductivity (*00) (756-10,140 μS cm^{-1}) are separated from more dilute systems (*01) (with an E.C. of 30-840 μS cm^{-1}). Laguna Quechulac is placed in with the dilute sites, even though it has an E.C. of 840 μS cm^{-1}. This is due to the occurrence of *Achnanthes minutissima* and *Fragilaria crotonensis* in samples from this site, which also occur in Juanacatlán. In general, further divisions of samples in these two groups separate out the different sampling sites. However, there is evidence that habitat is also important as group *001100 is made up entirely of vegetation samples and group *010010 represents the river stone scrapings. A larger dataset of different habitat types from different locations would be required to explore this further.

5.5.2: TWINSPAN Classification of Species

The 220 species in this dataset were classified into 28 groups after six divisions. The full TWINSPAN output is included in Appendix 5. This discussion is based on the 100 most common taxa in the dataset, the classification of which is summarized in Figure 5.10.

Groups *00000 and *00001 represent species which are widely distributed at low abundances across the study area, but are more common in samples which lie on the left-hand side of the primary sample dichotomy (i.e. group*0). These include *Nitzschia amphibia* and *Rhopalodia gibba*, which are common in the surface sediment sample from Lago de Yuriria (LYUR/SED) but also occur in small amounts in Zirahuén samples, which lie on the right hand side of the table. Similarly, *Navicula* *radiosa* var. *tenella* is common (25-50%) in Alchichica sediments, but is also recorded in small numbers from dilute lakes on the right hand side of the dichotomy.

*0001 groups (*000100, *000101, *000110, *000111) show a clear preference for those samples from sites with medium to high conductivity (i.e. sample groups *0010 and *0011). Groups *000100 includes species such as *Fragilaria capucina* var. *mesolepta*, *Rhopalodia gibberula* var. *vanheurckii* (fine type), *Gomphonema olivaceum* and *Cymbella cymbiformis* var. *nonpunctata*. Species in this group are restricted to those sites with medium conductivity (e.g. Lago de Yuriria, Cajititlán, Chapala, Pátzcuaro). Species in the *000101 group are most common in the most concentrated lakes (La Piscina de Yuriria, Alchichica and Cuitzeo). These include *Anomoeoneis costata, Anomoeoneis sphaerophora, Nitzschia romana, Mastogloia smithii* and *Nitzschia inconspicua*. Species in groups *000110 and *000111 are most common in the samples of medium to high conductivity, but also occur in small amounts in the more dilute lakes of the *0 sample group (e.g. Juanacatlán, Yerbabuena, Potrerillo). Species in these groups include *Aulacoseira granulata, Rhoicosphenia curvata, Amphora perpusilla* and *Cyclotella meneghiniana.*

Species in *001 groups (*001000, *001001, *001011, *00110, *00111) are widely distributed across the *0 sample group. These include *Aulacoseira granulata* var. *angustissima*, *Gomphonema parvulum*, *Nitzschia palea* and *Nitzschia palaecea*. The *01 groups (*0100, *010010, *010011, *0101, *01100, *01101, *0111) also have a wide distribution across the negative and positive sides of the sample dichotomy. They are, however, most common in the lakes with more dilute water chemistry on the negative side of the dichotomy, such as Potrerillo and Juanacatlán. These species include *Achnanthes lanceolata* (*010010), which is particularly abundant in the two river stone scrapings (RDA/STO and RDP/STO), *Navicula cryptocephala, Achnanthes minutissima* and *Synedra acus*. *Fragilaria crotonensis* is placed in a group of its own (*0111) due to the dominance of this species (abundance >50%) in samples from Juanacatlán, which were placed on both negative and positive sides of the dichotomy. As mentioned in the previous section, samples from Juanacatlán were not classified satisfactorily.

Those species on the positive side of the dichotomy (*1) are all found in samples from Lago de Zirahuén. Group *100 includes only 3 species which occur in small amounts in Lago de Zirahuén (0-2% abundance) but which are found in slightly higher numbers in the medium conductivity sites. These species are *Epithemia sorex*, *Fragilaria vaucheriae* var. *capitellata* and *Amphora ovalis*. Species in the *101 groups are closely related (*101000, *101001, *101010, *101011, *101100, *101101, *10111) and occur mainly in the samples from Zirahuén. Groups *101000 and *101001 represent those species which were more common in the lake margin samples taken by the author (AV/BVEG1-3, ZIR/SED1-2). These include benthic species such as *Brachysira neoexilis, Nitzschia valdestriata, Cymbella microcephala* and *Navicula globosa*. The *101010 and *101011 groups incorporate species that occur across the range of Zirahuén samples, such as *Cyclotella ocellata*, the dominant species in most samples, *Navicula cymbula* and *Cymbella cymbiformis*. *Fragilaria pinnata* is common in most Zirahuén samples (up to 10% abundance), but is also abundant in the surface sediment sample from Juanacatlán (JUA/SED1) which appeared as a misclassified positive on the primary sample dichotomy. The *1011 groups (*101100, *101101, *10111) represent those samples which are found in most of the samples on the positive side of the dichotomy, yet are also present in small amounts on the negative side of the dichotomy. These include *Cyclotella stelligera* and a number of *Fragilaria* species (*F. construens*, *F. construens* var. *venter*, *F. brevistriata* and *F. capucina*). Finally, groups (*110 and *111) represent species which occur in the lake margin samples from Lago de Zirahuén which also occur on the negative side of the dichotomy. *Fragilaria pinnata* var. *lancettula* is placed in this group. This species is found at up to 10% abundance in the Zirahuén margin samples, but is also highly abundant (25-50%) in the two samples from La Yerbabuena.

In order to obtain a meaningful interpretation of the TWINSPAN species classification of the modern diatom dataset, it is useful to consider the classification at the third and fourth levels of division. Although, TWINSPAN will continue to divide the dataset up to six divisions, the differences may be slight and broad trends with ecological significance cannot easily be identified. It should be pointed out that the distinctive species composition of samples from Zirahuén, which are all dominated by *Cyclotella ocellata*, has a significant effect on the species dichotomy. At the fourth level of division, 13 different species groupings are identified. Species group *0001 has a clear ecological preference for sites with medium to high conductivity and a high proportion of $Na^+ + K^+$. Group *0010 includes species which appear to have a broad ecological tolerance but do not occur in Lago de Zirahuén. Groups *0000 and *0011 are widely distributed amongst the sites sampled, also occurring in small numbers in Zirahuén samples. Species in groups *0100, *0101, *0110, *0111, *110 and *111 have an ecological preference for more dilute waters, with a high carbonate content and low sodium content. Species in these groups are found in some Zirahuén samples. Groups *100, *1010 and *1011 occur principally in Lago de Zirahuén, although are also found in smaller numbers in other dilute sites. From the hydrochemical variables measured, there was nothing to suggest that Zirahuén has any distinctive characteristics that would distinguish it from other sites of a more dilute nature. It is possible, however, that other variables which have not been measured, such as nutrient content, may be important. The separation of Zirahuén from the other dilute sites in the two-way table may be an artifact of the large number of Zirahuén samples in the dataset. As mentioned earlier in this section, at the higher levels of division (5 and 6), habitat preferences rather than water chemistry appear to be an important factor. The relationship between species composition and the measured environmental variables is explored further in the following section.

5.6: Ordination of the Modern Diatom Dataset.

Ordination techniques are an alternative means of interpreting large ecological datasets quantitatively. Rather than the classification approach of clustering programmes such as TWINSPAN, ordination techniques place sites along an axis based on their species composition. This distribution represents an ecological gradient. Correspondence Analysis (CA) and Principal Components Analysis (PCA) are the most widely used ordination methods (ter Braak, 1995). However, the development of Canonical Correspondence Analysis (CCA) by ter Braak (1986) has led to significant progress in the quantitative analysis of species-environment relationships. CCA involves the analysis of both species composition and environmental variables for a set of sites. Ordination of sites and samples is followed by the interpretation of the environmental gradient using the inputted environmental variables. CCA is designed to detect patterns of variation in species data which are best explained by observed environmental variables (ter Braak, 1995).

In CCA, a series of axes are derived which represent linear combinations of the inputted environmental variables. The first axis represents the best linear combination of environmental variables to explain the variance in the dataset. Further CCA axes are also derived, but the constraint is applied that they must be uncorrelated with previous CCA axes. The importance of each axis in explaining species distribution is illustrated by its eigenvalue. The closer the eigenvalue to 1, the greater the significance of the environmental gradient represented by the axis. Generally, the first two axes are the most significant and these are plotted against each other on scatter plots to illustrate species and sample distributions relative to the environmental gradient. The environmental variables are represented as arrows. The relative importance of individual variables in explaining diatom distributions is represented by the length of each arrow, whilst the direction of the arrow illustrates the relationship to the CCA axes.

As environmental data were not available for all sites, the dataset used for ordination is smaller than that used in the TWINSPAN classification. As with the TWINSPAN classification, Atotonilco was excluded from the final dataset. Only species which occurred at >1% abundance in at least one sample were included to avoid the problem of over-weighting the importance of rare taxa. The final species dataset used for ordination consisted of 159 taxa and 32 samples from 14 different sites. The environmental dataset consisted of 9 variables (pH, E.C., % K^+, % Na^+, % Ca^{2+}, % Mg^{2+}, % SO_4^{2-}, % Cl^-, % $HCO_3^- + CO_3^{2-}$). Given that only one water sample was taken at each site, the same water chemistry results have been used for multiple diatom samples. CCA was carried out using CANOCO version 3.12. (ter Braak, 1987-1992). Although collinearity was detected when fitting environmental variables % Ca and % CO_3, forward selection suggested that all variables except % K explain an independent and statistically significant proportion of the variance in the diatom data, according to Monte Carlo permutation tests (999 permutations; $P = 0.01$). It was therefore decided to keep all environmental variables in the ordination. Diagrams were plotted using CALIBRATE version 1.0 (Juggins and ter Braak, 1999).

5.6.1: Species and Sample Ordination Using CANOCO

The species- and sample-environment biplot in Figure 5.11 illustrates the results of the CCA analysis. The environmental variables included in the analysis explain a total of 27.9% of the variance in the diatom data. Axis 1 ($\lambda = 0.80$) and axis 2 ($\lambda = 0.75$) together account for 15.3% of this variance. Axis 1 corresponds to the pH gradient. The sample from La Piscina de Yuriria (pH = 10.18) lies at the upper extreme of this gradient on the left-hand side of the plot, whilst the Lagunilla de San Gregorio sample (pH = 6.57) lies on the extreme right hand side. These two samples, with totally different species compositions have the effect of enhancing the importance of pH in determining the species composition of the dataset as a whole. As Figure 5.11 illustrates, most sites lie at an intermediate point along this gradient, having a pH of between 8 and 9. Axis 2 reflects the percentage sulphate content of the water. Lagunilla de San Gregorio has the highest proportion of sulphate and hence has a high value for axis 2, whilst samples from Lago de Zirahuén contain almost no sulphate and plot along the lower part of the axis.

pH and sulphate content are important in explaining the species distribution in a limited number of sites with particularly distinctive floras. The rest of the sites, however, appear to be most influenced by a third environmental gradient, which reflects a number of closely related variables. E.C. shows a strong positive correlation to % Na and % Cl, whilst it is negatively correlated with % HCO + CO and % Ca (Table 5.4). Alchichica and Cuitzeo have a high E.C. and plot on the upper left-hand side of the diagram, whilst those with lower E.C. and higher % HCO_3 + CO_3 plot on the bottom right-hand side. As these low conductivity sites also have low sulphate values, they plot close to axis 2. These sites include Zirahuén and Juanacatlán. A group of sites cluster at the centre of the diagram. These sites are of medium conductivity and of sodium carbonate composition. The % Na and % HCO_3 + CO_3 are in effect pulling in opposite directions which accounts for the intermediate location of the sites along the gradient. This cluster of sites includes Pátzcuaro; Preciosa; Cajititlán; Lago de Yuriria and Chapala and corresponds to the *0011 groups of samples identified in the TWINSPAN classification. Laguna Potrerillo also plots within this group of sites, although it has a relatively low E.C. (158 $\mu S\ cm^{-1}$) and is of calcium-magnesium bicarbonate composition. *Aulacoseira granulata* and its variety, *angustissima* are common in this lake and are also abundant in Lago de Yuriria, Cajititlán and Pátzcuaro. All these lakes are relatively shallow and turbid. This suggests that other environmental variables apart from those included in this study may have an important role in diatom species distribution in central Mexico. As with the TWINSPAN classification, samples from Quechulac plot close to those from Juanacatlán due to the common occurrence of *Fragilaria crotonensis* var. *oregonica* and *Achnanthes minutissima* in samples from these two lakes.

Species representing systems with a very high pH are *Anomoeoneis costata* and *Anomoeoneis sphaerophora*. These plot on the far left of the diagram and are found in La Piscina de Yuriria. Species found in Lagunilla de San Gregorio are plotted on the top right hand side of the diagram. These include *Eunotia naegelii* and *Pinnularia viridis*. *Navicula mutica*, *Pinnularia subcapitata*, *Pinnularia maior* and *Gomphonema gracile* also plot out on the gradient towards lower pH preference, but not at an extreme position. *Amphora coffeaeformis*, *Mastogloia elliptica* and *Rhopalodia musculus* are found in the most concentrated systems and plot on the upper left-hand side of the diagram. Species that cluster in the centre of the diagram are most commonly found in those lakes of sodium carbonate composition and medium E.C. These include *Rhopalodia gibberula* var. *vanheurckii* (fine type), *Navicula capitata* var. *hungarica*, *Cocconeis diminuta* and *Fragilaria capucina* var. *mesolepta*. *Amphora veneta*, *Epithemia argus* and *Nitzschia romana* plot out between the cluster of species at the centre and those at the most concentrated end of the gradient. This is because they are found in significant numbers in both the most concentrated lakes and those which are at an intermediate stage of brine evolution, suggesting that they are tolerant of a wide range of E.C. Those species found in the bottom part of the diagram are characteristic of dilute, low E.C environments which are of calcium-magnesium bicarbonate composition. These include *Brachysira neoexilis*, *Fragilaria pinnata* (and var. *lancettula*), *Cyclotella stelligera* and *Cyclotella ocellata*, which are all found in Lago de Zirahuén. *Fragilaria crotonensis* var. *oregonica* and *Achnanthes lanceolata* also plot at this end of the gradient. These species are common in Laguna de Juanacatlán.

As the pH and sulphate gradients are largely the product of two samples with extreme values and very distinctive floras (La Piscina de Yuriria and Lagunilla de San Gregorio), it could be argued that these should be removed from the dataset. More subtle variations in diatom species distributions could then be explored. The effect of removing these two samples from the dataset was to spread the vectors representing the environmental variables into different directions (Figure 5.12), with no particular trend associated with an individual variable identifiable. This may be partly due to the fact that the dataset is small and some sites are dominated by taxa that do not occur in other samples. The environmental gradients which are shown in Figure 5.12 may well be real, but a larger number of samples is required to identify which are the most important in determining species distributions. The first ordination, which included all the samples, appeared to give a more sensible explanation for the diatom species distributions and also compared well with the TWINSPAN classification.

5.7: Initial Conclusions from the Modern Diatom Data

The TWINSPAN classification of the diatom data and the CCA ordination show broadly similar patterns. The TWINSPAN classification could clearly be related to differences in E.C., which was also apparent in the ordination. However, the CCA was useful in identifying the strong pH gradient in the dataset, which is not immediately obvious in the TWINSPAN classification. The environmental preferences of species in the dataset are consistent with previous studies of diatom ecological distributions in central Mexico. For example, Bradbury (1989) found *Fragilaria* species such as *F. construens* and *F. pinnata* and their varieties to be associated with shallow, freshwater and alkaline ponds. In this study, these species were abundant in shallow water samples from Zirahuén, Juanacatlán and Yerbabuena. Bradbury (1989) suggested that *Anomoeoneis costata*, *Amphora coffeaeformis*, *Navicula elkab* and *Chaetoceros muelleri* are characteristic of shallow, saline environments. In this study, these species were encountered in the shallow, concentrated waters of Cuitzeo and La Piscina de Yuriria. *Nitzschia palea* was considered by Metcalfe (1985) to be an indicator of anthropogenic disturbance. She found it to be common and abundant in many of the lakes she sampled. In this study, it was also found in basins where signs of eutrophication were evident, such as Cuitzeo, Potrerillo and Lago de Yuriria. Although these lakes have very different chemistries, they all yielded high phosphate readings (Table 5.1). Species common on stone scrapings from river samples were *Achnanthes lanceolata* and *Cymbella sinuata*. These were also found by Caballero in stream samples from Zempoala, south of Mexico City. Metcalfe (1985) also found *Achnanthes* species commonly occurring on stone surfaces.

Some discrepancies do occur, however. Caballero (1995) reported large quantities of *Cyclotella meneghiniana* in Lago Recreativo, Texcoco in the Basin of Mexico (E.C. 7,500 $\mu S\ cm^{-1}$). In this study, it was common in samples from Preciosa (E.C. 2,090 $\mu S\ cm^{-1}$), Lago de Yuriria (E.C. 1,885 $\mu S\ cm^{-1}$) and Cajititlán (756 $\mu S\ cm^{-1}$). This species clearly has a wider tolerance range of E.C than would be indicated by this or Caballero's study. Caballero (1995) points out that in her study, *Amphora veneta* is found in relatively concentrated environments such as Lago de Chalco in the Basin of Mexico, but does not appear to be tolerant of Cl^- dominated systems. Metcalfe, however, reported this species to be oligohalobous in central Mexico. In this study, it was found in a range of environments, from the shallow circum-neutral pond of Yerbabuena to the more concentrated sodium carbonate systems of Lago de Yuriria and Preciosa. It was also abundant in the vegetation sample from Cuitzeo, which has high levels of chloride. These examples highlight the problem of small datasets, which may not encounter the full ecological range of a species. By merging the data collected during this study with that of Metcalfe (1985, 1988) and Caballero (1995, 1996), it is more likely that the ecological tolerances of diatoms will be accurately understood. This is particularly important if modern data is to be used for quantitative palaeoenvironmental reconstructions. The following section focuses on the expanded Central Mexican Diatom Dataset and the development of diatom-based transfer functions. The ecological information from this larger dataset will then be compared with results of studies in other regions.

5.8: Towards a Diatom Calibration Dataset for Central Mexico

The importance of developing a diatom dataset, which will enable quantitative reconstruction of hydrochemical variables, has been discussed in Chapter 4. Modern diatom data from 3 separate studies (Metcalfe, 1985; Caballero, 1995, Davies, this study) have been merged to create a larger diatom calibration dataset for central Mexican lakes. Metcalfe and Caballero previously merged their datasets, whilst the author added data collected from this study and was responsible for checking the chemistry and diatom data of the enlarged dataset. Every effort has been made to ensure consistency in the taxonomic nomenclature used by the different analysts. Only surface sediment samples are included in the enlarged dataset as these are felt to be most analagous to assemblages in sediment core samples, which represent an average of species composition within the lake. This also avoids the problem of habitat preferences masking water chemistry variations as reported by Metcalfe (1988). Only those surface sediment samples which have full water chemistry data available (pH, E.C., major anions and cations) were incorporated into the dataset.

Samples collected by Caballero (MCM), however, were not analysed directly for sulphate, instead these values were inferred from the anion-cation balance. For some lakes where two or three samples were taken at the same time, only one set of water chemistry data is available. The Central Mexican Diatom Dataset consists of 54 diatom samples from 31 different sites.

In the following section, the environmental characteristics of the Central Mexican Diatom Dataset are described, before discussing the results of the statistical analysis of data and the development of the transfer functions in the remainder of this chapter. Dr. Steve Juggins of the University of Newcastle carried out statistical analysis of the merged dataset. The description of the data analysis in Section 5.8.1 is based on his account in Davies *et al.* (in press). The interpretation of the results of the statistical analyses is, however, largely the work of the author.

5.8.1: Water Chemistry

The 36 samples analysed for hydrochemical variables span a large environmental gradient. Results are summarised in Table 5.5. Conductivity ranges from $17\mu S\ cm^{-1}$ to $44{,}100\mu S\ cm^{-1}$. A wide range in pH is also observed, with values ranging from 4.9 to 11, although the majority of sites have a pH between 7 and 9. Figure 5.13 shows the distribution of the lakes according to their ionic composition, pH and conductivity. Most of the lakes are of bicarbonate-carbonate type, although those lakes with the highest conductivity values tend towards chloride dominance. Only three sites are dominated by sulphate anions: the two crater lakes (La Luna and El Sol) of the Nevado de Toluca (11, 12) and Zacapu Celanese (26). The cations of freshwater lakes comprise approximately equal amounts of calcium and magnesium. As conductivity increases, Mg^{2+} and Na^{+} + K^{+} begin to dominate. The dataset represents a clear evolutionary trend from fresh water systems of calcium-magnesium bicarbonate-carbonate type, through magnesium-sodium carbonate to the most highly evolved concentrated sodium-chloride systems. This corresponds to pathway IIIA of Eugster and Hardie's (1978) model of brine evolution with evaporative concentration. Figure 5.13 illustrates that, with the exception of sites 11 and 12, the crater lakes included in the dataset appear to have intermediate to well-evolved brines, being of either Mg^{2+}+ Na^{+} + CO_3^{2-} or Na^{+} + Cl^{-} composition, ranging in conductivity from 840 µS cm^{-1} to 26,000µS cm^{-1}. Water samples taken from the same lake, but at different times show a remarkable degree of correspondence. Alchichica (2), Pátzcuaro (13), La Piscina de Yuriria (16) and Zirahuén (30) were all sampled in both 1981 and 1997, producing very similar results in terms of the proportions of major anions and cations.

The two crater lakes of the Nevado de Toluca (La Luna and El Sol) (11, 12) are clear outliers in the dataset, as pointed out by Caballero (1996). They have the lowest pH and conductivity values. Their chemical composition is clearly different from the general trend in the dataset and may be a reflection of local geological and / or hydrological factors. These lakes are situated at 4,550m a. s. l., which is c. 2,000m higher than most other lakes in the dataset. The other site, which does not follow the identified evolutionary trend, is Zacapu Celanese (26). This is immediately downstream from a synthetic fibre factory and it is thought that the high sulphate concentrations reflect human impact (Metcalfe, 1988).

5.8.2: Data Analysis

The final dataset used for statistical analysis consisted of 53 samples from 30 different lakes across the TMVB (Figure 5.1; Table 5.5). Only species that were present in at least two lakes and reached a maximum abundance of at least 2% were included in the analysis. 186 diatom taxa were included in the analysis, the counts expressed as percentages. Relationships between diatom assemblage composition and water chemistry were explored using TWINSPAN (Hill, 1979), detrended correspondence analysis (DCA) and CCA (ter Braak, 1986). In the first instance, ordination was carried out using 16 environmental variables, which included pH, E.C., the percentage value of major anions (HCO_3^{-} + CO_3^{2-}, Cl^{-}, SO_4^{2-}) and cations (Ca^{2+}, Mg^{2+}, Na^{+} + K^{+}), their value in meq l^{-1} and the anion and cation ratios. Conductivity and all variables expressed as concentrations showed strongly right-skewed distributions and were $\log_{10}$-transformed prior to all statistical analyses.

It became apparent that the principal environmental gradients in the dataset are represented by a number of highly inter-correlated variables. This can make the ordination analysis unstable (ter Braak, 1995). To solve this problem, variables were divided into three groups representing gradients of electrical conductivity (ionic strength), ionic composition, and pH respectively, and used CCA with forward selection to select a subset of variables to represent each gradient (Gasse *et al.* 1995).

If a transfer function is to be developed for a particular variable, that variable must explain a significant amount of the total variance in the diatom data independently of other variables (Birks, 1995). The significance of the three main gradients identified was examined using variance partitioning. A series of CCAs and partial CCAs were used to estimate (1) the unique contribution of each gradient, (2) the contribution due to interaction between gradients and (3) unexplained variance (Gasse *et al.*, 1995). A Monte Carlo permutation test (999 permutations; $P = 0.01$) was used to establish the statistical significance of individual variables in forward-selection CCA, and of CCA and partial CCA ordination axes. Ordinations were performed using CANOCO (ter Braak & Šmilauer, 1998).

Transfer functions were developed using the method of weighted-averaging (WA) regression and calibration with inverse deshrinking (Birks *et al.*, 1990; Birks, 1995). The performance of the transfer functions is reported in terms of the root mean square of the error (RMSE) (observed - inferred) and the squared correlation (r^2) between observed and inferred values for the modern dataset. These two measures are useful for comparison with other published transfer functions, but because they use the same data to both develop and evaluate the transfer function they inevitably underestimate the true prediction errors. The jack-knife, or "leave-one-out" RMSE (RMSE of prediction, RMSEP; ter Braak & Juggins 1993) is therefore also reported, as this measure is less biased by sample re-substitution and is a more reliable indicator of true predictive ability (Dixon, 1993). WA calculations were performed using the program CALIBRATE (Juggins & ter Braak, 1999).

5.8.3: TWINSPAN Groupings

TWINSPAN classification was used to partition the sites into 11 main groups on the basis of their diatom assemblages. The diatom composition and chemical environment of each group is summarised in Figure 5.14. Group 1 represents the low pH and low conductivity crater lakes of La Luna (11) and El Sol (12) and is characterised by species such as *Navicula pseudoscutiformis* and *Cymbella perpusilla.* The dominant taxa within this group do not occur in any other samples. Groups 2, 3, 4, 5 and 6 all have broadly similar chemical composition dominated by bicarbonate/carbonate anions, with a range in conductivity from 119µS cm^{-1} to 399µS cm^{-1} and a pH of 7 to 8.8. A number of these samples have very distinctive species compositions, which accounts for the separation into different groups. For example, the Zirahuén samples 30ai and 30aii have been classified as a single group (Group 3). This is due to the high abundance of *Cyclotella ocellata*, which is not recorded at other sites. Species occurring across these five groups include *Fragilaria construens* var. *venter*, *Fragilaria pinnata* var. *lancettula*, *Cocconeis placentula* and *Nitzschia amphibia.* Group 7 is characterised by *Aulacoseira granulata*, its variety, *angustissima* and *Aulacoseira ambigua.* Sites in this group are of low to medium conductivity and a medium pH, but display a considerable range in carbonate-bicarbonate content, from 11 to 93%. Group 8 includes the large, shallow basins of Chapala (6), Chalco (7) and Pátzcuaro (13), which are all of medium to high conductivity, but also includes the 1982 Zirahuén sample (30b) and that of Lagunilla (9). These two are low conductivity sites and are included in this group due to the common occurrence of species such as *Gomphonema gracile, Cocconeis placentula* and *Navicula pupula.* Common taxa in Group 8 are *Aulacoseira granulata* var. *angustissima*, *Cocconeis placentula* and *Amphora veneta.* Group 9 represents the two crater lakes of Hoya La Alberca (1) and Lago Quechulac (18), the most common species being *Gomphonema parvulum*, *Gomphonema angustatum* and *Achnanthes minutissima.* The high conductivity samples from the Texcoco sites (21, 22, 23) and sample 7i from Chalco, all in the Basin of Mexico, are placed in Group 10. Common diatoms in this group include *Cyclotella meneghiniana*, *Nitzschia frustulum* and *Amphora veneta.* Group 11 includes the two crater lakes of Alchichica (2b) and La

Piscina de Yuriria (16a and 16b). Dominant species in this group do not occur elsewhere in the dataset and include *Nitzschia inconspicua*, *Navicula elkab*, *Anomoeoneis sphaerophora*, and *Nitzschia romana*.

5.8.4: Canonical Correspondence Analysis

Results of the CCA analysis are shown in Figure 5.15 as a species- and sample-environment biplot. CCA Axes 1 (λ_1=0.71) and 2 (λ_2=0.59) account for 9.9% of the total variation in the diatom data. The low percentage variance explained is typical of such noisy datasets with large numbers of taxa and many zero values in the species matrix. Despite the relatively low variance captured, the first two ordination axes are both highly significant ($P = 0.01$). Furthermore, eigenvalues for the CCA are similar to those obtained for DCA (λ_1=0.88) and 2 (λ_2=0.74). The similar configuration of samples and taxa in both ordinations suggests that the gradients of ionic strength, composition and pH included in the CCA account for the major patterns of variation in the diatom data.

Axis 1 clearly reflects the conductivity gradient, from fresh through to hypersaline waters. TWINSPAN groups 1-5, representing fresh water sites, plot out on the left-hand side of the sample biplot, whilst the more concentrated systems (TWINSPAN groups 8-11) are plotted on the right. Conductivity is closely related to the ionic composition of the samples, which is reflected in the biplot of environmental variables. Those sites with high percentages of Ca^{2+}, Mg^{2+} and $HCO_3^- + CO_3^{2-}$ also have low conductivity, whilst increasing proportions of Na^+ and Cl^- are indicated on the right hand side. Axis 2 is closely related to the percentage sulphate content. The Zacapu Celanese samples (26, TWINSPAN group 7) all have high scores for this axis. This gradient is somewhat exaggerated due to the small number of samples with high sulphate content and their distinctive species composition. These samples are dominated by *Melosira monospina*, a taxon not recorded elsewhere in the dataset. Species, which plot on the left-hand portion of the biplot representing fresh water environments, include *Navicula pseudoscutiformis*, *Fragilaria crotonensis*, *Cyclotella ocellata* and *Achnanthes lanceolata*. Those species identified with more chemically evolved, saline systems include *Anomoeoneis sphaerophora*, *Navicula halophila*, *Nitzschia inconspicua* and *Chaetoceros muelleri*.

5.8.5: Variance partitioning

Results of the variance partitioning are shown in Figure 5.16. The 12 environmental variables chosen by forward selection account for a total of 41 % of the variance in the diatom data. The total explained variance is predominantly composed of unique contributions from variables representing ionic strength (22.0 %) and ionic composition or brine type (11.1 %). pH makes a statistically significant but small contribution (2.3 %). Similarly, the variance due to interactions or conditional effects between pairs of gradients is low, indicating that gradients of ionic strength and ion type make large and unique contributions to the explained variance. These results indicate that statistically significant and independent transfer functions can be developed for variables representing ionic strength and ion type.

5.8.6: Transfer Functions

Transfer functions were developed for ionic strength and ion type using conductivity and alkalinity (percentage $HCO_3 + CO_3$). These variables were chosen as they have clear hydrochemical interpretations and account for the highest proportion of variance in the diatom data of the environmental variables tested. Scatterplots of observed against diatom-inferred values, and summary performance measures are shown in Figure 5.17. The transfer functions for both variables perform well and the squared correlations between observed and inferred values are high (0.91 and 0.90 for conductivity and alkalinity respectively). Jackknife estimates of the RMSEP are higher than corresponding RMSE, indicating the importance of cross-validation in estimating prediction error. However, the strength of the relationships between observed and diatom-inferred variables remain high after cross-validation, suggesting that conductivity and alkalinity ($\%HCO_3 + CO_3$) can both be accurately inferred using these transfer functions.

