LATE QUATERNARY ENVIRONMENTS OF CENTRAL MEXICO: A DIATOM RECORD



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Abstract

The nature and extent of environmental change over the Late Quaternary in Central Mexico is still uncertain. This study addresses the problem through an investigation of subfossil diatom assemblages in lacustrine sediments. As some doubt has been cast upon the reality of climatic change in Mexico, the variations in climate experienced over the archaeological and historical periods are described and possible explanations put forward in terms of the mechanisms of the present-day climate.

The choice of technique and background to the region of the Neovolcanic Axis (Central Mexico) are outlined. As little is known of the modern aquatic environment of Central Mexico, a limnological survey was undertaken. The results of the analyses are discussed and possible trends of chemical evolution described. The modern diatom flora is presented for three areas and the results analysed using multivariate statistical techniques (TWINSPAN and DECORANA). These techniques highlight the importance of habitat in determining diatom assemblages. Subfossil diatom sequences are described from the Zacapu Basin, Michoacán (covering the last 28,000 years) and from the Upper Lerma Basin, Estado de México (covering about the last 11,600 years). Additional palaeoenvironmental information is provided by analyses of

inorganic and organic geochemistry.

In Central Mexico, wetter conditions probably prevailed prior to 25,000 (possibly 28,000) yr BP. In the Holocene, a dry event occurred between 7,500 and 7,000 yr BP, followed by a (?) major transgression soon afterwards. The period 4,500 - 4,000 yr BP appears to have been very dry, becoming wetter in the period 3,000 to 2,000 yr BP. Conditions were dry again by 1,300 yr BP.

Man appears to have been an important agent of environmental change in Central Mexico over the last 3,000 years. His influence, extending into the Post-Hispanic period, is recorded in both the study areas.

The results from the Zacapu and Upper Lerma basins fit well into the chronology of climatic change being developed for Central and northern South America.

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Abstract

Compared with many parts of the world, the Late Quaternary of Mexico has been little studied. Evidence from the southwest U.S.A. indicates that the last glacial maximum (ca. 18,000 yr BP), was considerably wetter than present and that the area remained relatively moist into the early Holocene. Since the mid-Holocene, however, conditions have been dry, much as at present. In contrast, work in northern South America indicates dry full-glacial conditions there, becoming wetter during the Holocene. Mexico, therefore, lies at an interesting latitude for determining the extent of the climatic regimes bringing these wetter or drier conditions. Whether the pattern of climatic change in Mexico followed the 'temperate' or 'tropical' pattern is also open to debate.

Previous work in Central Mexico (Chapter 1) has tended to suggest that it might lie in a zone of 'no change', a hinge zone. Examination of records of climatic fluctuations provided by archaeological and historical sources, however, indicate that the climate is more variable than some studies might imply. Such recent fluctuations can be explained by reference to the present day influences on the climate of Mexico (Chapter 2).

It was decided that a study of climatic fluctuations, as recorded by variations in the levels of lakes closed during

part, or all, of the Late Quaternary would be valuable. The area of the Neovolcanic Axis, which straddles Mexico at about 19°N, was felt to be a suitable study area in view of the abundance of lake basins there (Chapter 3). There seemed to be a good chance that the lakes in this region would retain a continuous sedimentary record for the period since the last glaciation. The particular investigative technique chosen, was the study of subfossil diatom assemblages in lacustrine and marsh sediments. Other work in the tropics and subtropics had shown diatoms (unicellular algae) to be sensitive to changes in aquatic conditions, which might then be interpreted in terms of variations in climate. The structure of diatoms and the environmental variables to which they respond are described. Their sensitivity to changes in pH, alkalinity, salinity and water depth were felt to be very valuable in attempting a palaeoclimatic reconstruction. Diatoms have the added advantage of being indicators of cultural eutrophication. This was useful in view of the long history of sedentary agriculture and high density settlement in Central Mexico.

Lake basins in the states of Michoacán, Guanajuato and México were identified as being particularly promising and were sampled during seasons of fieldwork. Field sampling proce dures and laboratory analytical and preparation techniques are described in Chapter 4. A number of problems arose concerning the identification and naming of the diatoms found in the collection of modern and fossil material. The presence of heavily silicified girdle bands sometimes made

the identification of Melosira species difficult under the light microscope. A new species of Cyclostephanos seems to have been found in the sediments from Laguna Zacapu, Michoacán. An unusual form of S. acus was also recorded in that basin. The new combination S. acus var. neogena comb. nov. is proposed. As the terminology of Patrick and Reimer (1966 and 1975) has been adopted for the genus Pinnularia, the name P. abaujensis var. parva comb. nov. has also been put forward.

In view of the paucity of information on either the ecology of diatom taxa in the tropics or on the present day water chemistry of Central Mexico, a limnological survey was undertaken. Samples were collected from sites across Central Mexico and the results are given in Chapter 5. Clear variations in water chemistry were recorded and appear to follow the model of chemical evolution with evaporative concentration, outlined by Eugster and Hardie (1978). The waters of Central Mexico seem to fall into the Na^{+} - CO_3^{2-} - HCO_3^{-} - Cl range. Although Ca^{2+} or Mg^{+} may be the dominant cation at individual sites, Na^{+} is most abundant overall. Amongst the anions, CO_3^{2-} + HCO_3^{-} are replaced by Cl with increasing evaporation. Few lakes contained abundant SO_4^{2-}.

Diatoms were collected from a variety of habitats at the same time as the water samples. It was hoped that the known ecology of these assemblages would provide analogues for the interpretation of the subfossil material. The modern diatoms were analysed through the application of multivariate

statistical techniques. Programs for hierarchical classification (TWINSPAN) and ordination (DECORANA) were used. The data were run through these programs in three sets: Laguna Zacapu and associated sites; sites in the Zacapu Basin and Other Sites in Central Mexico. The results from Zacapu reflect the importance of habitat in determining species assemblages where there is little variation in water chemistry. These samples also highlight the differences between the assemblages of predominantly living diatoms and those found in sediment samples. The high abundance of N. palea in a number of water samples from this basin is attributed to anthropogenic influence, although there was no direct relationship between the amount of P_2O_5 and NO_3 in the waters and the numbers of this species.

The TWINSPAN results for the more heterogeneous set of samples collected from sites across Central Mexico, do seem to show some response to chemical gradients, particularly changes in alkalinity and Cl. DECORANA, however, again tends to emphasise the importance of habitat.

Species of Nitzschia, Fragilaria and Achnanthes are particularly abundant in the modern Mexican samples. A number of floristic and chemical similarities with East Africa are identified, providing a sounder basis for the application of ecological data from that area to the Mexican samples.

Results are presented of analyses of lacustrine sediments from two basins in the Neovolcanic Axis: the Zacapu

Basin in Michoacán (Chapter 6) and the Upper Lerma Basin in the Estado de México (Chapter 7). Both basins are drained in the present day, but retain clear evidence of containing extensive lakes in the past.

The geology, climate, vegetation, hydrology and archaeology of the Zacapu Basin are described. Diatomaceous sediments were collected from a number of points around the basin and results are presented from two surface sections and from a 14.3 m core taken in the remnant Laguna Zacapu. The Zacapu Brickpit Section dates from the Late Pleistocene. It records one major change in lake level followed by a series of minor fluctuations. The ^{14}C dates available suggest that a deep water episode occurred prior to 28,000 yr BP. As the section lies 15.82 m above the present lake, it clearly records a lake of considerably greater extent during this period.

Zacapu Section 1, 34.4m above present lake level, apparently dates from the Holocene. One ^{14}C date of 7,330 ± 70 yr BP (SRR-2256) was obtained from this section and there is reason to doubt its validity. If the date is accepted, the diatoms indicate deep water at the site prior to 7,330, shallowing by this date. The episode of deepest water in the basin apparently occurred soon after 7,330 ± 70 yr BP. A lake at this elevation would have extended far beyond the modern basin. An episode of increased salinity and alkalinity is recorded higher up the profile.

The core taken from Laguna Zacapu (Zacapu Core 1) provides a very detailed record of changes over the later

Holocene. Although the exact chronology is uncertain, due to a possible 'hardwater' error effecting the ^{14}C dates, the core probably covers the last 3,000 years. Changes in the diatom assemblages are interpreted as indicating variations in alkalinity, turbidity, silica content and temperature of the water. Using dates corrected for hardwater error, low lake levels seem to be recorded for the periods 3,000 to 2,000 yr BP; 1,600 to 1,360 yr BP (lowest?) and 210 to 110 yr BP. The abundance of small Stephanodiscus species in the top meter of the core is felt to be indicative of cultural eutrophication and may date from the post-Hispanic period.

In the Upper Lerma, or Toluca Basin, two pits were dug into the floor of the former Lake Chiconauhuapan. These records cover the Holocene. The presence of a number of pumice and ash layers in these sediments assisted in establishing both the correlation between the pits and their chronology, prior to ^{14}C dates being available. The basal unit of Pit 2, believed to be the oldest of those sampled, is a tephra thought to be the Upper Toluca Pumice, dating from ca. 11,600 yr BP. Although the diatom records are discontinuous in both pits, a series of fluctuations in water levels are recorded. After the deposition of the Upper Toluca Pumice, there was shallow, possibly deepening water at the site. The record was interrupted by the deposition of the Tres Cruces tephra at ca. 8,400 yr BP, Dry conditions and a hiatus in lacustrine sedimentation is suggested for about 7,000 yr BP. This was followed by a lacustrine

transgression peaking just prior to 6,000 yr BP. No diatom record was preserved for the period ca. 6,000 to 4,500 yr BP. A period of desiccation and a further hiatus in sedimentation may have occurred after 4,570 yr BP. A further transgression is then recorded, peaking at about 1,600 yr BP, after which water level again fell. Mineral magnetic measurements and sedimentological analyses suggest that there may have been human disturbance of soils from the basin slopes over at least the last 1,600 years.

In Chapter 8, the potential and problems of using subfossil diatom assemblages as palaeoenvironmental indicators are discussed. No modern analogues were found for a number of the fossil diatom assemblages and may reflect the impact of human disturbance on the modern Mexican aquatic environment. Diatoms did, however, prove to be sensitive indicators of environmental change in this region.

A comparison of the results from this study with those obtained from other parts of Central Mexico produces interesting parallels. In general, the period prior to 18,000 yr BP seems to have been wetter then present. The early Holocene was probably also wet, but a dry event may be indicated for the period 7,500 - 7,000 yr BP. Wetter conditions, however, seem to have been reestablished quickly. The climate then appears to have become drier again, culminating around 4,500 - 4,000 yr BP. Moister conditions may have returned by 2,000 yr BP. Dry and cool conditions are indicated for the period of the European Little Ice Age.

A survey of the evidence for climatic change from other

parts of the American tropics and subtropics, indicates that the trends in Central Mexico were more like those from Central and South America, than from the southwest U.S.A. Although not as dramatic as the climatic changes recorded elsewhere in the tropics, the reality of climatic fluctuations over the Late Quaternary in Central Mexico, seems to have been established. Archaeological evidence suggests that Man has been responsive to the changes. Over the last 3,000 years, however, the evidence of Man himself as an agent of environmental change has become increasingly clear. Although human impact complicates the environmental record contained in recent sediments, it does not seem to preclude the recognition of climatic changes over the Holocene, a period which is now being studied with great interest.

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Chapter 1

LATE QUATERNARY ENVIRONMENTS OF CENTRAL MEXICO - AN INTRODUCTION

1.1 Background

The Late Quaternary period has been the most intensively studied of the geological timescale, thanks to the better preservation of sedimentological and biological evidence, its suitability for isotopic dating methods (especially ^{14}C) and, over the last 10,000 to 15,000 years, through inference and information from the record of Man (Goudie, 1983). In spite, or perhaps because of this, the picture which has emerged is complex and often contradictory from different regions and from different sources. Whilst at the scale of the Quaternary as a whole (about 1.6 million years) the global climate has clearly oscillated between glacial and non-glacial modes, within this, regions have shown differences of 1000s of years in the peaks of these phases relative to the global or even continental average. Associated with this study of the growth and decay of large ice masses, has been the concern with the contemporaneous climatic changes in the non-glaciated tropics and subtropics and especially fluctuations in moisture availability in these latitudes. The overall aim of this thesis has been to investigate such climatic and environmental changes, as recorded by lacustrine sediments in Central Mexico.

At this stage it is perhaps unwise to talk in terms of the effects of changes in precipitation and evaporation, for

as will be discussed below, their balance and the question of their fluctuations relative to glaciation, is uncertain. It is worth reemphasising that whilst the events of the Quaternary may be associated with shifts of the global atmospheric and oceanic circulation patterns, their manifestations may be time transgressive (Grove, 1979) and to search for synchroneity may be to undertake a wild goose chase. It is only necessary to look at the complexity of today's climatic patterns to appreciate the problems of interpreting the limited data from the past.

`das Problem'

In 1926, Fritz Jaeger posed it thus:

> `The problem can be summed up in the following question: in the late glacial was the climate of the tropical dry zone wetter or drier than today?'

It has not yet been satisfactorily answered.

Early work on the climatic oscillations in lower latitudes was concentrated in the south-western U.S.A., in the Great Basin and Basin and Range areas, where workers such as Russell (1885, 1889) and Gilbert (1890) studied the fluctuations in lake levels in that semi-arid to arid area and recognised the environmental implications of a Lake Bonneville (Utah) the size of Lake Michigan; it being but one of a series of lakes filling, partly or wholely, the depressions in the area during the last glacial maximum. Within this region, a glacial = pluvial relationship was established, it being one of the few areas where glacial moraines run down to and can be correlated with, lacustrine

deposits. During the `pluvial' (after Tylor, 1868) it was believed that precipitation had increased in the semi-arid and arid areas of today and that this had resulted in more abundant surface run-off and hence, higher lake levels. In the 20th century, this view has undergone severe modification, mainly with the advent of ^{14}C dating. Part of the explanation for this shift must, however, lie in the change in the focus of much of the work to Africa, especially along the southern border of the Sahara and the area of the Ethiopian highlands and the East African Rift Valley. A general picture has emerged from here of aridity, especially along the tropical margin of the Sahara, during the period of the maximum of the last glaciation (the Wisconsin or Würm) at about 18,000 years BP (before present) but becoming most intense between 15,000 - 12,500 yr BP (Street and Grove, 1976; Sarnthein, 1978). There is however, evidence for high lake-level stands in the basins of the Atlas Mountains and in central southern Africa (Butzer et al, 1973) at this time. This problem of lack of synchroneity between the temperate and tropical margins of the subtropical arid zone was one which exercised Ellsworth Huntingdon as early as 1913 in his paper `The Shifting of Climatic Zones as Illustrated in Mexico'.

There might appear then, to be a simple division into two schools of thought concerning the tropics and subtropics, one favouring glacial aridity and the other glacial pluviosity. Clearly, this is a simplification based upon a

global-scale dependent view and is further complicated by discussion over the validity of the concept of `pluvials'. Galloway (1970), reviewing the evidence for the south-west U.S.A. suggested that a preferred term would be `minevaporals' since he believed that a lowering of annual temperatures by 10 to 11°C would be sufficient to allow for the expansion of lakes without any increase in precipitation. More recently, the same author (Galloway, 1983) has defended his view of a cold - dry climate in the south-west at the glacial maximum. He does, however, suggest that mild, `pluvial' climates may have occurred in the region, especially in the period 14,000 - 9,000 yr BP. That the idea of a dry glacial has been proposed from the area where a glacial-pluvial link seemed most valid (but see Brakenridge, 1978 suggesting a cold, dry full glacial) is indicative of the continuing state of flux in our knowledge of Quaternary palaeoenvironments.

Any recognition of a changed climate, has to be put within the framework of the global patterns of atmospheric circulation, with allowances for the more local controls of land and sea configuration, relief, degree of continentality, etc.. The general picture which has emerged is of an equatorward shift in the climatic belts during the glacial periods with a greater displacement in the northern hemisphere than in the south (Harrison et al, 1984). Originally, it was thought that such a shift was effected mainly through a compression of the sub-tropical belts, leaving the equatorial areas largely unaffected. More recent

work, however, such as Van der Hammen (1972) on the Amazon Basin and Talbot and Delibrias (1977) on Ghana, has shown that this was not the case. The area of the tropical rainforest was considerably reduced (except possibly in parts of Southeast Asia) and the present distribution of a number of species has resulted from their isolation in forest refuges (Brown et al, 1974). How far these shifts in the major wind belts extended is problematic, although Flint (1971) has suggested an equatorward depression of 15° in the northern hemisphere. In Africa, there is considerable evidence from ancient dune fields of a southerly extension of the Sahara in the Late Pleistocene by 450 km (Grove and Warren, 1968), as the Equatorial Trough moved equatorward and more southerly latitudes came under the influence of the descending limb of the Hadley cell. In the case of Mexico, however, where desert environments are today confined to a relatively small area in the north, the meteorological conditions are very different. How far a southward extension of aridity during the glacial Quaternary can be recognised is as yet unknown and would be constrained both by the effects of altitude and the more maritime conditions (relative to Africa) that would have prevailed, even allowing for a glacial fall in sea level of at least 100 m. The attempt to model global circulation at the last glacial maximum by the CLIMAP group (1976) and a discussion of the simulation based on this by Manabe and Hahn (1977) indicate drier conditions over the tropical continents. More recent modelling work by

Manabe and Broccoli (1985), indicates that the decrease in soil moisture in the tropics at 18,000 yr BP, derived from the model, was not statistically significant. The scale of this type of work, however, is such that it is difficult to determine the climatic conditions predicted by the models, for Mexico.