Figure 5.18 shows the weighted-average optima and tolerances for conductivity and alkalinity ($\%\ HCO_3 + CO_3$) of the most abundant taxa in the dataset. Species with the lowest conductivity optima, such as *Achnanthes levanderi* and *Cymbella perpusilla* also display the narrowest tolerance ranges, whilst a number of species are found in waters of varying E.C. These include *Nitzschia paleacea, Nitzschia palea* and *Fragilaria construens*. Species found in waters with the highest bicarbonate-carbonate content have narrow tolerances, whilst most of the taxa in the dataset display broad ranges, such as *Cyclotella meneghiniana, Aulacoseira ambigua* and *Fragilaria pinnata* var. *lancettula*.

5.8.7: Comparison with other Diatom-Based Calibration Datasets

Although this calibration dataset is relatively small (53 sampies), the apparent predictive ability of both the conductivity and alkalinity transfer functions (r^2=0.91 and r^2=0.90 respectively) is high. These values compare well with transfer functions developed for lakes in Spain (conductivity: r^2=0.91) (Reed, 1998) and Africa (conductivity: r^2=0.87, carbonate-bicarbonate and sulphate + chloride ions: r^2=0.82) (Gasse *et al.*, 1995). The trend in chemical composition of sites in the Central Mexican Diatom Dataset is similar to that reported for lakes in East Africa (Gasse *et al.*, 1983), which have since been incorporated into the larger African dataset (Gasse *et al.*, 1995). The British Columbia dataset (Cumming and Smol, 1993) also contains a significant number of bicarbonate and carbonate lakes. Carbonate lakes are poorly represented in the Northern Great Plains (Fritz *et al.*, 1993) and the Spanish (Reed, 1998) datasets, which are largely dominated by sites of sulphate or chloride composition. By comparing this dataset with those from other regions it is possible to explore the degree of consistency between datasets in the ecological optima derived for different species. Direct comparison is not possible with the Northern Great Plains and British Colombia datasets as transfer functions are based on salinity rather than conductivity. It is possible, however, to examine the broad trends in the data.

In general, the conductivity and salinity optima of species common to the datasets lie in similar positions along the ecological gradient identified in the different regions. Derived conductivity optima compare well between the Central Mexican and African datasets, particularly at the lower end of the conductivity spectrum. Estimated optima for *Fragilaria pinnata* are 205 $\mu S\ cm^{-1}$ (Mexico) and 145 $\mu S\ cm^{-1}$ (Africa), whilst

Aulacoseira granulata var. *angustissima* has optima of 375 µS cm^{-1} (Mexico) and 364 µS cm^{-1} (Africa). There is also good agreement with those species found at the lower end of the salinity spectrum in the British Columbia dataset. At the more concentrated end of the conductivity gradient, optima are similar for some species. For example, *Anomoeoneis costata* has estimated optima of 12,920 µS cm^{-1} (Mexico) and 12,280 µS cm^{-1} (Africa), although it is slightly lower in the Spanish dataset (9,760 µS cm^{-1}). This species has high salinity optima in the Northern Great Plains and British Columbia datasets.

There are, however, a number of significant discrepancies between the datasets. Reed (1998) has highlighted the large difference in the conductivity optima of *Cocconeis placentula* in different datasets. In Central Mexico, *C. placentula* tends to be found in fresh, slightly alkaline water (E.C. opt. = 433 µS cm^{-1}). This is consistent with an optimum of 469 µS cm^{-1} in the African dataset and a salinity optimum of 0.2g l^{-1} in British Columbia. In the Spanish and Northern Great Plains datasets, however, this species has optima of 20,700 µS cm^{-1} and 16,800 µS cm^{-1} respectively (Reed, 1998). Derived conductivity optima for *Navicula halophila* are 19,050 µS cm^{-1} (Mexico), 13,760 µS cm^{-1} (Spain) and 2,980 µS cm^{-1} (Africa). In British Columbia, this species has a salinity optimum of 0.9 g l^{-1}, whilst in the Northern Great Plains, its optimum salinity is 5.3 g l^{-1}.

Discrepancies between the regions could be due to the relatively small size of most of the datasets. The African dataset is the largest, with 282 samples, whilst the Central Mexican, Spanish, British Columbia and Northern Great Plains datasets have 53, 74, 59 and 63 samples respectively. It is therefore possible that the full ecological range of certain species has not been encountered in the individual regions. Differences may also be due to the sensitivity of taxa to different brine types, rather than to electrical conductivity / salinity alone. It is interesting to note that the Central Mexican dataset is most similar to the African dataset, which contains lakes of similar chemical composition. A further issue for consideration is that derived optima may be biased by the ecological gradient covered by the individual datasets. The

Central Mexican dataset has a clear bias towards sites with low to medium conductivity. Twenty-two of the 31 different sites in the dataset have a conductivity lower than 1,000 $\mu S\ cm^{-1}$. The Northern Great Plains and Spanish datasets have few freshwater samples and are biased to more saline lakes (Fritz *et al.*, 1993; Reed, 1998). It has been suggested that bias may also be introduced due to the fact that water chemistry measurements have been made at one time and therefore may not be truly representative of the range of conditions in which the diatom assemblage has been living (Fritz *et al.*, 1993). However, Mexican lakes sampled fifteen years apart show remarkable consistency in the environmental variables measured, suggesting that this factor is not significant with regard to the Central Mexican dataset. This preliminary comparison of species optima from different calibration datasets appears to confirm that merging the Mexican and African datasets would be a sensible step.

5.9: Conclusions

This survey of central Mexican lakes has revealed a clear evolutionary trend in ionic composition following pathway IIIA of Eugster and Hardie's (1978) model. Fresh waters have high proportions of calcium, magnesium and bicarbonate ions, whilst more saline systems are richer in sodium and chloride ions. Results from this study compare well with previous work on the lakes in the highlands of Central Mexico. The results of the combined Central Mexican Diatom Dataset demonstrate a strong correlation between diatom species distributions and ionic strength and composition, illustrating the potential for numerical palaeoenvironmental reconstructions. Transfer functions have been successfully developed for conductivity and alkalinity (% HCO_3 + CO_3. It is hoped to merge this dataset with the much larger, but chemically similar, African dataset (Gasse *et al.*, 1995), which as Reed (1998) suggests, will improve the quality of transfer functions and provide more analogues. This diatom calibration dataset is a valuable tool for reconstructing past environmental change from palaeolimnological records in Central Mexico. Its application to the palaeonvironmental records developed in this study is discussed in Chapter 6 (Lago de Zirahuén) and Chapter 7 (Laguna de Juanacatlán).

Chapter 6: The Palaeolimnology of Lago de Zirahuén

6.1: Introduction

This chapter focuses on the palaeolimnological record from Lago de Zirahuén. Before discussing the results in detail, the present-day physical characteristics of the basin are described. The history of human settlement and activity in the basin is also explored, as this is particularly important to consider when interpreting the palaeoenvironmental evidence. Results are presented from four cores taken at different points around the lake. The stratigraphic and chronological framework is described, before discussing in detail the results of diatom, mineral magnetic susceptibility and metals analysis of the individual cores. The palaeolimnological records from the individual cores are synthesized through the correlation of the cores. The combined records enable a detailed reconstruction of environmental change in the Zirahuén Basin during the last one thousand years.

6.2: The Zirahuén Basin: Physical Environment

Lago de Zirahuén lies within a lava-dammed basin in the highlands of Michoacán (Figure 6.1). The drainage basin covers an area of 261 km^2, of which the lake occupies approximately 10.5 km^2 (Chacón and Muzquiz, 1991). The basin is oriented in an east-west direction, with the lake lying in the west, at an altitude of 2,075m a.s.l (Figure 6.2). The basin is encircled by volcanic mountains, which range in altitude from 2,300 to 3,100m. The western part of the basin, particularly the north-west, is characterised by steeply sloping terrain, whilst in the eastern part the terrain slopes more gently towards the lake.

6.2.1: Geology and Soils

The Zirahuén Basin lies in the Michoacán-Guanajuato Volcanic Field (see Section 3.2.1). Based on the similarity of their icthyofaunas, it was traditionally thought to have been linked to the Pátzcuaro and Cuitzeo basins, which are located to the north, forming a tributary which fed into the Río Lerma (De Buen, 1943, Miller and Smith, 1986). However, this idea has been recently challenged by Bernal-Brooks (1998), who argues that a former link with the Balsas drainage system to the south is more likely. Whatever the original configuration of these basins, there has been substantial modification of the topography due to tectonic and volcanic activity during the Quaternary Period. During one such phase of volcanic activity, the Rio de la Palma was blocked by lava flowing from Cerro La Magueyera, forming the closed drainage system seen today. The lava flow is clearly visible in the aerial photograph in Figure 6.3. Although the lava flow, to the author's knowledge, has never been dated, it is thought that the blockage of the Río de la Palma occurred some time during the Pleistocene (Tamayo and West, 1964). Products of volcanic activity, extrusive igneous rocks, dominate the geology of the Zirahuén Basin. The rocks are basaltic and include some patches of breccia. Numerous cinder cones and extinct volcanoes are found within the basin (Figure 6.3). As a consequence, the principal soil type is andosol, covering approximately 75% of the area of the basin (Chacón and Muzquiz, 1991). Exposed soil around the lake has a striking red colour; being highly oxidised (Figure 6.4). Thin soils overlying bedrock, lithosols, are found in the north of the basin.

As it lies within a volcanically active region, the Zirahuén Basin and the surrounding area have been affected both by volcanic activity and associated tectonic activity throughout history. Two volcanic eruptions have occurred in the Michoacán-Guanajuato Volcanic Field during the historical period. The first was Volcán Jorullo (1759-1774), approximately 50km south of the Zirahuén Basin (Figure 6.1). The second, Volcán Paricutín, approximately 60km west of the basin (Figure 6.1) took place between 1943 and 1952.

The eruption of Jorullo is described in numerous historical documents (Gadow, 1930), which are useful in ascertaining the nature and extent of its impact. They show that although earthquakes and tremors were felt during the summer of 1759, the eruption proper of Jorullo began on 29th September of that year. It appears that until 1764, the eruption was explosive, with large volumes of ash being expelled. Lava flows only began in 1764 (Gadow, 1930). Tephra from the volcano was reported falling as far away as Queretaro (200km away), whilst the residents of Pátzcuaro and Valladolid (today called Morelia: shown in Figure 6.1) were plunged into darkness as the ash-laden sky obscured the sun (Ajofrin, 1764). It can be implied from this that tephra from Jorullo would have fallen in the Zirahuén Basin and would therefore likely be incorporated into the lake sediments.

Volcán Paricutín famously began to appear in a farmer's field on February 20th 1943. It became one of the most intensively studied volcanoes of the world as scientists monitored its progression from a mere opening in the ground to the impressive cone that exists today (Scarth, 1999). During the summer of 1943, as the eruptions grew more violent, ash periodically reached as far as Mexico City, 320km away. By the end of 1944, lava had engulfed the two nearby villages of Paricutín and San Juan Parangaricutiro. Although it remained active until 9.15am, March 1952, two-thirds of the ash and cinder output from Paricutín were produced within the first two years (Scarth, 1999). Given the proximity of this eruption to the Zirahuén Basin, it is presumed that its tephra should be encountered in sediments from Lago de Zirahuén.

In addition to volcanic eruptions, the fact that this region is in a tectonically active area has resulted in the occurrence of numerous earthquakes in Michoacán during the historical period (García and Suárez, 1996). In 1858, the level of Lago de Pátzcuaro, 15km north of Zirahuén (Figure 6.1) rose several metres, possibly as a result of a major earthquake (O'Hara, 1993). There are no reports of similar hydrological changes in the Zirahuén Basin following this earthquake, although historical records report structural damage of the church in the town of Zirahuén (García and Suárez, 1996).

6.2.2: Climate

The Zirahuén Basin lies within the *Tierra Fria* zone of the Michoacán highlands (Section 3.2.2). The average annual precipitation is 1182 mm yr^{-1} and the average annual temperature is 15.7°C. Precipitation in the basin is highly seasonal, with most falling between June and September. Winter precipitation is less than 5% of the annual total (Chacón and Muzquiz, 1991). More detailed information is available through the operation of a meteorological station on the northern shore of the lake between 1945 and 1992. The instrumental record was patchy, with some years having only 3 or 4 months data. However, for years where a full set of measurements was available, the broad trends in precipitation over the past 50 years can be examined (Figure 6.5). Rainfall data has been obtained from the Sistema de Informacion Climatica de Michoacán (SICM: Antaramian and Muzquiz, 1997). The precipitation record for Zirahuén is plotted alongside records from meteorological stations at Pátzcuaro and Morelia, whose locations are shown in Figure 6.1. Morelia has the longest instrumental record in Michoacán, extending back to 1910. From the graph, it can be seen that between 1945 and 1960, precipitation was generally higher than between 1960 and 1990. Annual totals of over 2,000mm of rainfall were recorded in 1946, 1952, 1958 and 1959. Analysis of precipitation data from a number of sites in Michoacán has shown a trend towards decreasing precipitation in recent years. This is particularly marked in the data from Zirahuén (Antaramian and Muzquiz, 1997). Average annual evaporation at the Zirahuén meteorological station between 1951 and 1992 was 1102 mm yr^{-1} (Antaramian and Ortega, 1996). The basin, therefore, has a positive hydrological balance. It would, however, only require a modest reduction in precipitation of 82mm yr^{-1} to produce a moisture deficit in the basin. Such a reduction is well within the observed interannual precipitation variability.

6.2.3: Vegetation

Perez (1991) carried out a detailed study of the vegetation of the Zirahuén Basin. The natural vegetation of the basin is pine and oak forest. Pine forests originally covered much of the basin between altitudes of 2,300m and 3,600m. As a result of human alteration of the landscape, they are much reduced in extent (60% of the catchment is used for agriculture or settlements, or is eroded). The most extensive remnants of forest today cover the slopes of the mountains in the north, north-east and south-east of the basin (Chacón and Muzquiz, 1991). Mixed oak and pine forests today occupy 19% of the catchment between an altitude of 2,080m and 2,500m (Perez, 1991). The rest of the basin is composed of small patches of mesophilic montane forest and grassland. Given the highly seasonal precipitation regime and the resulting cycle of crop cultivation, there is a marked contrast in the amount of vegetation cover in the basin between wet and dry seasons. Figure 6.6 illustrates these seasonal differences, indicative of the widespread growing of maize (*Zea mays*) between May and September.

In the lake itself, both submerged and emergent macrophytes are found in water of less than 5m depth. Common submerged macrophytes include species of *Potamogeton*, *Ceratophyllum* and *Myriophyllum*. Emergent macrophytes include *Cyperus*, *Phragmites* and *Typha* species as well as *Juncus ebracteatus* and *Scirpus californicus*. There is a marked absence of macrophytes close to the town of Zirahuén, where the turbidity of the water is higher (Perez, 1991).

6.2.4: Hydrology and Limnology

Fernando De Buen carried out the first detailed limnological investigations at Lago de Zirahuén in 1942 (De Buen, 1943). The lake has continued to be the focus of research efforts by Mexican limnologists (e.g. Bernal-Brooks, 1988, 1998; Chacón and Muzquiz, 1991) and is monitored regularly by staff and students of the Instituto de Investigaciones Sobre Recursos Naturales (INIRENA), Universidad Michoacana de San Nicholas de Hidalgo, Morelia. The wealth of limnological data available is rare for a Mexican lake and is invaluable for the interpretation of the palaeolimnological record.

Lago de Zirahuén receives water principally from the Rio de la Palma (also called Rio El Silencio), which flows into the lake from the east of the basin (Figure 6.2). This river passes through the town of Santa Clara (also known as Villa Escalante). The Rio de la Palma is a fourth order stream, which indicates an extensive network of tributaries (Chacón and Muzquiz, 1991). During the rainy season, the ephemeral Arroyo Zirahuén provides further inflow to the lake (Figure 6.2). The importance of groundwater in the hydrology of the basin is unknown. The dilute nature of the lake water, however, low in dissolved salts (see Chapter 5) indicates that there must be significant flushing through groundwater seepage. Describing the lake in 1943, Fernando De Buen remarked on the existence of inflow at Tembucharo on the western side of the lake and reported numerous small springs. This inflow no longer exists and the springs have since dried up (Bernal-Brooks and MacCrimmon, 1999). This corresponds with the general drying trend indicated in the precipitation data and is also consistent with decreasing regional groundwater levels associated with abstraction of water.

The bathymetry of Lago de Zirahuén has been the subject of a number of investigations (De Buen, 1943; SARH, 1980; Bernal-Brooks and MacCrimmon, 1999; Chacón, unpubl.). The bathymetry in Figure 6.7 is that produced by Chacón (unpubl. data) of INIRENA. The lake presently has a maximum depth of approximately 40m, which is located on the western side. The mean depth of the lake is 20.5m, with a volume of approximately 216 x 10^6 m^3 (Bernal-Brooks and MacCrimmon, 1999). As illustrated in Figure 6.7, the western portion of the lake is characterised by steeply sloping bathymetry. A small sub-basin is located in the south-west corner of the lake. Known as the Rincon de Agua Verde, this is separated from the main basin by a rock barrier, which rises to 4m below the water surface. The maximum depth of Agua Verde is 12m. The eastern part of the lake, where the Rio de la Palma flows in and around the town of Zirahuén, has a much gentler bathymetric profile. The maximum measured depth of the lake in 1942 was 46m (De Buen, 1943), whilst that measured in 1980 was 40m (SARH, 1980). In 1995, a maximum depth of 39.4m of depth was registered (Bernal-Brooks and MacCrimmon, 1999). Bernal-Brooks and MacCrimmon (1999) argue that a combination of climatically controlled water level fluctuations and increased sediment inputs were responsible for the observed 6.6m decline in water level since 1942. They suggested a sediment accumulation rate of 3.4cm yr^{-1} in the deepest point of the basin, with up to 1.4m yr^{-1} being deposited close to the Rio de La Palma inflow. These estimates are based largely on comparison with earlier echo sounding transects.

Lago de Zirahuén is a calcium-magnesium bicarbonate lake. Comparison of anion and cation data from different studies shows little variation over the last 25 years and has been discussed in Section 5.4.5. pH has remained relatively stable since monitoring of the lake began. In 1942, the pH of the surface waters was between 7.7 and 8.3 (De Buen, 1943). In 1987, Bernal-Brooks registered values of 7.9 to 8.2. The pH measured during this study was 8.4 (Table 5.1). Electrical conductivity measurements are also comparable, with 110 μS cm^{-1} registered in 1987 (Bernal-Brooks, 1988) and 119 μS cm^{-1} measured in this study. The transparency of the lake, however, appears to have changed in recent years. The reduction in secchi depth from 6.4-7.5m in 1942 (De Buen, 1943) to an average of 4.45m (Campos *et al.*, 1997) may be the result of increased sediment inputs or an increase in algal productivity in the lake.

Lago de Zirahuén experiences thermal stratification between April and October (Bernal-Brooks, 1988). A difference of 6°C has been recorded between the temperature of the surface waters and the temperature at the bottom of the lake, with an epilimnion approximately 15m deep (Chacón and Muzquiz, 1991). This seasonal stratification of the lake is accompanied by a decrease in dissolved oxygen (DO) at depth. DO levels at the end of summer (August-September) are approximately 7mg l^{-1} at the surface, whilst anoxic conditions prevail at the sediment-water interface (Campos *et al.*, 1997). In a previous study, Bernal-Brooks (1988) argued that cooler, denser waters entering from the Rio de la Palma prevented anoxia occurring in the interstitial waters. This stopped the release of phosphorus from the sediments, which remained insoluble as ferric phosphate. Phosphorus is regarded as the limiting nutrient in Lago de Zirahuén, so its availability in the lake waters has important implications for biological productivity. Bernal-Brooks (1988) highlighted the importance of the inflow of water from the Rio de la Palma in reducing the effects of a relatively high phosphorus loading (1.7 kg ha^{-1}) from agricultural activity and domestic waste. Measured total phosphorus concentrations in the lake remained relatively low (5-10 μg l^{-1}), with the lake classified as oligo-mesotrophic. Bernal-Brooks thought, however, that the lake was close to a critical threshold where further increases in phosphorus loading would lead to anoxia and hence the release of phosphorus from the sediments, resulting in eutrophication. From the results reported by Campos *et al.* (1997), it does indeed appear that thermal stratification is now associated with chemical stratification and deoxygenation.

According to Bernal-Brooks (1988), the most important component of the phytoplankton in Lago de Zirahuén is the desmid *Staurastrum. Closterium* is also common. Alvarado (1996) sampled the phytoplankton of the lake in 1991-1992. She found that the division *Chrysophyta* (i.e. diatoms) dominated in autumn, winter and summer, with *Chlorophyta* becoming dominant during spring. The most common species she encountered was *Cyclotella kuetzingiana* (see discussion of taxonomic nomenclature in Section 4.7). This corresponds with the results of this study, in which the modern diatom flora of Lago de Zirahuén was found to be dominated by *Cyclotella ocellata.* The modern diatom species composition is discussed in more detail in Chapter 5.

6.3: The History of Settlement in the Zirahuén Basin

The Zirahuén Basin lies close to the heartland of the Post-Classic Purépecha empire see Section 3.3.1). Their capital was Tzintzuntzan, on the shores of Lago de Pátzcuaro, approximately 15km to the north of Lago de Zirahuén. Despite its proximity to the Purépecha capital, it is thought that the Zirahuén Basin was not densely populated during the Post-Classic. Very few historical records refer to the basin and those found suggest that the land around the lake was used largely for ceremonial and recreational purposes by the Purépecha nobility (Endfield, 1997; Endfield and O'Hara, 1999). No archaeological sites have been discovered within the basin, although ceramic offerings have been found in the lake by divers (Madrigal, pers. comm.) supporting the belief that ceremonial activities took place. Whilst it seems that Post-Classic population pressure in the Zirahuén basin may have been considerably less than in the Basin of Pátzcuaro, this is nonetheless still based mainly on the absence of evidence.

Very little is also known about the early Colonial Period in the Zirahuén Basin. Again, few references are found in historical documents, which may be significant, given the great importance the Spanish placed on keeping detailed written records.

Endfield (1997) suggests that, following the arrival of the *Conquistadores* in Michoacán in 1522, the Zirahuén Basin remained relatively undisturbed until the 18th century. She argues that this area may not have been attractive to Spanish settlers, possibly partly out of respect for its traditional function. The 18th century, however, saw a marked increase in Hispanic settlement and exploitation in the Zirahuén Basin. By the mid-1700s, a number of haciendas had been established for the purpose of growing sugar, maize and wheat and also for rearing cattle (Endfield and O'Hara, 1999). Some archival documents from the early 18th century indicate environmental degradation in the basin, describing "infertile, rough and stony" land. By 1733, hills around San Juan Tumbio in the southern part of the basin had been "stripped of vegetation," whilst deforestation around Comienbaro, to the south-west of the lake had led to gullying, according to archival material (Endfield and O'Hara, 1999). The end of the 18th century saw significant agricultural developments, principally in fruticulture. Ajofrin in his description of his journey through New Spain in 1764 refers to the abundance of fruit and vegetables of all types in the town of Santa Clara.

In environmental terms, the most important development in the Zirahuén Basin during the Colonial period was the establishment of copper smelting works at the town of Santa Clara (Figure 6.2). The Spanish exploited the rich copper deposits of La Huacana, Jicalán, Sinagua and Inguarán, located to the south of the basin, along with the metallurgical skills of the indigenous population. Initially, copper smelting took place at Tzatzio, approximately 20 km south of Santa Clara. However, between 1607 and 1614, refining operations moved to Santa Clara due to deforestation around Tzatzio (West, 1948). Large amounts of wood were required to make the charcoal used in the smelting process. Ajofrin, writing in 1764, described the dense pine forests around Santa Clara, which were deemed to be the most appropriate wood for melting the metal. Santa Clara soon became the principal copper refining centre in Mexico. Spanish experts were drafted in to train the indigenous workers in more advanced techniques (Arriaga, 1968). By 1789, there were 8 royal refineries in Santa Clara, each employing between 30 and 40 men. The refined copper was used principally to manufacture copper bars for the royal artillery, although cauldrons and other vessels were also produced, which were sold throughout the country (West, 1948). By the turn of the 20th century, the copper industry at Santa Clara had diminished greatly. Today, only a handful of coppersmiths remain, producing goods to sell to tourists from scrap copper which has been melted down.

The pattern of development in the Zirahuén Basin during the Colonial Period is evident in the population records from two towns within the basin: Santa Clara and Zirahuén (Figure 6.2). Population was very low after the conquest, with 270 inhabitants in Zirahuén in 1619 and 130 in Santa Clara in 1600 (Carrillo, 1996). By the early 19th century, these small villages had become towns, with populations of 2,813 (Zirahuén) and 4,073 (Santa Clara) by 1822 (Lejarza, 1974). Zirahuén has remained fairly constant in size since then, although Santa Clara continued to expand. Today, Santa Clara is the largest town in the basin, with a population of 15,000. The town of Opopeo, approximately 3 miles from Santa Clara is also important, with approximately 11,000 inhabitants (INEGI, 1995).

The major agricultural activity in the basin today is the cultivation of maize, although small amounts of vegetables and wheat are also produced in certain areas. The majority of the crops are for subsistence use, with only 20% destined for the markets (Perez, 1991). Forest resources continue to be exploited, producing wood for construction and furniture, resin and charcoal. There have, however, been considerable developments in the nature of land use in the basin in recent years. Agricultural activities have intensified significantly. In 1986, it was estimated that 20 tonnes of ammonium sulphate and phosphate fertiliser were applied to the land within the basin (Bernal-Brooks, 1988). A commercial fruit farming operation has been established on the southern shore of the lake. A further development is tourism. The state government is promoting the clear blue waters of Lago de Zirahuén as a major tourist destination. A number of hotels are under construction around the lake and a golf course is planned above the steep slopes around Agua Verde on the western shore of the lake. To encourage visitors, an exit from the newly built toll road between Uruapan and Morelia has been constructed. Measures have been taken to prevent soil erosion (Figure 6.4), but considerable amounts of sediment can be seen entering the lake (Figure 6.8).

The impact of human activity on the landscape around Lago de Zirahuén clearly has to be taken into consideration when interpreting the palaeolimnological evidence, which is discussed below.

6.4: The Palaeolimnological Record

In February 1998, four sediment cores (AV/98, ZL/98, ZD/98, ZR/98) were taken from different points around Lago de Zirahuén using a micro-Kullenberg corer. Core locations are illustrated in Figure 6.7. In addition to those cores obtained during this study, a 1.5m sediment core (Core ZIR/1), collected by Dr. Sarah O'Hara and Dr. Georgina Endfield (University of Nottingham) from the Agua Verde sub-basin in 1995, was also made available for analysis. This core was analysed for diatoms and magnetic susceptibility. The stratigraphy and chronology of each core is described. First, the results from core ZIR/1 are presented, followed by the cores collected during this study, which are discussed in order from west to east across the lake (Figure 6.7). A list of all radiocarbon dates obtained for Lago de Zirahuén is provided in Table 6.1. Calibrated BC/AD ages are used in order to allow comparison with the tephrochronology and ^{210}Pb dates. Results of diatom, mineral magnetic and metals analysis of the cores are then presented. The full range of techniques was not carried out on each core as not all cores were appropriate for each technique and resources were limited. Reasons for this are explained in the discussion of results from the individual cores. The description of data from each core is followed by a synthesis of the individual palaeoenvironmental records to provide an overall interpretation of environmental change for the lake.

6.5: Core ZIR/1

Core ZIR/1 was extracted using a piston corer from the Agua Verde sub-basin in approximately 11 m of water (O'Hara, pers. comm.). Three sections of sediment were recovered, each approximately 50cm in length. Following diatom and magnetic susceptibility analysis of 40 samples throughout the core, it was discovered that the records from each of the three sections were almost identical (Figure 6.9). *Cyclotella* *stelligera* and *Diploneis elliptica* followed the same pattern of abundance in each core section, being abundant in the upper part of each section. It was therefore presumed that the three sections were replications of the same stratigraphic sequence. Two conventional radiocarbon dates were obtained from the second and third sections of the core (Table 6.1), providing ages of 200 ± 100 and 330 ± 100 ^{14}C yrs BP respectively. Although only rangefinder dates, they add weight to the argument that the individual core sections represent approximately the same time period. Given the uncertainty about the stratigraphic integrity, it was decided not to proceed with further work on this core. Even so, this analysis provided a useful introduction to the diatom flora of the lake. Furthermore, the radiocarbon dates also gave an indication of the sedimentation rate of the lake, suggesting that cores taken with a 1 metre long micro-Kullenberg core would extend back at least 500 years. The palaeoenvironmental interpretation for Lago de Zirahuén, however, is based solely on cores collected by the author and colleagues in 1998.

6.6: Core AV/98

6.6.1: Stratigraphy

A sediment core 62 cm in length was recovered from Agua Verde in approximately 12 m of water. As the core was taken in a clear plastic tube, it was possible to establish that the sediment-water interface was well preserved during coring. A layer of coarse, reddish coloured sediment at the top of the core, approximately 5 cm thick, was also clearly visible when the core was extracted (Figure 6.10).

The core stratigraphy is illustrated in Figure 6.11. From 62 cm to 24 cm, the core consisted of very dark greyish-brown gyttja (2.5Y 3/2). A minerogenic band ca. 3 mm thick at 42 cm depth, possibly a tephra layer, could be seen on the x-radiograph of the core, but was not visible to the naked eye. Between 24 cm and 21 cm, the sediment was darker in appearance (2.5Y 2.5/1), more organic and with a higher silt content. From 21 cm to 19 cm, the sediments returned to the dark greyish-brown gyttja of the lower part of the core. Another dark, organic band occurred between 19 cm and 15 cm. The dark greyish-brown gyttja was found again between 15 cm and 9 cm. A coarse grained layer of black volcanic ash, occurred between 9 cm and 8 cm. This tephra layer was clearly seen both in the x-radiograph and in the visible stratigraphy.

6.6.2: Chronological Control

A combination of three chronological techniques was applied to core AV/98: tephrochronology, AMS ^{14}C dating and ^{210}Pb dating.

Tephrochronology

The geochemistry of the two tephra layers was analysed by Dr. A. Newton (Department of Geography) using an electron microprobe. The results of the analyses of individual glass shards were then compared with tephra known to be the products of the volcanoes of Paricutín and Jorullo (Figure 6.12). Dr. Newton confirmed that the microscopic tephra layer found at 43cm depth was likely to be from Volcán Jorullo (1759-1777) (Newton, unpubl. data). As most of the tephra was produced in the first few years of the eruption, this horizon is likely to represent the years 1759-1764. The black, coarse-grained layer from 8-9 cm depth was identified as the Paricutín tephra (1943-1952) (Figure 6.12). Most of the tephra fallout occurred in the first few months of the eruption, so this layer corresponds to 1943.

^{210}Pb and man-made radionuclides

This core was selected for ^{210}Pb dating as the tephrochronology suggested that, out of the four cores, the sedimentation rate was most favourable for the technique. The profile of unsupported ^{210}Pb in core AV/98 is shown in Figure 6.13, whilst the primary radionuclide data are provided in Appendix 6. The calculated average depositional flux of unsupported ^{210}Pb to the lake is 48 Bq m^{-2} yr^{-1} and the activity of unsupported ^{210}Pb decreases downcore, as would be expected. The top three centimetres of the core have very similar levels of unsupported ^{210}Pb activity, which suggests some degree of mixing in the uppermost part of the core. Levels of unsupported ^{210}Pb fall dramatically between 4 and 9 cm depth but there is a small increase in activity between 11 and 16 cm depth. Although the amount of activity between 11 and 16 cm is very small, it is likely that some unsupported ^{210}Pb is still present in the sediment. Below 16 cm, there is no unsupported ^{210}Pb in the sediment.

^{210}Pb ages are provided in Table 6.2 and were calculated using both the CRS and CIC methods. CIC ages were calculated using firstly the unsupported ^{210}Pb concentrations in the top 10 cm as in the samples below this level, unsupported ^{210}Pb activity dropped to zero within 1 sigma error. The sediment accumulation rate including only these samples was 18.1mg cm^{-2} yr^{-1}. As Figure 6.13 illustrates, however, unsupported ^{210}Pb activity increased again below this depth. CIC ages were also calculated incorporating samples between 11 and 16 cm depth, which overlapped zero at the 2 sigma level. This produced an estimated sedimentation accumulation rate of 23 mg cm^{-2} yr^{-1}. As indicated in Table 6.2, although the two different CIC age calculations produce similar results in the first 6 cm, by 20 cm depth, there is a fifty year discrepancy between the two. The CIC ages calculated using the faster sedimentation rate of 23 mg cm^{-2} yr^{-1} are more similar to the ages calculated using the CRS model. These two sets of ages are reasonably similar to a depth of 9 cm, where the difference is 6 years. The discrepancy between the two models, however, increases upon moving down the core to a maximum of 31 years at 18-19 cm depth.

Given the somewhat irregular profile of unsupported ^{210}Pb in AV/98, which suggests that sedimentation rates have not been constant, it was decided to accept the ages from the CRS model. Furthermore, records of land use in the catchment also suggest that sedimentation rates are likely to have been variable as human activity in the basin has changed through time (see Section 6.3). The presence of the tephra layer from Paricutín also provides in independent assessment of the results obtained from the CRS model. This tephra layer from AD 1943 is found between 8 and 9 cm. The CRS age for this sample is 1940 ± 3.7 years (1σ).

A further means of constraining the chronology of the core is by using the profile of man-made radionuclides through the core. The profiles of ^{137}Cs and ^{241}Am in core AV/98 are illustrated in Figure 6.14 whilst the data are provided in Appendix 6. As the graph shows, ^{137}Cs is present between 3 and 10 cm depth. The peak in ^{137}Cs activity is between 4 and 7 cm. The presence of ^{241}Am was detected in samples from 4-5 and 5-6 cm depth. This radionuclide is not mobile in sediments and its presence, albeit at the limit of detection, indicates that the 1963 peak in weapons testing must lie between 4 and 6 cm. The sample from 5-6 cm depth lies at the mid-point of the small peak in ^{137}Cs activity, so it is likely that the 1963 weapons testing peak pertains to this depth. The CRS age for this sample is 1961 ± 2.4 years (1σ), consistent with the interpretation of the ^{137}Cs profile.

The ^{210}Pb chronology using the CRS method appears to be reliable in the top 10 cm of the core, as ages are in good agreement with the Paricutín tephra and the man-made radionuclide profiles. As Table 6.2 indicates, errors on the ^{210}Pb ages increase downcore. By 13-14 cm, the error is ± 6.1 yrs (1σ) whilst at 17-18 cm depth, the error increases to ± 12 yrs. This is due to the fact that the amount of unsupported ^{210}Pb present is decreasing and the errors on the measurements become greater. No CRS age could be obtained from 14-15 cm depth as no unsupported ^{210}Pb activity was detected at this depth. Ages below 14 cm depth should be regarded with some caution due to the larger errors.

AMS ^{14}C dating

Two AMS ^{14}C ages were obtained for core AV/98 (Table 6.1). ^{14}C dates are reported as calibrated BC/AD ages to allow comparison with the other chronological techniques. The basal date from 61-62 cm depth was 875 ± 45 ^{14}C yrs. BP and was calibrated to calendar years using the program CALIB 4.1 (Stuiver and Reimer, 1993). At this point on the calibration curve, there is a slight plateau, so the calibration curve was intercepted three times, at AD 1164, 1169 and 1186. The program produced a calibrated age range of AD 1029-1262 (2 sigma) for this depth. A ^{14}C sample was also taken above the Jorullo tephra to ascertain the degree of consistency between the different chronological methods. This sample, from 39-40 cm depth, should have yielded an age younger than 1759, however, the calibrated age range obtained was AD 1411-1640 (Table 6.1). The discrepancy between the radiocarbon date and the tephra date may be due to the contamination of the lake sediments with inputs of old carbon from the catchment. This problem has been reported from other lakes in Central Mexico, where inversions in the radiocarbon chronology of cores have occurred (Brown, 1984; Metcalfe *et al.*, 1989; Metcalfe *et al.*, 1994). The lake is not situated in an area of carbonate geology, so hard water error is not the cause of the problem. No problems were encountered during sample preparation and analysis (C. Bryant, pers. comm.).

Overall core chronology

An excellent chronology for the last ca. 100 years has been established for core AV/98 through a combination of the Paricutín tephra, the ^{210}Pb chronology and the man-made radionuclide profiles. The Jorullo tephra provides a further chronological marker in the middle of the core of AD 1759-1764. Unfortunately, the ^{14}C AMS dates cannot be relied upon. The radiocarbon date of (cal. AD 1411-1640: 2 sigma) is 3 cm above the Jorullo tephra, whose age is AD 1759-1764. As the calibrated age range of AD 1411-1640 is at least 120 years too old, this brings into question the accuracy of the basal age range of AD 1029-1262. It may be possible, however, to estimate the basal age of the core by extrapolating the ^{210}Pb and tephrochronology. Sedimentation rates in cm yr^{-1} are used rather than sediment accumulation in mg cm^{-2} yr^{-1}, as dry weights are not available for core sections due to the fact that material has been archived for future reference.

The sedimentation rate calculated from the reliable portion of the ^{210}Pb chronology is 0.14 cm yr^{-1} (97 years in 14 cm). This is reasonably consistent with a rate of 0.18 cm yr^{-1} based purely on extrapolation from the Jorullo tephra (239 years in 43 cm). The calculated sedimentation rate based solely on the basal AMS date is lower, however, at 0.08 cm yr^{-1}. Although, this may be due to compaction of the sediment or a slower sedimentation rate in the lower part of the core, this lower calculated sedimentation rate supports the notion that the basal AMS date may have been contaminated with old carbon. If the sedimentation rate extrapolated from the ^{210}Pb chronology is used, the estimated basal age of the core is ca. AD 1555. This is ca. 190-530 years younger than the calibrated AMS age of AD 1029-1262. This discrepancy is consistent with that found between the ^{14}C date from 39-40 cm and the Jorullo tephra. Given the uncertainty surrounding the ^{14}C chronology, the extrapolated basal age of ca. AD 1555 is regarded to be more reliable. There are problems with adopting this approach: as indicated by the ^{210}Pb profile and historical records, sedimentation rates in the basin are not likely to have remained constant throughout the time period covered by the core. In the absence of any other suitable dating methods, however, extrapolation is the only possible means of providing an, albeit provisional chronology for the lower part of the core.

6.6.3: The Diatom Record

The detailed diatom record from AV/98 is presented in Figure 6.15. A summary diatom diagram, illustrating habitat groups and diatom abundance, is shown in Figure 6.16. Using the CONISS zonation programme within TILIA, 5 separate zones were identified.

Zone AV-1, between 53 and 62 cm depth is dominated by small species of the genus *Fragilaria* (*F. pinnata*, *F. construens, F. construens* var. *venter* and *F. brevistriata*). *Fragilaria* cf. *capucina* also occurs throughout this zone, at levels up to 10 % of the total count. In the Central Mexican Diatom Dataset, small *Fragilaria* species tend to be found in shallow circum-neutral to slightly alkaline ponds, or in lake margins, a characteristic also reported by Bradbury (1989). These *Fragilaria* species are often found in benthic habitats, but can also occur in the plankton of shallower water. A number of periphytic and epiphytic species are found in Zone AV-1 in small but significant amounts (2-5 %). These include *Cymbella microcephala*, *Epithemia turgida*, *Epithemia adnata* and *Gomphonema intricatum* var. *pusilla*. As Figure 6.16 illustrates, approximately 50 % of the assemblage is composed of tychoplanktonic species. Epiphytic and peripyhytic species are also important, comprising approximately 40 % of the total. Planktonic taxa account for approximately 5 % of the total, whilst aerophilous species represent just 2 %. In this zone, diatom abundance rises dramatically, from 2.5 x 10^9 to 13.2 x 10^9 valves per gram of dry sediment.

Zone AV-2 covers 53-46 cm depth and is characterised by a significant change in species composition. Whilst the small *Fragilaria* species are still common, the zone is distinguished by the high abundance of small *Navicula* species. The two most common, *Navicula* cf. *seminulum*, which occurs at values of up to 40 % of the count, and *Navicula* cf. *absoluta* have not been conclusively identified (see section 4.8 for taxonomic discussion). A third species, *Navicula vitabunda*, is also present in small amounts (ca. 3 %), occurring in only trace amounts in the rest of the core. Although the question mark surrounding the taxonomic identification of these species makes interpretation of this zone problematic, it is likely that the water was shallow at this time. Small naviculoid species are usually associated with periphytic habitats such as bottom muds (Round *et al.*, 1990), whilst *Navicula seminulum* can survive in subaerial habitats (Gasse, 1986). The lack of epiphytic species in this zone (Figure 6.16) indicates that aquatic vegetation may have been sparse, or indeed absent. Diatom abundance is lower in this zone at approximately 2 x 10^9 valves per gram of dry sediment.

AV-3, from 46 to 36 cm depth, is again dominated by *Fragilaria* species. In this zone, *Fragilaria* cf. *capucina* becomes more common, rising to over 20 % of the count above the Jorullo tephra. Notable is the appearance of a number of species associated with slightly acidic waters. *Amphipleura pellucida*, a species commonly associated with acid conditions in ponds or bogs (Round *et al.*, 1990) is only found in this zone. This species has been found in small amounts in the modern flora of Lago de Zempoala (Caballero, 1995), which is chemically similar to the present day Lago de Zirahuén (see Section 5.8.1). *Eunotia naegelii* appears at values of up to 7 % of the count, a species that was also encountered in modern samples from Lagunilla de San Gregorio (pH 6.57). This is an acidophilous species found in subaerial habitats according to Gasse (1986). Fragments of species from the genus *Stenopterobia* are also present in this zone. Although identification to species level was not possible, the occurrence of this genus is significant, given that it is restricted to acidic habitats (Round *et al.*, 1990). The proportion of epiphytic species increases in this zone (Figure 6.16), which includes *Cymbella microcephala*, *Gomphonema acuminatum* and *Gomphonema gracile*. This suggests an increase in macrophyte abundance around Agua Verde. Also present is *Aulacoseira ambigua* cf. var. *robusta*, which is a planktonic species that is present in small numbers throughout the core, but reaches its highest abundance in Zone AV-3. *Cyclotella stelligera*, another planktonic species is also present here, increasing in abundance to approximately 10 % at the top of the zone. As Figure 6.16 shows, diatom abundance increases in this zone to around 8 x 10^9 valves per gram of dry sediment. Aerophilous taxa reach their highest abundance in the core, whilst facultative planktonic taxa, largely of the genus *Fragilaria* remain the most important habitat group.

Zone AV-4 represents a marked change in the diatom flora. Covering 36-3 cm depth, this zone sees the increase in abundance of *Cyclotella stelligera* to values of up to 40% of the total count. This freshwater planktonic species occurs in 11 of the 53 samples in the Central Mexican Diatom Dataset. Its optimum pH is 8.0 and E.C. is 166 $\mu S\ cm^{-1}$. In the Great Lakes of North America *Cyclotella stelligera* is tolerant of eutrophic conditions, having shown a rapid growth response to experimental additions of phosphorus (Stoermer *et al.*, 1985). In Florida, this species is tolerant of a wide range of nutrient conditions (Whitmore, 1989), whilst in other regions it is associated with eutrophic environments (Cholnoky, 1968). Also important in this zone are *Diploneis elliptica*, representing over 20 % of the total count in the upper part of the zone, and *Nitzschia amphibia* f. *rostrata*, which is found at levels of up to 12 % of the count. These species are regarded as alkalophilous (Gasse, 1986) and are typically found in lake margin environments. *Fragilaria* species are still common in this zone, but *Fragilaria* cf. *capucina* disappears from the record, with *Fragilaria brevistriata* increasing in importance. Other species found in this zone include *Brachysira neoexilis, Cymbella cymbiformis* and *Nitzschia denticula*, each with a 2-5 % relative abundance. At the very top of the zone (4-5 cm depth), *Aulacoseira distans* var. *alpigena* appears, forming 20 % of the total count. It is not encountered elsewhere in the core, but accounted for approximately 40 % of the total count of Metcalfe's modern sample from the lake in 1982 (Metcalfe, 1985). The proportion of epiphytic species is reduced in Zone AV-4 to less than 5 % in the upper part of the zone. The relative importance of planktonic species increases upward through the zone, although tychoplanktonic and periphytic habitats remain dominant. Diatom abundance in Zone AV-4, at between 1 and 2 x 10^9 valves per gram of dry sediment, is the lowest in the core.

The most dramatic change in the diatom record from Agua Verde is in the top 3cm. Between 3 and 0 cm depth (Zone AV-5), the assemblage is almost totally dominated by the planktonic *Cyclotella ocellata*, occurring at up to 80 % of the count. *Fragilaria crotonensis* appears for the first time in the core. The interpretation of this dramatic composition change is problematic. *Cyclotella ocellata* is generally regarded as indicative of dilute, oligotrophic conditions in North America (Stoermer *et al.*, 1985). In Africa, however, it is encountered in greatest abundances in highly productive, alkaline lakes with a high conductivity (>10,000 µS cm^{-1}) (Gasse, 1986). This species has not been found in modern material from Mexico other than at Lago de Zirahuén. The appearance of *Fragilaria crotonensis* in the diatom record suggests that the lake may have become more productive. This species is often associated with the onset of eutrophication through changes in the catchment, such as increased agricultural activity (e.g. Bradbury, 1975; Yang *et al.*, 1996). It is regarded as a mesotrophic species. Total diatom abundance increases to approximately 5 x 10^9 valves per gram of dry sediment at the top of the core (Figure 6.16).

6.6.4: Mineral Magnetic Properties

The results of mineral magnetic analyses are illustrated in Figure 6.17. At the base of the core, magnetic susceptibility is high, at approximately 5 μm^3 kg^{-1}. It then decreases between 58 and 50 cm to less than 2 μm^3 kg^{-1}. From this point, the mass specific susceptibility (χ) increases to approximately 8 μm^3 kg^{-1} at 30 cm. Levels remain fairly stable moving upward through the core, although decrease towards the surface to approximately 6 μm^3 kg^{-1}. The susceptibility profile indicates that, following a period of catchment stability between 58 and 50 cm, there was an increase in catchment disturbance and erosion from the surrounding slopes. The increase in erosion is most marked above the Jorullo tephra (AD 1759-1764), before levelling off up to the present day. It is interesting to note that in samples containing the tephra layers (43-44 cm and 8-9 cm), the susceptibility values show a slight decrease. The tephra layers are identified more clearly in the analysis of the anhysteretic remanent magnetization (ARM) and the saturation isothermal remanent magnetisation (SIRM) illustrated in Figure 6.17. The ratios of ARM-40 to SARM and of SIRM to χ indicate that those samples containing tephra are composed of harder magnetic material than the lake sediment. Essentially, this means that once the sample has been magnetised, it is then difficult to alter its magnetic properties. Measurements of this kind are clearly useful for identifying tephra layers which may not be visible or which have been overlooked on x-radiographs. The frequency dependent magnetic susceptibility in core AV/98 follows closely the pattern of χ. It is high, approximately 7 % in at the base of the core, before decreasing to almost zero between 58 and 54 cm. Above this, the frequency dependent susceptibility increases steadily to almost 10 % at the surface. The increasing frequency dependent susceptibilty indicates an increase in the amount of superparamagnetic minerals in the lake sediments in the upper part of the core. The presence of such minerals may be due to a number of factors, including burning of vegetation around the slopes, erosion of topsoil or increased activity of magnetotactic bacteria (Dearing, 1994).

6.6.5: Metal Concentrations

Results of the analysis of concentrations of iron (Fe), manganese (Mn), lead (Pb), zinc (Zn) and copper (Cu) in core AV/98 are presented in Figure 6.18. The metal profiles from Agua Verde have some similarities to the mineral magnetic results described above. All metal concentrations show a slight decrease in the samples containing the tephra layers (43-44 cm and 8-9 cm). Presumably, this is due to the dilution of the metal concentration in the sediment by the deposition of the volcanic ash. The percentage of Fe in each sample ranges from 1.4 to 5.2 %. The Fe profile is in broad agreement with the magnetic susceptibility record, with the lowest concentrations between 50 and 60 cm. Concentrations increase above 50 cm depth, whilst decreasing slightly towards the surface. The Mn profile is intriguing as concentrations between 62 and 8 cm are between 500 and 900 mg kg^{-1}, but rise dramatically to 1,720 mg kg^{-1} at the surface. Near-surface enrichment of Mn has been reported in other studies (e.g. Farmer and Lovell, 1984). Mn is released under reducing conditions through the decomposition of organic matter in lake sediments and will diffuse along concentration gradients. The upward-diffusing manganese will be precipitated out as manganese oxides when it reaches sufficiently oxidising conditions (Farmer, 1991). This Mn profile suggests that in the pore waters of the sediment water interface, conditions are aerobic. The Zn profile does not show any significant changes through the core, other than in samples containing the tephra layers. Pb and Cu results both indicate a peak in concentrations between 35 and 45 cm, although the metals record from this section is somewhat complicated by the presence of the Jorullo tephra at 43 cm. The profiles of Pb and Cu suggest that concentrations in the sediments were increasing before the deposition of the Jorullo tephra between 1759 and 1764. Cu concentrations of 71 mg kg^{-1} above the Jorullo tephra are double those at the bottom of the core, whilst lead concentrations peak above the tephra layer at 19.5 mg kg^{-1}. This peak in Cu is associated with the copper smelting activity in Santa Clara (see Section 6.3), which was at its height in the late 18th century. Although not used in the smelting process, Pb concentrations are also increased during this time, as this metal is present in copper-rich ores used for smelting.

6.6.6: Summary of the AV/98 Record

Diatom zone AV-1 is characterised by the high abundance of diatoms. The flora is dominated by *Fragilaria* species, epiphytic and periphytic taxa. The diatom assemblage is characteristic of a lake margin flora, suggesting that lake level may have been lower than the present level of 12 m at the core site. The species present suggest that the chemistry of the water was not different from the present day. During this period, magnetic susceptibility was low, indicating catchment stability. Diatom abundance is high as no dilution effects are experienced during this period of minimal catchment erosion. High magnetic susceptibility in the basal core sample suggests that there may have been a phase of catchment disturbance prior to the stability observed in the sediments immediately above, although the core does not extend back far enough to be certain of this. The age of this zone is unclear due to the unreliability of the radiocarbon dates. Using extrapolation of the ^{210}Pb chronology as an alternative means of dating, based on a sedimentation rate of 0.14cm yr^{-1}, indicates that this section of the core covers the period from approximately AD 1555 to 1620.

The estimated age of zone AV-2, using the extrapolated ^{210}Pb chronology, is AD 1620 to 1670. However, given that the Jorullo tephra lies 3 cm above the top of this zone at 43 cm, it is likely that the age of this zone is somewhat over-estimated..In this zone, magnetic susceptibility begins to rise. The increasing input of allochthonous material into the lake may have contributed to the dilution of diatom concentrations in core sediments at this time. This zone, however, is also distinguished by the presence in large quantities of *Navicula* cf. *seminulum* and *Navicula* cf. *absoluta*, taxa that are not found outside this zone. The lack of epiphytic species suggests a reduction in the amount of aquatic vegetation around Agua Verde, resulting in the domination of the periphyton by epipelic *Navicula* species. The reduction in aquatic vegetation may be the result of increased turbidity due to increased sediment inputs from the catchment.

Zone AV-3, which incorporates the Jorullo tephra at 43 cm depth, covers the mid- to late 18th century. Diatom abundance increases in this zone, although magnetic susceptibility is also increasing. This suggests that increased allochthonous material from the catchment is not affecting diatom concentrations. The increase in concentration may be the result of increased nutrient availability. A change in water chemistry is indicated by the presence of diatom taxa which prefer more acidic conditions, such as *Eunotia naegelii* and *Stenopterobia* spp. It is difficult to determine what may have caused this change in the chemistry of Agua Verde. One possible cause is the increased influence of springs flowing into the lake, which are likely to be more acidic than lake water. The existence of a spring in the Rincon de Agua Verde has been reported, but this has never been confirmed. In addition, it was not possible to analyse the chemistry of the springs around the lake reported by De Buen (1943), as these have since dried up. A lower lake level may have increased the habitat available to aerophilous taxa, which also increase in this zone. Close to Agua Verde, there are several small islands between which there are large areas of emergent aquatic vegetation (Figure 6.19). Should lake level have lowered, the expanse of this vegetation would likely have increased, providing habitat for epiphytic and aerophilous taxa. Zone AV-3 is also characterised by the peak in concentrations of copper and lead in the core sediments, which is consistent with the historical record of copper smelting activity in the basin.

Zone AV-4 represents the time period from the beginning of the 19th century to AD 1984. Magnetic susceptibility is high throughout this zone, indicating continued inwash of material from the slopes around the lake. Diatom abundance is low, but this is to be anticipated due to the dilution effect of the high proportion of allochthonous material being deposited in the lake. Diatom species composition shows a significant shift towards a plankton-dominated assemblage, principally composed of *Cyclotella stelligera* although *Diploneis elliptica* also becomes more abundant. The species present reflect a return to circum-neutral to slightly alkaline conditions, similar to the present day conditions in the lake. It is possible that the increase in *Cyclotella stelligera* reflects increased nutrient availability in the lake.

Zone AV-5 represents the last c. 15 years. During this time, the diatom flora of the lake has changed dramatically and is now almost totally dominated by *Cyclotella ocellata*, along with smaller amounts of the mesotrophic species *Fragilaria crotonensis*. Diatom abundance increases in this zone, suggesting increased productivity. The diatom evidence indicates that Agua Verde is becoming enriched in nutrients. Magnetic susceptibility remains high in AV-5, but is slightly lower than in zone AV-4. The subsurface peak in manganese in this zone indicates that conditions at the sediment-water interface in Agua Verde remain aerobic.

6.7: Core ZL/98

6.7.1: Stratigraphy and Chronology

ZL/98 was extracted from within the main basin of Lago de Zirahuén, close to the ridge that separates it from the Agua-Verde sub-basin. The core was taken using a 2.5 m polythene tube attached to the Kullenberg corer in approximately 25 m of water. 198 cm of sediment was recovered and the sediment-water interface was preserved. On opening the core, it was discovered that below 50 cm depth, where a sharp stratigraphic change occurred, the sediments appeared to be disturbed. This is thought to be due to pressure differences between the inside and outside of the core barrel as the core was being extracted (see Section 4.5.2. and Aaby and Digerfeldt, 1986). Two different types of sediment were found between 50 and 198 cm: a dark, organic silty sediment (2.5Y 3/1) and a "mousse" like clay rich material (2.5Y 4/1). Analysis of the diatom composition of the two different types of material from the same stratigraphic depth revealed very different assemblages. The organic-rich sediment was dominated by *Aulacoseira ambigua* cf. var. *robusta*, whilst the finer sediment consisted mainly of small *Fragilaria* species. This confirmed that the stratigraphy of the sediment below 50 cm depth had been disturbed and a reliable record of environmental change below this point could not be obtained. An AMS radiocarbon date from the contact at 50-51 cm (Table 6.1) produced an age of 965 ± 45 ^{14}C yrs BP (cal. AD 993-1188: 2 sigma). The sedimentation rate extrapolated from the intercept age of AD 1031 is 0.05 cm yr^{-1}.

The stratigraphy of the reliable part of the core (0-50 cm depth) is shown in Figure 6.11. Between 50 and 39 cm, a grey-brown gyttja was found, graduating from 2.5Y 3/1 at the bottom to 2.5Y 3/2 at the top of the section. A clay-rich section of sediment lay above this, between 36 and 39 cm. This was dark grey in colour (2.5Y 4/1), having a mousse-like consistency due to a high water content. Between 36 and 19.5 cm, the sediments were darker and more organic (2.5Y 3/1). The water content was lower and the sediment broke up when scraped. A gradual transition from 19.5 cm to 14.5 cm from dark brown sediments to a silty dark greyish-brown gyttja occurred. Between 14.5 cm depth and the surface, the sediments were dark brown and silty (10YR 3/3). Within this top section of sediment, a black, coarse-grained tephra layer was found. This is identified as the Paricutín tephra (AD 1943).

Given that there were some concerns about possible stratigraphic disturbance of this core, the full range of analytical techniques was not employed on ZL/98. The results of diatom and magnetic susceptibility analysis are outlined below.

6.7.2: The Diatom Record

The detailed diatom record from core ZL/98 is shown in Figure 6.20. A summary of the habitat groupings and an estimate of diatom abundance in the core are provided in Figure 6.21. The four diatom zones were identified in the CONISS analysis of the diatom data are evident in these figures. The bottom part of the core (ZL-1), between 50 and 42 cm, is markedly different from the rest of the core. *Aulacoseira ambigua* cf. var. *robusta* forms almost 40 % of the total count. In the bottom sample, *Aulacoseira granulata* var. *angustissima* and *Cyclostephanos* sp. comprise approximately 20 % and 10 % of the count respectively. Small *Fragilaria* species are also present (*F. construens* + var. *venter*, *F. pinnata*, *F. brevistriata*). In Central Mexico, *Aulacoseira granulata* var. *angustissima* is common in well-mixed, turbid waters, such as Lago Cajititlán, of medium conductivity and sodium carbonate-bicarbonate chemistry. Gasse (1986) observed the same ecological preference in East Africa. The ecology of *Aulacoseira ambigua* cf. var. *robusta* is not known as it is not encountered in modern material from Central Mexico (see Section 4.7.1). Its heavily silicified nature suggests that dissolved silica was readily available in the water column at this time (Bradbury, in press). The nominate variety (*A. ambigua*) is regarded to be a freshwater planktonic species, occurring in shallow lakes of low conductivity and alkalinity or in marginal areas of large lakes in Africa (Gasse, 1986). Small species of the genus *Cyclostephanos* are commonly associated with eutrophic lakes (Håkansson and Kling, 1990). The greatest abundance of diatoms in core ZL/98 is found in zone ZL-1 (7×10^9 valves per gram of dry sediment) which is dominated by planktonic diatoms (Figure 6.21).

Zone ZL- 2 (42-18 cm) sees the disappearance of *Cyclostephanos* sp. from the diatom record and a dramatic decrease in the abundance of *Aulacoseira ambigua* cf. var. *robusta*. The assemblage is dominated by a number of *Fragilaria* species. *Fragilaria construens* and its variety *venter*, *Fragilaria pinnata* and *Fragilaria brevistriata* are all common throughout the zone, whilst *Fragilaria* cf. *capucina* becomes abundant in the upper part, occurring at levels up to 20 % of the total. *Diploneis elliptica* occurs in significant numbers. This zone is also characterised by the presence in small amounts of *Epithemia* species (*E. turgida, E. sorex, E. adnata*).

Diatom abundance fluctuates in ZL-2, with low values between 40 and 32 cm, peaking at 7×10^9 valves per gram of dry sediment at 28 cm, before decreasing again in the upper part of the zone. Zone ZL-2 is dominated by shallow water facultative planktonic, periphytic and epiphytic species, being almost devoid of any truly planktonic species.

A return to a plankton-dominated flora is seen in zone ZL-3. Whilst *Fragilaria* species are still present, *Cyclotella stelligera* becomes the most important component of the diatom assemblage, occurring at values of up to 60 % of the total count. *Diploneis elliptica* is still present, but is less important and *Fragilaria* cf. *capucina* also declines in numbers. *Brachysira neoexilis* and *Cymbella cymbiformis* appear in the record for the first time, albeit in small numbers (<5%). These species were both found in modern vegetation samples from the margins of Lago de Zirahuén. Diatom concentrations remain low throughout this zone at approximately 2×10^9 valves per gram of dry sediment.

As seen in core AV/98, a dramatic change in the diatom flora is observed in the uppermost sediments (ZL-4). The surface sediment (0-1 cm) assemblage in this core consists of almost equal proportions of *Cyclotella ocellata* and *Cyclotella stelligera.* A very small amount of *Fragilaria crotonensis* is found in this sample, although other *Fragilaria* species which were abundant lower down the core are absent or reduced in numbers. In contrast to core AV/98, diatom concentrations do not increase in the surface sediments.

6.7.3: Mineral Magnetic Properties

The magnetic susceptibility results from ZL/98 are shown in Figure 6.22. Magnetic susceptibility at the bottom of the reliable portion of the core is low (2 $\mu m^3\ kg^{-1}$) and then rises dramatically between 36 and 40 cm to 8 $\mu m^3\ kg^{-1}$. This is followed by a return to low susceptibility levels between 32 and 24 cm, before rising again to approximately 8 $\mu m^3\ kg^{-1}$ in the uppermost 20 cm of the core. A slight decrease in susceptibility between 1 and 2 cm depth is associated with the Paricutín tephra. The magnetic susceptibility profile indicates that there have been two separate phases of catchment disturbance since AD 993-1188 (2 sigma range). The frequency dependent susceptibility throughout this core is high, ranging between 18 % and 8 %. In the natural environment, values above 12 % are unusual and values over 14 % should be regarded as erroneous (Dearing, 1994). It is unclear what may have caused errors. Care was taken to prevent contamination of samples and all samples were measured at low and high frequency in the same orientation to avoid the problem of anisotropy. The susceptibility meter appeared to be giving consistent results.

6.7.4: Summary of the Record from ZL/98

Zone ZL-1 is dominated by the planktonic species *Aulacoseira ambigua* cf. var. *robusta.* Dissolved silica must have been readily available in the water column to allow this heavily silicified species to flourish in the lake. The lake must also have been well-mixed in order for it to remain buoyant. The presence of *Aulacoseira granulata* var. *angustissima* and *Cyclostephanos* sp. indicate that the lake was turbid and eutrophic at this time. The high diatom concentrations in this zone support the notion of increased productivity. It is possible that the lake was significantly shallower than at present. The onset of catchment instability is recorded in Zone ZL-1 as magnetic susceptibility values rise towards the top of the zone. The age of this zone is unclear. The basal AMS age range of AD 993-1188 (2 sigma) may well be accurate, but should be regarded with some caution given the uncertainty over the ^{14}C chronology highlighted with core AV/98. As this sample was taken at a depth where magnetic susceptibility and hence, catchment erosion, was low, the problem of contamination with older carbon from the catchment is less likely. This section of core must, however, be older than the basal sediments from AV/98 as its distinct species composition was not detected in AV/98.