The importance of the temperature of the oceans and the paths of the major oceanic currents is clear in determining both the temperature and the precipitation that can be expected by neighbouring land masses. The differences between modern and glacial values of sea-surface temperature are at a minimum in the subtropical gyres and Manabe and Hahn (1977) point out the presence of warm anomalies, especially at 20°N. On the basis of faunal analyses from cores from the Caribbean, Prell and Hays (1976) suggest sea-surface temperatures during glacial winters of 22 to 23°C and in summers of 26 to 27°C, a considerably greater variation than at present. Using the technique developed by Imbrie and Kipp (1971), they calculate a glacial-interglacial ocean temperature variation of only 2-3°C. Brunner and Cooley (1976) also deduce a similar change in sea surface temperature (1 - 2 °C), with the greatest cooling in summer. Whilst Emiliani's isotopic work (Emiliani et al, 1975) suggests that the variation was greater (6 to 7°C), the Gulf of Mexico and Caribbean seem likely to have persisted as moderating influences on the climate. To the west of Mexico, however, a glacial southward extension of the cold California current would have tended to increase the stability of the

air and reduce precipitation. The reconstruction of surface conditions at the glacial maximum by the CLIMAP Project Members (1981), indicates that summer sea surface temperatures off the west coast of Mexico were 4°C cooler than present. Winter temperatures and temperatures in the Gulf of Mexico were, however, much as today. At this latitude, the only area with a land-sea distribution comparable to that of Mexico is the south-east Asian peninsula, which itself still needs further investigation.

1.2a Mexico and its setting

The funnel-shaped land mass of Mexico (Figure 1.1), lying within the tropics and sub-tropics between about 15° and 32°N, today displays an enormously wide variety of environments with hot desert in the north and north-west (Plate 1), remnant ice patches on the highest volcanic peaks and humid tropical forests along the Gulf coast and in the south-east (Plate 2). In summer, it lies mainly within the influence of the North-East Trades, drawn in by a monsoon circulation over the Gulf of Mexico and central North America. The effects of the Westerlies are generally confined to the north-west of the country and mainly to the winter months. Incursions of polar air, the nortes, affect the Gulf coast during the winter. However, as Mosiño and García (1974) have pointed out:

> `only a thorough understanding of the great influence that the orography of Mexico exerts on air temperature, precipitation distribution and even air circulation, can explain the diversity of climates found in this

country'

Clearly, any attempt to reconstruct past environments is going to have to heed this caveat. The present-day climate of Mexico and the factors influencing it are discussed in more detail in Chapter 2.

1.2b The Physical Environment

The main topographic feature of the Mexican land surface (Figure 1.2) is the Central Plateau, rising southward from the border with the U.S.A. to a maximum at about 19°N, attaining its greatest elevation (over 2,200 m a.s.l.) at Mesa de Anahuac. This plateau, which is largely responsible for the country's average elevation of approximately 1,500 m, is generally considered to fall into two sections. The northern one of these is the Mesa del Norte, which is a southerly extension of the Basin and Range country of the U.S.A and comprises a series of basins, some fed by endorheic streams from the Sierra Madre Occidental (see Figure 3.2). The southern section is the Mesa Central, which is higher and crossed from NW to SE by a series of ridges. The plateau is bounded to the west by the chain of the Sierra Madre Occidental and to the east falls steeply to the Gulf coastal plain, although this edge is referred to as the Sierra Madre Oriental. South of the Mesa Central is the Sierra Volcanica Transversal or Neovolcanic Axis, running from west to east at about 19°N. It includes the highest peaks in Mexico: Citlaltépetl (or Orizaba) 5,~~699~~ 750 m a.s.l. and Popocatépetl, 5,452 m. The geology of this Axis is described in some

detail in Chapter 3. Between the Neovolcanic Axis (N.V.A.) and the Sierra Madre del Sur lies the Balsas Valley, draining into the Pacific through the latter range. Further south still, the major physiographic provinces are the Isthmus of Tehuantepec, the Yucatán Peninsula and the Chiapas Mountains, which run south into Guatemala.

Mexico has a long and continuing history of volcanic and tectonic activity, which has played a major part in fashioning the landscape and in determining the environments within it. In addition, this activity has clearly had a considerable influence on Man (Mooser and González-Rul, 1961), at times disrupting life and yet in other ways, through the fertile volcanic soils, for example, bringing benefits. In investigations of the past, volcanic deposits have proven valuable where they have sealed soil surfaces and have been used as stratigraphic markers in both marine and continental sequences. Kennett and Huddlestun (1972) in studying cores from the Gulf of Mexico recognised three major volcanic ash horizons at 135,000, 90,000 and 75,000 yr BP, all of which coincide with climatic coolings. On a more local scale, a tripartite pumice sequence (pómez tripartita de grano fino) is used as a marker layer within the Basin of Mexico. Suggestions for the source of this vary. Cornwall (1971) proposes Iztaccihuatl, Mooser and González-Rul (1961) suggest Popocatépetl or Nevado de Toluca. Bloomfield and Valastro (1974) support the idea of the Nevado de Toluca as the source and suggest that it may be from a major, violent

Plinean type eruption dated at ca. 11,600 yr BP.

This brief consideration of vulcanicity in Mexico leads one naturally to the place of Man in that country. Evidence now suggests that Man had entered Mexico from the north, by the later part of the Pleistocene. The central part of the country has proven particularly attractive for settlement, partly due to the modifying effect of the altitude on temperature and to a fairly wide range of biota, but also to the suitability of the flat, alluvium-filled basin floors as sites for habitation, especially on lake shores. The Central Mexican lake area provided the most important centre of highland Indian civilisation in Meso-America. The archaeology of this area is discussed in Chapter 3.

1.3a Quaternary studies and Climatic Change in Mexico

The idea of climatic and of more general environmental change, initiated in the latter part of the 18th century, found a very early proponent with reference to Mexico in the person of Alexander von Humboldt, who in 1811 published his 'Essai Politique sur le Royaume de la Nouvelle Espagne'. He believed that the climate was then more arid than it had been at any time since the founding of the Aztec capital in ca. 1345 A.D. (see Chapter 3, section 3e). As mentioned above, Mexico was also used as an illustration of the shifting of climatic belts by Huntingdon in 1913, who cited the fall in the level of Lago Texcoco in the Basin of Mexico as the main evidence for climatic change. In spite of this early start, our knowledge of the Quaternary, even the later part, in

Mexico is as yet scanty (González Quintero, 1974). An indication of this uncertainty is provided by Sarnthein and Diester-Haass (1977) who, on a global map of aridity during the last glacial maximum simply have a ? over Mexico. To the north, few studies have extended far south of the Mexico-U.S.A. border and elsewhere, investigations have had a largely archaeological basis, with a marked tendency to concentrate on the Basin of Mexico (Limbrey, 1976; Mirambell, 1978; Niederberger, 1979). The work of Deevey (1944), Sears and Clisby (1955), Hutchinson et al (1956), Heine and his associates (1973 - 1984), Watts and Bradbury (1982) and Brown (1984a) have extended this range, but no consensus has yet been reached.

1.3b Problems and Prospects

The sheer diversity of conditions within a relatively small area makes Mexico of considerable palaeoenvironmental interest. Heine (1973a, 1978) has proposed a sequence of five glaciations extending back over the last 40,000 years, based on evidence from the moraines on the mountains of the Neovolcanic Axis (details in Chapter 8). There is some conflict, however, between this chronology and that developed by White (1962) and White and Valastro (1984). The proportion of the land covered by ice was not, however, very great and with the last maximum of glaciation being delayed until about 12,000 yr BP (cf. the global maximum at ca. 18,000 yr BP). Conditions over the North American land mass,

particularly changes in the extent of the Laurentide ice sheet, clearly played a forcing role. The lack of ice accumulation at the time of the global maximum is seen in terms of a want of sufficient precipitation (Heine, 1973a). It was probably only with the retreat of the Cordilleran glaciers and the Laurentide ice sheet, the reestablishment of warmer sea-surface temperatures and a subsequent increase in precipitation, that the Mexican glaciers grew. A similar situation has been proposed for the glaciers of Baffin Island (Miller, 1973). The inference of a reduction in precipitation raises the question of whether there was an extension southward of the deserts of northern Mexico and if so, how far?. Equally, one may ask how far the `pluvial' conditions inferred for the Great Basin area, extended south.

As was noted previously, much of the work on the past environments of Mexico has been associated with archaeological studies. The presence of Man since the Late Pleistocene, Mexico's position as an hearth area of sedentary agriculture and the importance of the early civilisations of Mexico and Central America, have provoked considerable interest. Much of the archaeological work, however, lacks a sound chronological framework and early excavations took little note of stratigraphic relationships. Nevertheless, publications such as those arising from the joint Mexican-German Puebla-Tlaxcala project (e.g. Heine, 1973b), can be most useful. Partly associated with these studies, the role of the study of fossil faunas in the reconstruction of past environments, must be mentioned. Examples of this in Mexico

are studies of mammoth remains, birds (Alvarez, 1977) and voles (Smartt, 1977). Some of the most contentious ideas concerning Late Quaternary climates in the semi-arid and arid south-west U.S.A. and northern Mexico, have come from the study of packrat middens undertaken by Wells (1966, 1979). His ideas are outlined below. Van Devender (1977) and Van Devender *et al* (1984) use the same method.

1.3c Work so far, a general appraisal

Piecing together some of the work carried out so far, it is possible to obtain an initial picture of the general conditions in Mexico at the peak of the global cooling of the last glaciation, concentrating on the area south from the U.S.A. to the Neovolcanic Axis. As indicated above, work has tended to polarise to the north and south of this belt, but a few comments may be useful. Studies undertaken in southern Texas, New Mexico (Markgraf *et al*, 1984) and in the present Chihuahuan Desert (Reeves, 1965) seem to agree that the glacial maximum was marked here by an increase in available moisture. In the border area, Wells' and Van Devender's studies of packrat middens both indicate the presence of quite widespread woodland in the present areas of desert. Wells (1978) proposes a post-glacial origin for the Chihuahuan Desert (developing from about 11,000 yr BP). There seems to be quite clear evidence that many of the basins of the Chihuahuan and Sonoran deserts contained lakes during the Pleistocene, for example the very large Laguna de

Guzman and Laguna de Palomas lying at about 30°N. In a study of the Palomas Basin, Reeves (1965) indicates that at one time the lake inundated about 7,700 km^2. He suggests that a belt of 'pluvial' lakes extended from Chihuahua across the Sierra Madre and as far as the Basin of Mexico. Smartt's (1977) study of Microtus (vole) species, slightly further north also indicates a late Pleistocene 'pluvial', supporting Antev's (1954) proposition of an increase in rainfall, rather than Galloway's 'minevaporal' idea. Smartt suggests that rainfall was fairly equally distributed between winter and summer at that time. The whole of the northern part of Chihuahua today bears clear evidence of formerly far more extensive surface drainage in dry or intermittently active stream channels and in drying lake basins. These basins were probably regionally integrated at some time during the Pleistocene (Groat, 1972), many linking up with the Río Grande.

Further south, at about 27°N, Meyer's (1973) study of the palaeoecology of the Cuatro Cienegas Basin, indicated the persistence of xeric scrub and grassland throughout the Late Quaternary. He commented upon the lack of geological evidence for large Pleistocene lakes in that area. However, at about the time of the global glacial maximum, a regional climate cooler and possibly moister than present is suggested, with edaphic conditions being the limiting factor on the spread of woodlands. One other study which comes from this 'middle' latitudinal section, is that undertaken by Dalquest and Roth (1970) in southern Tamaulipas (Figure 1.1),

at about 24°N. On the basis of late Pleistocene fossil mammals, they feel that there is some evidence for slightly greater aridity during this period, with a depression of the contact between the neotropical and nearctic faunas.

The area at about 20°N, roughly straddling the country through Lake Chapala, the Lerma Basin and across to the Basin of Mexico, seems to show the now more common picture of Late Pleistocene aridity, although of less severity than in Africa. Early studies, however, (Bryan, 1948; Arellano, 1953) had suggested that moist conditions prevailed during this period. Perhaps more problematic at this latitude, is the scale of climatic change, particularly to the centre and west of Mexico, along the dislocated drainage of the Río Lerma. Today, this region is one where there is little interannual variability in rainfall (Wallén, 1955) and with greater precipitation to the west than in the Basin of Mexico. It appears that this relationship persisted during the later part of the Pleistocene. On the basis of diatoms (Bradbury, 1971), pollen (Watts and Bradbury, 1982) and fossil avifauna (Alvarez, 1977), the environment over much of this area has been interpreted as remaining relatively stable, although dating control has generally been rather poor. The identification of changes less dramatic than those experienced in the East African Rift, for example, requires a careful interpretation of evidence and a good chronological framework. That lake levels in Central Mexico have fluctuated in response to climatic changes over the

historical period (West, 1948), however, suggests that similar changes could have occurred in the past. The apparent climatic stability of this west/central area of Mexico is in marked contrast to most of the tropical areas studied so far. This, in itself, makes the region worthy of further study.

The scantily studied area from about 20°N to just north of the tropic of Cancer would seem to be an area suitable for palaeoenvironmental study. Investigation of this area would help to resolve the problem of how climate altered south of the present Chihuahuan desert during the late Pleistocene and Holocene. Most studies would suggest that the full glacial climate became drier from north to south, although the degree of change was also reduced. Wells (1979), however, has proposed that there was actually a NW to SE gradient of increasing summer rain with decreasing distance from the summer monsoonal source area of the Gulf of Mexico. It may actually be possible to identify a turning point or hinge zone in the Central Mexico area, from more to less available moisture, during this period.

1.4 Some Questions to be Answered

In the central part of Mexico, therefore, a number of questions remain to be answered concerning environmental change over the Late Quaternary:

1) What was the nature and degree of environmental change experienced over this period?

2) Did the moister Late Pleistocene conditions of the south-

west U.S.A. extend as far as Central Mexico or did the more usual tropical 'aridity' prevail here too?

3) As suggested by evidence currently available, did Central Mexico lie on, or near, a hinge-zone of 'no change' between areas experiencing conditions markedly wetter or drier than present, during the Late Pleistocene?

4) What has been the pattern of climatic changes through the Holocene to the conditions of today?

5) How far has Man had to adapt to these changes in the natural environment and how far has he himself been an agent of change?

1.5 Approach and Outline

In view of the nature of the questions being asked (section 1.4) and the complexities of the present day environment of Central Mexico, it was clear that some study of the latter would have to be undertaken and that the choice of a suitably sensitive palaeoenvironmental tool was vital. Apart from the need to look at present day climate and the features of the atmospheric circulation affecting it, it was felt that establishing the reality of climatic changes over the recent past would provide a firmer foundation for their identification over a longer time scale. These two aspects are covered in Chapter 2.

On the basis that lake basins which have been closed for part, or all, of their Late Quaternary histories have been seen to provide particularly good records of environmental

change in the tropics and sub-tropics over this period (Street-Perrott and Harrison, 1985), parts of Central Mexico with potential for this type of study were identified. Lake basins in the Neovolcanic Axis of Central Mexico were selected as being the most suitable (see Chapter 3). The basis for studying lake-level fluctuations and the geological, climatic and archaeological context of Central Mexico is described in Chapter 3. Also in this chapter is a discussion of the reasons behind the choice of the study of diatoms as the main investigative technique. Previous studies in the tropics had suggested that diatoms would be sensitive to variations in climate (expressed as changes in the balance of P - E). The volcanic geology of the Neovolcanic Axis seemed likely to be favourable for their preservation. The value of diatoms as indicators of cultural eutrophication was also well established (Bradbury, 1975; Grimes et al, 1984).

Having selected the study area and technique, it became apparent that the paucity of information on the limnology and diatom flora of Central Mexico necessitated some work on these aspects. The results of the sampling programme and of the counts of collections of modern diatoms, with some tentative ecological interpretations, are presented in Chapter 5.

The results of investigations of sediment sequences from the Zacapu basin in Michoacán and the Upper Lerma basin in the Estado de México are reported in Chapters 6 and 7. Where possible, the collection of present day Mexican diatoms

has been used as a basis for interpreting the sub-fossil assemblages.

In Chapter 8, the value of the modern diatom collection as a source of analogues for the past is discussed, together with the general validity of using a limited number of sampling sites from a basin as a basis for palaeoenvironmental reconstruction. Both the advantages and handicaps of working in a densely settled area are also considered. By placing the results from the new study sites into both their Central Mexican and broader Central American (*sensu lato*) contexts, the validity of attempting palaeoclimatic interpretations is established. On this basis, some of the questions posed concerning the degree and nature of environmental change in Central Mexico over the Late Quaternary are addressed and some suggestions put forward.

Chapter 2

THE CLIMATE OF MEXICO, VARIATIONS AND VARIABILITY

2.1 Introduction

Before any attempt is made to reconstruct past climates and to interpret climatic changes in terms of variations in the atmospheric circulation, it is necessary to have both an understanding of the factors influencing the climate in the present day and to establish that climatic variability is a reality. The latter is of some importance, especially in Central Mexico, where previous studies have tended to suggest a rather monotonous climatic record over the Late Quaternary (Watts and Bradbury, 1982) and where many apparent changes have been attributed to tectonism rather than to climate. In this chapter the present-day climates of Mexico will be described and archaeological and historical records examined for evidence of climatic fluctuations.