In zone ZL-2, a pronounced peak in magnetic susceptibility and, hence, increased catchment erosion is observed. This is followed by stabilisation of the slopes around the lake, indicated by the dramatic reduction in magnetic susceptibility. Diatom concentrations in the core mirror the magnetic susceptibility signal, with low concentrations when susceptibility is high and vice versa. The phase of catchment instability in ZL-2 may relate to Pre-Hispanic settlement in the basin, probably by the Purépecha civilisation. The exact dates for this, however, are not known. The diatom flora between 42 and 18 cm indicates a relatively shallow, lake margin flora as it is dominated by facultative planktonic *Fragilaria* species and epiphytic and periphytic taxa.

A second peak in magnetic susceptibility is observed in zone ZL-3, presumably related to Post-Hispanic settlement in the basin. As seen in core AV/98, the increase in erosion from the catchment is accompanied by a change in the diatom flora, with *Cyclotella stelligera* dominating the assemblage. At the very top of the core, evidence for the rapid, recent change in the diatom flora is observed. However, in this core, *Cyclotella stelligera* and *Cyclotella ocellata* occur in almost equal amounts. Some mixing may have occurred in the uppermost layers of sediment, or the sedimentation rate may be so much lower than at Agua Verde that this core is not of sufficient resolution to identify the details of this more recent change in species composition.

6.8: Core ZD/98

6.8.1: Stratigraphy and Chronology

Sixty-nine centimetres of sediment were recovered from the deepest point of the lake in approximately 40 m of water. The sediment-water interface was again well preserved. The core stratigraphy is illustrated in Figure 6.11. Between 69 and 65 cm depth, the sediment was dark brown (2.5Y 2.5/1) with a high silt content, which broke up when scraped. From 65 to 58 cm, the colour of the sediment was slightly lighter (10YR 3/1). The silt content of this section remained high and single grains were visible. Between 58 and 39 cm, a mousse-like sediment was encountered (10YR 3/2), which was very wet and was composed mainly of clay. A return to the dark, organic sediment encountered at the base of the core was observed between 39 and 26 cm. A gradual transition occurred from coarser, silt-rich material at the base of the section towards finer clays. The colour became lighter moving up the core from 2.5Y 2.5/1 at 39 cm to 2.5Y 3/1 at 26 cm. The sediment broke up when scraped. Between 26 cm and the surface, the sediment resembled a fine brown mousse (10YR 3/2), having a high water content. Within this section, a coarse black tephra layer was found between 2 and 3 cm depth. Geochemical analysis confirmed that this layer was from the eruption of Volcán Paricutín in AD 1943 (Figure 6.12). A thin, patchy tephra layer was also discovered at 9 cm depth. Full geochemical analysis of this layer proved to be impossible as the glass shards were too degraded, but the silica content over 70 % suggests that this may originate from a stratovolcano rather than a cinder cone (A. Newton, pers. comm.). Examination of x-radiographs revealed two other minerogenic bands at 28-29 cm and 41 cm depth. Samples were taken from these depths and geochemically analysed. The layer from 28-29 cm was identified as the Jorullo tephra (AD 1759-1764). The layer from 40-41 cm was confirmed to be a tephra layer. This layer is distinguishable from the Jorullo and Paricutín tephras by its higher silica content of up to 64 % (A. Newton, unpubl. data: Figure 6.12). The origin of the layers at 9 cm and 41 cm are not known as data on the geochemical composition of tephras from volcanoes in the Michoacán-Guanajuato Volcanic Field, other than Paricutín and Jorullo are not available. Current research in the Department of Geography, University of Edinburgh, is focusing on this issue.

Two AMS ^{14}C dates were obtained from this core (Table 6.1). A basal age from 68-69 cm depth was 910 ± 50 ^{14}C yrs BP (cal. age range AD 1019-1245: 2 sigma). A date from above this at 53-54 cm depth, however, yielded an age of 1390 ± 40 ^{14}C yrs BP (cal. age range AD 601-688: 2 sigma). This inversion in the ^{14}C chronology is considered to result from the input of old carbon into the aquatic system caused by catchment instability. As discussed in Section 6.6.2, this problem has been encountered in several lakes from Central Mexico when attempting to date Late Holocene sediment sequences. This issue is also explored in more detail in Section 8.2.2.

6.8.2: The Diatom Record

The full diatom diagram for core ZD/98 is presented in Figure 6.23. A summary diagram of habitat groupings and diatom abundance is provided in Figure 6.24.

At the bottom of the core, zone ZD-1, between 69 and 58 cm is dominated by the freshwater planktonic *Aulacoseira ambigua* cf. var. *robusta*. In the lower part of ZD-1, this species is found in association with *Aulacoseira granulata* var. *angustissima* and *Cyclostephanos* sp. This coincides with the period of highest diatom concentrations throughout the core of 5-10 x 10^9 valves g^{-1}. Small *Fragilaria* species are also found in this zone at levels of 5 % or less of the total count. *Diploneis elliptica* becomes abundant towards the top of this zone. It is planktonic diatoms, however, which form the dominant habitat group in ZD-1.

Zone ZD-2, between 58 and 18 cm depth, has been divided into two sub-zones as the change in species composition is more subtle, yet still significant. Zone ZD-2a is characterised by a dramatic reduction in diatom abundance to 1 x 10^8 valves g^{-1}. *Aulacoseira ambigua* cf. var. *robusta* declines in numbers and *Aulacoseira granulata* var. *angustissima* and *Cyclostephanos* sp. disappear completely from the diatom record. *Diploneis elliptica* is the most common species in this zone, although *Fragilaria* species (*F. construens* var. *venter, F. brevistriata and F.* cf. *capucina*) also increase in numbers. *Diploneis elliptica* is a particularly robust diatom and the fact that its high relative abundance may be related to differential preservation should not be ruled out. *Epithemia sorex, Epithemia turgida and Epithemia adnata* occur at levels of between 2 and 10 % of the total count, their highest abundance in the core. *Gomphonema intricatum* var. *pusilla* is also at its most abundant in this zone. Zone ZD-2a is dominated by periphytic and epiphytic taxa (Figure 6.24), whilst the facultative planktonic *Fragilaria* species form approximately 30 % of the assemblage. Between 46 and 42 cm, diatom preservation was too poor to produce a full count. Above this zone of poor preservation, zone ZD-2b (41-18 cm) does not represent a major change in the species present. However, *Aulacoseira ambigua* cf. var. *robusta* increases in importance once more. *Fragilaria construens* and its variety *venter*, *Fragilaria brevistriata* and *Fragilaria* cf. *capucina* all increase in number. *Fragilaria* cf. *capucina*, in particular, shows a dramatic increase in relative abundance towards the top of the zone, making up approximately 40 % of the total count. In this zone, *Diploneis elliptica* is much reduced in number, although it is present throughout at approximately 5 % of the count. *Cyclotella stelligera* appears in the upper part of the zone from 28 cm upwards, although it is also present in small numbers in the lower part of the core. This zone shows an increase in planktonic taxa, although the facultative planktonic *Fragilaria* species dominate. Diatom abundance also increases significantly in ZD-2b, to 12 x 10^8 valves per gram of dry sediment.

Zone ZD-3 represents 18-2 cm depth. This zone is characterised by the low abundance of diatoms. Full counts could not be obtained from samples at 8-9 cm, 6-7 cm and 2-3 cm depth. Those diatoms present were poorly preserved. The most distinctive feature of the diatom assemblage is the dominance of *Cyclotella stelligera*, which makes up to 80 % of the count. *Diploneis elliptica* increases in numbers towards the top of the zone, whilst *Fragilaria brevistriata* also becomes more common. *Fragilaria crotonensis* and *Cymbella cymbiformis* appear for the first time in the diatom record. *Brachysira neoexilis* is also present in small amounts. Zone ZD-3 is dominated by planktonic taxa, principally *Cyclotella stelligera.*

Zone ZD-4 is represented by only one sample from 0-1 cm depth. As seen in the other cores described thus far, a dramatic change in species composition is observed. The planktonic *Cyclotella ocellata* is almost totally dominant, although *Fragilaria crotonensis* is also present in small numbers. Diatom abundance increases in this zone to 9 x 10^9 valves g^{-1}.

6.8.3: Mineral Magnetic Properties

The magnetic susceptibility record from ZD/98 is illustrated in Figure 6.25. Mass specific low frequency susceptibility is low at the very bottom of the core (2.2 μm^3 kg^{-1}), but rises steadily, peaking between 56 and 44 cm at around 10 μm^3 kg^{-1}. This suggests an increase in sediment input from the basin slopes. A sharp decline in magnetic susceptibility is then evident between 40 and 28 cm depth to approximately 4 μm^3 kg^{-1}. This indicates a reduction in allochthonous inputs, suggesting catchment stability at this time. A further rise in magnetic susceptibility is observed between 28 and 16 cm depth, after which levels of approximately 10 μm^3 kg^{-1} are maintained until 4 cm depth. Magnetic susceptibility decreases slightly towards the surface of the core. The lower susceptibility values between 2 and 3 cm depth are probably explained by the presence of the Paricutín tephra.

The amount of frequency dependent susceptibility shows a slow and steady increase from the bottom of the core upwards. The result from 68-69 cm depth was discarded as this gave a negative result. The most likely explanation is that, at this depth, the frequency dependent susceptibility was below the precision of the machine. The gradual increase in high frequency susceptibility may be the result of a number of factors. Firstly, it may represent a gradual increase in inputs of soil. Secondly there may have been an increase in the frequency of fires within the catchment, producing more super-paramagnetic minerals. Finally, there may be an increase in the amount of magnetotactic bacteria present in the sediments. John Braisby (Department of Geology and Geophysics, University of Edinburgh) is currently exploring the relative importance of the different sources of magnetic material further, investigating in more detail the magnetic properties of core ZD/98, as part of his doctoral research.

Preliminary results from the application of an unmixing model to the mineral magnetic data (Braisby, unpubl. data) revealed that inputs of soil from the catchment were the most important component of the magnetic signature during periods of high susceptibility. Peaks in the activity of magnetotactic bacteria were found between 30 and 42 cm, which coincides with low magnetic susceptibility values. The occurrence of these bacteria explains why the frequency dependent susceptibility does not decrease during this period. These bacteria produce superparamagnetic minerals, whose magnetic susceptibility is frequency dependent (Dearing, 1994).

6.8.4: Metal Concentrations

Results of metal analysis of core ZD/98 are illustrated in Figure 6.26. The analysis of Pb in one sample, 3-4 cm, gave an anomalously high result of 168 mg kg^{-1}, in comparison to values of less than 20 mg kg^{-1} for the rest of the core. Although this was close to the Paricutín tephra, a similar response was not seen in the Pb record from core AV/98. It was therefore assumed that this result was due to sample contamination either before or during preparation and was therefore disregarded.

Analysis of Pb isotopes in the sample was undertaken with the objective of determining whether there had been a different source of lead, but this was unsuccessful due to problems with the analytical equipment.

For all five metals measured, the lowest concentrations are observed at the very bottom of the core. This also corresponds to low magnetic susceptibility levels and a diatom flora very different to that of the rest of the core. As found in core AV/98, a small decrease in metal concentrations is evident in the samples containing tephra (2-3 cm and 40-41cm). Between 32 and 42 cm depth, both Fe and Mn concentrations show a marked increase in concentrations. Fe levels rise from approximately 6 % to 9 % of the total sample, whilst Mn concentration increases from approximately 1400 mg kg^{-1} to over 2,000 mg kg^{-1}. These depths coincide with a period of lower magnetic susceptibility illustrated in Figure 6.25. In contrast to core AV/98, there is no sub-surface peak in manganese concentrations. Anoxic conditions at the sediment-water interface prevent the precipitation of manganese oxides in the sediment, allowing the release of manganese in solution back into the water column. Limnological data have indicated that anaerobic conditions prevail at the sediment-water interface during the summer months (Section 6.2.4).

The most distinct feature of the metals record in ZD/98 is the almost doubling of copper concentrations from 47 mg kg^{-1} to 87 mg kg^{-1}, Beginning around 32 cm depth, this rises to a peak at 24 cm depth, a few centimetres above the Jorullo tephra (28-29 cm depth). The same pattern is replicated in the Pb record, in which concentrations also double. Above 24 cm depth, Cu and Pb concentrations decline, but they remain higher than in the bottom part of the core. The increase in Cu and Pb in the sediments during the latter half of the 18th century is clearly a reflection of the smelting operations at Santa Clara, also evident in the metals record from AV/98.

6.8.5: Summary of the record from ZD/98

Zone ZD-1 charts the onset of catchment instability. Magnetic susceptibility is low at the base of the core, but begins to rise. During this period, diatom productivity was high and the flora was dominated by *Aulacoseira ambigua cf.* var. *robusta,* *Aulacoseira granulata var. angustissima and Cyclostephanos sp.* This assemblage is also found in core ZL/98 but not in AV/98. Turbid, eutrophic conditions are inferred from the diatom species composition. The lake level was possibly shallower, with higher concentrations of sodium than at present. It is difficult to provide a chronology for this part of the core owing to the reversals in the ^{14}C AMS dates. However, given that this diatom assemblage is not encountered in core AV/98, it must pre-date this core and it is therefore probable that it is at least 500 years old.

In Zone ZD-2a, diatom concentrations are low. The low concentrations in the sediment are most likely to be due to dilution by the increased inputs of allochthonous material, indicated by the higher magnetic susceptibility. Analysis of the magnetic properties of the sediments suggests that the magnetic signal in the core is dominated by soil from the surrounding slopes. This phase of catchment erosion is likely to be associated with settlement of the basin by the Purépecha civilisation. The diatom assemblage in ZD-2a is dominated by lake margin periphytic and epiphytic taxa, such as *Epithemia* spp. and *Diploneis elliptica.* Facultative planktonic *Fragilaria* species are also common. This indicates that the lake may have been significantly shallower than at present, as the lake is currently 40 m deep at the core site. The flora does not, however, suggest that the water chemistry of the lake was different from present day conditions. Furthermore, the Agua Verde core site would have been desiccated if lake level had dropped substantially and there is no record of this in the palaeoenvironmental record from core AV/98. Palaeolimnological records from elsewhere in the region do not record significantly drier conditions around this time. The absence of a truly planktonic flora is therefore curious, but most likely to be related to competition with other forms of planktonic algae.

Zone ZD-2b marks a subtle shift in the diatom flora, with a recovery in numbers of *Aulacoseira ambigua* cf. var. *robusta.* Diatom concentrations in this zone also increase as the magnetic susceptibility reduces again. Prior to this phase of catchment stability, manganese and iron concentrations in the sediments are elevated. Analysis of the magnetic properties of the sediment indicates an increase in bacterial activity during this period. The exact cause of this is unclear. Magnetic susceptibility rises towards the top of zone ZD-2b, above the Jorullo tephra. The onset of this increased erosion, presumably the result of Spanish settlement in the basin, is accompanied by the appearance of *Cyclotella stelligera*, as seen in the other cores analysed.

Diatoms are low in numbers and poorly preserved in Zone ZD-3, with samples uncountable between 5 and 9 cm depth. The cause of poor preservation in this core is not clear. It is possible that dissolution of diatoms occurred as they sank through the water column in this deepest point of the lake, but increased turbidity of the water may have led to more breakage of valves. The assemblage is, however, evidently dominated by *Cyclotella stelligera.* Magnetic susceptibility remains high throughout this section, with catchment soil providing the strongest signal in the magnetic record. *Fragilaria crotonensis* also appears in the record, somewhat earlier than in the other cores, which indicates nutrient enrichment of the lake.

As with the other cores described thus far, the most clearly marked change in the diatom flora is in the most recent sediments. *Cyclotella ocellata* is almost totally dominant. Diatom concentrations increase significantly, implying an increase in algal productivity. Pollen samples from this core, analysed by Dr. J. P. Bradbury (written communication), were rich in *Coelastrum* sp. aff. *C. cambricum.* The presence of this green alga suggests an increase in the trophic level of the lake, supporting the interpretation made from the diatom record.

6.9: Core ZR/98

6.9.1: Stratigraphy and Chronology

Sixty-one centimetres of sediment were recovered from close to the inflow of the Rio de la Palma in approximately 11m of water. Again, the sediment-water interface was well preserved. The core stratigraphy is illustrated in Figure 6.11.

From 61 to 46 cm depth, the sediment was clay-rich with a high water content. It appeared similar to the mousse-like gyttja recovered in cores ZL/98 and ZD/98, with a colour of 2.5Y 4/1. A coarse, black tephra, identified as that from Paricutín (AD

1943) was found within this section between 54 and 55 cm depth. Between 46 and 24.5 cm depth, the sediment was darker and more organic. Distinct dark bands (10YR 2/2) occurred at 30.5-31 cm, 38.5-39 cm and 42-42.5 cm. Inspection of the x-ray images revealed weakly laminated sediments between 37.5 and 46 cm, although these were not clearly evident in the visible stratigraphy. The upper part of the core, from 24.5 cm to the surface was characterised by reddish coloured silt (7.5YR 3/2). This appeared to correspond to that found in the upper part of core AV/98. Given that the Parícutin tephra was found almost at the base of this core, it was not appropriate to use ^{14}C dating to improve the chronology. Furthermore, it was felt that ^{210}Pb dating would not be successful, as the high sedimentation rate of c. 1cm yr^{-1} would dilute concentrations of ^{210}Pb too much. As no other chronological methods were available, a constant sedimentation rate of 1cm yr^{-1} has been assumed in the following discussion of the palaeoenvironmental data. Metal concentrations were not analysed for ZR/98 as the sediments appear to post-date the peak in industrial activity in the basin.

6.9.2: The Diatom Record

The diatom record from core ZR/98 is illustrated in Figure 6.27. A summary diagram of habitat groupings and diatom abundance is provided in Figure 6.28. Three diatom zones were distinguished. Zone ZR-1, from 61 to 44 cm, represents the period from AD1936 to 1954. *Diploneis elliptica* is the most abundant diatom in this zone. Also common are: *Nitzschia amphibia* f. *rostrata*; *Diploneis pseudovalis*, *Cyclotella stelligera*, *Fragilaria brevistriata* and *Fragilaria construens* var. *venter*. *Nitzschia denticula* and *Nitzschia amphibia* are present at the bottom of the zone. This zone is dominated by benthic taxa. Diatom abundance is lower than in the upper part of the core. Preservation in the sample from 44-45 cm depth was insufficient to obtain a diatom count.

Above this level of poor preservation, the diatom assemblage changes significantly. Zone ZR-2 is almost entirely dominated by *Cyclotella stelligera* and *Diploneis elliptica*. In the uppermost part of the zone (20-21cm), *Aulacoseira distans* var. *alpigena* appears, comprising almost 40 % of the total count. This species was encountered in large numbers in modern samples from Lago de Zirahuén in 1982 (Metcalfe, 1985). The calculated age of this depth of ca. 1978, based on a sedimentation rate of 1cm yr^{-1}, is consistent with the date of Metcalfe's sample.

The top 16cm of core are dominated by *Cyclotella ocellata*, which replaces *Cyclotella stelligera* as the main component of the diatom flora. The mesotrophic species, *Fragilaria crotonensis,* becomes abundant in the top 8 cm, representing approximately the last 8 years. *Diploneis elliptica* disappears from the diatom record in zone ZR-3. Diatom abundance in core ZR-98 peaks at the bottom of this zone then decreases towards the surface.

6.9.3: Magnetic Susceptibility

The magnetic susceptibility record from ZR/98 is illustrated in Figure 6.29. The record is relatively stable, with high values of χ throughout the core (7.7-8.9 $\mu m^3\ kg^{-1}$). The frequency dependent susceptibility does decrease towards the top of the core from 11 to 7 %, possibly indicating a reduction in the amount of super-paramagnetic minerals in the lake sediment. The potential unreliability of frequency dependent measurements, however, has already been raised in section 6.7.3 and therefore these trends should be regarded with extra caution.

6.9.4: Summary of the record from ZR/98

The high resolution of ZR/98, which covers approximately the last 60 years, allows a more detailed examination of recent environmental change than is possible from the other cores. The much higher sedimentation rate in this core is to be expected, given that the core site is close to the mouth of the principal river flowing into the lake. The rapid deposition of sediment is likely to change the topography of the basin floor and result in the reduction of water depth at the eastern end of the lake. Magnetic susceptibility has remained high throughout the last 60 years, indicating that there has been no decrease in the catchment erosion, which began during the mid-1700s. Diatom abundance in this core is lower than in the other cores analysed, because of the greater sedimentation rate at this site.

In the lower part of the core, between ca. AD 1937 and 1952, periphytic species, such as *Diploneis elliptica* and *Nitzschia amphibia* var. *rostrata* dominate the diatom assemblage. This core was taken in a part of the lake where the lake floor slopes gently. A reduction in water depth of only 4-5 m would be required to greatly expand the habitat available to periphytic species in this part of the lake. The meteorological record during this period suggests that conditions were actually wetter than at present, but the record is not complete for this time period. A comparison of aerial photographs of Lago de Zirahuén from 1954, 1974, 1990 and 1995 by Bernal-Brooks and MacCrimmon (1999) revealed 1954 to have the lowest lake level. Instrumental data from nearby Lago de Pátzcuaro indicate a particularly low lake level in 1955 in response to drought during the 1940s and early 1950s (O'Hara, 1993; Chacón and Muzquiz, 1997). If the expansion of *Diploneis elliptica* is indeed a response to lower lake levels, its relative abundance in the cores from other parts of the lake which extend further back in time, may yield clues about the nature of the climate.

Cyclotella stelligera is dominant in zone ZR-2 (ca. AD 1952-1980), although *Diploneis elliptica* remains common. The lake level may have recovered sufficiently during this period to reduce the habitat available for periphytic and epiphytic species. It seems that the onset of the eutrophication process began in the early 1980s when *Cyclotella ocellata* became dominant. The appearance of *Fragilaria crotonensis* within the last decade indicates that the lake is progressing towards eutrophication.

6.10: Magnetic Analysis of Soil Samples

It was hoped that by understanding the magnetic signature of the soils around the catchment, more information could be gathered regarding the major sources of sediment which has been deposited in the lake during the last ca. 1,000 years. A total of 11 soil samples were taken from around the lake for the analysis of magnetic susceptibility. The sample locations are described in Table 6.3.

The magnetic susceptibility of all the soil samples was high, ranging between 8 and 14 $\mu m^3\ kg^{-1}$ (Table 6.3), with the exception of sample 10, which had a magnetic susceptibility of 5 $\mu m^3\ kg^{-1}$. This sample was taken from within a heavily forested area around Agua Verde and was rich in organic material. It is possible that the presence of organic matter, which has a weak negative susceptibility (Dearing, 1994), may have had the effect of diluting the susceptibility signal from this soil sample. The highest magnetic susceptibility was found in sample 3 ($14\ \mu m^3\ kg^{-1}$), from a drainage ditch on the southern side of the lake. The soil here was a distinctive red colour, probably due to the formation of iron oxides through weathering (Dearing, 1994), which accounts for the high magnetic susceptibility of the sample. It is interesting to note that the sample from Arroyo Zirahuén (sample 8) had a markedly higher magnetic susceptibility ($13\ \mu m^3\ kg^{-1}$) than the two samples from the Rio de la Palma (samples 1 and 6), which yielded values of 9 and 8 $\mu m^3\ kg^{-1}$ respectively. The difference between the sediments from these two principal inflows into the lake may be the result of local geological variations and warrants further investigation.

The samples collected here provided preliminary data for a wider study of mineral magnetic properties in soils and lake sediments in several basins in Michoacán, which is being carried out by John Braisby (Dept of Geology and Geophysics, University of Edinburgh). He carried out a more detailed analysis of the mineral magnetic properties of these samples. His preliminary findings indicate that these soil samples are likely to be composed principally of magnetite (Fe^3O^4). He also found that core samples with a high magnetic susceptibility plotted close to soil samples on biplots of anhysteretic remanent magnetisation against isothermal remanent magnetisation (Braisby, unpubl. data). This supports the argument that high magnetic susceptibility values in core sediments are the result of soil erosion from the catchment.

6.11: Synthesis of the Individual Records

This section draws together the data from the four individual cores. The stratigraphic correlation between the cores is discussed first of all as this helps to provide a general chronological framework. The palaeoenvironmental data are then analysed using multivariate statistics. Firstly, the Central Mexican Diatom Dataset is applied to core data to produce numerical reconstructions of key environmental variables.

Results are compared with those obtained using the African calibration dataset to test the applicability of the two datasets to Lago de Zirahuén. Secondly, canonical correspondence analysis is used to explore the relationship between diatom species assemblages in the core material and the other variables measured. An overall interpretation of environmental change in the Zirahuén Basin over the last ca. 1,000 years is then presented.

6.11.1: Core Correlation and Chronology

The stratigraphy and chronology of the four cores is presented in Figure 6.11. The clearest means of correlating between the cores is by using the tephra layers from Paricutín and Jorullo. The Paricutín tephra is a clear marker horizon across the basin, whilst the Jorullo tephra is less easy to identify and the use of x-radiographs has proved to be a most useful aid. The thinner Jorullo tephra has not been encountered in core ZL/98. This suggests that its deposition across the basin may have been patchy. The microscopic, more silicic tephra found in the sample from 40-41cm depth has not been found in the other cores. It is possible that this predates the time period covered by core AV/98 and again, its deposition across the lake floor may have been intermittent. The most striking feature of the comparison of relative positions of the tephra layers in the cores is that the sedimentation rates of the individual cores vary greatly. ZR/98, closest to the Rio de la Palma has a sedimentation rate up to twenty times as fast as ZD/98 at the deepest point of the lake. The distinct reddish, oxidised layer of sediment, which occurs in the more recent sediments, also picks out the difference in sedimentation rates between the cores. In ZD/98 and ZL/98, this only forms the uppermost 1-2 mm of the core, whilst in AV/98 it forms the top 5cm (Figure 6.10) and in ZR/98, it forms the top 20cm. The inferred sedimentation rates are, however, much slower than those suggested by Bernal-Brooks and MacCrimmon (1999) who used a comparison of bathymetric surveys from a number of studies to infer sedimentation rates of up to 1.4 m yr^{-1} (see section 6.2.4). As the sediment-water interface was preserved in each of the cores, the results from the present research are reliable. This study does, however, agree, with Bernal-Brooks and MacCrimmon's (1999) conclusion that the deposition of sediment is greater closest to the inflow of the Rio de la Palma.

A robust chronology has been developed for the most recent ca. 250 years for the Agua Verde core, using a combination of ^{210}Pb dating and tephrochronology. This framework can be applied to the other cores as there is a remarkable degree of consistency between results of diatom, magnetic and metals analysis from the four individual records. Unfortunately, the chronology for the lower part of cores AV/98, ZD/98 and ZL/98 is less reliable. Basal AMS ages of 875 ± 45, 910 ± 50 and 965 ± 45 ^{14}C yrs BP respectively, all suggest that the cores are of comparable age. However, the reversal in the ^{14}C chronology from ZD/98 and the discrepancy between the ^{14}C date from AV/98 and the Jorullo tephra, indicates that older carbon washed in from the catchment may be contaminating the core sediments. Magnetic susceptibility is high at the points where these samples were taken for radiocarbon dating, supporting the hypothesis that catchment erosion may be responsible for erroneously older dates. As the basal dates from cores ZD/98 and ZL/98 were taken from a period of low magnetic susceptibility in the cores, the catchment was more stable and it is more likely that these dates are reliable.

Correlation of the magnetic susceptibility records between the three sites does indeed suggest that ZD/98 and ZL/98 cover a greater time period than AV/98 (Figure 6.30). AV/98 only records the most recent phase of catchment disturbance, which occurs during the mid-1700s. ZD/98 and ZL/98, however, indicate that an earlier period of increased erosion occurred. The cores can therefore be correlated on the basis of the peaks and troughs in the magnetic susceptibility records (Figure 6.30). The greater age of ZD/98 and ZL/98 is supported by the existence of a diatom assemblage at the base of these two cores, which is not present in AV/98. Given the relative position of the Jorullo tephra in core ZD/98, it would appear that both ZD/98 and ZL/98 extend back into the Post-Classic Period, prior to the arrival of the Spanish in AD 1521. From the results of the four individual cores, a reconstruction of environmental changes since the Post-Classic period, with the greater resolution of core ZR/98 providing a more detailed record of the most recent 60 years. The palaeoenvironmental record from Lago de Zirahuén is discussed below.

6.11.2: Numerical Reconstructions of Environmental Change

To provide a quantitative interpretation of the diatom record from Lago de Zirahuén, the transfer functions which were developed from the Central Mexican Diatom Dataset, described in Chapter 5, were applied to the core data. In the first instance, it was decided to apply the modern diatom calibration dataset to core AV/98 as this has the best chronology. Numerical reconstructions of conductivity, pH and carbonate content (%) were obtained using the weighted averaging model in the program CALIBRATE (Juggins and ter Braak, 1999). Only those taxa occurring at a relative abundance of 2 % or above, in at least one core sample, were included in the analysis. The core dataset therefore consisted of 49 diatom taxa. To allow a comparison between the quantitative reconstructions produced by different datasets, the African diatom calibration dataset (Gasse *et al.*, 1995) was also used to reconstruct conductivity and pH. The results from the two different datasets are presented in Figure 6.31.

Of the 49 taxa included in the core dataset, 25 are found in the Central Mexican Dataset and 26 are encountered in the African calibration dataset. The poor overlap between the modern and fossil species suggests that the numerical reconstructions provided by the datasets should be regarded with some caution. Only 5 of the 22 core samples were represented at levels of over 70% of the count in the Mexican calibration dataset. In fact, in 5 samples, the overlap between the fossil and modern data was less than 50 %. The African dataset performed equally poorly, with 5 out of the 22 samples having an overlap greater than 70 % and 6 below 50 %. The poor overlap between the diatom assemblages in the core and the modern dataset is partly due to the fact that some taxa have not been conclusively identified, such as *Fragilaria* cf. *capucina* and *Navicula* cf. *seminulum*. Other taxa common in core AV/98 include *Diploneis elliptica*, which has not been encountered in modern samples from Mexico and Africa. Given the poor comparison between the modern and fossil data, the diatom-inferred reconstructions presented in Figure 6.31 cannot be used with any degree of confidence.

It is interesting to note, however, that a very good match was found between the fossil and modern datasets for the top two core samples. These samples were almost entirely dominated by *Cyclotella ocellata*, which is found in both the Mexican and African datasets. As surface sediment samples from Lago de Zirahuén are included in the modern dataset, the reconstructed E.C., pH and % carbonate are very similar to values measured at the lake (E.C. = 119 μS cm^{-1}, pH = 8.4, % CO_3 = 91). The diatom-inferred pH from the African dataset is slightly higher at 8.7, whilst the inferred E.C. is much higher at 1065 μS cm^{-1}. In samples from Africa, *Cyclotella ocellata* was encountered in concentrated systems and has an optimum of 1503 μS cm^{-1} for E.C, compared with an optimum of 127 μS cm^{-1} in the Central Mexican Dataset, where it was only found in Lago de Zirahuén. Either this species has different ecological requirements in Africa compared with Mexico, or its full ecological range has not been encountered in the two datasets. Discrepancies in the optima of species between different diatom-based calibration datasets have been discussed in section 5.8.7., clearly having implications for quantitative palaeoenvironmental reconstructions. Disappointingly, it is not possible to produce a reliable numerical reconstruction of hydrochemical variables for Lago de Zirahuén, using either the African or the Mexican datasets.

6.11.3: Statistical Analysis of the Palaeoenvironmental Data

Canonical correspondence analysis was used to explore how far the mineral magnetic properties and metal concentrations were associated with the changes in the diatom assemblages observed in the cores. Core ZD/98 was chosen initially for this analysis as it has the longest record of environmental change. The analysis was performed using the program CANOCO (ter Braak, 1987-1992) (see Section 5.6.1). 16 core samples were included in the analysis, whilst the environmental dataset consisted of 6 environmental variables (mass specific magnetic susceptibility; % Fe; Mn; Zn; Cu and Pb – all mg kg^{-1}). The species dataset included 32 taxa, all of which occurred at a relative abundance of over 2% in at least one core sample.

The results of the CCA are illustrated in Figure 6.32. As the biplot shows, samples from 68-69cm depth and 0-1cm depth are clear outliers. These two samples have the most distinctive species composition, with the lower sample composed of *Aulacoseira ambigua* cf. var. *robusta, A. granulata* var. *angustissima* and *Cyclostephanos* sp. and the surface sample dominated by *Cyclotella ocellata.* Most other samples cluster around the centre of the diagram. The low eigenvalues for Axis 1 and Axis 2 (0.6263 and 0.4742 respectively) indicate that the changes in diatom species composition in the core are not fully explained by the environmental variables included in the analysis. No particular variable can be easily associated with a particular axis and the short length of the arrows representing the individual variables indicates that they are not important in explaining the variation in species composition. Whilst it is evident from the palaeoenvironmental results from ZD/98 that the diatom assemblage does change in accordance with variables such as magnetic susceptibility, its response is non-linear in that it does not revert back to its original state. This is likely to be due to the influence of other environmental variables that have not been measured, such as nutrient concentrations. This statistical analysis does not therefore add any further information to that gained from the qualitative interpretation of the results from the individual cores. It is that qualitative interpretation of the data, therefore, which forms the basis of the synthesis of environmental change across the basin presented below.

6.11.4: The Sequence of Environmental Change in the Zirahuén Basin

The results from the four different cores analysed provide a spatially and temporally coherent record of environmental change over the last ca.1,000 years in the Zirahuén Basin, which is summarized in Figure 6.33.

The basal sediments from ZD/98 and ZL/98 indicate that Lago de Zirahuén was probably substantially different around AD 1000 to 1100 compared with today. The catchment slopes were stable, with no evidence of inwash of allochthonous material. The diatom record indicates a shallower, turbid environment with a high flux of dissolved silica. The combination of low catchment erosion and lower lake level indicates that conditions may have been substantially drier than at present. This evidence for a drier climate appears to be correlative with evidence from other lake basins in the central Mexican highlands for a prolonged period of drought between

1500 and 900 yrs BP (Metcalfe *et al.*, 1994). It is disappointing that the core sequences do not extend back further in time as this means the timescale of this event cannot be established from the existing evidence. Further work is needed in the Zirahuén Basin to obtain longer sediment cores that would extend the palaeoenvironmental record further back into the Holocene. This would allow a more complete record of drought history to be obtained.

Catchment disturbance is inferred from changes in the mineral magnetic properties of the core sediments between ca. AD 1000 and 1550. The increased soil erosion from the basin slopes is likely to be related to Pre-Hispanic settlement and agricultural activity in the area. Indeed, preliminary pollen data from core ZD/98 indicate that maize has been cultivated in the basin throughout the time period covered by the core (Bradbury, written communication). The catchment instability inferred from the magnetic record was significant and appears to have lasted for several hundred years before subsiding. Such a signal had not been anticipated given the lack of historical and archaeological records pertaining to the basin. It would appear, however, that anthropogenic impact on the environment in the Zirahuén basin was indeed substantial during the height of the Post-Classic Purépecha empire. It is important to point out that archaeological work in Michoacán has largely focused on the larger basins of Pátzcuaro and Zacapu. Future research efforts in the Zirahuén Basin may help to provide more clues as to the nature and extent of Pre-Hispanic activity here. Analysis of longer sediment sequences would also help to identify the onset of anthropogenic disturbance in the basin. It would be particularly interesting to determine whether any environmental disturbance can be detected in the sediment record, prior to that caused by the Purépecha.

The poorly developed planktonic flora in Lago de Zirahuén between ca. AD 1100 and 1750 is difficult to explain. A shallow, circum-neutral to slightly alkaline environment is suggested by the species present, chemically similar to the present day lake. A significantly shallower lake is not likely, however, as there is no evidence in the palaeoenvironmental or historical record to indicate that a significant drought period occurred during this time. One possible alternative explanation is that other types of algae were dominating the phytoplankton, meaning that epiphytic and periphytic diatoms from the lake margins dominated the core assemblages. The potential impact of tectonism on the hydrology of the basin has been considered, but there no historical evidence has been found for a major earthquake affecting the Zirahuén Basin at this time (see García and Suaréz, 1996). During this period, the catchment restabilised, between ca. AD 1550 and 1750. This corresponds to the catastrophic decline in indigenous population following the Spanish Conquest in 1521. Reduced disturbance in the catchment during the early Colonial period allowed vegetation to become re-established on the basin slopes, thus reducing soil erosion.

From the mid-1700s, a second phase of catchment disturbance is recorded in Lago de Zirahuén. The diatom assemblage changes to a plankton-dominated flora, composed principally of *Cyclotella stelligera* coincident with a dramatic increase in soil erosion from the catchment. This disturbance is associated with Colonial settlement in the basin, which included the establishment of numerous *haciendas* and, most notably, the development of copper smelting operations in the town of Santa Clara, pollution from which is also evident in the sedimentary record. The increase in human activity in the Zirahuén Basin during the 18th century and associated environmental degradation are well documented in the historical record (Endfield, 1997; Endfield and O'Hara, 1999). Catchment disturbance in the basin has continued to the present day.

More acidic conditions than present are inferred from the diatom record from Agua Verde during the mid to late 1700s, which may be the result of increased influence of spring water and expansion of marsh habitats around the sub-basin due to a decrease in lake level. This interpretation is consistent with historical records, which document prolonged drought conditions during the latter part of the 18th century (Metcalfe, 1987; O'Hara and Metcalfe, 1995; 1997). As suggested by Endfield and O'Hara (1999), it is likely that the combination of increased pressure on natural resources and a drier climate served to exacerbate the environmental degradation experienced in the lacustrine basins of the Michoacán highlands. The palaeoenvironmental record from Lago de Zirahuén certainly supports the evidence from the historical record.

There have also been considerable changes in the diatom flora of Lago de Zirahuén during the last century. A lower lake level during the 1940s and early 1950s is inferred from the higher proportion of periphytic and epiphytic species in core ZR/98 during this time. This is consistent with meteorological records, which report drier conditions during this time and decreasing lake levels at nearby Lago de Pátzcuaro, which reached their lowest point in 1955 (O'Hara, 1993; Chacón and Muzquiz, 1997). It is clear that, although Lago de Zirahuén has not experienced major changes in chemistry during the historical period, the diatom flora is sensitive to climatic fluctuations through the expansion and contraction of different habitat types.

The most significant change in the diatom flora of Lago de Zirahuén has been experienced in the last fifteen years. During this time, the species composition has become less diverse and indicates that the lake is progressing towards eutrophication. Although the species now present in the lake do not represent highly eutrophic conditions, it is clear that the lake is responding rapidly to increased nutrient inputs. Pollen analysis of recent sediments supports the interpretation from the diatom record of increasing trophic status (Bradbury, written communication). Intensification of agriculture and domestic waste from an increased population in the basin have resulted in an increased phosphorus loading to the lake. This is evident in the limnological data that is available (section 6.2.4.). Now that the lake is stratifiying, both thermally and chemically, in response to increased productivity, more phosphorus will be released from surface sediments due to the anoxic conditions at the sediment-water interface. High-resolution sampling of core material for the analysis of phosphorus content may help to confirm the interpretation of recent eutrophication.

It is clear that the biota of Lago de Zirahuén is responding rapidly and dramatically to anthropogenic activities within the basin. The Zirahuén Basin is currently being heavily promoted as a major tourist destination for the state of Michoacán. Whilst, superficially, it appears to be in a pristine state, this investigation has shown that the quality of the ecosystem is beginning to deteriorate and will continue to do so unless appropriate land management strategies are adopted. Major tourist developments, such as the planned golf course at Agua Verde and hotel complexes should not be allowed to proceed. Future tourist activity should focus on the conservation importance of this lake and strict controls should be placed on the amount of development that is permitted within the basin. Domestic waste should be treated before entering the lake and reforestation and soil conservation programmes should be implemented. Only then may it be possible to avoid further deterioration of Lago de Zirahuén.

6.12: Conclusions from the Zirahuén Basin

The main conclusions drawn from the palaeolimnological record from Lago de Zirahuén are as follows:

- Tentative evidence from the diatom record is presented for drier climatic conditions around AD1000. Further work is required to clarify the precise timing and extent of this drought episode.
- A significant phase of catchment disturbance occurred after ca. AD1100, continuing until approximately AD1550. This is likely to be the result of Purépecha settlement within the basin. Such disturbance was not anticipated from archaeological and historical records pertaining to the area.
- Between AD 1550 and the early 1700s, soil erosion into the lake decreased dramatically. It is postulated that indigenous depopulation in the region during the early Colonial period had a beneficial impact on the environment, as vegetation was able to regenerate on the slopes surrounding the lake, thus greatly improving catchment stability.
- During the early to mid 18th century, the diatom assemblage changes significantly alongside a dramatic increase in soil erosion from the catchment. This second phase of catchment disturbance is related to increased Hispanic settlement in the basin, which is documented in the historical record. Metal pollution from

Colonial copper smelting operations at Santa Clara is clearly recorded in the sediments of Lago de Zirahuén.

- In the last 15 years, the lake ecosystem has undergone dramatic changes. The palaeolimnological evidence indicates that the lake is progressing rapidly towards eutrophication in response to the intensification of agriculture and increased settlement and tourism. The findings of this investigation are in agreement with limnological data.
- Lago de Zirahuén is perceived by many in Mexico to be in a pristine condition. Evidence from this and other studies indicates that the lake is highly sensitive to human activity in the catchment and will deteriorate rapidly and irreversibly if appropriate management practices are not adopted.

Chapter 7: The Palaeolimnology of Laguna de Juanacatlán

7.1: Introduction

In this chapter, the palaeoenvironmental record from Laguna de Juanacatlán is presented. Background information on the physical characteristics of the basin is provided, including the geology, climate, vegetation and hydrology of the area. The results of a preliminary limnological survey are also discussed. In contrast to Lago de Zirahuén, there is no published work on the history of settlement around Laguna de Juanacatlán and the surrounding area. It was possible, however, to obtain limited information on the cultural setting of the basin using secondary historical sources and through discussions with local people. This contextual information is important for the interpretation of the palaeolimnological record. Results are presented for 3 sediment cores taken from different points around the lake. The results of diatom, magnetic and metals analysis are presented for each core. In addition, the results of a more detailed analysis of the nature of laminated sediments found in Laguna de Juanacatlán are presented. Data from the different core sites is then compared to provide an overall interpretation of environmental changes during the last ca. 500 years in Laguna de Juanacatlán. The palaeoenvironmental record from this study is also compared with previous unpublished work undertaken at Laguna de Juanacatlán by R. Byrne (University of California at Berkeley) and S. Metcalfe (University of Edinburgh).

7.2: The Physical Environment

Laguna de Juanacatlán (20°37'N, 104°44'W) lies in a remote location in the Sierra de Mascota in the westernmost portion of the TMVB at an altitude of ca. 2000 m a. s. l. (Figure 3.3). The lake appears to have been formed through the blockage of the Arroyo de Laguna Juanacatlán by the formation of Cerro el Malpais, an igneous intrusion with an elevation of ca. 2100 m (Figure 7.1). This small basin, of about 10 km^2, is oriented in a north-west to south-east direction. The lake occupies an area of approximately 0.5 km^2 at the north-west end of the basin. The slopes surrounding the basin are very steep, rising to some 2300 m at their highest point.

7.2.1: Geology

Laguna de Juanacatlán lies within the Mascota Volcanic Field at the western edge of the TMVB (see Section 3.2.1 and Figure 3.2). Numerous studies focusing on the volcanic geology of this region have been undertaken (e.g. Wallace and Carmichael, 1989; Wallace *et al.*, 1992; Carmichael *et al.*, 1996). The Mascota graben lies internally within the Jalisco Block, so the volcanic activity here is not directly related to the subduction of the Cocos Plate. Rather, it is thought to be the result of crustal extension and rifting associated with the re-organisation of plate boundaries (Wallace *et al.*, 1992; Carmichael *et al.*, 1996).

Due to their unusual tectonic setting, the volcanic rocks of the Mascota Volcanic Field have a distinct geochemical composition, dominated by potassic and hydrous types, which are not found elsewhere in the Trans-Mexican Volcanic Belt. The basin itself is composed largely of basaltic andesite (CETENAL, 1971), whilst Cerro el Malpais, at the western boundary of the basin is a spessarkite, a lamprophyric form of andesite (Carmichael *et al.*, 1996). Volcanic activity in the Mascota Volcanic Field began during the late Pleistocene, ca. 0.5 Ma, according to potassium-argon dates (Carmichael *et al.*, 1996) and the area is believed to have remained active through to the mid-Holocene. Carmichael *et al.*, (1996) suggest that a tephra layer found at 6.5 m depth in a 9 m core from Laguna de Juanacatlán (Byrne, unpubl. data) may correlate to a sparsely vegetated basaltic andesite lava flow of youthful appearance from Volcán Malpais, ca. 5km north of Mascota. The tephra layer in the core has been dated to 5,600 ^{14}C yrs BP (Byrne, unpubl. data, cited in Wallace *et al.*, 1992) although no geochemical data linking it to the eruption of Volcán Malpais have been published. The age of Cerro el Malpais (Figure 7.1) and its associated lava flow that led to the formation of Laguna de Juanacatlán is not known.

Due to the rifting and crustal extension within the Jalisco Block, the area is tectonically active, with earthquakes occurring throughout the historical period. In 1568, a massive earthquake affected the whole region, causing structural damage and hydrological changes, which included changes in lake level, damming of rivers and alterations in the flow of natural springs (Suaréz *et al.*, 1994). Earthquakes in 1875 and 1909 led to structural damage in the town of Mascota, ca. 12 km south-west of Laguna de Juanacatlán (García and Suaréz, 1996). Furthermore, in 1932 and 1995, major earthquakes measuring 8.2 and 7.9 on the Richter Scale respectively were experienced across the Jalisco Block (Carmichael *et al.*, 1996). Tectonic activity may have had an impact on the hydrology of the basin in the past and must therefore be considered in the interpretation of the palaeoenvironmental record from Laguna de Juanacatlán.

7.2.2: Climate

The closest meteorological station to Laguna de Juanacatlán is at Mascota. The instrumental record is short, only extending back to 1961, with incomplete records for some years. The average annual temperature is 21.8°C, with a maximum of 29.3°C and a minimum of 14.3°C (Gobierno del Estado de Jalisco, 1992). The town of Mascota, at 1200 m a. s. l., is approximately 800 m lower in altitude than the lake, so it is likely that the average annual temperature at Laguna de Juanacatlán itself is considerably lower. Certainly, frosts are common during the winter months at the lake. Rainfall is highly seasonal in this region, with most precipitation occurring between June and August. Given that the lake is just 30 km away from the Pacific Ocean, it is likely that this is an important moisture source, although the lake lies east of the Sierra Madre Occidental (see Section 2.3). Average annual precipitation at Mascota is 1026 mm yr^{-1}, based on data from 1961-1988 (IMTA, 1996). It is assumed that precipitation at the lake itself is higher, due to the higher altitude and cooler temperatures. According to unpublished data from the Secretaria de Agricultura y Recursos Hidraulicos for October 1986 to September 1987 the total precipitation during this period at Laguna de Juanacatlán was 1041.9 mm, whilst total evaporation was 1642.3 mm. Although limited to one year, these data indicate that Laguna de Juanacatlán is situated in an area of moisture deficit. During late summer, tropical storms are likely to be an important moisture source in the area due to its proximity to the Pacific Ocean. In September and October of 1865 and in 1943, hurricanes caused extensive flooding in the town of Mascota (Salcedo-Robles, 1994).

7.2.3: Vegetation

The slopes around Laguna de Juanacatlán are dominated by dense pine forest. Cerro el Malpais, however, is covered in *Quercus* (oak). Numerous *Salix* (willow) trees are found lining the river flowing into the lake and also along edge of the lake. There is a marked seasonal contrast in the characteristics of the vegetation, as illustrated in Figures 7.2 and 7.3. Vegetation cover, as would be expected, is much thicker during the wet season. When the lake was visited in September 1998, aquatic vegetation was abundant around the lake margins, particularly close to the mouth of the Arroyo de Laguna Juanacatlán. This included water lilies, *Myriophyllum* and *Potamogeton*. At the end of the dry season, in March 1997 and March 1998, however, there was very little aquatic vegetation around the fringes of the lake.

7.2.4: Hydrology and Limnology

Unlike Lago de Zirahuén, there are no published data available on the hydrology and limnology of the Juanacatlán Basin. It was therefore necessary to undertake more detailed limnological measurements. Hydrological information has been gained from topographic maps. Laguna de Juanacatlán lies in a naturally closed basin. The principal surface inflow to the lake is the Arroyo Laguna de Juanacatlán, which flows in from the east (Figure 7.1). The Arroyo El Astilladero joins the Arroyo de Laguna de Juanacatlán from the north approximately 0.5km before it enters the lake. Two minor ephemeral streams flowing into the northern part of Laguna de Juanacatlán are marked on the topographic map (INEGI, 1973). When the lake was visited in September 1998, towards the end of the wet season, these were dry. The influence of groundwater in the basin is unknown. However, the fact that the lake waters are chemically dilute (Table 5.3) suggests that there must be a certain amount of groundwater seepage, which prevents the lake from becoming concentrated with dissolved salts. During the 1950s, an artificial exit channel was dug out at the western end of the lake, which provides irrigation water for crops. The lake is therefore no longer a surficially closed system and water is extracted from the lake between December and April (SARH, unpubl. data).

Laguna de Juanacatlán has a volume of approximately 2,930 m^3 (SARH, unpubl. data). There is evidence that the lake level has fluctuated in the order of at least 1-2 m in the recent past. Firstly, the line of dead willow trees, approximately 1 m above the current lake level, indicate previous higher water levels (Figure 7.4). Secondly, comparison of aerial photographs taken at different times illustrates fluctuations in water level (Figure 7.5). The first photograph was taken in May 1991, however, the date of the second photograph remains unknown, despite efforts to find out this information. In the records held by INEGI, the photographs from this flight line are marked simply "*vuelo especial*" (special flight). In the photograph from the *vuelo especial*, the water level is higher, the lake having extended in area around the side of Cerro el Malpais. These photographs may have been taken in different seasons or the difference in lake level may be associated with short term climatic fluctuations.

A preliminary bathymetric survey of Laguna de Juanacatlán was undertaken in September 1998, by measuring water depth along two transects across the lake. Although it was not possible to produce a detailed bathymetry for the lake, the principal features could be identified, which are illustrated in Figure 7.6. This contour map was produced using the software package SURFER to plot the GPS co-ordinates of depth measurements onto a 1:50 000 scale topographic map of the lake. As the data points used to produce this map were fairly sparse, this map should be considered as preliminary and a more detailed study is required to further constrain the topography of the basin floor. The lake reaches its deepest point in the middle of the lake close to Cerro el Malpais. The deepest point measured was 25 m. The most striking feature identified was the presence of a deep channel with steeply sloping sides which appeared to continue along most of the length of the eastern flank of the lake. Even relatively close to the inflow of the Arroyo de la Laguna de Juanacatlán, the depth of this channel-like feature was as great as 10 m. From the western end of the lake, the basin floor slopes more gently towards the deepest point.

Laguna de Juanacatlán is a calcium-magnesium bicarbonate lake with an alkalinity of 1.39 meq l^{-1}. In 1997, the surface waters had a pH of 8.78 and an E.C. of 148 µS cm^{-1} (Table 5.3). A more detailed limnological survey was carried out in September 1998 in order to explore the changes in physical and chemical limnological variables through the water column. Five depth profiles were obtained from different points along the lake, the locations of which are illustrated in Figure 7.6. The data obtained are provided in Appendix 7.

Figure 7.7 illustrates the results of temperature, dissolved oxygen (DO) and pH measurements for each depth profile. It is evident from these results that Laguna de Juanacatlán experiences thermal stratification, with a three layered system comprising a hypolimnion, metalimnion and epilimnion. The three deeper profiles show that in the cooler hypolimnion, below 10 m depth, the water temperature is relatively stable, rising slowly from 13.1°C at 20 m depth to 14°C at 10 m depth. The metalimnion is found between ca. 10 and 7 m depth, characterised by a rapid change in water temperature known as the thermocline. Here, the water rises steeply at a rate of ca. 1.5°C m^{-1}. Horne and Goldman (1994) state that tropical lakes have a thermocline spanning only 1 to 3°C, whilst the evidence from Laguna de Juanacatlán indicates a thermocline of approximately 5°C (14 – 19°C). The warmer epilimnion extends to 7 m depth, having a temperature of ca. 19°C at 7 m and rising to between 21.5 and 22.5°C at the surface. As only one set of measurements were obtained in September 1998, it is impossible to ascertain how long this thermal stratification prevails each year. Stratification is likely to be triggered by the heating of the lake during early summer and so the lake may remain stratified for several months. It is also possible, however, that mixing events such as big storms, may disrupt the thermal stratification of the lake.

Associated with the thermal stratification of the lake is the depletion of DO in the hypolimnion (Figure 7.7), anoxic conditions are found below 8 m in the water column. In the epilimnion, however, levels of DO are significantly higher, reaching approximately 6 mg l^{-1} at the surface. The DO profile from Laguna de Juanacatlán is a typical clinograde curve, which is characteristic of productive lakes. Higher DO concentrations in the epilimnion are due to photosynthesis, whilst oxygen in the hypolimnion is depleted by the decomposition of dead organisms which sink from the epilimnion. The clinograde curve of DO is typical of tropical lakes that mix only on rare occasions (Horne and Goldman, 1994). The fact that chemical as well as thermal stratification occurs in Laguna de Juanacatlán indicates that the lake must be of mesotrophic or eutrophic status, as a certain degree of productivity is required to initiate the depletion in hypolimnetic oxygen.

As Figure 7.7 indicates, pH increases towards the surface of the lake. The lowest pH of 6.8 was recorded from 20.75 m depth (Site 1), whilst at the base of the epilimnion (ca. 7 m depth) it rises to 7.5. The pH increases more quickly in the epilimnion, reaching 8.7 at the surface. The increase in pH in the epilimnion is probably due to the removal of CO_2 from the water column by photosynthetic organisms.

Results of nitrate, turbidity and E.C. measurements are shown in Figure 7.8 for the deepest profile obtained (Site 1). Nitrate levels are low at the deepest point of the profile (0.14 mg l^{-1}), but rise significantly to a maximum of 2.8 mg l^{-1} at 14.7 m depth. Above 10 m depth, nitrate concentrations fall to less than 1 mg l^{-1}, decreasing to 0.14 mg l^{-1} at the surface. The other sites did not exhibit the same nitrate profile as Site 1, with nitrate concentrations remaining low throughout (< 0.4 mg l^{-1}). The low nitrate levels in the epilimnion are likely to be due to assimilation by phytoplankton (Hutchinson, 1957). Due to the stratification of the lake, the nitrate present in the hypolimnion is prevented from mixing upwards into the epilimnion. The decrease in nitrate at the bottom of the water column is likely to be the result of nitrate reduction in the anoxic interstitial waters.

The turbidity profile at Site 1 is similar to those observed for the other sites. For each site, the deepest reading has been rejected as the multiparametric probe may have disturbed the sediment and affected the turbidity readings. Turbidity is slightly higher in the hypolimnion than the epilimnion, whilst there is a marked peak in the metalimnion. A similar profile was observed in Lago Cadagno, Switzerland, where turbidity was highest in the oxic-anoxic transition zone due to the presence of a dense population of photo-autotrophic sulphur bacteria (Imboden and Wüest, 1995).

The profiles of E.C. for each site also compare well. Values are slightly higher at depth, decreasing to 0.136 mS cm^{-1} (136 μS cm^{-1}) at the surface. The highest reading was obtained at Site 1 (Figure 7.8), where E.C. at 20.75 m depth was 0.192 mS cm^{-1}.

During the field visit of February 1998, the lake was a distinctive green colour which appeared to be the result of a phytoplankton bloom. Analysis of modern plankton samples revealed that the bloom consisted almost entirely of the diatom *Fragilaria crotonensis*. Species of the genus *Staurastrum* were also encountered in small numbers in plankton samples. Scrapings of algae from vegetation samples also contained *Cocconeis placentula* and *Gomphonema acuminatum*. *Synedra ulna* and *Nitzschia palea* were also found in large numbers in vegetation samples taken from the eastern edge of the lake in March 1997. Other types of algae were not identified from vegetation and surface sediment samples as they were destroyed during the diatom sample preparation procedure.

The results presented in this section are the first limnological data to be obtained from Laguna de Juanacatlán. Whilst preliminary, they are a valuable aid for the interpretation of the lake sediment record. Further limnological monitoring is required, however, in order to understand in more detail the seasonal dynamics of this aquatic ecosystem.

7.3: Magnetic Susceptibility of Soil Samples

Soil samples were obtained from different sites around the lake for analysis of mineral magnetic susceptibility in order to determine any differences in the magnetic signature of sediments around the catchment. Seven different samples were analysed, the location and results of which are described in Table 7.1.

Four of the seven samples had a relatively low magnetic susceptibility of 0.25 to 0.35 $\mu m^3\ kg^{-1}$. These included sample 3, taken from the dry stream bed close to Cerro el

Malpais and a soil sample from the western edge of the lake (sample 5). Two soil samples were obtained from the same profile, close to the road on the southern side of the lake: one contained charcoal fragments, the other did not. The magnetic susceptibility of these samples was also low, but the sample which contained charcoal had a slightly higher susceptibility than that which did not, at 0.35 $\mu m^3 kg^{-1}$. The sample taken from the Arroyo de la Laguna de Juanacatlán had a significantly higher magnetic susceptibility at 0.75 $\mu m^3 kg^{-1}$, whilst a sample from the steep, pine covered slope on the northern shore of the lake recorded a value of 0.96 $\mu m^3 kg^{-1}$. The highest magnetic susceptibility value recorded was 1.24 $\mu m^3 kg^{-1}$, in a sample from the C horizon of an exposed soil profile alongside the edge of the road. This material was pale orange in colour and did not appear to contain any organic matter.

It would appear, from this preliminary analysis of the magnetic susceptibility of soils in the Juanacatlán basin, that there is considerable variability in magnetic properties around the catchment. Samples from the western end of the lake had a lower magnetic susceptibility than those from the eastern end. The difference in mineral magnetic properties may be associated with local variations in geology. For example, the geochemical composition of Cerro el Malpais is clearly distinguishable from the extrusive igneous rocks which make up most of the basin (see Section 7.2.1 and Carmichael *et al.*, 1996). Further work to establish a more detailed picture of the nature of the magnetic signal from different types of material in the basin will help to clarify the principal sediment sources that are contributing to deposition in the lake. Nevertheless, this preliminary information is a useful aid to interpreting the data from sediment cores.

7.4: Human Settlement around the Juanacatlán Basin

There is very little information concerning the history of settlement in the region around Juanacatlán. To the author's knowledge, there have been no archaeological studies in the area, so nothing is known about the nature and extent of any pre-Hispanic settlement. A number of secondary historical sources were consulted in order to build up a picture of changing land use in the area following the arrival of the Spanish in Jalisco (then Nueva Galicia) in 1524. These include several geographical descriptions of Jalisco during the Colonial Period, such as those by Don Alonso de la Mota y Escobar (ca. 1604), Fray Antonio Tello (1653), Domingo Lazaro de Arregui (1621) and Matias de la Moto Padilla (1742). The 16th century *Relaciones Geográficas* pertaining to Nueva Galicia, which were collated by Acuña (1988) also provided some useful background information.

Although there are no settlements within the basin itself, Laguna de Juanacatlán lies close to a number of towns and villages mentioned in historical accounts, which are illustrated in Figure 7.9. The largest settlement in the vicinity of Laguna de Juanacatlán is the town of Mascota (historically also known as Mascotlán or Amaxocotlán), which lies approximately 12 km south-west of the lake. During the 16th century and early 17th century, Mascota was a small village (Mota y Escobar, ca. 1604; Lázaro de Arregui 1621). In 1579, members of the Augustinian religious order established a monastery at El Ixpostli, north-west of the present day town (Salcedo-Robles, 1994). By 1742, according to Matias de la Moto Padilla, there was a substantial population of Spanish settlers in Mascota, as well as numerous *haciendas*. The most important *hacienda* to be established during the mid- to late 18th century was that of San Nicolás, which was owned by the Augustinians and from where agricultural production in the valley was controlled (Salcedo-Robles, 1994). Attempts were made to access archival material in Mascota, but this proved to be problematic as in December 1860, General Antonio Rojas set fire to the town and all historical documents were destroyed. Only archive material post-dating 1860 was therefore available.

The principal agricultural activities in and around Mascota were the cultivation of maize, wheat and the rearing of cattle. By the latter part of the 19th century, Mascota had increased significantly in size, having a population of 7,732 by 1880 (Salcedo-Robles, 1994). At the beginning of the 20th century, fruit cultivation was important in the valley around Mascota, which included peaches, avocados, guayabas, limes and mangoes[1]. The small ranches closest to Laguna de Juanacatlán (Juanacatlán, Ixtolo

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[1] Archivo del Ayuntamiento, Mascota. Seccion: Presidencia; Asunto: Estadistica de la producción agricola y explotación de madera de Mascota; Fecha: 1909.

and Galope) employed a total of 47 men, producing mainly maize and wheat, with some land provided for cattle pasture.