2.2 Factors Influencing the Climate

As has been pointed out in Chapter 1, the climate of Mexico is extremely diverse. The factors responsible, and the resulting distribution of temperature and rainfall through the year, will be discussed below. In very crude terms, Mexico can be divided into three climatic zones: the humid tropical south; a central area of winter-dry, summer-wet conditions and the semi-arid to arid northern plateau. This general pattern, however, shows many local variations. The factors determining climate operate at a number of

different spatial and temporal scales. Mosiño (1966) has suggested that for Mexico, the influences on climate are, in order of importance: latitude, altitude, land/sea distribution, ocean currents and the occurrence of hurricanes and their trajectories. Variations in solar radiation, both spatially and temporally, must also be considered. Jauregui (1978) provides a discussion of the seasonal distribution of solar radiation across Mexico.

2.2a Latitude

Mexico straddles the boundary between the zones of influence of two major features of the atmospheric circulation: the Trade winds and the sub-tropical high pressure belt. During the winter, the northern part of the country is affected by a third major feature, the Westerlies. Seasonal shifts in the latitude of these major circulation features are the primary influence on the distribution of precipitation through the year. In the northern hemisphere winter (Figure 2.1), when the Intertropical Convergence Zone (I.T.C.Z) is displaced equatorward, only the southern part of Mexico lies in the path of the north-east Trades. Most of the rest of the country, including the Neovolcanic Axis and the northern plateau (see Chapter 3), comes under the influence of the sub-tropical high pressure belt, with a westerly flow aloft. This results in stable, dry conditions over much of the country. In the late winter and early spring, however, depressions or cold vortices, which tend to

develop along the leading edge of Rossby waves, can produce precipitation. This is most common in north-west Mexico where the resulting rains are called equipatas, but the precipitation may extend across the northern plateau, falling as snow on the Sierra Madre Occidental and as far south as the Bajío depression (as the cabañuelas). Also during the winter, in periods of meridional flow (i.e. low-index conditions), when the amplitude of the waves in the upper westerlies increases, outbreaks of cold Polar air, called nortes, may affect the areas bordering the coast of the Gulf of Mexico. Nortes may last from 2 to 3 days, in any period between October and May. The cold air, coming down through the centre of the North American continent, is modified as it passes over the warm waters of the Gulf. The nortes lead to sharp falls in temperature along the coast, but also bring winter rainfall, mainly to the highlands, as far south as the Yucatan Peninsula. In the extreme north-west of Mexico and especially the west coast of Baja California, the influence of the mid-latitude Westerlies predominates. Depressions associated with these are a major source of rainfall in this region.

In summer (Figure 2.2), as the I.T.C.Z. moves north, accompanied by the semi-permanent Bermuda-Azores and the East Pacific highs, a deep easterly trade-wind flow, covers most of Mexico. As this flow crosses the Caribbean and the Gulf of Mexico, it picks up moisture and brings the major rains to much of the country. Within the trades, the so-called easterly waves may produce periods of continuous rain,

lasting 2 to 3 days. These are known as temporales. The main rainy season is often interrupted, in August, by a drier period called the canícula. This is due to the temporary disruption of easterly flow across the country. The length of the canícula is very important in determining whether rainfall is above or below normal in any particular year (Toledo, 1980). In some years, the I.T.C.Z. travels as far north as southern Mexico and disturbances associated with this may bring heavy rains, especially on the Pacific side of the country.

2.2b Altitude

The relief of Mexico has a profound effect upon the actual distribution of temperature and precipitation resulting from the large-scale shifts in wind regime outlined above. A general description of the main relief features was given Chapter 1, section 2b. The effects of the large mountain masses may be summarised as follows:

1) the blocking of shallow, stable air masses

2) the diversion of winds; for example the Trades are deflected at low altitudes by highland adjacent to the Gulf of Mexico, to blow as southeast winds (Mosiño, 1964)

3) orographic lifting and cooling, especially of saturated air, for example along the eastern flank of the Sierra Madre Oriental where they cause heavy precipitation (> 3,500 mm) between 100 and 600 m a.s.l. (Mosiño and García, 1974).

4) adiabatic warming, leading to warm, dry conditions in the

lee of mountain barriers, especially where the wind is more or less unidirectional. This effect is particularly important in the south of the country where the Trades predominate throughout most of the year and it can create great variations in precipitation over short distances. Locally, the influence of katabatic winds may also be important.

Overall, the high elevation of much of Mexico gives rise to temperatures well below those expected in these latitudes. The altitudinal zones traditionally recognised are the tierra caliente, <1000 m a.s.l.; the tierra templada, 1000 to 2000 m a.s.l. and the tierra fría > 2000 m a.s.l. (Vivó Escoto, 1964). For part of the Sierra Madre del Sur, on the Pacific coast at about 17°N, González Quintero (1980), has established that the average rate of temperature decline with increasing altitude is 0.6°C/100 m.

Whilst latitude is probably the main control on air temperature north of the Tropic of Cancer, to the south of it, altitude is probably the more important. The highest peaks in Mexico, at > 4,500 m, support permanent snow and ice caps.

2.2c Land/Sea Distribution

The shape of the Mexican landmass, tapering in the south, results in a decrease in continentality from the border with the U.S.A. equatorwards. In the southern part of the country, the climate is strongly influenced by both the Pacific and the Gulf of Mexico-Caribbean. Towards the border

with the U.S.A., however, such maritime influences are greatly reduced, and diurnal and annual variations in temperature and precipitation increase. The heating of the continental interior during the summer, reinforced by that over the U.S.A., creates a monsoon-type circulation. A comparison of the temperature and pressure changes over the North American Plateau (the Mexican Plateau, the Sierra Nevada, the Great Basin and the Rockies), with those over the Tibetan Plateau, and the resulting monsoon circulation and precipitation patterns, has been made by Tang and Reiter (1984). These authors highlight that the main area of monsoonal influence over North America covers northern Mexico and extends north, bifurcating around the North American Plateau with one `tongue' going up the west coast and the other across the central plains. A further small `wedge' of monsoonal influence is identified over the lower Mississippi Valley. Tropical maritime air is drawn in over Mexico mainly from the Gulf and up across the central and southwestern U.S.A. This Mexican monsoon is particularly important in bringing rain to the north of the country. The influence of the Gulf of California (Mar de Cortés), on Mexico, is rather limited, due to the large area of land surrounding it, although it is an important moisture source for the region of Nevada (Tang and Reiter, 1984). The area east of the Baja California watershed, including the lowlands of Sonora and Arizona, exhibits the greatest annual temperature variations in Mexico.

2.2d Ocean Currents

The major ocean current affecting the climate of Mexico is the cold California current. This flows southward, off the west coast of Baja California and produces a temperature inversion there in summer. The coolness of the ocean in this area leads to a very delayed temperature maximum (in August or September) in this part of the country.

In contrast, sea surface temperatures over the Gulf of Mexico and Caribbean are quite high, throughout the year. The waters of the northern Gulf are cooled in winter by cold air from the interior of the North American continent. In winter, the sea surface temperature ranges from about 19°C in the north of the Gulf, to 25°C in the south. In summer, the average for the whole Gulf is about 29°C. In the Caribbean, the annual temperature range is less, from about 25°C to 29°C. The warm surface water temperatures encourage instability over the area in summer and create a warm, moist air mass (Collier, 1964). In a study of water vapour flux over North America Rasmusson (1967), identified the Gulf of Mexico as a major source. Although the meridional (poleward) moisture flux from the Gulf was the more important, the Gulf of California was identified as a secondary source.

2.2e Hurricanes

Hurricanes (tropical cyclones) may develop off either the Pacific or Gulf coasts of Mexico during the late summer and early autumn. Generally, they are more numerous in the

Gulf, but there is considerable variation from year to year related to the relative strengths and positions of the Bermuda-Azores and East Pacific high-pressure areas (Jauregui, 1979). A greater abundance of Pacific coast hurricanes tends to lead to wet conditions over much of the central and northern plateaux. When cyclone activity is mainly over the Gulf, however, the associated rains are more localised and of greater intensity, near the Gulf coast itself.

2.3 Temperature and Precipitation Patterns for Mexico

2.3a Temperature

The pattern of temperature distribution in Mexico, resulting from the factors listed in section 2.2, shows a reversal between winter and summer. In the winter, temperatures decrease from south to north due to greater continentality away from the equator, to incursions of cold arctic air and to cold air brought into the central plateau area by vortices in the upper westerlies. The nortes may also bring cold conditions to the Gulf coast.

In the summer, however, the pattern is one of temperatures increasing from south to north. Again, this is partly as a result of heating of the northern interior of the landmass, but it is also due to the modification of temperatures further south due to altitude and to the cooling effect of the onset of the summer rains. The month of maximum temperature across the country is shown in Figure

2.3. The warmest month generally occurs before the summer solstice and is May over much of the country. It tends to occur later in the year moving northward and is latest in western Baja California due to the influence of the cool California current. South of the Tropic of Cancer, there may be two peaks in temperature before and after the main part of the rains, although the first is generally the larger. Temperature variations on both a monthly and annual basis tend to increase northwards. In terms of monthly temperatures, north-west Baja California is again an exception due to the modifying influence of the ocean.

2.3b Precipitation

The amount of precipitation occurring over Mexico as a whole is determined by changes in:

1) the location of the I.T.C.Z.

2) the strength of the Trade winds, associated with

3)the location and intensity of the semi-permanent high pressure cells over the Atlantic and Pacific Oceans

4)the number and intensity of disturbances in the Trade winds, including hurricanes

5) the influence of depressions associated with the mid-latitude Westerlies

The spatial distribution of annual average rainfall is shown in Figure 2.4. The wettest parts of Mexico lie south of 22°N, on the mountain slopes facing the Gulf of Mexico and exposed directly to the Trades, nortes and tropical cyclones. Some places receive >3,500 mm per year. The Gulf coast is

generally wetter than the Pacific coast, although the Sierra Madre de Chiapas, in the south-east, is very wet. The interior basins of the south, such as the Balsas, are much drier due to the blocking and adiabatic effects of the highland. Rainfall in these areas is usually between 600 and 1000 mm.

The southern part of the central plateau (Altiplano) and the Neovolcanic Axis, receive an average of 1000 mm per year, decreasing northward. Precipitation occurs mainly as convective rain, associated with moist air from the deep trades which cover the area in the summer. In the early autumn, tropical cyclones may bring rain, especially to the south facing slopes of the Neovolcanic Axis. The winter in this region is generally dry, except when mid-latitude depressions or cold vortices track this far south. There can also be some precipitation from nortes if they are very deep. Most rainfall in this central area falls in June and July.

The northern plateau area is very dry, much receiving <500 mm per year. There is some summer rain due to convection and occasional winter rain brought by depressions. The driest part of the country, receiving <50 mm per year, lies around the mouth of the Colorado River, under descending dry air from the sub-tropical high. The west coast of Baja California, north of 26°N, is slightly wetter and, unusually, receives most of its rain in winter due to depressions and cold vortices (Figure 2.5).

The year- to -year variability in precipitation is

indicated in Figure 2.6, giving the coefficient of variation of annual precipitation for 53 stations with reliable records of at least 20 years (Wallén, 1955). In general, low precipitation is associated with high variability and high precipitation with low variability. There are, however, several areas of Mexico that have high or moderate rainfall, but which also show quite high variability. The lowest variability (coefficient of variability ca. 15%) occurs in the area of the Neovolcanic Axis and Central Plateau, extending north along the Sierra Madre Occidental. This is probably because this area can receive precipitation under a range of different climatic circumstances (see section 2.4). The major transition zone from low or moderate to high variability, lies between the central plateau and some surrounding areas. There is also a sharp change between the Sierra Madre Occidental and the coastal areas of the states of Sinaloa and Sonora. Highest variability occurs mainly in the low precipitation areas of north and north-west Mexico. In Baja California, the coefficient of variation is about 50%, probably due to the influence of the occasional Pacific hurricane hitting the south of the peninsula in the autumn. Other areas with high variability are in Tamaulipas, northern Veracruz and the coast of the Gulf of Tehuantepec. High variability along the Gulf coast tends to be associated with those areas receiving a significant part of their annual precipitation as spring and autumn rainfall from nortes and hurricanes. The presence of highland near the coast, especially in the south, can lead to major local variations

due to minor changes, from year to year, in the exact direction of the Trades.

In order to highlight the relationship between rainfall and circulation regimes, Wallén (1955) also looked at monthly relative interannual variability. Usually, low precipitation months showed high variability and vice versa. Coastal areas were shown to have variability maxima in April and minima in July, whilst for inland areas these occurred in January and July. As summer rainfall predominates over most of Mexico, it is not surprising that this is the time of least variability. The coastal April maximum is particularly pronounced along the Gulf coast and appears to be related to the variability of nortes. Over the interior of the country, October variability is greater than that of April, even though precipiatation is higher. This is probably because much of the autumn rain is brought by easterly waves in the trades and hurricanes which affect the coastal areas more regularly than those inland. The unusual precipitation regime of western Baja California, where most of the precipitation is brought by depressions in the westerlies, is indicated by having a variability maximum in October and minimum in January to April.

2.4 Changes in the Atmospheric Circulation and Climatic Variation

In addition to the relatively simple changes in climate (especially precipitation), determined by latitude, variations in the zonality of the atmospheric circulation are

of major importance for the climate of Mexico. The significance of such changes and in particular, their relationship to levels of precipitation in Central and northern Mexico has been discussed by Klaus and Jauregui (1975) and Jauregui (1979). Under conditions of highly zonal flow in the Upper Westerlies, the I.T.C.Z. moves well to the north in the summer, bringing a strong trade wind flow over the whole of Mexico. This results in high summer precipitation (Wallén, 1955) as the sub-tropical high pressure areas are displaced far poleward. A more meridional flow, however, with large amplitude waves in the Upper Westerlies, tends to block the penetration of the moist tropical air during the summer `monsoon'. An area of high pressure, separate from the main Bermuda-Azores anticyclone, develops over the northern and central plateaux. In August 1969, conditions such as these led to rainfall 25% below normal in the states of Zacatecas, Chihuahua and Coahuila. The south-east of the country, however, receives above normal precipitation under these circumstances, due to an upper atmosphere wave separating the two high pressure areas (see Klaus and Jauregui (1975), figures 9 and 10). In winter, a meridional flow also leads to more incursions of polar air from North America, resulting in very cold conditions with early and late frosts. Cold arctic air also blocks the penetration of the mid-latitude Westerlies into the northern plateau, reducing precipitation. Only the Gulf coast receives more winter precipitation than normal in a meridional situation, due to the increased frequency of

nortes with the larger-amplitude Rossby waves.

In some areas, a decline in rainfall during one season from one source, may be compensated for by increased precipitation during other seasons or from other sources. Between 1950 and 1970, for example, although circulation patterns became more meridional and the sub-tropical high shifted equatorward, no decline in precipitation was recorded in Central Mexico. Klaus and Jauregui (1975) suggested that this was probably due to to an increase in precipitation from both winter rainfall and from tropical cyclones (hurricanes). In a later work, however, the same authors (Jauregui and Klaus, 1976) suggest that this high precipitation over Central Mexico in the 1960s was due to a westward shift in the longitude of a trough usually located east of the Atlantic coast of the U.S.A.. In northern Mexico, no such compensatory precipitation was available, resulting in a series of droughts as high pressure dominated the interior in summer.

2.5 Climatic change over the last 2,000 years

In the absence of written records, the earliest information on climatic changes is that associated with archaeological investigations. Although descriptions of major events such as floods and droughts become available after the Spanish conquest, the first description of the climate of Mexico was not made until the 1670 s, by Francisco Hernández. Although the first systematic meteorological

observations date from the 18th century, regular reports of temperature and precipitation did not appear until those for Mexico City in the newspaper 'El Sol', in 1826. The longest single record comes from the Tacubaya observatory in Mexico City, which started in 1884. Precipitation trends, as 5-year running means, for the period 1884 - 1974 are shown in Figure 2.7. During the 19th century, there was a gradual spreading of meteorological stations, especially after the creation of the Central Meteorological Observatory in 1877 (Jauregui, 1979). Late 19th and early 20th century records, however, were badly disrupted, especially by the revolutionary war. In 1921, the Servicio Meteorológico de Mexico was established with more than 600 stations. At present, there are still relatively few meteorological stations either in the arid north of the country or in the south, especially the mountains of Chiapas.

In view of the wealth of archaeological evidence from the Basin of Mexico, it is easiest to attempt to look at early climatic fluctuations there. It appears that the climate of the Basin of Mexico, in the Neovolcanic Axis, was probably relatively wet during the foundation of Teotihuacán (see chapter 3, section 3e) (Sanders et al, 1979), although both precipitation and lake levels probably started declining sometime after 300 A.D.. García (1974) attempted to reconstruct the climate during the rise and fall of Teotihuacán. She concluded that at the city's peak, the climate was as wet as that during the wettest year in the period covered by meteorological records. She felt that this

wetness suggested a very zonal circulation, with strong trade winds and westerlies. It was concluded that the decline of Teotihuacán could be related, in part, to a period of intense drought starting 700 to 750 A.D..

For northern Mexico, Armillas (1969) has suggested that the northward expansion of the frontier of agriculture and central Mexican culture, between ca. 600 and 900 A.D. was due to a favourable (i.e. wetter) climate. He attributes the abandonment of the north in the 12th and 13th centuries to drought. Although Brown (1984a) has disputed the timimg of this episode, there is some evidence to support increasingly dry conditions in the 12th and 13th centuries. Schulman (1938), using dendrochronology, identified a drying trend in the southwest U.S.A. during this period. Between 1276 and 1299 was the Great Drought, which was catastrophic for the Indian peoples in the area and led to a great abandonment of pueblos. The contraction of agricultural settlement in the southwest has also been investigated by Woodbury (1961), who calculated that the farmed area there declined from 600,000 km^2 to 220,000 km^2 in less than 300 years. Drought also seems to have played a part in the collapse of the Toltec empire in the 12th century (Snow, 1969). Sanders et al (1979), believe that the collapse of Tollan was accompanied by frosts and droughts and invasions of Chichimecs (nomads) from the north. Such climatic conditions would be consistent with a very meridional circulation, as it is seen to affect Central Mexico at present (see section 2.4).

The Aztec period (15th and 16th centuries), during the establishment of Tenochtitlán (now Mexico City), seems to have been one of increasing rainfall and rising lake levels in the Basin of Mexico. Clearly, there were high water levels there by the time of the conquest, which were reported by Cortes in 1519. According to Moriarty (1968), there was a series of extreme wet seasons between 1440 and 1450 A.D., leading to the flooding and partial destruction of Tenochtitlán. In spite of an early record of drought in 1450-1454 (Florescano, 1980), a dyke was constructed in the Basin of Mexico in 1446. A major problem was the flooding of the food-producing chinampa areas of Xochimilco and Chalco by the saline waters of Lake Texcoco (Coe, 1964). The chinampas (sometimes mistakenly called 'floating gardens') were fields built up on the lake margin and cultivated intensively. This system was best developed in the southern part of the Basin of Mexico, near Xochimilco and Chalco, and was the major source of foodstuffs for the Aztec capital. The dyke was constructed by Nezahualcóyotl (ruler of Texcoco) for the Aztec ruler Montezuma I, in order to seal off this valuable chinampa area from the flood waters.

Using information from crop yields and other documentary evidence Florescano (1980), endeavoured to trace the history of drought in Mexico. His findings may be combined with evidence of flooding and hydraulic works in the Basin of Mexico, to yield a picture of climatic variations from the 16th to the 19th century. The three centuries from 1521 to 1821 had drought periods of 3,4,5 and 9 successive years,

except for the periods 1520-1529, 1580-1589 and 1600-1609. There was major flooding of Tenochtitlán in 1555, 1604 and 1607. The situation in 1604 was described by Torquemada (Rojas et al, 1974):

> 'llovió tanto por el mes de agosto.... que cubieron sus aguas casi todo el suelo de la ciudad y llegó a un punto, en algunas calles, que se pasaban en canoas'
>
> (it rained so much in the month of August... that the waters covered most of the ground in the city and reached a point, in some streets, where one could travel by canoe)
>
> (1723, p.729)

The flooding in 1607 was just as bad and resulted in the excavation of a canal through the northern end of the basin. Based on present-day conditions, it would seem that a more zonal circulation was again predominating. The situation soon changed, however, and in 1624 severe drought resulted in a clash between the people of Mexico City and the Viceroy. Further droughts occurred in 1661 and 1692 (Florescano, 1969). In the 18th century, drought was often combined with frosts (as in 1749-50, 1771-72 and 1785-86), suggestive of a meridional circulation. In 1763, however, very heavy summer rains over the Basin of Mexico led to a major period of construction of dykes and other drainage works. In the 19th century, there were successive, countrywide droughts between 1808 and 1810, which were followed by the revolution of Hidalgo. In the south-east of the country, the first half of the 19th century was marked by a series of droughts, floods and plagues of locusts. The Yucatan Peninsula was declared a disaster area in 1822-23 and again in 1834-35. Between 1877

and 1891-92, there were twenty drought years over the central plateau (including the Neovolcanic Axis), the north and the Bajío. The drought intensified between 1900 and 1910, affecting the whole country.

The drought of the late 19th century was the first recorded in actual precipitation records. Using various sources Jauregui (1979), has compiled a record of precipitation data for the last 100 years, which he has related to changes in the atmospheric circulation. The records show a general drying over the period 1878 to 1901, 1892-1896 being the driest interval over central and northern Mexico and the driest ever recorded at Tacubaya (Figure 2.7). Dry conditions extended into the south-western U.S.A. and are also shown by the precipitation records for stations such as El Paso and Galveston in Texas. The aridity was associated with summer drought and with cold winters and frosts. In February of 1896, for example, heavy snows fell in Zacatecas. These conditions would be in keeping with a meridional circulation pattern. In the early 20th century, there was a general trend of increasing precipitation, in spite of the 1900 to 1910 drought in the north. A more zonal circulation was established in the northern hemisphere, which was also indicated by a greater frequency of westerly flow over Europe (Lamb, 1966). The peak of wetter conditions in Mexico occurred between 1921 and 1930. Although the Bermuda-Azores high continued to move north until the decade 1935-45, precipitation in Mexico was decreasing again by this time. A very severe drought affected northern Mexico in 1935. The

1940 s to the early 1950 s was another period of widespread drought, the most serious since that in the late 19th century. In 1944 and 1945, the centre and north were badly affected and in 1946, the whole country. This drought was strongly associated with a decline in cyclone (hurricane) activity off both coasts. During this period, the Bermuda-Azores high moved south and east and the Pacific anticyclone moved north and west (where it remained until the 1960s). Meridional flow prevailed over North America and in November 1950, a number of people died of cold in Mexico City due to an incursion of cold, arctic air.

During the second half of the 1950 s and the 1960 s, rainfall increased in Central and Southern Mexico, due mainly to an increase in cyclonic activity, especially off the Pacific coast. This was probably due to a northward shift in the I.T.C.Z. and the East South Pacific anticyclone and resulted in high levels of precipitation over Central America at this time. Between 1966 and 1970, the highest precipitation ever, was recorded at Tacubaya (see earlier comments). There were still intense droughts in the north of Mexico, however, in 1957, 1960, 1962 and 1969. A band of decreased precipitation extended from northern Mexico into the southeastern U.S.A. during this decade (1960s) (Sanchez and Kutzbach, 1974).

In the early 1970s, there was a return to a more pronounced meridional circulation, resulting in deficient rainfall, especially in the north. There was also a decline

in the number of hurricanes, although winter storms and rainfall increased along the Gulf Coast. This period was also one of drying in other parts of the sub-tropics, for example the Sahel, as well as in areas such as the mid-west of the U.S.A.. Lamb (1982) points out that the year 1972, in addition to being a drought year in all the areas mentioned above (as well as India and north China), was one with a very meridional circulation pattern and an El Niño off the coast of Peru. The nature of the relationship between precipitation over Mexico and the occurrence of El Niño currents off the west coast of South America, does not seem to have been established. Mexico displayed no major changes in precipitation over the El Niño period from 1982 to 1984, although sea-surface temperatures were anomolously high along the west coast (World Climate Data Programme, 1985).

Dry conditions persisted during the decade with severe drought in northern Mexico in 1977 and 1980 (Toledo, 1980). In 1981, however, rainfall was abundant, but has continued to be extremely variable. The distribution of precipitation for a dry year (1982) and a wet year (1984) at Tacubaya in Mexico City is shown in Figure 2.8. It is interesting to note that in the dry year (1982) there was greater rainfall early in the year (possibly due to nortes or to mid-latitude depressions tracking far south), but that the summer, monsoonal rains were very diminished, especially by comparison with those of 1984.

The records show clearly, that the climate of Mexico has varied over the recent past. The general trends of these

variations are illustrated in Figure 2.9. It would seem likely, therefore, that the climate has also changed over the longer term. Using the period of meteorological observations to provide analogues for the past, it is possible to attempt to interpret changes between wetter and drier conditions, beyond the period of records, in terms of variations in the atmospheric circulation.

2.6 Longer term climatic change and the response of Mexico

During the course of the Late Quaternary, the global climate underwent a series of marked changes. In the northern hemisphere, these changes were a response to latitudinal shifts in the major wind belts and fluctuations in the zonality of the circulation and in the intensity of the major features of the atmospheric circulation. These changes were determined, in part by the growth and decay of the large ice sheets. Variations in orbital parameters, as described by Milankovitch and the resulting changes in solar radiation during the Late Pleistocene and Holocene, have been described in some detail (Berger et al, 1984). Particular emphasis has been placed upon the implications of such variations for the operation of monsoon circulations (Kutzbach and Otto-Bliesner, 1982; Kutzbach, 1983; Kutzbach and Street-Perrott, 1985). Clearly, all these changes will have had an impact upon the climate of Mexico, given the influences on its present-day climate, which have been described above. Some of the implications of such global-

scale variations for the sub-tropics in general and Mexico in particular, have been outlined in Chapter 1, section 1. A brief summary of work carried out so far in Mexico and its results have also been described. Evidence is, however, fragmentary and no clear, overall picture for Mexico and Central America has yet emerged (Bradbury, 1982).

Whilst the diversity of Mexican climates has been emphasised and the many factors which play a part in creating this, the three major climatic zones identified in the introduction appear to retain some validity. The southern part of Mexico, which usually falls within the trade-wind belt is part of a larger climate regime covering the whole of Central America. Hastenrath (1976), using rainfall observations from 48 weather station for the period 1911 to 1972, has identified a region of broadly homogeneous behaviour covering southern Mexico, Central America and the Caribbean (CARIB for short). The northern part of Mexico, particularly the northern plateau, is part of a different climatic regime. This is the area affected by the sub-tropical high pressure belt, which extends up into the interior of the south-west U.S.A.. The rather anomolous conditions in western Baja California, put it outside this larger region. The reponse to a climatic change within the two zones discussed above (southern and northern Mexico) is likely to be similar to that experienced in the larger region influenced by that climatic regime. Unless the site selected for palaeoenvironmental study lies near the margin of the larger climatic region, it is unlikely to be sensitive to

minor fluctuations in the climate.

The central part of Mexico, however, (including the Neovolcanic Axis and the southern part of the central plateau) lies at an intermediate latitude between the regimes dominated by the Trade winds, or CARIB, and the sub-tropical high. Its location in what might be described as a hinge zone, suggests that the area should be sensitive to climatic variations over the Late Quaternary. A shift in mean latitude of either the Trade winds or the sub-tropical high would make the influence of one regime or the other predominant. Although this central area displays low precipitation variability at present, any change in climate would probably lead to a marked increase in this. It would appear to be better suited than either northern or southern Mexico, to registering minor increases or decreases in precipitation. The climate of this area and its potential for preserving a detailed record of climatic variations over the Late Pleistocene and Holocene are discussed further in Chapter 3.

Chapter 3

BACKGROUND, TECHNIQUES AND STUDY AREA

3.1 The Study of Lakes

> Now I conceive that as well as all these Lakes do receive Rivers and have no Exits or Discharge, so 'twill be necessary that their Waters rise and cover the Land... and consequently that Lakes must be bigger or lesser according to the Quantity of the Fresh they receive.
>
> Edmund Halley, 1715

Fluctuations in lake levels due to changes in climate, have been recognised for more than 250 years. Lakes vary markedly, however, in their sensitivity to these changes and in the quality of the record which they preserve. The major factors effecting such sensitivity are: the presence or absence of an outlet, the water-balance type of the lake, the basin relief, the nature of the sedimentary record and the extent of human disturbance (Street-Perrott and Harrison, 1985). Closed-basin lakes, i.e. those lacking surface outlets, are generally the most suitable for studying changes in climate since, under natural conditions, the area of the lake is strictly controlled by precipitation and evaporation over its catchment and water surface. Assuming equilibrium with climate and negligible groundwater flows, the resulting relationship of lake area to catchment area may be described as follows:

$$z = \frac{A_L}{A_B} = \frac{P_B - E_B}{E_L - P_L}$$

where: z = lake area:catchment area ratio
A_L = lake area
A_B = catchment area
P_B = precipitation over catchment

E_B = evapotranspiration over catchment
E_L = evaporation over lake
P_L = precipitation over lake

This z ratio serves as a useful climatic and palaeoclimatic index (Mifflin and Wheat, 1979).

At the present day, closed-basin lakes are most common in arid to subhumid regions, particularly in the tropics and subtropics, on either side of the subtropical deserts, where $E_L >> P_L$ (Schuiling, 1977). During the drier periods of the Quaternary, however, many lakes in mid-latitudes also became temporarily closed (Street-Perrott, pers. comm.).

The hydrological characteristics of a lake are also important in determining its response to changes in climate. Street (1980) and Street-Perrott and Harrison (1985), following Szestay (1974), attempted a classification of lakes on the basis of the relationship of runoff, as a percentage of annual inputs, to discharge from the lake as a percentage of the outputs. Lakes for which runoff provides nearly all of the inputs were called `amplifier lakes'. Closed amplifier lakes are likely to be the most sensitive group of lakes to variations in climate and have provided most of the best Late Quaternary lake-level records. An example is Gasse's (1977a), study of Lake Abhé, Ethiopia/Djibouti.

In selecting a basin for the study of lake-level fluctuations, other factors which must be considered are: basin topography, the effects of tectonic disturbance and volcanic activity, the type of lacustrine deposits, their suitability for ^{14}C dating and the degree of human interference with the natural basin hydrology. Street-Perrott

and Harrison (1985, p. 297) conclude, however, that: `The most suitable lakes to choose for a study of water level fluctuations are closed, amplifier lakes, occupying volcanic, meteoric or fault-bounded basins with moderate relief'. Such considerations must be taken into accountwhen choosing a particular basin to study.

The reconstruction of lake-level fluctuations, which may then be used to infer changes in the relationship of precipitation minus evaporation (P-E), may be achieved by many different techniques. The choice of technique, or techniques, will depend upon the nature of the basin being studied and the overall aims of the investigation. The study of basin geomorphology, especially of lake shorelines, has been the foundation of lake-level investigations for many years. A number of the classic studies of the `pluvial' lakes of the American Southwest were based upon this technique (e.g Gilbert, 1890), as was early work in Kashmir (Drew, 1875). Unfortunately, not all basins retain former shorelines, especially where the basin floor is rather flat or where the lake level has oscillated rapidly without cutting a clear shoreline. Hence, this technique is generally used in conjunction with others.

Sedimentology (Cowgill et al, 1966), geochemistry (Yuretich, 1976) and oxygen isotope analysis (Covich and Stuiver, 1974; Durand et al, 1984) ($^{18}O/^{16}O$ ratios) have all been applied to the study of lacustrine sediments and are particularly valuable for the study of cores. In some cases,

sediment type may be related to particular lacustrine environments from which relative changes in water depth may be reconstructed. Studies of geochemistry and stable isotopes ($\delta^{18}O$ and δD) give an indication of the degree of evaporative concentration of a lake. As evaporation increases and the volume of the closed lake is reduced, its chemical and isotopic composition evolve systematically. Eugster and Hardie (1978) have summarised the major geochemical pathways followed as evaporation proceeds. Although the original chemical composition of the lake inflows, as determined mainly by catchment lithology, is predominant in determining the pathway followed, the various pathways show two major stages 1) the precipitation of alkaline-earth carbonates and 2) crystallisation of other salts and silicates. The Eugster and Hardie model has proven very valuable in palaeoenvironmental reconstructions and will be discussed more fully in Chapter 5. The possibility of using the model as a basis for linking the type of sedimentation to the water balance of the lake has been proposed by Street-Perrott and Harrison (1985).

Studies of landforms and sediment types are not, however, always the most sensitive techniques for the reconstruction of lake level and environment. Palaeoecological techniques, especially those which use organisms living in the water body itself (such as ostracodes, molluscs or diatoms), may provide more direct evidence of variations in water depth and chemistry. Ideally, a combination of one of these techniques with

geochemical and geomorphological or sedimentological data should provide a precise record of variations in lake level and the lacustrine environment. Of the palaeoecological techniques currently used, the analysis of diatom assemblages is probably one of the more common and the most versatile, due to the abundance and environmental sensitivity of diatoms. In view of the potential of this technique, it was decided that a study of the diatom record would provide the basis for this investigation of Late Quaternary environmental change. When available, additional evidence from other techniques will also be cited.

3.2a Diatoms and Their Uses in Environmental Reconstruction

Diatoms, or Bacillariophyta, are microscopic, unicellular plants (algae) ranging in size from approximately 5 to 500 μm. They are distinguished from other groups of algae by their production of a frustule (shell) of silica. It is the distinctive morphologies of these frustules which provide the basis for diatom taxonomy. Diatoms are virtually ubiquitous, occurring in almost all types of water bodies and damp habitats over the globe (Barbour and Haworth, 1981). There is a general division between marine and freshwater forms (Patrick and Reimer, 1966), of which only the latter will be considered here. Upon the death of the plant, the silica frustule becomes incorporated in the inorganic sediment fraction. Under extremely alkaline conditions, dissolution of the silica may occur, but the frustules are

generally very resistant to weathering processes (Lewin, 1962). Fossil freshwater forms have been found throughout the geological record since the Miocene.

Structure of the Diatom valve

Diatoms may be divided into two major forms, the Centrales (or centrics) which are generally circular in valve view and without a raphe, and the Pennales (or pennates) with apical or transapical symmetry (Figure 3.1). The latter are further divided between those with and without a raphe. The diatom frustule consists of two valves which fit together like a box (Figure 3.1). Each 'lid' consists of a flat valve surface and a girdle band or bands. The outer valve is called the epitheca and the inner valve the hypotheca. It is the valve surface which is the most commonly seen and it is the pattern and structure of this surface which forms the basis for identification under the light microscope (L.M.). Whilst the Scanning Electron Microscope (S.E.M.) and the Transmission Electron Microscope (T.E.M.), have clearly been of great value in diatom studies, characteristics which are going to be used to distinguish one variety from another need to be identifiable under the L.M. to be of general application.