The principal attraction of this remote and mountainous region to Spanish settlers in the first instance was the existence of rich deposits of silver and gold. During the Colonial period, many mines were established in this part of Jalisco. The extent to which pre-Hispanic populations had exploited these resources is not known, although, Fray Francisco Lorenzo, when in Mascota in 1553, encountered Indians wearing "beards" made from gold, silver and copper (Amaya, 1983). The first mining development in the area was around San Sebastian, approximately 40 km north of Juanacatlán. Together with nearby mines at Los Reyes and Oxtoctipac (Figure 7.9), this was one of the principal production centres of gold and silver during the 16th and 17th centuries (Rodríguez, 1995). Mineral deposits were also discovered in the vicinity of Mascota and Navidad, although there is a discrepancy in the literature concerning the commencement of mineral exploitation in this area. Salcedo-Robles (1994) states that mining operations began during the 17th century with the discovery in 1662 of the rich vein of Las Loberas, to the north of Navidad, whilst Rodríguez (1995) argues that mineral deposits in the Mascota-Navidad area were not discovered until 1902. The silver mines of Navidad, as well as those of Oxtoctipac are, however, mentioned by Fray Antonio Tello, writing in 1653, whilst Lazaro de Arregui (1621) refers to mining around Mascota. It seems more likely, therefore, that mineral exploitation around Mascota and Navidad began during the 17th century. Unfortunately, it has been impossible to pinpoint the exact location of most of these mines. Mines were also established during the Colonial period around Jolapa, approximately 10km north-west of Juanacatlán. A map of the jurisdiction of the Real de San Sebastian dating to 1777, reproduced in the Cartografía Histórica de Jalisco (Universidad de Guadalajara, 1984), depicts the mine at Jolapa, describing its location as forested and difficult to access.

Gold and silver mining declined in the region during the 19th and early 20th century (Rodríguez, 1995). According to archives held in Mascota, in 1899, only three of the ten mines around Navidad were still producing ore[2], whilst in 1927, the mine of La Estrella on Cerro el Ponto was closed[3]. Today, a small mining operation continues in Navidad, which now has a population of ca. 500 (Gobierno del Estado de Jalisco, 1992), but the potential of the area for future exploitation is considerable (Rodríguez, 1995).

Agriculture (maize, wheat and cattle rearing) is the principal economic activity in the vicinity of Laguna de Juanacatlán today, although there is very little exploitation in the basin itself. A small amount of maize cultivation occurs along the flanks of the Arroyo Laguna de Juanacatlán, close to the lake itself, which is farmed by the people of Juanacatlán and had a population of 230 according to the 1970 census (Salcedo-Robles, 1994). The local authority in Mascota is currently promoting the area is a tourist attraction, one of the highlights of which is the secluded Laguna de Juanacatlán. In September 1998, the construction of several small log cabins was underway and a number of travel agencies from Puerto Vallarta offer excursions for foreign tourists to the lake and its environs.

Whilst human activity within the catchment of Laguna de Juanacatlán appears to have been minimal, it is clear that during the Colonial period there may have been significant impacts in the area associated with mineral exploitation. Determining the exact timing and location of mining operations has not been possible, but the potential implications for the interpretation of the palaeolimnological record, which is presented in the rest of this chapter, must be considered.

A detailed archival study was not possible during this study. Further information pertaining to Mascota and the area around Juanacatlán should, however, be available in archives held in Guadalajara and in the Archivo General de la Nación in Mexico City and will be invaluable for future research projects.

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[2] Archivo del Ayuntamiento, Oficina del Registro Civil, Mascota, Jalisco. Seccion: Presidencia; Asunto: Datos sobre mineria; Fecha: 1900.

[3] Boletin de la Industrias minerales Tomo II, no 4, April 1927, Secretaria de Industria, comercio y trabajo.

7.5: The Palaeolimnological Record.

In February 1998, three sediment cores were extracted from Laguna de Juanacatlán: JL/98, JD/98 and JR/98. Core locations are illustrated in Figure 7.6. All cores were analysed for diatoms and magnetic susceptibility. Metal concentrations were analysed in core JL/98 to determine whether any impact of mining activity was evident in the lake sediments. The chronological framework for the cores has been based on AMS ^{14}C dating and ^{210}Pb dating was carried out on core JL/98.

As expected from previous palaeoenvironmental research at the lake (Byrne and Metcalfe, unpubl. data) cores JL/98 and JD/98 had sections of finely laminated sediments. It was beyond the scope of this study to produce a high-resolution palaeoenvironmental record based on the analysis of individual laminae. More detailed work has, however, been carried out on small sections of laminated sediment from these cores in order to better understand the nature of their composition, which may help determine the mechanism for their formation.

The palaeoenvironmental record for each individual core is described below, followed by a discussion of the nature of the laminated sediments. The palaeoenvironmental evidence is then drawn together to provide a record of environmental change over the last ca. 500 years for Laguna de Juanacatlán.

7.6: Core JL/98

7.6.1: Stratigraphy

Core JL/98 was obtained in 11.3 m of water. A 2.5 m tube attached to the Kullenberg corer was used and a total of 190 cm of sediment was recovered. Below ca. 80 cm depth, the stratigraphy of the sediment was disturbed, the outer part of the core containing dark, organic lake sediment and the inner part consisting of pink, clay-rich material. This problem was also experienced at Laguna Zirahuén (see Section 6.7.1). As a consequence, a reliable record is only available for the uppermost 80 cm of core JL/98, the stratigraphy of which is described below and illustrated in Figure 7.10.

From 80 to 69.5 cm depth showed no sign of laminations. The sediment appeared to have a high organic content and was dark greyish-brown in colour (2.5Y 3/2). Between 69.5 and 58.5 cm depth, the sediments were finely laminated, alternating between dark layers of organic-rich material (10YR 2/1) and paler clay layers (7.5YR 3/2). The sediment between 58.5 and 54.7 cm depth showed some degree of lamination, but contained macrofossil remains and was dark olive in colour. From 37 to 54.7 cm, the sediments were also laminated, but included the three different types of layer identified: dark organic, olive green organic and pale pink. Distinct pale layers were found at 40.7, 42.5 and 50.2 cm depth, whilst prominent olive green layers occurred at 39-39.5 and 48-48.3 cm. Between 37 and 38 cm depth, a layer of pink oxidised clay was encountered (5YR 4/3) which had sharp stratigraphic boundaries with the sediment to either side. Sediments between 36 cm and 13.1 cm were moderately laminated. Clear pale layers could be identified at 18.1, 18.7 and 20.9 cm depth. Sediments were not laminated between 13.1 and 10.3 cm depth, but above this, a section of well-laminated sediments, alternating between dark and pale layers, continued up to 5.3 cm depth. From 5.3 cm depth to the surface, the sediments were not laminated.

No tephra layers were identified from Core JL/98, although it was anticipated that tephra from the Volcán de Colima might be present. It is possible that thin layers were present in the core, but identification using x-radiographs proved to be impossible due to the presence of large numbers of pink, minerogenic clay layers.

7.6.2: Chronology

Laminations in Core JL/98 were not continuous and it could not be established that the light and dark couplets represented annual cycles, particularly given the change in the nature of the laminae at the base of the core, where olive green layers were also present. It was therefore decided not to use laminae counts to provide a chronology.

^{210}Pb Dating

^{210}Pb measurements were carried out on the top 15 cm of JL/98. The profile of unsupported ^{210}Pb obtained is illustrated in Figure 7.11, whilst the detailed radionuclide data are provided in Appendix 8. Below 6 cm depth, there is no discernible ^{210}Pb activity. In the uppermost 6 cm, activity is very low and for 3 out of the 6 samples overlaps zero at the 2 sigma level of error. The samples from the top 5 cm have significantly larger errors than those from 5 to 15 cm, which is due to the very small sample size of the uppermost sediments. As samples were very small, spectra were recorded over at least a week. ^{210}Pb ages were calculated for the top 6 cm using both the CRS and CIC methods and are illustrated in Table 7.2. These dates should be regarded with caution, however, due to the low levels of unsupported ^{210}Pb activity. In addition to the very low activity of unsupported ^{210}Pb in this core, ^{137}Cs was also difficult to detect. The ^{137}Cs activity could not be detected in any individual 1 cm slices of core, however, when the top three centimetres of sediment were combined, ^{137}Cs was found to be present, but at a level too low to quantify. It was therefore impossible to use ^{137}Cs as a means of validating the ^{210}Pb chronology.

There are a number of possible explanations for the low activity of ^{210}Pb and ^{137}Cs in the sediments from JL/98. Firstly, the uppermost sediments may have been lost when coring the sediment. Although the sediment-water interface was not as distinct as that sampled at Laguna Zirahuén, care was taken to ensure that sediments settled out before the core was placed horizontally. The core did suffer some shrinkage during storage, but to the author's knowledge, no material was lost during transportation or subsequent sub-sampling. The second explanation is that the radionuclides were deposited in the sediments and were then subsequently removed by an erosive event or through some form of geochemical process. There is no evidence to suggest that an erosive event may have removed the surface sediments. It is possible, however, that geochemical removal may have occurred. Under reducing conditions in organic rich sediments, ^{210}Pb and ^{137}Cs may become mobile. Post-depositional mobility of ^{210}Pb has indeed been observed in lakes that experience deep water anoxia (Benoit and Hemond, 1987) and in ombrotrophic peat bogs, where it was removed from anaerobic peat (Damman, 1978). Damman suggested that lead occurs as lead sulphide (PbS) in anaerobic peats, but during dry conditions is oxidised to $PbSO_4$, which is sparingly soluble and can therefore be lost into the water. A similar scenario might be expected from lake sediments that fluctuate between aerobic and anaerobic conditions at the sediment-water interface. The limnological data in Section 7.2.4 indicates that Laguna de Juanacatlán is anoxic at depth for at least part of the year. Low inventories of ^{137}Cs in organic sediments have also been reported from lakes with organic rich sediments (Torgerson and Longmore, 1983; Bryant *et al.*, 1993). The radionuclide is not bound within organic sediment as effectively as in minerogenic sediments and consequently diffuses back into the water column (Bryant *et al.*, 1993). This site-specific explanation for low radionuclide inventories is potentially important and warrants further investigation. The final possible explanation is that deposition of ^{210}Pb is very low at Laguna de Juanacatlán. The depositional flux of unsupported ^{210}Pb to Laguna de Juanacatlán appears to be unusually low at 12 Bq m^{-2} yr^{-1}. This value is considerably lower than the global average 185 Bq m^{-1} yr^{-1} (~0.5 pCi cm^{-2} yr^{-1}) (Appleby and Oldfield, 1983), although a low depositional flux of 33 Bq m^{-2} yr^{-1} (0.09 pCi cm^{-2} yr^{-1}) was also reported at Lake Miragoane on Haiti in the Caribbean (Brenner and Binford, 1988). If depositional fluxes are really this low, this implies that ^{210}Pb fallout is much more variable in different regions than has been previously anticipated. Further work in Central America is necessary to establish independent estimates of fluxes of ^{210}Pb. This could be done through either direct measurement of annual deposition or through the use of an environmental medium other than lake sediments, such as peat bogs. Such work will help to determine whether site-specific factors or more regional influences are the dominant cause of low ^{210}Pb activity.

^{14}C Dating

Two AMS ^{14}C dates were obtained for core JL/98, the details of which are provided in Table 7.3. Material immediately below the onset of laminated sediments (69-70 cm) was analysed, yielding an age of 485 ± 50 ^{14}C yrs BP. The calibrated calendar age range, calculated using CALIB 4.1 (Stuiver and Reimer, 1993), was AD 1330-1480 (2 sigma). The sediment immediately above the oxidised clay layer (36-37 cm) was also dated. This provided an age of 365 ± 45 ^{14}C yrs BP. This age intercepted the calibration curve at 1488 and 1605, giving a range of AD 1439-1644 at the 2 sigma level. The calibrated age ranges for the two dates obtained from these cores overlap at the 2 sigma level and it is impossible to establish the time interval between the two. The only conclusion that can be drawn from these calibrated ages is that the core covers approximately the last 500-600 years.

The stratigraphy of the core indicates that sedimentation rates have been variable, with clay layers possibly representing single events. It is therefore inappropriate to calculate an estimate of the sedimentation rate of this core, particularly given that there are also question marks over the ^{210}Pb chronology.

7.6.3: The Diatom Record

The diatom record for Core JL/98 is presented in Figure 7.12. The diatom assemblages throughout the core are dominated by *Cyclotella stelligera*, except for the surface sample. Using the CONISS zonation programme, however, changes in the relative abundance of the other species present led to the identification of three separate zones. Zones 1 and 2 were each separated into two sub-zones on the basis of more subtle changes in species composition.

In addition to diatoms, *Mallomonas* scales were encountered in the sediments. The concentrations of these through the core are also reported in this section (Figure 7.13). The genus *Mallomonas* represents a group of silicic, unicellular algal species. The species present in core material from Laguna de Juanacatlán has been identified as *M. pseudocoronata* (Metcalfe pers. comm.). The ecology of this species is poorly understood, but based on limited information, it appears to be alkaliphilous and is common in meso-eutrophic waters (Siver, 1991).

Diatom Zone JL-1, from 80 to 46 cm depth, is divided into Zone 1a (80-66 cm) and Zone 1b (66-46 cm). In Zone 1a, the freshwater planktonic diatom *Cyclotella stelligera* and the smaller taxa classified as "stelligeroid group" (see taxonomic discussion in section 4.7) together make up approximately 80% of the count. This sub-zone is differentiated from Zone 1b by the presence of *Aulacoseira granulata* var. *angustissima* at ca. 10 % of the count. A number of species from the genus *Synedra* are also present: *Synedra nana* increases in abundance towards the top of the sub-zone; *Synedra acus, Synedra delicatissima* and *Synedra ulna* are present in small numbers, whilst *Synedra tenera* occurs at a maximum relative abundance of 15 %. *Fragilaria brevistriata*, which does not occur elsewhere in the core, and *Cymbella microcephala* are also found at levels of up to 5 % in sub-zone 1a. In this sub-zone, diatom abundances are at their highest in the core at ca. 3 x 10^{10} valves g^{-1}, whilst the number of *Mallomonas* scales is low compared with the rest of the core (Figure 7.13). The flora is dominated by planktonic taxa, but there are also small amounts of epiphytic, periphytic and facultative planktonic species.

In sub-zone 1b, *Cyclotella stelligera* (+ stelligeroid group) still represent approximately 80 % of the diatom assemblage. *Synedra acus,* however, becomes more abundant, occurring at up to 15 % of the count, whilst *Aulacoseira granulata* var. *angustissima* almost completely disappears from the record. *Synedra delicatissima* also increases in numbers to 5 % of the count. *Synedra ulna* is present at the top of the sub-zone. The proportion of planktonic taxa increases in this zone and the number of benthic and facultative planktonic species falls. Diatom concentrations are lower than sub-zone 1b, between 1.5 and 2.5 x 10^{10} valves g^{-1}, whilst the abundance of *Mallomonas* scales increases to between 6 and 7 x 10^{9} g^{-1}.

In sub-zone JL-2a, between 46 and 14 cm depth, *Cyclotella stelligera* (+ stelligeroid group) continue to dominate the diatom assemblage. *Aulacoseira granulata* var. *angustissima* reappears in the diatom record, occurring at a maximum relative abundance of 40 % in this sub-zone. *Fragilaria construens* and the epiphytic *Cocconeis placentula* also appear for the first time in the record. *Synedra delicatissima and Synedra ulna* continue to occur at levels of 2-5 %, whilst *Synedra acus* is rare, apart from in the sample from 40 cm depth, where it makes up approximately 15 % of the count. Although planktonic taxa dominate the habitat groupings, facultative planktonic, epiphytic and periphytic species recover in number during sub-zone 2a. Within this sub-zone, both diatoms and *Mallomonas* scales experience a sharp decline in abundance between 37 and 38 cm depth and diatoms were too sparse to obtain a count. This is associated with the oxidised clay layer described in section 7.6.1. Although numbers recover above the clay layer, diatom abundance is at its lowest throughout the core at ca. 1 x 10^{10} valves g^{-1}. *Mallomonas* scales also increase in number to between 4 and 6 x 10^{9} g^{-1}.

Aulacoseira granulata var. *angustissima* declines in number in sub-zone 2b, between 14 and 3 cm depth. *Synedra tenera*, however, recovers in number, occurring at a maximum of approximately 12 % of the total. *Synedra nana* also reappears in the record at the top of this sub-zone, with a relative abundance of approximately 7 %. *Fragilaria construens* and *Cocconeis placentula* decline in abundance to less than 1 % of the count. Facultative planktonic and epiphytic taxa decline slightly, whilst periphytic species experience a slight increase in abundance. Between these depths, diatom concentrations begin to increase, from ca. 0.5 x 10^{10} valves g^{-1} to 1 x 10^{10} valves g^{-1}. The abundance of *Mallomonas* scales remains stable (Figure 7.13).

The most striking feature of the diatom record from core JL/98 is the very recent, dramatic change in species composition. In the surface sample from the core, *Cyclotella stelligera* (+ stelligeroid group) has almost completely disappeared and are replaced by the planktonic *Fragilaria crotonensis*, which totally dominates the assemblage. There is no trace of any *Mallomonas* scales, whilst diatom abundance continues to increase to ca. 2 x 10^{10} valves g^{-1}.

7.6.4: Phosphorus Analysis

Analyses of total phosphorus (TP) were carried out using an ICP-MS. The profile of TP is shown in Figure 7.13. The highest levels of P were encountered between 72 and 60 cm depth, where it reached over 1200 mg $kg^{-1}$and a further peak of 1100 mg kg^{-1} was observed at 40 cm depth. Between 36 cm depth and the surface, P remained fairly stable at around 850 – 900 mg kg^{-1}.

7.6.5: Magnetic Susceptibility

The magnetic susceptibility record from core JL/98 is presented in Figure 7.13 Problems were encountered when trying to determine the frequency dependent susceptibility for this and the two other cores from Juanacatlán. As the magnetic susceptibility of the sediments was relatively low, the accuracy of the machine was not sufficient to provide a reliable reading for the high frequency susceptibility. In many cases, readings for high frequency susceptibility were greater than for low frequency susceptibility. As a consequence, frequency susceptibility results are not reported here.

In the lower part of the core, between 80 and 56 cm, magnetic susceptibility is low (less than 0.1 $\mu m^3\ kg^{-1}$). It then doubles to 0.2 $\mu m^3\ kg^{-1}$ between 52 and 48 cm, , before decreasing slightly at 44 cm depth. A dramatic increase in magnetic susceptibility to 0.47 $\mu m^3\ kg^{-1}$ occurs between 37 and 38 cm, corresponding to the layer of pink oxidised clay described in section 7.6.1. Above this layer, magnetic susceptibility falls again, but remains significantly higher than at the base of the core. A smaller peak in magnetic susceptibility is observed between 16 and 12 cm depth, reaching 0.35 $\mu m^3\ kg^{-1}$. It then declines steadily towards the surface.

Magnetic susceptibility values of ca. 0.2 $\mu m^3\ kg^{-1}$ in JL/98 above 56 cm are similar to the susceptibility of soil samples from around the western end of the lake, which is where the core was taken. Inputs of sediment from the catchment are therefore most likely to have led to the higher magnetic susceptibility values above 56 cm, indicating that soil erosion from the basin slopes increased. The peak in magnetic susceptibility at 37-38 cm depth likely represents a major catchment disturbance event. The highest susceptibility values in soil samples were recorded in samples 2 and 5, which indicates that erosion may have increased enough to strip away the C horizon. More detailed mineral magnetic data would be required to confirm this.

7.6.6: Metals analysis

Results from the analysis of concentrations of iron (Fe), lead (Pb), copper (Cu), manganese (Mn), silver (Ag) and zinc (Zn) in JL/98 are shown in Figure 7.14. Gold (Au) was also measured, but concentrations were below the detection limit for all samples.

Fe concentrations at the base of the core, between 80 and 68 cm, are approximately 4% of the total dry weight of the sample. Above this, Fe concentrations are lower, remaining at around 2.5% for the remainder of the core. Given that magnetic susceptibility values are lowest at the base of the core (see Section 7.6.4), the type of iron present between 80 and 68 cm must be of a type that does not contribute to magnetic susceptibility.

The Pb profile shows a striking similarity to the magnetic susceptibility curve. Concentrations are low up to 56 cm depth, then increase from between 5 and 7 mg kg^{-1} to 10 mg kg^{-1} by 52 cm depth. Above 52 cm depth, Pb concentrations in the sediment are consistently higher than at the base of the core and two distinct peaks are observed. The peak of 14 mg kg^{-1}, between 38 and 32 cm, is less pronounced and more diffuse than that in the magnetic susceptibility curve. The highest concentration of Pb (17 mg kg^{-1}) in the core is found between 16 and 12 cm depth, which also corresponds to a peak in magnetic susceptibility. Levels of Pb in the core decrease above this towards the surface.

Values of Cu show little change throughout the core, fluctuating between 24 and 28 mg kg^{-1}, although a slight decrease in concentration is observed at the very top of the core. The Mn profile, however, shows a general increase in concentrations above 48 cm depth. There is no increase in Mn in the surface layers of the core. This suggests that conditions at the sediment-water interface must be anaerobic, as in aerobic environments, subsurface peaks of Mn are associated with the oxidation of Mn as it moves up through the sediment column (Farmer, 1991).

The most striking profile of metal concentrations in the sediments from JL/98 is that of Ag. Below 38 cm, concentrations are below the detection limit of the ICP-MS. A dramatic peak of 12 mg kg^{-1} is observed between 38 and 37 cm depth, which corresponds to the oxidised clay layer. Above this, levels of Ag decline, but remain higher than in the lower part of the core. A further, smaller peak is can also be identified at 13-12 cm depth. Whilst the Zn profile is relatively uniform throughout the core, there is a peak in concentration at 38-37 cm and also a small increase in levels at 12 cm.

The peaks in Ag, Zn and Pb at 38-37 cm characterise a significant catchment disturbance event, which is also evident in the magnetic susceptibility record. The marked peak in Ag and its continued presence in the core sediments above this depth suggest it is most probable that this is associated with the onset of mining activity in the area (Section 7.4). A further peak in Pb, Zn and Ag at ca. 12 cm depth also indicates more recent human impact.

7.6.7: Discussion of the Palaeoenvironmental Record from Core JL/98

As discussed in section 7.6.2, obtaining a reliable chronology for core JL/98 has proved to be problematic and results are inconclusive. The date of 485 ± 50 ^{14}C yrs. BP (cal. AD: 1330-1480) from 69-70 cm depth was taken from a part of the core where magnetic susceptibility is very low, suggesting that contamination by old carbon from the catchment should not be a problem. It is probable, therefore, that the core spans at least the period since the Spanish Conquest.

The diatom species present in Zone 1 do not indicate a major difference in chemical composition from the present lake. In the Central Mexican Diatom Dataset, *Cyclotella stelligera*, which dominates the diatom assemblage, has an optimum E.C. of 166 μS cm^{-1} and an optimum pH of 8.03 (Davies *et al.*, in press). Unfortunately, *Synedra acus* and *Synedra tenera* have not been encountered in modern material in the Mexican dataset, but Gasse (1986) found the association of *Cyclotella stelligera* and *Synedra acus* in East African lakes to be indicative of calcium-magnesium carbonate-bicarbonate waters, with a low E.C. and a pH of 6.6-7.5. The abundance of *Synedra* species suggests that silica-phosphorus ratios were high, work by Kilham *et al.* (1986) revealed that *Synedra* species have low phosphorus and high silica requirements, being the most effective competitors in systems with a limited supply of phosphorus. There is a small difference in the diatom species present in the two sub-zones. In sub-zone 1a, *Aulcoseira granulata* var. *angustissima, Fragilaria brevistriata* and *Cymbella microcephala* are found, but disappear in sub-zone 1b.

These species are associated with shallower habitats in central Mexico. Diatom sub-zone 1b (66-46 cm), with increased amounts of *Synedra* species, indicates continued low levels of phosphorus availability in the lake. *Mallomonas* scales reach their greatest abundance in this zone, suggesting that conditions in the lake during this period were the most favourable for the growth of *Mallomonas pseudocoronata.* In zone 1, high silica: phosphorus ratios are inferred, but TP results indicate that phosphorus levels in the sediments were at their highest over the last ca. 500 years during this period. It may be that the diatom flora is responding to some other environmental variables, but more likely that the levels of TP recorded do not actually reflect the phosphorus that was biologically available to organisms.

The very low magnetic susceptibility and high diatom concentrations throughout Zone 1a indicate that the catchment was stable, with very little erosion from the surrounding slopes into the lake. (see Section 7.6.2). Levels of Fe are high in sub-zone 1a, but fall significantly in sub-zone 1b. Concentrations of other metals measured remain low throughout zone 1. In the upper part of sub-zone 1b, however, magnetic susceptibility begins to increase, coincident with a rise in levels of Pb, marking the onset of disturbance of the slopes around the lake.

The increase in abundance of *Aulacoseira granulata* var. *angustissima* and decline in *Synedra* species indicate increased phosphorus availability in the lake during sub-zone 2a. According to Kilham *et al.* (1986), *A. granulata* and its varieties have higher phosphorus requirements than species of the genus *Synedra.* This species is commonly associated with more turbid, eutrophic environments (Bradbury, 1975; Kilham *et al.*, 1986). In central Mexico, this species is also encountered in turbid, nutrient-rich environments, such as Lago de Cajititlán. The appearance of the epiphytic *Cocconeis placentula* and *Fragilaria construens*, which occurs in shallow water, suggest that the lake level may have been lower, increasing the habitat available to these diatom species. Magnetic susceptibility continues to rise through this zone, indicating that the catchment disturbance evident in the upper part of sub-zone 1b persisted.

Within zone 2, a 1cm thick layer of oxidised clay was found. The high magnetic susceptibility and very low microfossil abundance of this deposit suggest that it was related to a significant erosive event within the catchment. There are a number of possible causes, such as tectonic activity or a high magnitude flood event. The metals results, however, show that this layer contains significant quantities of Ag, Pb and Zn. Ag, below this layer, was undetectable in the sediment, whilst found in every sample above it. It is likely, therefore, that there is some connection with the onset of silver mining in the area (see Section 7.4). The calibrated age range immediately above the clay layer is AD 1439-1644 (Table 7.3). Unfortunately, the history of mining in the area is not sufficiently well known to help constrain the age of this disturbance event. Such information would also be of use in determining the overall core chronology.

In diatom zone 3, there is evidence of restabilisation of the catchment. *Aulacoseira granulata* var. *angustissima* is greatly reduced in number and *Synedra* species return to the diatom record. Furthermore, magnetic susceptibility declines and diatom abundance increases. There is, however, a peak in Ag, Pb and Zn and magnetic susceptibility at 12 cm depth that may be associated with a more recent disturbance event within the catchment.

In the uppermost part of the core, there is a dramatic change in the diatom species composition from a *Cyclotella stelligera* dominated assemblage to an almost mono-specific assemblage of *Fragilaria crotonensis.* Results from a sediment-water interface core obtained in 1990 (Byrne and Metcalfe, unpubl. data) recorded no trace of this species. *Fragilaria crotonensis* was blooming in Laguna de Juanacatlán in February 1998, with only few other diatom species present in small numbers. This change in the diatom flora therefore occurred some time after 1990. *Fragilaria crotonensis* is regarded as a "weed" in the Great Lakes of North America and is indicative of nutrient enrichment (Bradbury, 1975; Stoermer *et al.*, 1985; Sabater and Haworth, 1995; Yang *et al.*, 1996). *Mallomonas* scales are not present in the most recent sediments, suggesting that *M. pseudocoronata* is no longer able to compete effectively for resources, or that conditions in the lake have become unsuitable for its growth.

7.7: Core JD/98

7.7.1: Stratigraphy and Chronology

Core JD/98 was obtained using a 1 m length tube attached to the Kullenberg corer in approximately 22 m of water. The sediment-water interface was obtained but was not a clear boundary and the core was left to settle before lying flat. A total of 75 cm of sediment was recovered. The stratigraphy of core JD/98 is illustrated in Figure 7.10.

From 75 cm to 60.5 cm, the sediments were laminated and contained a number of olive green layers (5Y 3/2), like those described from core JL/98. A particularly distinct green layer was found between 64.8 and 65 cm depth. The sediments between 60.5 and 50 cm were not laminated, grading upwards from dark silty clay (7.5YR 2.5/2) to pink oxidised clay (5YR 4/2). The lower 2 cm of the section contained small plant macrofossils. Above 50 cm depth to the surface, sediments were laminated, alternating between pink clay layers and dark organic layers. Two thicker bands of dark sediment were identified at 16.5 and 17.5 cm, each 2-3 mm wide. Distinct oxidised clay layers occurred at 21.3, 29, 32.7 and 48.5 cm depth.

The AMS ^{14}C age obtained from the base of core JD/98 (74-75 cm) was 635 ± 40 ^{14}C yrs BP (Table 7.3). This ^{14}C age intercepted the calibration curve at AD 1303, 1368 and 1383 (range = cal. AD 1284-1406: 2 sigma). Material was also dated immediately above the unlaminated clay section at 49-50 cm depth, yielding an age of 395 ± 55 ^{14}C yrs BP (cal. AD 1420-1640: 2 sigma).

It is not possible to derive estimated sedimentation rates for this core as it is apparent from the stratigraphy that sediment accumulation has varied considerably. Given the uncertainty surrounding the core chronology, particularly regarding the ^{210}Pb profile from core JL/98, ^{210}Pb dating is also being carried out on core JD/98 at the Scottish Universities Environmental Research Centre by Dr. A. MacKenzie and Mrs A.

Stewart. This may help to clarify the rate of sedimentation in this core and to answer the questions raised by the weak ^{210}Pb profile from core JL/98. Analysis of the core is in the early stages and results are not expected for several months due to the long counting time required for the very small samples.

7.7.2: The Diatom Record

The diatom record from core JD/98 is presented in Figure 7.15. As with core JL/98, *Cyclotella stelligera* (+ stelligeroid group) dominate the diatom assemblage throughout the core. It was possible, however, to identify four separate diatom zones using the CONISS zonation programme within TILIA.

At the base of the core in Zone JD-1, between 75 and 70 cm depth, in addition to *Cyclotella stelligera* (+ stelligeroid group), *Synedra acus* and *Synedra ulna* are present at 5 % and 15 % relative abundance respectively. *Achnanthes minutissima* and *Cymbella microcephala* each make up between 2 and 5 % of the count, their highest abundance in the core. Also present in small numbers are *Fragilaria construens* and its variety *venter* and *Synedra delicatissima.* Although planktonic taxa dominate Zone JD-1, epiphytic species make up almost 20 % of the count. This is largely due to the presence of *Synedra ulna.* This species is widespread in fresh water (Patrick and Reimer, 1966) and occurs in either the epiphyton or the plankton (Gasse, 1986). In modern samples from Juanacatlán, it was found amongst floating vegetation and algae samples from the edge of the lake. It has therefore been classified as epiphytic. In this zone, *Mallomonas* scales are at their greatest abundance, of approximately 5 x 10^9 scales per gram of dry sediment. Diatom abundance is similar, between 4 and 6 x 10^9 valves g^{-1} (Figure 7.16).