Although studied almost since the microscope was invented, serious study of diatoms began in the early 19th century (Round, 1971; Barber and Haworth, 1981). Examples of these early works are those of Ehrenberg (1838, 1840), Ralfs (1843), Kützing (1833, 1844) and William Smith (1853-1856). The study of diatom taxonomy, although still fundamental, has

been joined by the study and use of diatoms for many other purposes. In particular, the sensitivity of diatom species to changes in their aquatic environment has led to their use in many types of studies of environmental change, over both long and short time scales (e.g. Bradbury and Waddington, 1973; Rushforth et al, 1981; Serieyssol, 1984).

There are a number of factors which contribute to the potential of diatoms as environmental indicators:

1) they are very widely distributed
2) the frustules are generally readily identifiable to species and varietal level
3) their fossils are often well preserved in lake and mire sediments
4) many have distinct ecological tolerances and diatom associations may provide a good record of local conditions
5) they respond rapidly to changes in environmental conditions, even annually
6) they are abundant and can be counted in numbers felt to yield significant results.

3.2b Diatoms and the Aquatic Environment

The use of diatoms as environmental indicators is based upon the changes in species composition which occur as the physical, chemical and nutrient status of the site alters (Patrick, 1977). Species are most sensitive to changes in habitat (altering the life form), pH, salinity and productivity. Although they may be used as direct

temperature indicators (Servant-Vildary, 1982), the value of most freshwater diatoms for this is questionable (c.f. Battarbee, 1979a and Patrick and Reimer, 1966). Optimal growth temperatures vary, but many taxa are capable of growing over a wide range. These major environmental influences on diatoms are reflected by the various systems used for grouping taxa, for example the classifications by Hustedt for pH (1937-39), by Kolbe for salinity, based on NaCl concentrations (1927, 1932) and by Hustedt for temperature (1956). See Appendix 1 for details of these. The distinction of life form, or habitat (Appendix 1), may be of value either to detect changes in lake morphology or/and to indicate changes in productivity. A change from a mainly planktonic flora to one dominated by epiphytic and aerophilous species may, for example, indicate a fall in water level in a lake or pond. The application of life-form types to studies of trophic status is far less secure. Although centrics are generally planktonic and pennates are generally benthic, the application of ratios of these two major groupings to eutrophication studies has become rather contentious. Nygard (1949), used the ratio of centricsto pennates (C:P) to determine the trophic status of a lake, believing that the higher the ratio, the more eutrophic the lake. Stockner and Benson (1967), however, believed that an increasing ratio of araphids to centrics (A:C), was indicative of increasing eutrophication. There seems to be no real case for the identification of a taxonomic grouping with an ecological one in this manner. The known ecological

preferences of species, or groups of species, seem to be more valuable environmental indicators.

Other factors which may limit, or encourage, the growth of particular diatom species include turbidity (Lund, 1954), the quantity of calcium in the water (Kolbe, 1932), the ratio of phosphate to nitrate (Patrick, 1977), the amount of copper and other metals (Rushforth et al, 1981b), the presence of humates and the availability of silica. It has been suggested that diatoms need at least 0.5 mg/l of silica and that when the silica content of water drops below this or, when supply is insufficient to meet demand (as with increasing eutrophication), diatoms are replaced by other forms of algae (Kilham, 1971). Some species of diatoms (e.g. Melosira spp.) occur only in waters with high levels of dissolved silica (Gasse, 1977b). Diatoms may, however, actually control silica levels. After a diatom bloom, for example, silica levels fall markedly and a self-regulating annual diatom succession may evolve. The control of diatoms over silica levels is particularly important in high pH lakes. Hecky and Kilham (1973), in a study of alkaline and saline lakes in East Africa, found that neither were silica levels as high as might be expected , nor was there very much dissolution of the diatom frustules. Hence, a diatom record may be preserved from environments with high pH values.

Recently, increasing emphasis has been placed upon studying the environmental sensitivity of assemblages of species, rather than individual species. As Bradbury (1975),

has pointed out: `it is nearly impossible to say anything about the ecological significance of the presence or absence of a single diatom "indicator" species. In particular, this approach has been combined with consideration of the role not only of total chemical concentrations, but also of particular anion groupings and of other environmental variables, which may be clustered using statistical techniques. The value of carrying out this kind of study and its applications to palaeoenvironmental reconstructions has been well illustrated by Gasse and Tekaia (1982) and Gasse et al (1983).

3.2c Problems

As in all areas of study, the diatomist encounters a number of difficulties, both potential and real. Van Landingham, at the beginning of his vast work 'Catalogue of the fossil and recent genera and species of diatoms and their synonyms' (1967-75), lists a number of reasons why so few people study diatoms:

1) the morphology and terminology is extremely complex
2) the literature is scattered and in many different languages...
3) there is a great total of taxonomic names (over 80,000) and confusion is great

Whilst this is , perhaps, a rather pessimistic view, there are a number of problems and limitations which have to be considered. Diatom taxonomy and nomenclature are extremely complex, in spite of attempts to reach a consensus (e.g. Anonymous, 1975). Different authors may often call the same

diatom by different names and the use of an S.E.M. may clarify or confuse the process of assigning a name to a particular diatom form. Although very abundant, diatoms are not always preserved, especially in the fossil record. They may be broken, badly dissolved or have suffered predation (Beyens and Denys, 1982), making meaningful identification and counting impossible. The effects upon environmental interpretation of variable preservation both between samples and between species, need to be considered.

Perhaps the greatest handicap to using diatoms as indicators of past environments is the relatively poor state of knowledge of the ecology and environmental significance of both individual species and assemblages of species, in the present. This is particularly a problem when working outside temperate latitudes, which have been the study area for almost all the major floras. When working on fossil material, the possibility that there is no modern analogue for some past assemblages, has to be considered.

In spite of these caveats, diatoms have been shown to be both sensitive to the physical and chemical characteristics of their environments and responsive to changes in these conditions in a consistent way (Lund, 1954; Hutchinson, 1967; Rushforth et al, 1981; Merilä̈inen et al, 1982; Battarbee et al, 1985).

3.2d Applications of Diatom Studies

As indicated above, diatoms may be studied to a wide

variety of ends. Of particular interest to this study is their value as ecological or environmental indicators over the recent geological past. In using diatoms as palaeoenvironmental indicators, the diatom record has to be combined with the information derived from other techniques, such as sediment chemistry and grain size, ostracodes and other microfauna, other algal remains and the pollen record. By placing these results in a well dated chronological framework, it is possible to produce a detailed palaeoenvironmental reconstruction for a particular basin. On the short time scale (tens to hundreds of years) the effects of cultural eutrophication (e.g. Davis and Norton, 1978; Schuette and Bailey, 1980), industrial pollution (e.g. Ahtianen et al, 1983) and acidification (e.g. Flower and Battarbee, 1983) may be studied. Over longer periods, particularly for the Late Quaternary, they may provide a valuable record of lake-level fluctuations which may then be related to climatic changes at the regional, or larger, scale. As Gasse (1975), points out, however,:

> `Les diatomées ne peuvent pas intervenir dans l'etablissement des hypothèses concernant les mécanismes généraux du climat. Mais, une fois ces hypothèses émises, elles peuvent être utiles pour les préciser'

It is in this spirit that the work presented here was undertaken.

3.3a MEXICO - Selection of Study Area

In Mexico, areas of internal drainage are found principally in two regions, corresponding to two broad

categories:

1) the large basins in dry, northern Mexico
2) smaller lake basins, resulting from recent volcanic activity, concentrated along the Neovolcanic Axis (N.V.A.) at ca. 19° N.

The location of these areas is shown in Figure 3.2.

The basins in the north are an extension of the Basin and Range country of the southwestern U.S.A.. This region of internal drainage is divided into two by the Río Conchos (Tamayo, 1964). The northern part, including northwest Chihuahua and southern New Mexico has three sizeable rivers feeding into the major lake basins of Guzman, Santa Maria and de Los Patos. These are known to have shown high stands during the Pleistocene and probably flowed into the Río Grande. The southern section, covering parts of Chihuahua, Coahuila, Durango, Zacatecas, Nuevo Leon and San Luis Potosi (S.L.P.), includes the remnants of Laguna de Mayran, Laguna Viesca and Laguna de las Palomas. The first two of these contain fish species from the Río Grande and are believed to have fed into this river via an integrated regional drainage system, during the wettest periods of the Pleistocene. At the present day, all these lakes are dry, or in the process of desiccation, in an area which receives less than 250 mm of precipitation per year. This central desert area, which lies in the middle of the northern plateau (Mesa del Norte) at 1,200 - 1,500 m a.s.l. extends from the Mexico/U.S.A. border southward as far as S.L.P.

The smaller closed-basin lakes of the Neovolcanic Axis (Figure 3.3) include the present lakes Chapala, Cuitzeo, Pátzcuaro and Zirahuén. Eastward along the Axis lies the Basin of Mexico, where there is evidence of a series of lakes, sometimes separate, sometimes united, the artificial drainage of which has been completed this century (Rojas et al 1974). Northeast of the Basin of Mexico is a further series of small, internally drained basins, the Llanos de Apam, containing partially desiccated lakes. At the extreme eastern end of the Axis is the Oriental Basin, which is still largely occupied by marshes and has a number of maar lakes (Demant, 1981).

The lakes associated with the Neovolcanic Axis have a number of advantages for palaeoenvironmental study over the basins in what is now the Chihuahuan Desert. In general, the basins are smaller and better defined. Most will have a continuous, or near continuous, sedimentary record over the Late Quaternary. By contrast, very dry conditions in northern Mexico seem to have been established by the mid-Holocene (Wells, 1966 and 1978; Van Devender, 1977), resulting in breaks in the sedimentary record, the deflation of sediments from earlier moister periods and a paucity of material datable by radiocarbon methods. In addition, the harsh climate of the area has discouraged settlement. Even during the periods of densest occupation (from ca. 900 to 1350 A.D., although the timing of this is disputed by Brown, 1984a), the population was sparse and often semi-nomadic (Kelley, 1956). As a result, the archaeological record, even

from sites such as Casas Grandes (Di Peso et al, 1974) is poor, especially when compared with the wealth of material available from the Basins of the Neovolcanic Axis (e.g. Mirambell, 1978; Piña Chan, 1975). The basins of the Neovolcanic Axis, therefore, were felt to be more likely to retain a good record of environmental change, fulfilling most of the criteria set out by Street-Perrott and Harrison. Of these basins, those in the states of Michoacán, southern Guanajuato and México, were felt to be particularly promising. The discussion of geology, climate and hydrology which follows will concentrate on these areas, whilst the archaeology of Central Mexico will be presented in a broader, regional context.

3.3b The Geology of the Neovolcanic Axis

The Neovolcanic Axis (or Eje Neovolcanica) straddles Mexico at about 19°N. It is the product of mainly Quaternary volcanism, associated with a subduction system in the East - Central Pacific between the Rivera and Cocos plates (Figure 3.4). In the past, it had been ascribed to the Clarion Fracture zone (De Cserna, 1958; Mooser and Maldonaldo-Koerdell, 1961) but this explanation of the relationship of the Axis to the Central American Trench is contested. A fuller discussion of this problem is given in Demant (1981). The Axis forms the southern edge of the Central Plateau (Mesa Central), linking the Sierra Madre Oriental (folded Mesozoic rocks) and the Sierra Madre Occidental (Tertiary andesitic

and ignimbritic volcanics). Its structure is complex, due to the tectonic changes affecting the southern part of the North American plate since the beginning of the Tertiary. A simplified geology map is shown in Figure 3.5. This map and the following discussion are drawn mainly from Demant (1981).

The Axis may be divided up into five volcanic districts which are numbered as on the figure:

I) **Tepic-Chapala Graben**, forms the westernmost part of the Neovolcanic Axis. It trends NW - SE and ends at Lake Chapala. The graben resulted from Miocene basin-and-range type tectonism. The lavas in this area, which are mainly andesitic to dacitic, predate those of the rest of the Axis, although they are younger than the Oligocene Sierra Madre Occidental. The major volcanoes in this district are San Juan, Sanganguey, Ceboruco and Tequila.

II) the north - south **Colima graben**, south of Guadalajara. Two major stratovolcanoes occupy the southern end of the graben, the Nevado and Volcan de Colima. The Volcan de Fuego, a lava cone in the caldera of the Volcan de Colima is, historically, the most active volcano in Mexico and emits nuées ardentes. Its last eruptions occurred in 1975-76. The Colima graben is an extensional feature limiting the two parts of the N.V.A.: the western part, which is orientated NW - SE and the eastern part, where the volcanoes are located on NE - SW trending fractures. Near Guadalajara, a complex fracture system, due to the meeting of the Colima graben with the Tepic-Chapala graben and with an E-W to ENE-WSW fracture system from western Michoacán, has produced a series of

large, flat-floored depressions. Many of these are occupied by playas (such as the 'lagunas' San Marcos and Sayula) or by lakes (e.g. Atotnilco and Zocoalco). Lake Chapala itself occupies a tectonic depression.

III) **Michoacán** - Quaternary volcanic activity was very extensive in this area and there are more than 3000 cones, with volcanic products covering more than 40,000 km^2. Large strato-volcanoes are rare (Cerro Tancitaro being an exception) and most volcanoes are small (< 1 km^2), monogenetic cones. Lavas range from basalts to dacites and olivine is common, occuring with plagioclase, clinopyroxene and orthopyroxene.

The volcanic zone of Michoacán is bordered in the west by the Sierra de Jiquilpan, which separates it from the Colima graben; in the south by the complex sierra; in the east by the NNW - SSE fracture zone of Queretaro - Taxco and in the north by the Bajío, a Plio-Quaternary lacustrine depression. The zone itself may be subdivided into three parts. A small northern area, lying north of the main Axis is composed of late Tertiary ignimbritic tuffs and acid domes. The west-central part is the mountainous core of the zone, reaching 3,900 m at the summit of Tancitaro. This peak bears no evidence of glacial activity. The many monogenetic cones appear to follow no particular lines of weakness and were probably related to small pockets of lava rising to the surface. The volcano Paricutín, which erupted from 1943 to 1952, lies in this region. The lavas range from basalts to

dacites with 62% silica and are poor in potassium. In northeast Michoacán, volcanic activity is restricted to a narrow zone. The lavas are much richer in potassium, especially in the dacites and rhyolites, and are typically calc-alkaline. This chemical difference between the west and the northeast region may be due either to the increasing distance from the subduction zone, or to the thinning of the continental crust towards the east. The Holocene maars of Valle de Santiago are, chemically, something of an exception in the northeast region. They are a series of small cones, aligned at N 150°, and are composed of alkaline basalts. Volcanic activity has had a major impact on the drainage of the whole of this area, creating many closed lake basins. Its effects will be discussed in more detail in section 3.3d.

IV) **Toluca - Puebla region**, lies east of the Queretaro - Taxco fault system and includes, from west to east, the valleys or basins of Toluca, Mexico and Puebla, all of which were once occupied by an extensive lake or lakes. The Toluca, or Upper Lerma basin (2,575 m), is dominated by the Nevado de Toluca (or Xinantecatl) which reaches 4,575 m. It is one of the country's four biggest stratovolcanoes, all of which lie in this region. K/Ar dating of the oldest, andesitic lavas indicate that the first period of activity occurred 1.5 - 1.2 million years ago (Robin et al, 1980). The Toluca Basin is separated from the Basin of Mexico (2,240 m), by the Sierra de las Cruces (Ajusco), formed of Upper Miocene dacitic volcanics. The eastern boundary of the Basin of Mexico is formed by the Sierra Nevada, a series of

volcanic vents aligned N - S. The volcanoes Popocatépetl (5,452 m) and Iztaccihuatl (5,200 m) are part of this chain. The oldest lavas of Iztaccihuatl have been dated to 900,000 years, whilst Popocatépetl is much more recent. The upper cone of the latter volcano is Holocene and the last eruption was in 1920 A.D. The Basin is closed in the south by the Sierra Chichinautzin which is composed of about 200 volcanic cones, aligned NNE - SSW. Palaeosols underlying cinders from these cones, have yielded dates ranging from 40,000 to 8,000 ^{14}C years BP (Bloomfield, 1975). The last eruption in this Sierra occurred about 2,400 years ago when the lavas of the Xitle volcano covered part of the temple at Copilco, south of the present Mexico City. East of the Sierra Nevada is the Puebla Basin (2,200 m). The fourth large volcano, La Malinche, lies in the middle of this basin. A lake filled the basin floor during periods of the Late Quaternary and lacustrine, diatomaceous deposits have been dated to 25,000 - 12,000 years BP. The remains of large mammals and human occupation sites, found in the lacustrine sediments, have been dated 9,500 - 9,000 yr BP (Heine and Heide-Weise, 1973).

V) the **Oriental Basin** occurs at the eastern end of the N.V.A., in a small north - south graben cutting the Sierra Madre Oriental. The eastern limit of the Axis is marked by the chain of the Cofre de Perote and Pico de Orizaba volcanoes. Orizaba, or Citlalteptl (5,750 m), is the highest peak in Mexico and in Central America. This chain follows the same trend as the Sierra Nevada. The lavas in this area are

almost equally divided between rhyolites and basalts. Near El Carmen lies Laguna de Totolcingo and there are extensive marshy areas. Maars around the basin include Laguna Alchichica and Laguna Preciosa. In the southern part of the basin outcrop the Mesozoic, calcareous rocks which were the prevolcanic basement over much of the Central Mexican region.

The Neovolcanic Axis, therefore, occupies most of Central Mexico, from the Pacific in the west to the Sierra Madre Oriental in the east. The Gulf Coast area has not been considered in this discussion, but will be mentioned in the context of the archaeological background to the study area. The creation of the N.V.A. over the Quaternary has had a major effect upon the climate and drainage of the region. The latter, in turn, have been largely responsible for the region's attractiveness for human settlement and for the complex archaeological record.

3.3c Climate

The main features of the climate of Mexico as a whole, and the forcing mechanisms of the atmospheric circulation, have been outlined in Chapter 2. This section, however, will try to present a more detailed picture for Central Mexico and, in particular, for the area between ca. 99° and 102° W, identified above.

The ancient name for Central Mexico was Anahuac, the land between the waters (Bernal, 1980). Whilst maritime influences are important, they are overshadowed by the orographic effects of the mountain chain of the Neovolcanic

Axis. Topography is the major factor controlling temperature and precipitation distribution and leads to great local variability. Away from the coastal lowlands, the high elevation of the region means that much of Central Mexico has a humid, temperate climate (of the C type according to Köppen). The mean annual temperature over the greater part of the Axis is about 15° C and spatial variations are closely related to topography. The general pattern of average annual temperature is shown in Figure 3.6. In the highest parts of the Sierras (the tierra fría), frosts are common from November to March. The high-altitude Toluca (Upper Lerma) Basin, for example, experiences 80 - 90 days with frost per year (S.A.R.H., 1966). This number declines generally northward across the region, into the lower tierra templada (Cwa according to Köppen), before increasing again as continentality becomes more pronounced in the north. Pátzcuaro has 40 - 50 frosty days per year, Zacapu 30 - 40, Cuitzeo 20 - 30 and Moroleon/Yuriria only 10 days or less. Lumholtz (1902) states that in Zacapu, water was known to have been frozen as late as 10th June. Radiation fog is also quite common in late summer and early winter in the high mountain basins. The warmest month is usually April or May, generally becoming later in the year from southeast to northwest. Thus, it is April in the Basin of Mexico, May in Michoacán and June in Durango. The date of the warmest month is related to the arrival of the rainy season, usually preceeding it by a month or two.

Central Mexico lies in the summer rainfall belt of Mexico, receiving 80% of its annual precipitation between June and September. This is due to the movement of the I.T.C.Z. (Equatorial Trough) and the drawing in of the Trade Winds associated with the monsoonal circulation over northern Mexico and the U.S.A., described in Chapter 2. As might be expected, the month of maximum precipitation also varies across the region. At Puebla, in the east, it is June; in Toluca, July and at Zacapu, August. North of the semi-arid Balsas Valley, the greatest precipitation falls along the windward (south-facing) side of the Neovolcanic Axis. Uruapan, for example, receives more than 1600 mm per year. North of the N.V.A., there is a general decrease in precipitation northward (see Figure 3.7) towards the desert interior of the northern plateau. The increase in interannual variability in rainfall also follows this general south - north trend, although a tongue of higher variability, reaching as far south as Morelia, is noteworthy (Figure 3.8). In the mountains themselves, there may also be summer rain of local, cyclonic origin. Over much of the region the onset of the true rainy season is heralded by isolated thunderstorms due to local overheating. The wet season is not, however, always a period of predictable afternoon rainstorms, as it is frequently interrupted in July or August by a short dry period known as the veranillo. Whilst the winter is predominantly dry, light rains may occur in December or January which are called cabañuelas or janínderkua (West, 1948). These are common over western Mexico when cyclonic

disturbances from the Pacific move inland. This precipitation often falls as snow on the highest peaks, such as Cerro Tancitaro. Mid-latitude fronts tracking south from the U.S.A. may also bring winter snowstorms and precipitation to the Central Plateau and Neovolcanic Axis, reaching as far south as Mexico City. The effects of these `northers' or nortes are, however, more often confined to the Gulf Coast.

The quantity and distribution through the year, of rainfall for selected stations across the region, from Guadalajara in the west to Puebla in the east, is shown in Figure 3.9. The diagrams illustrate the delay of the wettest month moving northwest across the area and the general reduction in total precipitation northwards. The trend in annual average evaporation (Figure 3.10) is approximately the reverse of that for precipitation, increasing markedly towards the north and west. Conditions of water deficit, or surplus, based on P - E, are also indicated. It is interesting to note that at present, there is no surplus recorded for Mexico City, Teotihuacán (in the north of the Basin of Mexico), Cuitzeo and Queretaro.

Thus, over Central Mexico the general picture is of a summer - wet/ winter - dry regime, in which temperature, precipitation and evaporation are strongly modified by differences in elevation. From south to north, there is a general decrease in precipitation, an increase in continentality and an increase in interannual variability. The steepness of the precipitation gradients and the

transition from semi-arid to humid temperate climates which occurs across the region, suggests that it should be sensitive to relatively minor changes in climate.

3.3d Hydrology

The present drainage system of Central Mexico consists of a number of closed basins, many containing lakes (Figure 3.3), and west of the Basin of Mexico, the through drainage of the Balsas and Lerma-Santiago rivers to the Pacific. The Lerma-Santiago valley is the largest river basin in Central America. The course of the river is divided into two by Lago de Chapala, the largest lake in Mexico. The Río Lerma, rising in the spring-fed marshes and lakes at the southern end of the Toluca Basin, drains the eastern part of the catchment and feeds into Lago de Chapala. The Santiago then drains from the lake to the Pacific and is thought to have captured the headwaters of the Río Lerma. As indicated above, this configuration is largely a product of Quaternary volcanic activity associated with the Neovolcanic Axis, although river capture and basin alluviation have played a part.

There is, however, evidence to suggest that this is at least the second period during which a series of lakes, some closed, others not, has occupied the region (Clements, 1963). Fish of the species Chirostama (Pisces: Antherinidae) are found in lakes and rivers right across Central Mexico, from the Puebla Basin in the east, westward through the Llanos de Apam, the Basin of Mexico, lakes Zirahuén, Pátzcuaro and

Zacapu, to lakes Atotnilco and San Marcos near Guadalajara and as far as Laguna de Santiaguillo in Durango in the west (Barbour, 1973). This indicates that they were all once part of an earlier Río Lerma drainage system. During the Late Tertiary/ Early Pleistocene the river probably drained into the Pacific through a series of lakes, decreasing in elevation from east to west (Waitz, 1943; De Buen, 1943). Tamayo (1964), believes that this Tertiary lake system fed into Lago de Chapala and the Zocoalco-Sayula depression in Jalisco and found an outlet to the Pacific, possibly *via* the Río Ameca (Osorio Tafall, 1946). Of these Tertiary lakes, only Lago de Chapala remains. Quaternary (mid-Pleistocene) volcanic activity compartmentalised the drainage system and the connection between the Río Lerma, the Basin of Mexico and the Puebla Basin was probably severed in the Late Pleistocene.

The largest of the areas of naturally internal drainage are the Basins of Oriental, Puebla and Mexico. Groups of smaller closed drainage basins occur in the Llanos de Apam (or Apan), Michoacán (Zirahuén, Pátzcuaro, Zacapu, Cuitzeo) and around Guadalajara. There are also a large number of crater lakes dotted across the Neovolcanic Axis, for example the maars of the Valle de Santiago. The creation of the larger basins has been outlined above, in the section on the geology of the Axis. The largest of these closed basins is the Basin of Mexico, covering an area of some 8,000 km^2 (Maldonaldo-Koerdell, 1954-55). Although drained externally today *via* the Gran Canal de Desagüe to the Río Moctezuma, the

Basin of Mexico has been occupied by a lake, or series of lakes, throughout the Late Quaternary. The major sub-basins from north to south are: Zumpango, Xaltocan, San Cristobal, Texcoco, Xochimilco and Chalco (Figure 3.11). Texcoco is the lowest lying (ca. 2,230 m a.s.l.) and the most saline of these. A rise in water level of only six metres, however, would be sufficient to form a single lake occupying the whole basin. Such high-water level conditions prevailed at the time of the Spanish Conquest (1521 A.D.), when Cortés recorded that Texcoco was several metres deep (Sanders *et al*, 1979). Major inundations of Mexico City in the colonial period occurred in 1555, 1580, 1604 and 1607 (Rojas *et al*, 1974). This last episode led to a plan for the general drainage of the basin, the *Desagüe General*. Particular problems were caused by flooding from the relatively saline Lake Chalco, of the intensively cultivated *chinampa* areas (see Chapter 2) around Xochimilco. These difficulties were not fully resolved until the drainage of the area, *via* the Chalco Canal, at the end of the 19th century. Today, the basin floor is mainly dry, with considerable salt extraction. The provision of adequate fresh water for Mexico City is a major problem.

West of the Basin of Mexico lies the Toluca, or Upper Río Lerma Basin (Estado de México), the highest in elevation of the major lacustrine basins. It is not hydrologically closed at present but appears to have been so, for periods, in the past. This basin will be discussed in more detail in Chapter 7.

The state of Michoacán includes a number of important lakes, from Zirahuén in the south to Cuitzeo in the north, on the border with Guanajuato. The former links between these basins and the Río Lerma were studied by De Buen (1943). He suggested that the separation of Laguna Zirahuén from Lago de Pátzcuaro occurred first, then of Pátzcuaro from Cuitzeo and finally, of Cuitzeo from the river itself. Subsequent work, however, has shown that Zirahuén is actually the youngest of the lakes, having been dammed by a lava flow. Today, the basins of Zacapu and Cuitzeo are both artificially drained. A canal from Laguna Cuitzeo leads north into Lago de Yuriria, a man-made water body created by Fr. Diego de Chávez y Alvardo in 1548 (de Cserna et al, 1974), before finally draining into the Río Lerma.

The lakes of Michoacán are quite well documented in historical sources, particularly the ecclesiastical histories of the 17th and 18th centuries. Fr.Alonso de Rea, writing in 1643, devoted a chapter to lakes. Fr. Pablo de la Purísima Concepción Beaumont (1775?) wrote about Pátzcuaro and the idea of a subterranean drainage from Tzintzuntzan, the Tarascan capital, to the Río Angulo in the Basin of Zacapu. Fr. Diego de Basalenque (1673), wrote mainly about Yuriria and Cuitzeo. These documents provide valuable background information for any study on variations in lake levels and their possible climatic significance. In common with almost all the lakes across Central Mexico, the majority of the lakes in this area are decreasing in size at present. Only

Laguna Zirahuén and Lago de Pátzcuaro appear to be able to maintain themselves as permanent water bodies under current climatic and land-use conditions.

3.3e Archaeology

> The lake area of central Mexico coincides with the most important locale of highland Indian civilization in Mesoamerica, represented on the eve of the conquest by the cores of the Aztec and Tarasacan States. The capital center of each state lay within or on the shores of lakes: Tenochtitlán of the Aztecs on Lake Texcoco and Tzintzuntzan of the Tarascans on Lake Pátzcuaro.
>
> Tamayo, 1964

Although Man arrived relatively late in Central America, the cultures which developed and flourished in the fertile lake basins and valleys of the highlands of central and southern Mexico were complex and agriculturally advanced. One of the earliest dates for human occupation is 24,000 $\pm$ 4000 ^{14}C yr BP in the Basin of Mexico, at Tlapacoya (Alverez, 1969). The groups which emerged have been identified as belonging to the cultural area of Mesoamerica (e.g. Kirchoff, 1943), extending from Central Mexico south into the Central American states of Guatemala, Belize, Honduras and El Salvador. Mesoamerican prehistory is generally divided up into three periods: Formative, Archaic or Pre-Classic (2500 B.C. to 300 A.D.), Classic (300 to 900 A.D.) and Post-Classic (900 to 1520 A.D.). Between about 2500 B.C. and the Spanish Conquest, this area was united by widespread trade routes, cultural exchanges and military conquest. Within this larger cultural unit, distinct regional centres emerged which

dominated supra-regionally at different times.

The adoption of sedentary agriculture and in particular, the domestication of maize (Zea mays) was of fundamental importance for the evolution of the later, highly cultured groups. Mesoamerica was probably an area where agriculture, the deliberate selection and cultivation of plants, developed quite independently from the Old World. Sauer (1959) suggested that seed agriculture (e.g. beans, maize and squashes) originated in, and spread from, Mesoamerica whilst agriculture based on vegetatively propagated crops (tubers) began in the tropical lowlands of South America. In the case of many plants there appears to have been independent, parallel domestication in Central and South America (Bray, 1980). The ancestry of maize is particularly controversial.

The best evidence for early agriculture in Mexico comes from Tehuacán (near Puebla), Tamaulipas in north-east Mexico and the Valley of Oaxaca in the south (Figure 3.12). The Guila Naquitz cave, near Mitla in Oaxaca has yielded a maize-like plant apparently being cultivated in the period 8,860 ± 180 to 10,700 ± 350 yr BP (Schoenwetter, 1974). This falls within the period identified by Flannery et al (1967) as one of food collecting and incipient agriculture in the Valley of Oaxaca. The subsequent period 1500 to 600 B.C. (ca. 3,450 - 2,550 yr BP) was of early village farming and was followed by the rise of towns and ceremonial centres between 600 and 200 B.C. (ca. 2,500 - 2,100 BP).

Some of the oldest maize cobs have been found in the

caves of the Tehuacán Valley, near Puebla. These have included the wild progenitors of two indigenous races of maize (Manglesdorf *et al*, 1967). In this area, a modern type of maize seems to have developed over the period 5000 to 1500 B.C. (ca. 6,950 - 3,450 BP). This was, however, probably predated by the cultivation of nopal (*Opuntia* spp.), maguey (agave) and chili pepper (*Capsicum* spp.). Earle Smith (1967) suggests that the last was probably cultivated from the early or mid El Riego phase, dated 6500 to 4900 B.C. (8,450 - 6,850 yr BP). Agriculture probably came to have a significant impact on food production only with the improvement in the productivity of maize. Tehuacán is also interesting for the occurrence of abundant remains of both the vegetatively reproducing maguey (*Agave* spp.) and the seed maize (*Zea mays*) at the same time (González Quintero, 1969). Similar evidence comes from Tamaulipas, although in work on the Ocampo caves, Callen (1967) has shown that early cultivation was of oxtail millet and that maize was not introduced until ca. 2200 B.C. (ca. 4,150 BP).

All the regions cited above experience a semi-arid climate at present, although Tehuacán and Oaxaca may have been cooler, if not wetter, in the late Pleistocene and early Holocene (Flannery, 1967). Under such dry conditions, occupation at these sites was mainly seasonal (probably during the wet season), until crop yields were quite high.

Some of the earliest evidence for a sedentary settlement comes from Zohapilco in the south of the Basin of Mexico (Niederberger, 1979). Occupation at this former lake-margin

site dates from about 6000 B.C. (ca. 7,950 yr BP). Unlike the semi-arid areas, Zohapilco was in an area of high floral and faunal diversity and productivity which encouraged stability. Such conditions would be in keeping with the concept of plant domestication under optimal conditions proposed by Flannery, Sauer and others. Palerm (1968), however, believes that it was a drying of the climate from the beginning of the Formative period that, through the necessity for irrigation schemes, provided the basis for first fixed and later, urban , centres. Another site in the Basin of Mexico with very early signs of agricultural activity is Tlapacoya. There, teosinte (Zea mexicana) was found in a preceramic cultural horizon dated 7,040 ± 115 yr BP, which is about the same time as agriculture started at Tehuacán (Lorenzo and González Quintero, 1970).

The adoption of sedentary agriculture, therefore, provided the foundations for the high civilizations of Mesoamerica in the late Formative to Post-Classic periods. As the most favourable areas for agriculture were the lowlands of the Gulf Coast and the alluvial valleys and lacustrine basins of the highlands, it is not surprising that these were the focus of later developments. A general chronology for the most important groups is set out in Table 3.1. The locations of the major centres referred to in this table are shown in Figure 3.12.

The first of the major high culture groups were the Olmec. They probably originated in the highlands of the

Neovolcanic Axis, before developing fully on the Gulf Coast, in the Veracruz region (Burland and Forman, 1975). The Olmec were responsible for the introduction to Mesoamerican culture of monumental sculpture, planned religious and ceremonial centres, intensive regional exchanges, hieroglyphic writing and the 260-day Mesoamerican calendar. Starting around 1200 B.C., Olmec culture reached its apogee between 900 and 600 B.C. (ca. 2,850 - 2,550 BP), when its main centre was at La Venta. The regional exchange system which they developed linked up a number of smaller, preexisting networks in the Maya area, the Central Mexican highlands and on the Gulf Coast itself. After the Olmec decline, from 600 B.C., developments in the lowlands and in the highlands of Mexico, diverged. In the lowlands of Yucatán, the Maya civilisation developed based upon extensive agriculture and scattered ceremonial centres. By contrast, in the highlands, development was characterised by a few large cities, supported by intensive agriculture (Katz, 1969).

In the central Mexican highlands, the first major centre in the Basin of Mexico was Cuicuilco, south of the current Mexico City. As described in the section on the geology of the area, this was destroyed by the eruption of Xitle volcano and was abandoned. After this event, the major centre was Teotihuacán in the north east of the basin. Between 200 B.C. and A.D. 700, Teotihuacán united and controlled, by mainly peaceful means, the whole of Mesoamerica. Teotihuacán was probably the first truly urban state, with a population of about 125,000 (Millón, 1970), based on crafts and trade,

especially long-distance trade in pottery and obsidian and supported by intensive agriculture. Teotihuacán had as one of its deities, the rain god Tlaloc, who continued to be of great importance for most groups through to the Aztecs. While Teotihuacán was developing, larger settlements with ceremonial architecture also grew up in Oaxaca (particularly Monte Albán) and in the Maya lowlands.