In sub-zone 2a, between 70 cm and 51 cm depth, *Aulacoseira granulata var. angustissima* appears for the first time in the core, with a relative abundance of up to 15 %. *Synedra acus* also becomes more abundant at ca. 10-12 % of the total count. *Synedra ulna*, however, declines dramatically in number, whilst *Aulacoseira granulata, Fragilaria construens* and *Synedra tenera* become common towards the top of the sub-zone. The proportion of planktonic taxa increases, whilst the percentage of epiphytic species decline. Diatom abundance decreases significantly, especially between 52 and 60 cm depth, where it drops to 0.24×10^9 valves g^{-1}. A similar pattern is observed in the abundance of *Mallomonas* scales, which are reduced to 9.45×10^6 g^{-1} between these depths. This section of core corresponds to the thick deposit of oxidised clay.

In sub-zone 2b, from 51 to 26 cm depth, there is a change in the relative abundance of the species present, rather than the appearance of other taxa. At the boundary between sub-zones 2a and 2b, there is a single peak in *Synedra ulna*, which occurs at ca. 20 % relative abundance. This coincides with the uppermost section of the oxidised clay layer. Above this, the rest of the sub-zone is characterised by the increased abundance of *Aulacoseira granulata* var. *angustissima*, which rises to 25 % of the total count. *Fragilaria construens* also becomes more common, but disappears towards the top of the sub-zone. *Aulacoseira granulata*, on the other hand, is more abundant in the upper part of the sub-zone at levels of 2-5%. In sub-zone 2b, facultative planktonic taxa increase, represented mainly by *Fragilaria construens*. The peak of epiphytic species at 50-51 cm is due to the occurrence of *Synedra ulna*. The abundance of *Mallomonas* scales and diatoms is higher than in the previous sub-zone, but still considerably lower than in Zone 1.

Zone 3, between 26 and 3 cm depth, sees the return of *Synedra tenera* to the diatom record at a maximum relative abundance of ca. 15 %. *Synedra acus* and *Synedra nana* also reappear in this zone, but only in the upper part and *Synedra delicatissima* is present throughout the zone in small numbers. *Cocconeis placentula* becomes more abundant, with a maximum relative abundance of ca. 5 %, although this species disappears at the top of the zone. *Aulacoseira granulata* var. *angustissima* continues to be abundant up to 12 cm depth, then disappears from the record. The relative abundance of epiphytic species declines in this zone, following the profile of *Cocconeis placentula*. Diatom concentrations increase dramatically through this zone, rising from 2.53×10^9 valves g^{-1} at 24 cm depth to 13.8×10^9 valves g^{-1} at 4 cm depth. The abundance of *Mallomonas* scales is higher throughout the zone, peaking at 4.1×10^9 g^{-1} at 12 cm depth. Both diatoms and *Mallomonas* scales, however, experience a significant decrease in abundance at 16 and 8 cm depth. At 16 cm depth, there is a peak in magnetic susceptibility, which indicates that increased inputs of allochthonous material may have diluted the concentration of microfossils being deposited in the lake sediment at this time.

In the surface sample, represented by Zone JD-4, *Fragilaria crotonensis* replaces *Cyclotella stelligera* as the dominant species present. Unlike the top sample from JL/98, the latter is still present at ca. 25 % of the total count. *Aulacoseira granulata var. angustissima* also makes up 10 % of the count. It is therefore possible that this sample has a lower temporal resolution than the surface sample from JL/98. In any case, the dramatic shift in species composition points towards a significant change in the lake system, which is probably the result of nutrient enrichment.

7.7.3: Magnetic Susceptibility

The magnetic susceptibility profile for core JD/98 is shown in Figure 7.16. At the base of the core, between 75 and 60 cm, magnetic susceptibility is around 0.2 μm^3 kg^{-1}, although there is a noticeable decrease at 68-69 cm to less than 1 μm^3 kg^{-1}. Above this, there is a dramatic rise in susceptibility between 60 and 50 cm depth, which corresponds to the unlaminated section of oxidised clay described in Section 7.7.1 and indicates a phase of increased erosion from the catchment. Input of allochthonous material decreases rapidly by 48 cm depth, but then displays two further peaks at 29-28 cm depth and 17-16 cm depth (0.32 and 0.38 μm^3 kg^{-1} respectively). As in core JL/98, magnetic susceptibility decreases at the top of the core, falling to 0.03 μm^3 kg^{-1} in the surface sample.

7.7.4: Summary of the Record from Core JD/98

The palaeoenvironmental record from core JD/98 reflects the same general pattern of change as observed in core JL/98. The available radiocarbon chronology indicates that this core spans at least the period since the Spanish Conquest in AD 1521.

The diatom record of zones 1 to 3 from JD/98 appears to reflect changing silica-phosphorus ratios as discussed in relation to core JL/98. The dominance of *Cyclotella* *stelligera* (+ stelligeroid group) throughout these zones supports the idea that the ionic composition of the lake did not change significantly, so changes in the species composition are more likely related to nutrient availability. The larger proportion of epiphytic species, such as *Achnanthes minutissima* and *Cymbella microcephala,* in zone 1 suggests that there may have been a greater amount of aquatic vegetation within the lake margins. Increased phosphorus availability is inferred in sub-zone 2b due to the replacement of *Synedra* species by *Aulacoseira granulata* and its variety *angustissima.* The abundance of *Aulacoseira granulata* var. *angustissima* in zone 2 (particularly in sub-zone 2a) suggests that the turbidity of the water may have been greater at this time, possibly due to catchment disturbance. In zone 3, a return to low phosphorus levels is likely, due to the increased abundance of *Synedra* species and the decline in *Aulacoseira granulata* var. *angustissima.*

In the lower part of the core, magnetic susceptibility is low and the abundance of microfossils in the sediments is high, indicating that the catchment was stable at this time. A thick deposit of oxidised clay between 60.5 and 50 cm, which is likely correlative with a similar layer found in core JL/98, indicates a major erosive event within the catchment. The radiocarbon age obtained immediately above this section was 395 ± 55 ^{14}C yrs. BP (cal. AD: 1420-1640). During this period, magnetic susceptibility increases substantially and the concentration of microfossils declines dramatically. This layer is much thicker than in JL/98, where it is only 1 cm thick. It may be that this deepest part of the lake is an area of sediment focusing. Alternatively, slumping of material may account for greater thickness of this deposit. The potential causes of this clay layer are explored further in Section 7.10.4.

Towards the top of the core, the reappearance of *Synedra* spp. indicates a reversion to high silica: phosphorus ratios within the lake. A further peak in magnetic susceptibility and associated decrease in microfossil abundance at 16 cm depth signifies a more recent catchment disturbance event. Two distinctive dark bands were identified in the core stratigraphy around this depth.

The most distinctive feature of the palaeoenvironmental record from JD/98 is the recent rapid change in the diatom flora. *Cyclotella stelligera*, which has been the dominant component of the diatom flora in the lake over at least the last ca. 500 years, has been almost completely replaced by *Fragilaria crotonensis*. This dramatic change is also evident in core JL/98, and is probably the result of increased nutrient availability in the lake.

7.8: Core JR/98

7.8.1: Stratigraphy and Chronology

Core JR/98 was retrieved close to where the Arroyo de Laguna de Juanacatlán flows into the lake. A total of 74 cm of sediment was recovered. The core stratigraphy is illustrated in Figure 7.10.

Unlike the two previous cores, the sediment was not laminated from this site. Between 74 and 13 cm depth, the core consisted of dark, organic gyttja (10YR 2/2) composed of silt and clay. Remains of reed roots and other macrophytes were encountered throughout this section of the core. A dark band of particularly organic rich sediment occurred between 13 and 8 cm depth, which had a Munsell colour of 7.5YR 2.5/1. From 8 cm to the surface, the sediment was redder in colour (7.5YR 3/2) and contained some plant remains. This uppermost section of the core was coarser, with a high proportion of sand sized grains.

An AMS ^{14}C date from the base of the core yielded an age of 250 ± 40 ^{14}C yrs BP (Table 7.3). At the 2 sigma level, the calibrated age range of this sample is cal. AD 1522-1946. This means that there is a possibility that the core only covers a very short length of time (ca. 50 years). This is entirely feasible, as sedimentation rates would be expected to be faster close to the river input. A core of similar length from close to the river input at Lago de Zirahuén (Section 6.9) only covered the last ca. 60 years. The age of that core was constrained by a historical tephra, but in this case, ^{14}C dating was the only means of obtaining an age estimate for the core. Core JR/98 may represent anywhere between 450 and 50 years of sediment deposition.

7.8.2: The Diatom Record

The diatom record from core JR/98 is illustrated in Figure 7.17.

In Zone JR-1, from 72 to 30 cm depth, *Cyclotella stelligera* (+ stelligeroid group) dominate the diatom assemblage, with a combined relative abundance of ca. 80 %. Also common in this zone is *Aulacoseira granulata* var. *angustissima*, which increases from between 5 and 10 % abundance in the lower part of the core, to 15 % at the top of the zone. *Synedra tenera* is present in small numbers throughout this zone, except at 64 cm depth, where it reaches a peak in relative abundance of ca. 20 %. *Cocconeis placentula* makes up 5 – 10 % of the total count throughout Zone JR-1, whilst *Achnanthes minutissima*, *Synedra acus* and *Synedra ulna* all occur at levels of 1-2 % throughout. Planktonic taxa dominate this zone, although epiphytic species make up between 10 and 15 % of the total throughout and periphytic species account for approximately 5 % of the diatom assemblage. The pattern of abundance of diatoms and *Mallomonas* scales in Zone JR-1 is shown in Figure 7.18. At the base of the core, both have high abundances of 1.47 x 10^9 g^{-1} (diatoms) and 1.34 x 10^9 g^{-1} (*Mallomonas*). These microfossils, however, decline in number significantly by 68 cm depth. Above this, the abundance of diatoms increases gradually through the zone, peaking at 1.64 x 10^9 g^{-1} at 32 cm depth. The abundance of *Mallomonas* scales also increases, reaching 0.96 x 10^9 g^{-1} at 32 cm, but numbers fluctuate between 52 and 36 cm depth.

Zone JR-2, from 30 to 14 cm depth, sees the disappearance of *Aulacoseira granulata* var. *angustissima* from the diatom record, whilst *Synedra tenera* increases to a relative abundance of ca. 15 %. *Cyclotella stelligera* and those classified as "stelligeroid group" still make up approximately 80 % of the total count. *Cocconeis placentula, Synedra acus* and *Synedra ulna* continue to occur at the same levels as in zone 1, whilst *Achnanthes lanceolata* var. *dubia, Fragilaria pinnata* and its variety *lancettula* also appear in small numbers. In this zone, there is a small peak in the number of facultative planktonic taxa present and periphytic species also increase in number, reaching 10 % of the total count. The proportion of epiphytic taxa, however, declines towards the top of the zone. Diatom abundance remains fairly constant at ca.

1.6×10^9 g^{-1}, whilst the amount of *Mallomonas* scales present declines significantly to 0.36×10^9 g^{-1} at the top of the zone.

In Zone JR-3, the assemblage is totally dominated by *Fragilaria crotonensis*. *Cyclotella stelligera* (+ stelligeroid group) are no longer present in the diatom record, but *Aulacoseira granulata var. angustissima* is present in very low numbers. Small amounts of *Epithemia adnata* and *Cocconeis placentula* are present, which accounts for the slight rise in the proportion of epiphytic taxa. The fact that this zone covers the top 14 cm of the core indicates that the sedimentation rate at this site is considerably faster than in core JL/98 and JD/98. This core does not record the earlier zone of abundant *Synedra* species that was found in the two other cores, adding support to the notion of faster sedimentation at this site. As this core is close to the input of the Arroyo de Laguna de Juanacatlán, it is to be expected that sediment accumulation is higher here due to the input of sediment by the river. In general, the abundance of diatoms in this zone remains relatively high, apart from the sample from 4-5 cm depth, where diatoms were too sparse to count. *Mallomonas* scales were not present in this zone.

7.8.3: Magnetic Susceptibility

In general, magnetic susceptibility values in core JR/98 are higher than for the other two cores. This is to be expected as the core site is close to the inflow of the Arroyo Laguna de Juanacatlán, which will bring a large amount of sediment into the lake. Furthermore, soil samples taken from around this end of the lake had a higher magnetic susceptibility than those from the western end (Section 6.3: Table 6.1). The profile of magnetic susceptibility for core JR/98 is shown in Figure 7.18. Levels of susceptibility are higher in the lower part of the core, up to 32 cm depth, than in the upper sediments, fluctuating between 1.0 and 0.6 μm^3 kg^{-1}. Between 28 and 12 cm depth, the lowest values of magnetic susceptibility in the core are observed (0.45 μm^3 kg^{-1}), suggesting a decreased input of allochthonous material. Above 10 cm depth, susceptibility increases again, peaking at 0.8 μm^3 kg^{-1}. This may indicate a recent phase of catchment disturbance.

7.8.4: Summary of the Record from Core JR/98

It appears that the core from JR/98 covers a considerably shorter timescale than JL/98 and JD/98. *Aulacoseira granulata* var. *angustissima* is present throughout this core, whereas in the other two cores there is an assemblage of *Cyclotella stelligera* and *Synedra* spp. prior to the appearance of *Aulacoseira granulata* var. *angustissima* in the diatom record. The basal ^{14}C age on this core is 250 ± 40 ^{14}C yrs BP (cal. AD 1522-1946). *Fragilaria crotonensis* dominates the diatom assemblage from 12 cm to the surface, but it is thought that this species has only flourished within the last decade, as it was not encountered in a sediment-water interface core obtained in 1990 (Byrne and Metcalfe, unpubl. data). It seems likely, therefore, that the basal age of the core is closer to the younger end of the calibrated age range. In fact, the top 12 cm of the core post-date 1990, therefore representing a maximum of 8 years.

The palaeoenvironmental record from core JR/98 is, however, consistent with the evidence from the upper sections of other two cores. Increased phosphorus availability and turbidity of the water in the lower part of the core are indicated by the presence of *Aulacoseira granulata* var. *angustissima*. This is followed by a more recent period of high silica: phosphorus ratios, identified by an increase in *Synedra* spp. Some time after 1990, a dramatic change in diatom species composition occurred, as *Fragilaria crotonensis* completely replaced *Cyclotella stelligera* as the dominant component of the diatom flora. AS discussed in relation to core JL/98 and JD/98, this shift in the diatom flora is most likely the result of nutrient enrichment in the lake.

A recent increase in erosion from the catchment is observed in core JR/98, indicated by a peak in magnetic susceptibility and very poor diatom preservation at 4 cm depth. This peak is not recorded in the other cores, which may be a consequence of the sampling interval, or alternatively, this event may have been associated with increased input from the river and more localised in its effect.

The following section examines in more detail the nature of the laminated sediments that were encountered in core material from Laguna de Juanacatlán.

7.9: Analysis of Laminated Sediments

The nature of the laminated sediments in cores JL/98 and JD/98 was explored using three different techniques. Firstly, digital sediment colour analysis (DSCA) was applied to the cores. Secondly, thin sections of laminated sediment were prepared and examined using back-scattered electron microscopy. Thirdly, the diatom assemblages within individual laminae were examined for short sections of sediment in order to identify any differences in composition between different types of laminae. The results from these techniques are discussed below.

7.9.1: Digital Sediment Colour Analysis

It was hoped to produce a high-resolution time series of grey scale values for cores JL/98 and JD/98 using DSCA. Each of the four images obtained for each core were analysed using ERDAS IMAGINE software. A one-pixel wide line was drawn vertically through each image and the grey scale values obtained. The quality of the images was poorer than hoped for due to reflectance from water in the sediment cores. Although efforts were made to reduce this, results were still not ideal. Furthermore, the existence of tiny cracks in the cores meant that the grey scale values might not be truly representative of the colour of the sediment. Care was taken when drawing the line through the image to avoid cracks in the sediment, although this was not always possible. A correction factor also had to be applied to each image to account for the fact that there was less light at the edge of the field of view of the camera than at the centre. A seventh order polynomial curve was applied to the grey scale values of each image and values obtained from the curve were subtracted from the measured grey scale values. This produced a straight profile rather as opposed to the parabolic curve in the original profile. When an attempt was made to match the individual images to produce a profile of grey scale values for the core, it was discovered that the grey scale values for the overlapping sections did not match. Given the poor quality of the images, the problems of cracking and the problems in overlapping the different images, it was decided to abandon this analysis. It was felt that any palaeoenvironmental interpretations based on the grey scale data might not actually be a true reflection of changes in the laminae themselves.

One alternative method of obtaining a high-resolution time series would be to analyse the grey scale values on digitised images of the x-radiographs. Attempts were made to digitise the x-radiographs themselves, but the images produced were too dark. Again, the quality of the time series produced is highly dependent on the quality of the image from which the grey scale values are obtained.

7.9.2: Back Scattered Electron Microscopy

Four thin sections were prepared: two from JL/98 (16-21 cm and 39-44 cm) and two from JD/98 (11-16 cm and 41-46 cm). Difficulty was encountered in the preparation of slides, as the resin did not fully impregnate all of the thin sections. The particularly high organic content of some layers in sections JL/98 39-44 and JD/98 41-46 also led to problems with resin impregnation. In some cases, cracking occurred between the different laminae as samples had been dried to remove the acetone. As a consequence, a detailed examination of the microstructures within the laminae was not possible. The quality of the thin sections was, however, sufficient to allow an examination of the major differences between the laminae types.

Figure 7.19 illustrates the differences between the laminae. Organic-rich layers appear darker under the microscope as these are more porous, whilst the minerogenic clay rich layers appear lighter. A more detailed view of the individual laminae is shown in Figure 7.20. The organic layers are rich in diatoms with a very low mineral content, whilst the light layers are composed primarily of mineral matter. Some diatoms can be seen, but they are lower in number and less diverse. A further interesting feature of the organic layers was the presence of numerous spheroidal particles, illustrated in Figure 7.21. The chemical composition of these was analysed using the Link ISIS electron dispersive spectrometry system, which was attached to the SEM. These particles are composed of Fe (iron) and S (sulphur), indicating that they are iron sulphide spherules, which suggests that reducing conditions prevailed at the sediment-water interface during the deposition of organic layers. These organic layers therefore must be deposited when the lake experiences thermal and chemical stratification (see Section 7.2.4).

7.9.3: Diatom Composition

A more detailed examination of the diatom assemblages in individual laminae was carried out on two sections of JL/98 and JD/98. For each core, the upper section focused on the alternating pale and dark bands described in the stratigraphy, whilst the lower section also included analysis of the olive green layers. The characteristic species composition each different type of layer could therefore be established. The results of these analyses are illustrated in Figure 7.22 (JL/98) and 7.23 (JD/98).

Although diatom abundances could not be calculated, as the very small samples obtained were not weighed, it did appear that there were considerably fewer diatoms in the pink clay layers. The most interesting feature to note from the four different sections analysed is that the relative abundance of *Cyclotella stelligera* fluctuates significantly, from 25 % (JD/98 63-63.9 cm) to over 80 % (JL/98 9-9.5 cm). In core samples, which were 1 cm slices, the proportion of this species was at least 60 %. The second feature of interest is that *Aulacoseira granulata* var. *angustissima* only occurs in large numbers in the pink clay layers. This suggests that the water was more turbid and well-mixed during the deposition of these layers. The number of laminae examined is, however, small and it is possible that this species may also be encountered in the organic layers. *Synedra* species appeared to be associated with the organic-rich layers. *Synedra acus* was found at ca. 30 % relative abundance in an organic layer from JL/98 (9-9.5 cm) and at ca. 55 % in an olive green layer from JD/98 (63-63.9 cm), whilst *Synedra delicatissima* occurred at ca. 25 % in an organic layer from JD/98 (20.5-21 cm depth). A more detailed examination may establish whether or not this pattern is consistent throughout the core.

7.9.4: Discussion of the Laminated Sediments

The different methods used to examine the laminated sediments have yielded some interesting results. The dark, organic layers appear to be associated with reducing conditions. Diatom concentrations are higher, suggesting increased productivity in the lake. It is likely, therefore, that these layers are deposited when the lake is thermally and chemically stratified. At present, there is insufficient information to determine how long during the year the lake remains stratified. The pink layers are largely minerogenic, although they do contain diatoms. These are likely to be the result of increased inwash of material from the catchment during the wet season. Given the dense vegetation cover of the slopes that was observed at the end of the rainy season in September 1998, it is possible that these clay layers are deposited within a relatively short space of time at the onset of the rainy season, before seasonal vegetation has been able to establish itself. A more detailed survey, involving the use of sediment traps and regular limnological monitoring is required in order to establish a more complete picture of the mechanism for the formation of these laminations.

Diatom analysis of the individual laminae revealed significant differences in species composition. This has important implications for the palaeoenvironmental record. Resolution is lost by analysing 1 cm sections of sediments and there is clearly the potential for a sub-annual resolution record from this lake. Although image analysis of the cores proved to be unsuccessful in this study, future work on the x-radiographs may help to provide a high-resolution grey scale time series. Alternative coring methods would be preferable for any detailed investigation of the laminated sediments, however. Whilst the micro-Kullenberg corer preserved the stratigraphy of the core well, ideally a large box corer would be used. This would provide a greater amount of material for analysis of these very thin layers. Furthermore, flat surfaces could be easily obtained which would help to produce better x-radiographs and digital images. The sediments from this lake clearly have a great potential for high-resolution climate reconstruction. At present, however, there is no basis for interpreting changes in the nature of the laminae as there is insufficient information concerning the mechanisms for their formation. A high-resolution palaeoenvironmental record from this site will therefore only be of value if a detailed limnological monitoring programme is established. If this can be done, the resolution of the record from this site should be comparable to the evidence from tree ring records from western Mexico (e.g. Cleaveland *et al.*, 1992; Stahle and Cleaveland, 1993).

7.10: Synthesis of the Individual Records

This section draws together the palaeoenvironmental evidence from the individual cores described earlier in this chapter and also compares the results with those obtained previously by Byrne and Metcalfe (unpubl. data). The correlation of the individual cores is discussed, the principal aim being to provide an overall chronology for the sequence of environmental change within the basin, although this has proved to be problematic. As with the palaeoenvironmental data from the Zirahuén Basin, the diatom record from Laguna de Juanacatlán is analysed using multivariate statistics. Both the Central Mexican and African diatom datasets are applied to the data from core JL/98 to provide numerical reconstructions of both E.C. and pH. The palaeoenvironmental record from this core is explored further using canonical correspondence analysis in order to examine the relationship between the diatom assemblages and the magnetic susceptibility and metal content of the sediments. The results from this study are then used to provide a reconstruction of environmental change in Laguna de Juanacatlán over the last ca. 500 years.

7.10.1: Core Correlation and Chronology

Correlation of the individual cores obtained during this study is problematic based on stratigraphy alone as JD/98 is laminated throughout most of the core, whilst JL/98 is not consistently laminated and JR/98 is not laminated at all. The clearest link between cores JL/98 and JD/98 is the oxidised clay layer (Figure 7.24). This layer is much thicker in JD/98 (10.5 cm) than in JL/98 (1cm) which indicates that the former is a focus for sediment deposition and has a faster sedimentation rate. This is also indicated by a comparison of the magnetic susceptibility curves for the two cores. In JL/98, a period of very low magnetic susceptibility is recorded at the base of the core (Figure 7.13) which is not evident in the profile from JD/98 (Figure 7.16). The peak in susceptibility at 16 cm in JD/98 may, however, correlate with that recorded between 12 and 16 cm in JL/98, which indicates that sedimentation rates may be similar in more recent times.

The clay layer does not occur in core JR/98, which means that this core covers a shorter time period than JL/98 and JD/98. This is also indicated by the younger basal

^{14}C date for core JR/98 (see Table 7.3). The diatom assemblage in core JR/98, however, suggests that the sedimentation rate here may be significantly faster than that suggested by the basal ^{14}C date. *Fragilaria crotonensis,* which has only appeared in the lake since 1990 dominates the top 12 cm of sediment in this core. It is possible, then, that this core only represents the most recent 45 to 50 years. Furthermore, as this core is located close to the input of the Arroyo de Laguna de Juanacatlán, it may be that deposition of sediment here has not been continuous and erosion of some material may also have occurred.

Obtaining a reliable chronology for Laguna de Juanacatlán has proved to be difficult, despite the potential high resolution of the sedimentary record. The radiocarbon chronology obtained suggests that cores JL/98 and JD/98 represent at least the Post-Hispanic period. Although the basal age of JD/98 is older than that for JL/98, the magnetic susceptibility and diatom evidence indicates that this core covers a shorter period of time than JL/98. It is therefore possible that the basal date from JD/98 has been contaminated with old carbon from the catchment. The ^{14}C dates for the oxidised clay layer are, however similar, at 395 ± 55 (JD/98) and 365 ± 45 14C yrs, with the calibrated AD ages covering a range of AD 1420-1640 (JD/98) and AD 1439-1644 (JL/98). The problems with the ^{210}Pb chronology for core JL/98 have been discussed in detail in section 7.6.2 and it has not been possible to use this technique as a means of verifying the radiocarbon ages obtained. Byrne (unpubl. data) established a chronology for his core using a combination of laminae counting and ^{210}Pb, although it is not known exactly how this was achieved. His estimate for the age of the clay layer is ca. AD 1820. It is hoped that the results of ^{210}Pb analyses on core JD/98 will help to determine the age of the clay layer. Analysis of metals in core JL/98 indicates that the deposition of the clay layer was related to the onset of mining activity in the area. The history of mining in the area around Laguna de Juanacatlán is not known in sufficient detail to help to constrain the likely age of this catchment disturbance event. More detailed archival work may help to unravel this problem. In addition, it may be possible to obtain a high-resolution chronology for the core if it can be established that the sediments are annually laminated. Even then, this information may be of limited use as it appears that laminated sediments are not always deposited. In a 9 m core obtained by R. Byrne in 1990 (unpubl. data) there were large sections of unlaminated sediment.

Given the large degree of uncertainty surrounding the chronology of the cores from Laguna de Juanacatlán, it would be unwise to propose a detailed age-depth estimate for the palaeoenvironmental record. At present, all that can be established is that the results from this study represent the Post-Hispanic period. The nature of the palaeoenvironmental record is now discussed in more detail.

7.10.2: Numerical Palaeoenvironmental Reconstructions

The diatom record from JL/98 was chosen for the application of transfer functions as this appeared to have the longest sequence of environmental change of the three cores. As with the data from the Zirahuén Basin, the weighted averaging model within the programme CALIBRATE was used to produce the diatom-inferred reconstructions based on the Mexican and African datasets. The transfer functions were applied to a dataset which included 26 species (all those > 1 % relative abundance). The results are illustrated in Figure 7.25

Considering first the results from the Mexican dataset, there was a good overlap between the modern and fossil datasets with 21 of the 26 taxa found in the core represented in the modern dataset. For all samples analysed, over 70 % of the total count was represented in the calibration dataset. Indeed, for nine of the samples, the degree of overlap was greater than 90 %. This is largely due to the fact that both *Cyclotella stelligera* and *Fragilaria crotonensis* are both included in the modern dataset and these species dominate in the core samples. Given that *Cyclotella stelligera* dominates throughout most of the core, very little change was observed in the diatom-inferred pH and E.C. Reconstructed pH between the bottom of the core and 4 cm depth was 8.05 and 8.3, whilst diatom-inferred E.C. ranged from 122 to 169 $\mu S\ cm^{-1}$. At the very top of the core, however, the inferred pH and E.C. decreased to 7.8 and 90 $\mu S\ cm^{-1}$ respectively. This is an underestimation of the present values at the lake, which has a pH of 8.78 and an E.C. of 148 $\mu S\ cm^{-1}$. In the Mexican calibration dataset, *Fragilaria crotonensis*, which is present at 92 % relative abundance in this sample, has a pH optimum of 7.84 and an E.C. optimum of 115 μS cm^{-1}. The pH reconstruction is considered to be less reliable given that this variable was found to explain considerably less of the variance in the modern diatom dataset than E.C. (see Section 5.8.5.).

There was also a good correspondence between the fossil taxa and those in the African calibration dataset. Twenty of the twenty-six species included in the analysis were also found in the African dataset, with all but one sample having an overlap between the datasets of more than 70 %. Diatom-inferred pH from the base of the core to 4 cm depth was lower than that estimated by the Mexican dataset, ranging from 7.6 to 7.8. Reconstructed E.C., on the other hand, was similar, fluctuating between 148 and 188 μS cm^{-1}. In the surface sample, reconstructed pH was considerably higher at 9.2 and E.C. was estimated at 219 μS cm^{-1}. In the African dataset, the pH optimum of *Fragilaria crotonensis* is 8.76, whilst its optimum E.C. is 344 μS cm^{-1}.

There are several points to note regarding these diatom-inferred environmental reconstructions. Firstly, both datasets indicate that between 4 cm depth and the base of the core, there was little change in the pH or E.C. of Laguna de Juanacatlán. Secondly, the predictions of pH and E.C. for the most recent period of time did not compare very well with measured modern values. This may be because *Fragilaria crotonensis* has a wide ecological range in terms of pH and E.C. and its optimum depends on the range of sites included in the modern dataset. Thirdly, the numerous *Synedra* species, which fluctuate significantly in their relative abundance through the core, were poorly represented in both calibration datasets. The Mexican dataset does not include *Synedra acus*, *Synedra delicatissima*, *Synedra tenera* or *Synedra nana*, whilst the African dataset does not include *Synedra nana* or *Synedra tenera*. Therefore, any variations in water chemistry indicated by these taxa would not be identified in the quantitative reconstruction. As discussed previously in this chapter, the fluctuation in the abundance of *Synedra* species is more likely to be the result of changing nutrient availability, for which data is not available in either modern dataset. Although there is a good general overlap between the modern and fossil data for both the Mexican and African datasets, the application of these transfer functions to the diatom record from Laguna de Juanacatlán appears to be limited.

7.10.3: Statistical Analysis of Palaeoenvironmental Data

The programme CANOCO was used to examine the relationship between the diatom assemblages in core JL/98 and the other environmental variables measured, these included magnetic susceptibility, concentrations of Fe, Pb, Cu, Mn, Zn and Ag and total phosphorus. A total of 19 samples were selected, as these had a full dataset of all the variables and the 26 taxa which occurred at greater than 1 % relative abundance were included in the analysis.

The first analysis, including all samples and all environmental variables produced a very marked environmental gradient along axis 1, which has an eigenvalue of 0.6978 (Figure 7.26). The eigenvalue of 0.1325 for axis 2 indicated that this axis was not significant and that Axis 1 explains the majority of variation in the diatom data. The large gradient on this axis is driven by the markedly different diatom flora found in the surface sample compared with the rest of the core. The arrows on the biplot indicate that the environmental variable most associated with axis 1 is copper. The low concentration of copper in the surface sample relative to the rest of the core has caused the pattern illustrated in Figure 7.26. It is likely, however, that the importance of copper has been over emphasised, due to the very large difference in species composition between the surface sample and the rest of the core.