The Classic period, from A.D. 300 to 900, was the high point of Mesoamerican civilisation, with the emergence of true states in both the Basin of Mexico and the Maya lowlands. Although influenced by Teotihuacán, other important centres were Cholula near Puebla, the highland Maya site of Kaminaljuyú, the principal lowland Maya site at Tikal and the Miztec centre of Monte Albán, mentioned above. During this period, a group called the Matlatzincas, who probably originated in the present-day state of Guerrero, founded the city of Teotenango in the Upper Río Lerma Basin (Davies, 1983). Teotenango survived as a centre until the Spanish Conquest. The importance of this centre and the possible environmental impact of the Matlatzincas, will be discussed in Chapter 7. The burning and collapse of Teotihuacán, was followed by the breakdown of the major cultures and a period of 'Balkanisation' of the highland power structure (Dumond and Muller, 1972). New groups moved in and Cholula and Tollan (which may be Tula), emerged as the new, principal centres. Tollan was the city of the Toltecs, who came from northern Mexico and dominated first the Central

Mexican highlands, then Oaxaca and Yucatán. The Toltecs were the first of the militaristic groups, basing expansion upon military conquest and placing greater emphasis upon human sacrifice. They were probably Nahua-speaking, like the later Aztecs. The Toltec empire was, however, fairly short lived and collapsed during the 12th century. Tollan was destroyed about 1168 A.D. (O'Shae, 1980) due to civil unrest, possibly triggered by famine due to drought, following a drying of the climate in north-central Mexico. With the collapse of Tollan, new waves of nomadic invaders came from nothern Mexico, known under the name of Chichimecs, possibly driven south by worsening drought. One group of these was the Azteca or Mexica, who attempted to settle in the Basin of Mexico. The Aztecs finally managed to establish a centre on the island of Tenochtitlán, in Lake Texcoco, in 1345. Through political and military manoevering, particularly the Triple Alliance of Tenochtitlán, Texcoco and Tlacopan, they developed a major power base. In addition to continuing the Toltec traditions of military conquest and human sacrifice, the Aztecs also preserved many cultural practices from the Classic period. These were particularly clear in their intensive agriculture, based upon water-control systems and the use of chinampas or 'floating' gardens (Moriarty, 1968; Armillas, 1971). Such intensive cultivation was necessary to support a very large population, possibly of 150,000 to 200,000, in Tenochtitlán at the end of the 15th century (Sanders et al, 1979). The second element continuing from the Classic period was that of local and long-distance trading.

Since, by the end of the 15th century, most food had to be brought in to Tenochtitlán by canoe from other parts of the basin, the local food trade, which later became tribute payments from subject settlements, was vital. A powerful merchant group actually developed a separate centre on Tlatelolco, which Tenochtitlán overthrew in 1473.

The Triple Alliance came to control much, but not all of Mesoamerica. The Miztecs and Zapotecs in Oaxaca, the Mayan city states and the Tarascans (see below), occupying present day Michoacán, remained independent. The Tarascans actually won a major victory over an Aztec invasion force in 1480 A.D. The military and economic oppression by the Aztecs was such that when they did try to resist the Spanish, they received little help from their subject groups or from the neighbouring Tarascans.

3.3f Michoacán and the Tarascans

In view of the potential of Michoacán and Guanajuato for palaeoenvironmental reconstruction studies, further consideration of the historical background to the region is merited. Little is known of the pre-Tarascan cultures. A very early group was the El Lopeño culture, probably dating from about 1400 B.C. (ca. 3,350 yr BP) (Miranda, 1980). The last centuries B.C. saw the flowering of the Chupícuaro culture. The actual Chupícuaro site, near Cuitzeo, seems to have had its main period of occupation from 350 B.C. to A.D. 300 (Piña Chan, undated). The same cultural traditions can

be identified in Yuriria and Valle de Santiago in southern Guanajuato. At its peak, the influence of Chupícuaro reached as far as the Basin of Mexico. In Michoacán it is, however, not possible to identify the traditional Archaic-Classic-Post-Classic sequence, probably due to insufficient studies. Some indications of the influence of Teotihuacán have been found, but 'las luces teotihuacanas no brillaron mayormente en Michoacán' (FONOPAS, 1980).

The Purépecha, or Tarascans, entered the area in the 14th and 15th centuries A.D. They probably came from northern Mexico, like the Aztecs, but their abilities in metal working (not shared by other Mesoamerican groups) may suggest a South American origin. According to the Relación de Michoacán, the Tarascans were led by Ticátame and first settled around the town and lake of Zacapu, before finally establishing their centre at Tzintzuntzan (Place of the Hummingbirds) on the shores of Lake Pátzcuaro, under the leadership of Tariácuri. From this base, they set about conquering towns and islands in the basin before extending their power north to Zacapu, west to Chéran and then south. In 1470, they moved their capital from Tzintzuntzan to Pátzcuaro. In spite of their domination of most of present-day Michoacán, there were cultural groups independent from the Tarascans. The Spanish, led by Cristobal de Olid, first entered Michoacán in a major way, in 1522, following the Tarascans' denial of help to the Aztecs. The last Tarascan ruler was put to death in 1530 by a Spanish expedition under the leadership of the brutal Nuño de Guzman.

Unlike the rest of Mesoamerica, the Tarascans had no rain god, although the cult of fire was very important. Their principal god was Curicaueri, the great burner and god of volcanoes. Much of the clearance of the natural forests of Michoacán was to make offerings to this god. The introduction of Christianity by the Spanish and the consequent cessation of offerings to Curicaueri were believed to have been responsible for the major earth tremors which occurred in Michoacán in 1567 and 1575. Thus, their beliefs had a profound effect upon the way in which the Tarascans viewed and dealt with, their natural environment.

3.3g Settlement and the Natural Environment

The occupation history of Central Mexico, outlined above, gives some indication of the areas subject to the most intense exploitation of natural resources. The long history of agriculture and the associated clearance of natural vegetation and control of water resources, means that in favourable locations, such as those around lake margins, there is likely to have been considerable human disturbance. In addition, the building of large-scale ceremonial and military centres in the Classic and Post-Classic periods would also have had a considerable impact on the local environment. The effects of the prehispanic, protohistoric and historical settlements in a lake basin are likely to be recorded by changes in the rate and nature of sediment deposition and, possibly by increasing eutrophication of lake

waters. There is also clear-cut evidence provided by increasing quantities of pollen from cultivated plants, especially maize. In the post-Conquest period, the adoption of metal farming implements, especially the plough, and of cattle, introduced new factors into Man - land relationships. The effects of these different periods and types of activities and their distinction from changes in the environment due to fluctuations in the climate, have already been studied in some parts of Central Mexico (Cook, 1963; Perlstein-Pollard, 1982). Whilst complicating any attempts at palaeoenvironmental reconstruction, an appreciation of the archaeology of the study area may assist in the interpretation of environmental changes indicated over the recent past and the record of human impact is, in itself, of considerable interest, especially in an environment where disturbance all too easily results in landscape degradation.

3.3h Selection of Study Sites

The states of Michoacán, Guanajuato and México, in the Neovolcanic Axis of Central Mexico, were identified as being particularly suitable for palaeoenvironmental study in view of the volcanic terrain, the predominance of closed drainage basins, their location on a clear climatic gradient and interesting archaeology (section 3.3a). The more detailed discussion of geology, climate , hydrology and archaeology which has been presented in sections 3.3b to 3.3e of this chapter, provide a broader context into which records from individual sites may be placed. A reconnaissance was carried

out by Dr. F.A.Street-Perrott and R.A.Perrott in 1980 and seasons of fieldwork undertaken in 1981 and 1982. A number of basins were visited during these periods and samples collected. The records presented here come from the Basin of Zacapu in Michoacán and the Toluca or Upper Río Lerma Basin in the state of México. The interpretation of the fossil diatom record from these sites will be supported both by the ecological information derived from a collection of modern diatom samples and by evidence from other techniques of sediment analysis.

Chapter 4

FIELD AND LABORATORY TECHNIQUES

4.1 Field Sampling Procedures

Two seasons of fieldwork were undertaken in Mexico, the first from March to May 1981 and the second from March to August 1982. Both fell mainly during the dry season, although in 1982, the last three months were within the rainy season. The aim of the fieldwork was to collect lacustrine sediments for the analysis of fossil diatom assemblages and to carry out a modern limnological survey, collecting modern diatom samples to provide analogues for interpreting fossil material.

4.2 Sediments

4.2a Coring

Cores of lake sediments were taken using a modified, 1m long Livingstone corer, with a barrel diameter of 50 mm (Wright, 1967). Coring was done either from an inflated dinghy or from a platform constructed across two boats (Plate 3). At Lake Zacapu in 1982, rowing boats were hired for this purpose and a 14.3 m core was obtained. Sediment was collected in 1 m drives, although where the sediment was very compacted a full metre was not always obtained. The material was extruded on the raft, described and wrapped in clingfilm, silver foil and finally thick plastic sheeting (Plate 4). The segments were then taped into lengths of plastic

drainpipe to prevent damage in transit. Core material was sent back to Oxford by air freight and kept in cold storage at 4°C. The top metre of sediment was collected using a perspex core barrel. This was later extruded by pushing up, with a piston, from the bottom of the barrel and slicing off the core at 1 cm intervals. The `slices' of sediment were then put into petri dishes. Further cores were also taken from Lake Cuitzeo and La Piscina de Yuriria.

4.2b Pits

In the Upper Lerma basin, two pits were dug into the marshy basin floor to collect samples. This technique is particularly useful in sediments unsuitable for coring with a Livingstone corer and in order to see the stratigraphy in three dimensions. The actual digging of a pit may be combined with the use of an Hiller corer or auger to penetrate tougher sediments or when the pit becomes deep. The possibilites for taking quite large samples of sediment and duplicate samples for ^{14}C dating, are also an advantage. Upper Lerma Pit 1 was dug in 1980 by F.A.Street-Perrott and R.A.Perrott, to a depth of 180 cm. It was sampled at 5 cm intervals from 0 to 170 cm with one or two bulk samples below this (to 185 cm), due to flooding. In 1981, a second pit was dug. This pit bottomed out in a thick layer of pumice which extended from 180 to > 270 cm. Attempts were made to punch through this pumice using an auger. Although the auger got through the pumice, no sediment was retained on withdrawal. The upper part of the pit, to 130 cm, was sampled at 1 cm

intervals to collect the sediment from 65 - 130 cm in a sequence of ash, lacustrine mud and tephra. In 1982, a 110 cm pit was dug at the east end of the Basin of Zacapu and sampled at 5 cm intervals.

4.2c Sections

Surface exposures of lacustrine sediments were sampled in a number of locations, especially around the Basin of Zacapu. As with pit sampling, sections allow for a larger-scale appreciation of sedimentary structures and for larger samples. Having cleaned the face of the section, sequences of beds were identified, labelled and measured. The sections were described in terms of Munsell colour, a field assessment of texture and most likely composition. Dilute HCl was used to test for carbonate. Samples were collected either by bed, or at a fixed interval and put into plastic bags. Separate ^{14}C samples were collected where the sediment appeared to be sufficiently organic. In the Basin of Zacapu, the elevation of the sections was determined by levelling, using a Wild level. Unfortunately, precise details of nearby military bench marks were not available, so the height of the sections was measured relative to present lake level.

4.3 Limnological Survey

The survey was carried out mainly in 1982, to provide information on the variety of present-day aquatic environments. Its purpose was also to collect modern diatoms

for which the chemical and physical characteristics of their habitat were known.

4.3a Water Sampling

In 1982, 70 water samples were collected from 47 sites across Central Mexico. The majority of the sites were in the states of Michoacán, Guanajuato and México. Samples were collected using 500 ml or 1000 ml polythene bottles. Generally, a near-shore and a deep-water surface sample were taken. At lakes of particular interest: Laguna Zacapu, La Piscina de Yuriria and Hoya Rincón de Parangueo, samples were also taken down a profile, using a spring-topped depth sampler designed by Myszka Guskowska of the School of Geography, Oxford (Plate 5). In the field, a record was made of pH, electrical conductivity (E.C.) in $\mu S\ cm^{-1}$, water and air temperature and transparency. A note was also made of any visible signs of pollution, human use of the water body etc. These samples were coarse-filtered (using Watman 40 or 41 ashless filters) on the same day and field assessments of silica (SiO_2), phosphate (P_2O_5) and chloride (Cl^-) made using Merck test kits. Samples were kept refridgerated to minimise gas exchange, until laboratory analysis was possible.

4.3b Algae

Collections of algae were made at all the sites where water samples were taken and at some additional locations. In the latter cases, a record was made in the field of pH, conductivity and temperature, although no chemical

characteristics were determined. Samples were taken from the surface in shallow and deep water, in 500 ml plastic bottles, to collect littoral and planktonic forms. Scrapings of algae from rock and plant surfaces were also collected. Alcohol was added to all samples immediately after collection to prevent zooplankton from grazing on the algae.

4.3c Bottom Sediments

Samples were collected from the sediment/water interface using a grab. The sediment was taken to provide information both on the salts being precipitated under present water chemistry conditions and to give an indication of the diatom record being preserved in the sediments in comparison with those collected live. Some of these samples were centrifuged to remove excess water and all were kept in cold storage.

4.4 Laboratory Techniques

4.4a Water Analysis

Full chemical analyses of the water samples were undertaken in the laboratories of the Instituto de Geografía and the Instituto de Geología, Universidad Nacional Autonoma de Mexico. Where it had been necessary to record field pH using pH papers, readings were repeated using a laboratory meter. The pH papers were shown to be unreliable. Prior to analysis, all samples were filtered using Millipore filters and allowed to reach room temperature.

Calcium (Ca), magnesium (Mg) and iron (Fe) were determined using a Perkin-Elmer 403 atomic absorption spectrophotometer (A.A.S.). For calcium determinations, a 5% lanthanum solution in 25% (v/v) HCl was added to standards and samples as a releasing agent. Sodium (Na) and potassium (K) were determined by standard flame-photometer procedures. All the cations were originally expressed in milligrams/litre (mg/l).

Carbonate (CO_3) and bicarbonate (HCO_3) were determined by titration with 0.02N sulphuric acid to colour change endpoints at pH 8.3 and pH 4.5. Where there was a discrepancy between field pH results and the presence/absence of CO_3, pH readings were repeated in the laboratory. Spot checks were also made to see the effects of storage. The same 50 ml aliquot of sample was used to determine chloride using the Mohr titration with silver nitrate ($AgNO_3$) (0.1N) (method from Manual del Curso de Analysis de Aguas y Aguas de Desecho, tomo 1, Secretaria de Agricultura y Recursos Hydraulicos). Sulphate was determined gravimetrically through its precipitation in the form of barium sulphate ($BaSO_4$). Alkalinity, chloride and sulphate results were expressed in milliequivalents / litre (meq/l). Nitrate was determined using an Orion research probe 93-07, with an electrode range of 10^{-1}m to 10^{-5}m nitrate (6000 - 0.6 mg/l). 2 ml of ammonium sulphate (2M $(NH_4)_2SO_4$) was added to each 100 ml standard and sample to reduce the ionic background to 0.12M. A calibration curve was prepared to convert mv to

mg/1.

Dissolved solids were derived separately from 100 ml aliquots.

The results from these analyses are discussed fully in Chapter 5.

4.4b Sediment Analysis

Loss-on-ignition was determined by drying the sample at 105°C, cooling in a desiccator and weighing. The organic matter was then burnt off in a furnace at 550°C for 1 hr. After cooling, the samples were reweighed to determine the percentage weight loss. The grain size of the sediments from the sections was derived by sieving followed by hydrometer analysis (Day, 1965). Other analyses of sediment chemistry, grain size and mineral-magnetic measurements have been carried out by P.E.Hales, S.P.Harrison and Dr.F.A.Street-Perrott.

As part of the sedimentological analyses, mineral-magnetic measurements were carried out. Mass specific magnetic susceptibility (Thompson et al, 1975) and frequency depedent susceptibility (formerly quadrature susceptibility (Oldfield, pers. comm.)) were measured. It has been shown that, in many lakes, magnetic susceptibility is largely a function of the influx of detrital allochthonous material, resulting from the erosion of substrates and soils in the drainage basin (Oldfield, et al, 1978). Frequency dependent susceptibility indicates that concentration of magnetic minerals of a fine-viscous (0.02 - 0.05 μm) grain size. Such a mineral grain size is characteristic of many soils with

secondary magnetic minerals from the effects of fire and pedogenesis (Oldfield, unpublished ms.). Thus, mineral-magnetic measurements can help to identify episodes of increased soil erosion in lake basins and may help to identify Man, rather than climate, as the cause.

4.5 Preparation of Diatom Samples

4.5a Modern

In the laboratory of the Instituto de Geografía, U.N.A.M., a 1% solution of Lugol's iodine was added to the algal samples, which were then left 24 hours to settle out. The top part of the sample was then decanted and the lower part shaken and divided into two. The first half was simply put into washed glass tubes, labelled and sealed up. The second half of the sample was treated specifically for making up diatom slides. In order to make the slides from modern and fossil material as directly comperable as possible, the modern diatom samples were treated in the same manner as the fossil material (see below). Rock and plant surfaces were washed with distilled water. The larger stones were boiled separately in hydrogen peroxide (H_2O_2) to strip off adhering algae. The solution of algae, distilled water and preserving alcohol was then treated in the same way as the other diatom samples.