In order to explore more subtle differences in species composition, the surface sample was removed from the analysis. In this case, the eigenvalue for axis 1 was 0.1428, whilst for axis 2, a value of 0.0700 was obtained. This suggests that there is little or no relationship between the diatom assemblages in the core and the measured environmental variables. This indicates, therefore, that other factors that have not been included in the analysis must be important in determining the diatom species composition of Laguna de Juanacatlán.

7.10.4: Synthesis of the Palaeoenvironmental Data

The palaeoenvironmental records from the three cores obtained during this study are now compared with Byrne and Metcalfe's unpublished results to present an overall record of environmental change over the last ca. 500 years.

The diatom record produced by Metcalfe is illustrated in Figure 7.27. The first point to note is that, at the base of their core, *Nitzschia gracilis* and *Nitzschia paleacea* are common. This diatom assemblage is not found in either of JD/98 and JL/98 and indicates that the previous study extends back further in time than the present investigation. Above this, however, the diatom records are broadly consistent, with a clear record of change from a *Cyclotella stelligera-Synedra* flora to an assemblage of *Cyclotella stelligera-Aulacoseira granulata* var. *angustissima.*

A summary of environmental change in Laguna de Juanacatlán is provided in Figure 7.28. In the early part of the Colonial Period, silica: phosphorus ratios were high in the lake, which indicates a low input of nutrients from the catchment. Catchment erosion was minimal, suggesting that there was little or no anthropogenic disturbance. A significant change in the diatom assemblage and increased magnetic susceptibility, however, implies that catchment disturbance increased subsequently and the nutrient flux to the lake altered, with phosphorus becoming more readily available in the water column. Pollen evidence (Byrne, unpubl. data) also indicates a significant change in the vegetation around the same time, with pine replacing oak as the dominant tree species and *Potamogeton* replacing *Cyperaceae* as the dominant component of the aquatic flora. During the early part of this catchment disturbance, a distinctive layer of oxidised clay was deposited in the lake. Given its high content of Ag, Zn and Pb, it is likely to be associated with Colonial mining activity although this alone may not have been responsible for the vast amount of sediment which must have been deposited in the lake. It is possible that deforestation and disturbance of material for mining may have made large areas susceptible to erosion from the surrounding steep slopes. Subsequent erosion due to run-off in a high-magnitude flood event, or even tectonic activity, may have then caused the exposed sediment to be deposited in the lake.

In the upper part of the cores examined, nutrient availability appears to have reverted to pre-disturbance conditions of high silica: phosphorus ratios. This suggests that inputs of phosphorus to the lake decreased, possibly as a result of decreased catchment disturbance and lower input of nutrients from allochthonous sources. Mines in the area ceased to be operational around the turn of the 20th century, so this period of increased stability is likely to post-date this.

The most significant change in the diatom species composition is the dramatic switch from a *Cyclotella stelligera* dominated flora to one composed almost wholly of *Fragilaria crotonensis*. This is not recorded in the sediment-water interface core obtained by Byrne (Figure 7.27) and must therefore have occurred since 1990. It is most evident in core JR/98. Whilst the change in species composition does not signify a change in the ionic composition of the water, there must have been some fundamental alteration within the lake system. It is possible that this has been caused by increased phosphorus and nitrate availability in the lake. The source of this is unknown, but may be the result of fertiliser application to the maize fields close to the eastern edge of the lake either side of the Arroyo de Laguna de Juanacatlán.

Perhaps the most important comment regarding the palaeoenvironmental record from Laguna de Juanacatlán is that, whilst there have been significant changes in the diatom flora of the lake within the last ca. 500 years, there is no conclusive evidence to relate this to climatic variability. The major features of the palaeoenvironmental record appear to be associated with anthropogenic activity, even though this lake was thought to be in a location that was relatively undisturbed in comparison with other lakes in Central Mexico. It is therefore apparent that this lake is highly sensitive to even minor changes in catchment use, which has implications for the future management of the watershed. The lake is currently being promoted by the local government as a major tourist attraction for the area, so careful consideration needs to be taken with regard to the management of this resource.

7.11: Conclusions from Laguna de Juanacatlán

The principal conclusions drawn from the preliminary limnological survey and palaeolimnological record of Laguna de Juanacatlán are as follows:

- Laguna de Juanacatlán is a calcium-magnesium bicarbonate lake with a pH of 8.78 and an E.C. of 148 $\mu S\ cm^{-1}$. The lake has a maximum depth of ca. 25 m and is thermally and chemically stratified for at least part of the year.
- The laminated sediments of this lake are likely to provide a sub-annual resolution palaeoenvironmental record. Further work is required, however, to establish whether the laminations are indeed seasonal.
- Establishing a reliable chronological framework for the palaeolimnological record from Laguna de Juanacatlán has proved to be very difficult. All that can conclusively be said is that the record presented in this thesis covers the last ca. 500 years. Further work may help to clarify some of the problems highlighted here.
- During the early Colonial period, the catchment appears to have been stable and the nutrient flux to the lake was low. Subsequently, significant catchment disturbance is evident in the palaeolimnological record, which is probably associated with Colonial mining operations.
- The lake was affected by a dramatic erosive event which lead to the deposition of a distinct layer of oxidised clay. It is likely that this was caused by a combination of anthropogenic disturbance and subsequent stripping of material from slopes by either heavy rainfall, tectonic disturbance or slope failure. It was not possible to establish the date of this event.
- The diatom flora of the lake has changed dramatically since 1990, highlighting the sensitivity of this aquatic ecosystem to changing nutrient inputs. This clearly has implications for the future management of this catchment if environmental degradation through increased usage is to be avoided.

Chapter 8: Discussion and Conclusions

8.1: Introduction

In this chapter, the results presented in Chapters 5, 6 and 7 are discussed in the light of the original objectives outlined in Chapter 1. These were: 1) to identify climatic change in central Mexico during the Late Holocene; 2) to explore the extent of human impact on the environment away from major population centres and 3) to compare the palaeoenvironmental record with available historical evidence. Reflecting on the results obtained from Lago de Zirahuén and Laguna de Juanacatlán, it is evident that the issue of anthropogenic disturbance has become the main focus of this thesis. This is particularly interesting, given that these two sites were chosen because of the perceived lack of catchment disturbance. The implications of this are explored by comparing the palaeoenvironmental records from the two sites and discussing the results in a wider regional context. Before this, however, a number of methodological issues that have arisen during the course of this thesis are explored.

8.2: Techniques

8.2.1: Diatom Analysis and Numerical Reconstructions

Chapter 5 focused on the development of a surface sediment diatom calibration dataset for central Mexico. Sampling of modern diatoms and water chemistry focused on lake types which were perceived to be poorly represented in a pre-existing dataset produced from the results of Metcalfe (1985, 1988) and Caballero (1995). The sampling strategy proved to be successful, with the resulting merged dataset spanning a large gradient in terms of ionic composition, ionic strength and pH (see Section 5.8.1). The principal aim was to use the calibration dataset to produce transfer functions for key hydrochemical variables, which would enable diatom-based numerical environmental reconstructions. Although the final dataset of 53 samples is relatively small, the results were encouraging, with the successful development of transfer functions for electrical conductivity (representing ionic strength) and alkalinity (% HCO_3 + CO_3: representing ion type). The dataset can also be used to create pH reconstructions, although this variable explains less of the variance in the diatom data (see Section 5.8.5 and Figure 5.16).

The large environmental gradient of this dataset means that the full ecological range of diatom species is more likely to be encountered, so numerical reconstructions are more likely to be reliable. Furthermore, the strong relationship between observed and diatom-inferred hydrochemical variables (Figure 5.17) highlights the importance of this dataset for palaeoenvironmental research in central Mexico. Its application is likely to be particularly effective for lakes that experience large fluctuations in their ionic strength and composition, such as Lago de Cuitzeo, whose chemistry has varied considerably, even over the past 25 years (Figure 5.7).

Whilst the development of this calibration dataset has provided a much improved insight into diatom species distributions in central Mexico, its application to the palaeoenvironmental records from Lago de Zirahuén and Laguna de Juanacatlán was not as successful as had been hoped for. The first problem arising from the results of this study is that the diatom records from both Lago de Zirahuén and Laguna de Juanacatlán appear to reflect changes in nutrient availability, rather than ionic composition or concentration. These environmental variables, such as nitrate and phosphorous content, have not been considered in the modern calibration dataset. It is possible that their inclusion may lead to the masking of the importance of ionic composition in the same way that habitat preferences interfered in Metcalfe's (1988) dataset. The palaeoenvironmental records from Zirahuén and Juanacatlán have, however, illustrated that nutrient availability has a considerable influence on the diatom species composition of central Mexican lakes. There is therefore, great potential for the future development of a diatom-based calibration dataset that will enable numerical reconstruction of nutrient levels in central Mexican lakes. Such a dataset would provide valuable information on the response of lake ecosystems to anthropogenic nutrient inputs in the absence of an extensive monitoring network.

Further problems were encountered when making numerical reconstructions due to a lack of modern analogues for key diatom species. This was particularly evident at Lago de Zirahuén where many of the fossil diatom assemblages were poorly represented in the calibration dataset (see Section 6.11.2.). At Laguna de Juanacatlán, the core assemblages were well represented in the modern dataset as the core was dominated by *Cyclotella stelligera.* The absence of other taxa in the modern dataset that were important in the diatom record, (mainly *Synedra* species) meant that is was likely that the numerical reconstructions were not providing a true reflection of changes which occurred in the lake. The lack of modern analogues is not just a problem with the two sites examined in this study, as a number of important fossil species encountered in previous palaeolimnological studies are either absent or poorly represented in the dataset. For example, the fresh water planktonic species *Stephanodiscus niagarae* is abundant in Late Pleistocene material (Metcalfe, 1992; Metcalfe *et al.*, 1997; Caballero & Ortega, 1998; Caballero *et al.*, 1999) but has not been reported in the present day environment. *Eunotia* species are common in the Late Pleistocene and Holocene flora of some central Mexican lakes (e.g. Bradbury, 1989; Metcalfe, 1992; Caballero *et al.*, 1999) but are rare in the calibration dataset.

Although this study has improved the environmental gradient covered by the Central Mexican Diatom Dataset, there are still few samples from low pH environments, which explains the poor representation of acidophilous taxa, such as *Eunotia* species. Future sampling should target lakes with a lower pH, but the main problem is that such environments are rare in Mexico. The lack of modern analogues may also be due to important climatic changes in the region and to prolonged and significant human impact on many lakes in central Mexico, which have resulted in changes in the diatom flora (Metcalfe, 1988). Many basins within the TMVB have experienced significant human impact during the last 3,000 years (Metcalfe *et al.*, 1989). More recently, deliberate drainage, excessive groundwater abstraction and cultural eutrophication have all contributed to the significant alteration of many lakes from their natural state (Alcocer and Escobar, 1996). Given the extent of human impacts on many Mexican lakes, further sampling may not be sufficient to resolve the problem of no-analogue situations.

It is possible that the merging of the central Mexican dataset with the larger African calibration dataset will increase the likelihood that modern analogues will be encountered. Furthermore, the accuracy of transfer functions should be improved as it is more likely that the full ecological tolerances of species will have been captured (Reed, 1998). There are potential problems with this approach, however, which need to be addressed before any merging between datasets from different regions can be carried out. Firstly, although the species optima and tolerances derived for taxa in central Mexico are most similar to those obtained using the African dataset, there are still significant discrepancies (see Section 5.8.7 for a comparison of different datasets). This may be simply due to the truncation of ecological gradients of species in the individual datasets. It is possible, however, that taxa identified under the same name in the individual datasets actually represent closely related but separate species or variants which have differing ecological requirements. Only once this is established will it then be appropriate to consider the inter-regional merging of calibration datasets.

8.2.2: Chronological Methods

Three dating techniques were applied to the sediment cores from Zirahuén and Juanacatlán: ^{210}Pb dating, tephrochronology and AMS ^{14}C dating. At Zirahuén, the combination of ^{210}Pb dating and tephrochronology provided a robust chronology for the last ca. 250 years. Beyond this, however, estimating the age of the sediments became more problematic due to discrepancies between tephra and ^{14}C ages and the inversions in the ^{14}C chronology. It proved impossible to construct a detailed chronological framework for the record from Juanacatlán, due to the failure to obtain a reliable ^{210}Pb profile and the indication that ^{14}C dates could be contaminated with older carbon.

The ^{210}Pb results from Lago de Zirahuén were most encouraging and highlight the potential of this technique in reconstructing recent environmental change in central Mexico. The opportunity to compare the ^{210}Pb ages with the profile of manmade radionuclides and the AD 1943 tephra layer from Paricutín provided an independent means of validating the ^{210}Pb chronology. Unfortunately, the application of the technique was less successful at Laguna de Juanacatlán. The possible reasons for this were discussed in more detail in Section 7.6.2. Work is ongoing to establish whether a reliable ^{210}Pb chronology can be obtained for another core from this lake. If not, it may be that the site is unsuitable for the application of this technique. Regardless of the problems encountered at Juanacatlán, the calculated depositional flux of ^{210}Pb for both lakes (Zirahuén: 48 Bq m^{-2} yr^{-1}, Juanacatlán: 12 Bq m^{-2} yr^{-1}) are considerably lower than the global average of 185 Bq m^{-2} yr^{-1} (Appleby and Oldfield, 1983). It is possible therefore, that the global flux of ^{210}Pb is more variable than has previously been suggested. Further work needs to be undertaken to establish this.

Radiocarbon dating has proved to be of limited use in this study. There are a number of reasons for this. Firstly, the time period covered by this study is at the lower limit of the range of this technique (Bowman, 1990). Secondly, it is desirable to calibrate radiocarbon years to calendar years in order that the palaeoenvironmental record can be interpreted with reference to historical evidence and to allow. The level of precision of radiocarbon dating, however, is insufficient to be able to do this with certainty as, when calibrated age ranges are obtained at the two sigma level of error, the age range may span two to three hundred years or more. Furthermore, errors can be increased when the radiocarbon age intercepts the calibration curve at more than one point, due to wiggles in the curve. This was the case for several samples dated for this study (see Tables 6.1 and 7.2). It is therefore, often the case in more detailed palaeolimnological studies, such as this, that events identified in the sediment record are of a shorter duration than the errors inherent in ^{14}C dating (Pilcher, 1991). The third problem relates to the contamination of lake sediments with old carbon washed in from the catchment. At Lago de Zirahuén, there was clear evidence that some radiocarbon dates were artificially old due to the inversion of the radiocarbon chronology and the discrepancy between ^{14}C dates and the tephrochronology (see

Section 6.11.1). It was also thought that radiocarbon dates from Laguna de Juanacatlán may have been contaminated with old carbon, but this was more difficult to establish as there were no tephras or reliable ^{210}Pb chronology to provide a means of comparison. At both sites, the magnetic susceptibility profiles proved to be useful in establishing whether contamination through erosion from the catchment was a possibility. Dating Late Holocene lake sediments in central Mexico has, in the past, been identified as problematic due to catchment disturbance associated with human settlement (Brown, 1984; Metcalfe, 1992; Metcalfe and Hales, 1994). It was thought that this problem could be avoided by the careful selection of sites where anthropogenic influences were not as great. It appears, though, that even where catchment disturbance histories are shorter and less intense, obtaining a reliable ^{14}C chronology is still a major stumbling block.

The problems highlighted by this study do not just apply in the context of central Mexico. There have been numerous palaeoenvironmental investigations which have focused on identifying the impacts of human activity on the environment during the Late Holocene (e.g. Elliott *et al.*, 1995; Dumont *et al.*, 1998). Efforts have been hampered in many cases, however, by poor radiocarbon chronologies (e.g. Kjellmark, 1996; Dumont *et al.*, 1998). Currently, ^{14}C dating is the only radiometric technique which can be applied to Late Holocene lake sediments, apart from ^{210}Pb dating which only extends back ca. 150 years. A new chronological technique, based on the cosmic ray produced radionuclide silicon-32, is however being developed (Nijampurkar *et al.*, 1998). This radionuclide has an estimated half-life of 178 ± 10 years, which means that it could be used as a geochronological tool for sediments ranging from ca. 50 to 500 years old. At present, the technique is in the early stages of development and there are a number of problems that need to be overcome before it can be widely applied in palaeoenvironmental research. Firstly, a large sample of 50-100 g is required, which is simply not feasible from a single sediment core. Secondly, the counting time of samples is long (ca. two months). Finally, the activity of ^{32}Si should be measured in biogenic silica, which may be difficult to extract from minerogenic sediments that include large amounts of detrital silicates (Nijampurkar *et al.*, 1998). Still, as this technique is further refined, it should provide palaeoenvironmental scientists with a means of bridging the gap between ^{210}Pb and ^{14}C dating and, unlike the ^{14}C method, should not be compromised by the effects of catchment erosion.

The presence of tephras from eruptions of known historical age in Lago de Zirahuén provided an important means of further constraining the chronology of the palaeoenvironmental record. The Jorullo tephra (AD 1759-1764) is particularly important as its date is beyond the range of ^{210}Pb dating, which only covers the last ca. 100-150 years. Furthermore, it is an extremely useful marker horizon that helps link the palaeoenvironmental record to evidence from historical sources. The Paricutín tephra (AD 1943) not only helps to validate the ^{210}Pb chronology but also provides a means of examining variation in sedimentation rates in different parts of the basin. The Paricutín and Jorullo tephras are likely to become important chronological markers for lake records from the highlands of Michoacán. Tephra from Jorullo has also been encountered in Zinzaro, a small lake between the basins of Pátzcuaro and Zacapu, whilst the Paricutín tephra has been found in a core from Lago de Pátzcuaro (A. Newton, pers. comm.). Given that the Jorullo tephra is thin and patchy in Lago de Zirahuén (50 km from Jorullo), it is unlikely that it will be encountered in lake sediments much further away from the source of the eruption.

Although the tephras from Paricutín and Jorullo are only likely to be useful over a restricted area within the TMVB, this study has shown that the identification of tephras from historical eruptions is crucial for building an effective chronological framework for the more recent past. There have been other historical eruptions that may prove to be important marker horizons elsewhere along the TMVB. For example, Volcán Ceboruco in Nayarit erupted in AD 1870 (Carmichael *et al.*, 1996) and its tephra should be encountered in nearby lakes such as Santa Maria del Oro and Laguna San Pedro. The most active volcano in Mexico during the historical period is the stratovolcano, Volcán de Colima (Figure 3.2), which has erupted numerous times since the Spanish Conquest in 1521 and it is possible that the silicic tephra layers encountered in Zirahuén are the products of this volcano. There is considerable potential then, for the application of tephrochronology to palaeoenvironmental studies focusing on the historical period (the last ca. 500 years) in central Mexico. It must be pointed out, however, that this technique is still in its infancy in this region and much work is needed before it can be widely implemented.

Even taking into account the problems outlined above, the palaeoenvironmental record from Lago de Zirahuén represents the most reliable chronology of environmental change over the last 1,000 years in central Mexico. Ongoing ^{210}Pb work at Laguna de Juanacatlán may help to refine the chronology for the record from this site. The palaeoenvironmental evidence from these two sites is now discussed below.

8.3: Discussion of the Palaeoenvironmental Records

The palaeolimnological records from Lago de Zirahuén and Laguna de Juanacatlán invite comparison in that both are lava-dammed lakes, having a similar water chemistry in terms of ionic composition, pH and electrical conductivity. It was also originally thought that both lakes had suffered relatively little anthropogenic disturbance in comparison with other lakes along the TMVB and would provide a detailed picture of climate change in the region over the Late Holocene. The palaeoenvironmental evidence that emerged from Lago de Zirahuén and Laguna de Juanacatlán was therefore somewhat surprising; it was not expected to encounter such a strong human impact signal in the sediments from these two lakes. The record of environmental change at the two lakes is therefore interpreted largely in terms of a response to basin-specific factors, which are discussed in detail in Chapters 6 and 7. There are, however, a number of more points that should be highlighted here.

The palaeoenvironmental record from the Zirahuén Basin extends back to cal. AD 1000-1200, whilst that from Laguna de Juanacatlán only covers the last ca. 500 years. It was therefore impossible to obtain a record of environmental change from Laguna de Juanacatlán during the Pre-Hispanic period and a number of questions remain unanswered. Firstly, it could not be established whether the intense drought centred around AD 900, identified in numerous lake basins within the TMVB (Metcalfe and Hales, 1994; Metcalfe *et al.*, 1994), affected this westernmost part of the central Mexican highlands. Secondly, it was not possible to determine the extent of Pre-Hispanic human impact in the Juanacatlán Basin. It was disappointing not to produce a palaeoenvironmental record from this site due to problems with coring apparatus, but it is hoped that future work could yield longer records from this site and possibly others in this region.

The longer palaeoenvironmental record from Lago de Zirahuén, however, yielded some important results. Tentative evidence was presented for a significantly drier climate around ca. 900 yrs. BP (cal. AD 1000-1200). Unfortunately, the record does not extend back far enough to establish the timing of the onset and duration of this drought episode. Obtaining a longer core from this basin would help to clarify this issue. As discussed in Section 2.4.4, prolonged drought conditions have been identified in numerous lakes across the TMVB. For example, lake level dropped dramatically in the Zacapu Basin around 1100 yrs. BP (Metcalfe, 1992), whilst an intense dry phase was identified at La Piscina de Yuriria between 1400 and 900 yrs. BP (Metcalfe *et al.*, 1994). At Lago de Pátzcuaro, a severe drought between 1100 and 1200 yrs. BP was inferred from high Sr/Ca ratios in the sediment (O'Hara, 1991), although ostracode evidence suggested a more complex pattern of climatic change with large fluctuations in available moisture (Bridgwater *et al.*, 1999). These lakes are all close to Lago de Zirahuén (Figure 3.3), so it seems likely that the evidence presented here is correlative with the other palaeoenvironmental records.

It appears that widespread drought occurred right across the region, with particularly dry conditions occurring on the Yucatán Peninsula around 1,000 yrs. BP (Curtis *et al.*, 1996). At Lake Miragoane in Haiti, a drought episode occurred between 2,400 and 1,500 yrs. BP (Hodell *et al.*, 1995). Correlating these drought phases is plagued with uncertainty, due to the problems discussed in the previous section and exacerbated in the Yucatán and Haiti as hardwater errors have to be considered. It does seem likely, however, that this dry phase affected the whole of central and southern Mexico and possibly the Caribbean.

The palaeoenvironmental record from Lago de Zirahuén also provides important evidence for Pre-Hispanic human impact in the basin. The magnitude of human impact was not expected as previous archival work pertaining to the basin indicated that the slopes surrounding the lake were much less densely settled than the nearby basins of Pátzcuaro and Cuitzeo (Endfield, 1997; Endfield and O'Hara, 1999). The phase of increased soil erosion identified in the sediments from Lago de Zirahuén beginning around cal. AD 1000-1200 is likely to be the result of deforestation by the Post-Classic Purépecha civilisation, whose population was largely based in the basin of Pátzcuaro, ca. 15 km to the north. Evidence for Post-Classic large-scale environmental degradation was also found in the palaeolimnological record from Lago de Pátzcuaro (O'Hara, 1991; O'Hara *et al.*, 1993). The discrepancy between the archival and the palaeoenvironmental records from the Zirahuén Basin is intriguing. It may be that documentary or archaeological evidence for Pre-Hispanic human activity in the basin is not there, or has not been discovered yet. A second possibility is that the basin was not intensively settled, but that this catchment is highly sensitive to even small scale anthropogenic disturbance. Significant environmental degradation caused by Pre-Hispanic civilisations has been identified in numerous other basins in the highlands of Central Mexico (e.g. O'Hara *et al.*, 1993; Metcalfe *et al.*, 1994; see Section 3.3.1.), although the timing of such disturbance phases is poorly constrained. It is becoming more apparent that the notion of the Spanish *Conquistadores* encountering a pristine environment is an idealised and romanticised view of Pre-Columbian civilisations (Denevan, 1992; Whitmore and Turner, 1992).

The nature and extent of the impact of Pre-Hispanic populations on the environment needs to be tackled in more detail. To date, all palaeolimnological studies in Central Mexico, including the present study, have set out with the aim of investigating climatic change and each has been faced with the complicating factor of anthropogenic disturbance. Environmental degradation has apparently been more intense during the Pre-Hispanic period than has been previously anticipated with disturbance records from basins examined so far extending back around 3,500 years (Metcalfe *et al.*, 1994). A longer sediment sequence is required from Lago de

Zirahuén to determine whether this basin has suffered the same degree of modification. It may be that, even in lake basins which were thought to be relatively undisturbed, obtaining an unambiguous climatic signal for the Late Holocene in Central Mexico remains elusive.

In both Lago de Zirahuén and Laguna de Juanacatlán, there is a detailed record of environmental change since the Spanish Conquest in 1521. Interestingly, in the Zirahuén Basin, where the chronology is better constrained, there is a phase of reduced soil erosion and catchment stability corresponding to the early part of the Colonial Period. Very few archival references are found pertaining to the Zirahuén Basin during this period (Endfield, 1997) and church records suggest that populations were small (Section 6.3). The palaeolimnological evidence presented here supports the idea that the immediate impact of Colonial rule may actually have been beneficial to the environment (Endfield, 1997). The decimation of the indigenous population during the early Colonial period, through disease and famine (Borah and Cook, 1994), is likely to have eased pressure on natural resources and allowed vegetation on slopes surrounding the lake to recover. The palaeolimnological record from Hoya San Nicolás de Parangueo appears to record a similar pattern of environmental change during the Colonial Period to that of Lago de Zirahuén. The pollen record from Hoya San Nicolás de Parangueo reveals the recovery of pine in the upper part of the core, which may be associated with a reduction in pressure on natural resources during the immediate post Conquest period. An increase in catchment disturbance occurred at this site from the late 18th century (Metcalfe *et al.*, 1989). The chronology of the record from Hoya San Nicolás de Parangueo is not well constrained, but the similarity between these two sites is interesting. It may be that pattern of environmental change during the Colonial period observed at Lago de Zirahuén was a more widespread phenomenon.

The palaeoenvironmental records from Lago de Zirahuén and Laguna de Juanacatlán both show a marked response to increased nutrient inputs during the later Colonial Period. At Zirahuén, the increase in catchment disturbance associated with Colonial activity is well-dated to the mid-18th century due to the presence of the Jorullo tephra, whilst the onset of Spanish exploitation around Laguna de Juanacatlán has not been established. In both basins, clearance of slopes for agricultural purposes is likely to have been important, but probably the most important activity was Colonial mineral exploitation. In the Zirahuén Basin, there is a clear record of copper pollution resulting from smelting operations at Santa Clara del Cobre, whilst the record from Juanacatlán provides evidence of silver mining. The profiles of metal concentrations in these two lakes provide the first evidence from Mexico of pollution resulting from Colonial mining and smelting operations. Both basins also show a response to increased nutrient inputs during the Colonial Period. It is likely that the source for this would have been eroded slope material. Palaeolimnological records from other lake basins in the highlands of Mexico likely record the impact of Hispanic settlers, although chronologies are not sufficiently well constrained. Elsewhere in the circum-Caribbean region, palaeoenvironmental records indicate significant vegetation and sedimentological changes resulting from Colonial settlement (e.g. Brenner and Binford, 1988; Kjellmark, 1996).

The most striking features of the palaeolimnological records from Zirahuén and Juanacatlán are the rapid and dramatic changes that have occurred in the diatom flora during the last 10-20 years. At Lago de Zirahuén, this recent change can clearly be associated with increasing settlement and intensification of agriculture around the lake. There is now also limnological evidence of increased nutrient loading in Lago de Zirahuén (Chacón, pers. comm). Bernal-Brooks (1988) did not detect any perceptible deterioration in water quality of Lago de Zirahuén in 1986, classifying the lake as oligo-mesotrophic, although the palaeolimnological results presented here indicate that his study post-dates the change in the diatom flora. This highlights the use of palaeolimnological studies as an early warning signal for lake eutrophication as changes in the diatom assemblages may occur before there is any change in nutrient availability can be detected by instrumental measurements (Bennion *et al.*, 1996). At Laguna de Juanacatlán, there has been no obvious increase in activity or settlement during the last decade and the diatom flora may be responding to increased fertiliser applications, although farming is very small scale in this basin.

This highlights the sensitivity of this lake to what must have been a fairly small scale change within the catchment.

The two lakes selected for this palaeolimnological study are both responding rapidly to changing nutrient availability within the ecosystem. Even small changes in the level of human activity within the basins appear to be having a major impact on the lake biota. The relevant local authorities are currently heavily promoting these lake basins as major tourist destinations. There are already numerous hotels and cabins around Lago de Zirahuén, which is likely to increase with the construction of an exit from the toll road designed to attract more visitors. At Laguna de Juanacatlán, a number of small cabins are being built at the side of the lake. In both basins, waste produced by tourists goes straight into the lake waters. Given the sensitivity of these two basins to changing nutrient inputs into the aquatic environment, it is inevitable that further environmental degradation will ensue if development is not strictly controlled. Future land management strategies must take into account the impact of increasing pressure on the environment, otherwise, these important natural resources will deteriorate further and, ironically, will no longer be attractive to tourists.

8.4: Conclusions

This study has provided the most detailed picture so far of environmental change in the central Mexican highlands over the last 1,000 years. Despite problems obtaining reliable chronologies, the resolution achieved is greater than that of previous studies. In addition, data collected across central Mexico have added significantly to our understanding of modern ecological distributions of diatom species in central Mexico. The principal conclusions drawn from the results presented in this thesis are as follows:

- Present day diatom species distributions in Central Mexico are closely related to the ionic strength and composition of lake waters. The development of a surface sediment diatom calibration dataset enables the numerical reconstruction of key hydrochemical variables. The problem of obtaining modern analogues for key taxa persists, probably due to the sustained anthropogenic disturbance of many lakes.

- Even lake basins which are perceived to be relatively undisturbed have experienced significant human impact, thwarting attempts to reconstruct Late Holocene climate in central Mexico from lake sediments.
- Contrary to historical evidence, the Zirahuén Basin suffered considerable environmental degradation during the Post-Classic period. The arrival of the Spanish in 1521, however, may have served to ease pressure on the environment.
- As a result of Colonial settlement and exploitation during the later Colonial period, there is substantial evidence in the palaeolimnological records from Lago de Zirahuén and Laguna de Juanacatlán for increased soil erosion and nutrient enrichment of the aquatic environment.
- This study presents the first evidence of metal pollution resulting from Colonial mineral exploitation. Increased copper concentrations in Lago de Zirahuén resulted from 18th century smelting operations at Santa Clara del Cobre. At Laguna de Juanacatlán, pollution from silver mining is registered in the sediment record, but a precise date has not been established.
- The sensitivity of small, tropical highland lakes to anthropogenic disturbance has been highlighted by their response to recent changes in land use practices. This has clear implications for future management strategies for such ecosystems.

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