4.5b Fossil

Sediments collected for the purposes of diatom analysis

were first dried at low temperature before 0.1 g of sediment was weighed out. The sediment was then rewetted using distilled water. The following treatment was then applied to all diatom samples. 30% H_2O_2 was added to each sample and heated to remove all organic matter. When most of the peroxide had evaporated off, 10% HCl was added to remove any carbonate. For all samples, except those from Zacapu core 1, the samples were washed in distilled water and centrifuged both between the peroxide and acid treatments and after the removal of the carbonates (Battarbee, 1979a). The final suspension was then made up to 30 ml with distilled water. The samples from Zacapu core 1 were not centrifuged, but were left to settle out in 400 ml beakers over at least 36 hours before decanting the upper part of the solution and refilling the beaker with distilled water. This process was repeated 2 or 3 times.

Slides were prepared by plating out 0.2 ml of diatom suspension onto alcohol-washed round, 19 mm coverslips using a Pipetman P200 micropipette. The water was allowed to evaporate off at room temperature. The dried coverslips were mounted onto slides using Naphrax high-resolution diatom mountant. An initial slide was examined to determine whether any further treatments were necessary to produce an even distribution of clearly visible valves across the coverslip. Additional preparation procedures have included the use of a mechanical shaker to disperse clumps of diatoms and the addition of ammonia to help separate out clays (Miller,

1964). In most cases, only further dilution of the samples was necessary. Three or four slides were prepared for each sample from which at least 400 diatom valves were identified and counted. A count of this size appears to give a valid representation of the species present (Battarbee, 1979a).

4.6 Microscopy Techniques

The examination and counting of diatom slides was carried out at high magnification (>1000x) under oil immersion. Some preliminary work was done using a Zeiss Ampival Pol-D (x1000) in the School of Geography. Most of the counts, however, were carried out using an Olympus VANOX with Normarski illumination (at the U.S.G.S., Denver and the École Normale Supérieure, Fontenay-aux-Roses) or a Zeiss Ultraphot (Department of Botany, Oxford). At the E.N.S., some samples were counted using an Olympus BH-2, although a number of identifications were subsequently checked on the VANOX.

For each sediment sample, the number of diatoms encountered on a traverse across the coverslip was recorded and averaged over 3 slides. As the initial weight of dry sediment and the dilution factor were known, it was then possible to calculate the number of diatom valves per gram of dry sediment. For all samples the full count was completed with reference to a number of slides.

Scanning Electron Microscope (S.E.M.) work has been carried out using a Cambridge Stereoscan 150 at the Department of Botany, Oxford. Diatom samples were prepared

by giving the original suspensions a second treatment with H_2O_2 and carrying out further dilutions. 13 mm coverslips were then stuck on to S.E.M. stubs using silver paint. Once the paint had dried, the diatoms were plated out onto the coverslips and left to evaporate in the usual manner. In order to identify the stubs under the S.E.M., a fine brush was used to put an identifying mark on the edge of the coverslip surface, with silver paint. The stubs were sputter coated with gold for use in the microscope and viewed, on emissive mode at 5.2 Kv with magnifications of x 500 and x 20K.

4.7a Diatom Identification

Diatoms were identified with reference to standard floras, particularly Patrick and Reimer (1966,1975); Hustedt (1930, 1930-1966); Cleve Euler (1951-55); Schmidt's Atlas (1874-1959) and Germain (1981). Other reference works used are given in the list of species in Appendix 2. Many of the species encountered have been both drawn and photographed under the microscope and are illustrated in Plates 17 to 49.

4.7b Nomenclature and Problem Species

Melosira

In Zacapu core 1, a form of Melosira was identified which, under the light microscope, initially appeared to be intermediate between M. granulata (Ehr.) Ralfs and M. ambigua O. Müller. Samples of the material were sent to Dr. M.Davey

of the Freshwater Biological Association, who identified it as M. italica (Ehr.) Kütz. subsp. subarctica O. Müller (Plate 17, figures 15 - 17). Lund (1954 and 1955) carried out a detailed study of the seasonal cycle of this diatom. He pointed out that in the U.K. it had been recorded as both M. granulata and M. italica, differing from the latter by its deeper sulcus and the spiral arrangement of the longitudinal rows of striae. It may be more difficult to distinguish from M. ambigua, although the sulcus in M. italica subsp. subarctica is more `v' shaped and the long, tappered spines of M. italica subsp. subarctica (Plate 19) mean that chains of valves are likely to be shorter. The form of the spines may, however, be difficult to recognise in material where the valves have suffered breakage or abrasion. In view of the apparent preference of this species for cool water and its widespread distribution in temperate and subarctic lakes (Lund, 1954), its presence, in large quantities, in Central Mexico was somewhat unexpected. Water temperatures at Zacapu are, however, probably lower than might be expected at this latitude due to its altitude (1,980 m a.s.l.) and to the major role played by springs in feeding the lake. This species was also recorded by Gasse (1980) in sediments from the Gadeb Plain, Ethiopia ($7^{o}02'$ - $7^{o}13'$N), although she emphasises the difficulty of distinguishing it from M. ambigua under the light microscope.

In the lower parts of the core, a form showing only a very small (present ?) sulcus was recorded as M. af. granulata (Plate 17, figures 4 - 5). Under the light

microscope it was not possible to assign this form to either M. granulata or M. italica subsp. subartica with any confidence.

Cyclotella

The species C. quillensis Bailey (see Battarbee et al, 1984) was recorded in a sample from the crater lake Alchichica in the Oriental Basin of eastern Central Mexico (Plate 20, figures 7 - 9 and Plate 21, figure 2). Previously this species has been reported in Mexico in Pleistocene sediments from L. Texcoco (Bradbury, 1971). This new record adds to its known distribution in the Americas.

The two small Cyclotella species C. stelligera Cl. & Grun. and C. glomerata Bachmann, were distinguished following the criteria suggested by Bradbury (1978). It is, however, possible that the smaller forms of C. stelligera have been confused with C. glomerata.

Stephanodiscus

The difficulties of distinguishing the smaller species of this genus under the light microscope have been pointed out by Round (1981) and Theriot and Stoermer (1982). The limited amount of S.E.M. work possible on the Mexican material has helped to resolve some questions, but has left many more unanswered.

In general, species of Stephanodiscus have been identified following Gasse (1980). Although the name S. astraea has been declared invalid by Round (1981) it has been retained in this study, for as Round points out, not all the

taxa called by this name may be covered by the revised name S. rotula (Kütz.) Hendey. Following Round (1981), however, the name S. astraea var. minutula should be replaced by S. minutula (Kütz.) Round, which is felt to be a distinctive species (see Figures 45 - 48 in Round, 1982a).

The identification of valves as S. minutus Cleve & Möller, followed comments from Dr. J.P.Bradbury and the illustrations in Bradbury (1975). Bradbury (1975) had, however, previously reported some S. minutus as S. hantzschii.

The identification of S. hantzschii Grunow and its varieties followed Haworth (1981). In samples from Zacapu core 1, a number of valves originally recorded as S. hantzschii were later assigned to S. tenuis Hustedt. Theriot and Stoermer (1982) point out that S. tenuis may be differentiated from S. hantzschii by the absence of a central rosette from the latter. In addition, under the S.E.M. S. tenuis lacks a central strutted process. Håkansson and Stoermer (1984), however, following detailed examination of the type material of S. hantzschii, believe that S. tenuis Hustedt is actually a finely structured form of this species. As S. hantzschii and the former S. tenuis do appear to be ecologically distinct in North America, the authors suggest that the name S. hantzschii fo. tenuis should be adopted. In the diagrams in this study, the name S. tenuis remains. In the core, a number of valves of S. subtilis Van Goor looked rather like S. tenuis (S. hantzschii fo. tenuis) under the L.M., but S.E.M. pictures revealed the presence of a central

process (Plate 26, figure 1).

Cyclostephanos

This new genus was established by Round (1982b) for diatoms showing a mixture of features of the two genera Stephanodiscus and Cyclotella. The genus Cyclostephanos was distinguished externally by having a ring of solid spines around the valve, and internally by the presence of ribs around the margin, forming chambers. S. dubius (Fricke) Hustedt and S. novaezelandiae Cleve were assigned to this new genus. S. damasii Hustedt was transferred to Cyclostephanos by Stoermer and Håkansson (1983). A species of Cyclostephanos was identified in Zacapu core 1 and is illustrated in Plate 20, figures 14 - 16; Plates 22, 23 and 24, figure 1). Initially, some of the smaller forms were called S. astraea var. minutula (S. minutula), whilst the larger forms were thought to be C. dubius. A sample was examined by N.J.Anderson (U.C.L.) who suggested that the latter were closer to C. damasii. S.E.M. pictures indicate that this is indeed so, as the struts formed by the interfascicular ribs as they go from the valve surface to the margin of the valve mantle, bifurcate in a similar manner (see Figures 7 - 10 in Stoermer and Håkansson, 1983). The form from Laguna Zacapu is, however, clearly not this species. Schoeman et al (1984) describe similar problems in the identification of small centric diatoms, which were initially thought to be close to S. minutula (S. astraea var. minutula), but which probably belong to Cyclostephanos.

These authors also believe that their form lies between C. dubius and C. damasii. Dr. Schoeman has seen electron micrographs of the Zacapu Cyclostephanos sp. and has confirmed that it is similar to the type found near Pretoria. Until further work has been carried out, the Zacapu form has been recorded as Cyclostephanos sp.

The smaller form of the Cyclostephanos sp. has proven even more difficult to identify than the larger. Diatoms looking much the same under the L.M. appear to have been called variously S. minutula (S. astraea var. minutula), S. dubius (see Germain, 1981 plate 10, figures 5 and 7) and S. minutus (see Gasse, 1980 plate 16, figure 30). Where uncertainty remained, small valves of this type have been recorded as Stephanodiscus/Cyclostephanos sp. 1 in the core counts, but may be S. minutula (Plate 25, figure 17).

Unfortunately, no Cyclostephanos sp. were identified in collections of modern diatoms, so that the ecology of this diatom remains uncertain.

Synedra

This generic name has been retained, in spite of the suggestion of Lange-Bertalot (1980c) that the genus should be merged with, and included in, Fragilaria. Round (1984) has rejected this combination as it would obscure aspects of diatom biology, especially since separate taxa may be identified on the basis of ecology rather than morphology alone. Round points out that species of Synedra may be distinguished by the absence of spines from the valve face mantle.

In water, bottom sediment and fossil material from the Zacapu Basin, a form of Synedra acus Kützt. was recorded. This is illustrated in Plate 28, figures 1 - 2 and Plates 29 and 30. It shows a distinctive bilaterally gibbous central area. Gasse (pers. comm.) found this type in Lake Naivasha. Richardson (1968) also refers to S. acus? from this lake and Richardson and Richardson (1972) report S. acus and several very similar types. Unfortunately, no illustration of of S. acus? was provided. Reexamination of slides including the type material of S. acus, held at the B.M. (Natural History), has revealed that a number of different forms were present. Which was actually that designated as S. acus is not clear (D. Williams, pers. comm.). S.E.M. pictures of the Zacapu S. acus type shows that it is a true Synedra (in the sense of Eusynedra in Round, 1979), with apical pore fields, labiate processes (rimoportulae) at each pole, complete girdle bands, lacking spines and with double rows of simple areolae. The new combination S. acus var. neogena is proposed from S. acus Kützt. and S. rumpens var. neogena Grun. (illustrated in Huber-Pestalozzi 1942, plate 134/537). Unfortunately, no type material of the latter was obtained for examination. Further work on the Synedras may, however, prove this combination to be invalid.

S. goulardi Bréb. was also common in samples from Zacapu. The valve shapes, although displaying quite a wide variation (especially in length), were like those illustrated in plate 300 of Schmidt's Atlas (1874-1959), but not like the

form shown in plate 6, figure 8 in Patrick and Reimer (1966). This species has been described in more detail by Schwarzwalder and Postek (1981) and the apparent 'ghost striae' in the central area identified as internal costae. Their specimens from Costa Rica are very like the Mexican examples (see Plate 28, figures 8 - 10; Plates 31, 32 and 33, figures 1 - 2).

Pinnularia

Following Patrick and Reimer (1966), the name P. abaujensis (Pant.) Ross has been used for those diatoms formerly called P. gibba Ehr. Although these authors renamed the former P. gibba var. linearis, P. gibba. var. rostrata and P. gibba fo. subundulata as varieties and forms of P. abaujensis, P. gibba var. parva (Ehr.) Grun. was not altered. The new combination P. abaujensis var. parva is therefore proposed (Plate 42, figures 4 - 5). Patrick and Reimer (1966) point out, however, that Ehrenberg (1841) cited P. gibba occurring at two sites in Mexico, but that this is neither the same taxon as P. gibba as it is usually identified, nor the same as P. abaujensis (Pant.) Ross.

Navicula

For the Lineolatae (N. lanceolata, N. viridula and N. cari), the terminology of Lange-Bertalot (1980b) has been applied.

A number of isolated forms of unidentified Navicula spp. were recorded in both modern and fossil material from Mexico. These are given in the checklist of taxa as Navicula sp. 1 - 12. Some of the forms are illustrated in Plate 41.

Rhopalodia

J.P.Bradbury (pers. comm.) suggested that there were two types of R. gibberula var. Van Heurckii occurring in Mexico. Type 1 having distinctly punctate striae between the costae and type 2 with less distinct punctae and stronger costae. Bradbury felt that these two types were ecologically distinct, type 1 being found in brackish water and type 2 in freshwater. In order to see whether this apparent ecological preference would be supported by further studies, this species was recorded as either of the two types in this investigation (see Plate 46, figures 9 - 10 (type 1) and figures 11 - 12 (type 2). The presence of the types under different water-chemistry conditions, did appear to be consistent with Bradbury's proposal.

Nitzschia

Terminology for this genus generally followed that proposed in Lange-Bertalot (1976), Lange-Bertalot (1978), Lange-Bertalot and Simonsen (1978) and Lange-Bertalot (1980a). However, in view of the confusion over the relationship of N. palea and its varieties, N. paleacea and N. gracilis (cf Lange-Bertalot, 1976 and Lange-Bertalot, 1980a), the forms have all been recorded separately. This seems to be advisable as they appear to show distinct distributions (see Round (1984), cited above, for comments on the problems of 'clumping').

A small Nitzschia sp., at first tentatively called N. microcephala, was later identified as N. tropica Hustedt,

recorded in Hustedt (1949). The valve ends in the Mexican form were usually capitate to subcapitate (see Plate 48, figures 4 - 5).

4.8 Radiocarbon Dating

The radiocarbon dates cited in this text have been provided by three laboratories. Conventional dates were supplied by the N.E.R.C. Radiocarbon Laboratory at East Kilbride and the Carbon-14/Tritium Measurements Laboratory at Harwell. The Radiocarbon Accelerator Unit, Oxford have provided dates on material from the Basin of Zacapu as part of A.J.Fowler's D.Phil. thesis on the 'Radiocarbon Dating of Lake Sediments and Peats by Accelerator Mass Spectometry' (1985).

Chapter 5

THE MODERN AQUATIC ENVIRONMENT

5.1 Introduction

Before attempting any reconstruction of past changes in the chemical and physical natures of lakes in Central Mexico, it was necessary to undertake a survey of the aquatic environment at the present day. A particularly important aspect of this survey was to make a collection of diatom samples for which habitat conditions were known. It was hoped that these samples could then be used as analogues to assist in the interpretation of fossil assemblages from core, section and pit material. As pointed out by Richardson et al (1978) 'modern diatom studies and fossil diatom studies benefit one another in reciprocal fashion'. Such a collection was particularly necessary in view of the lack of published ecological data for diatoms found in the tropics. Only the East African flora has been investigated with any thoroughness (Hustedt, 1949; Talling, 1965; Richardson, 1968; Richardson and Richardson, 1972; Richardson et al, 1978; Gasse et al, 1983). In spite of the dearth of material, it is, however, clear that species often occupy different ecological niches under temperate and tropical conditions. A good example, is the occurrence of species in the tropical plankton which are considered to be non-planktonic in temperate areas (Hustedt, 1949; Richardson, 1968; Gasse, 1980). Also, many species considered to be indicative of oligotrophic or mesotrophic waters in temperate latitudes are

found in abundance in eutrophic waters in the tropics. Ecological information provided in diatom floras based on collections from mid- and high- latitudes must, therefore, be employed with considerable caution.

Samples were taken from many different types of sites across Central Mexico, from the Oriental Basin in the east to the Basin of Zacapu in the west. A summary of sample sites and collections made is given in Table 5.1. The majority of the sites were located in the states of Michoacán, Guanajuato and México and are shown in Figure 5.1. In this chapter, the results of the chemical and physical analyses will be presented, followed by a discussion of the modern diatom flora.

5.2 Water Chemistry

Since the early work of De Buen (1943, 1944) and Deevey (1957), little has been published on the the chemistry of freshwaters in Mexico. Data are collected on a regular basis by the Secretaria de Agricultura y Recursos Hidraulicos (S.A.R.H.), but are used mainly to monitor water quality in irrigation schemes and reservoirs.

The geological and hydrological setting of Central Mexico has been outlined in Chapter 3. In addition to the influence on water chemistry of factors such as bedrock composition and climate, the effects of tectonic activity causing the closure and opening of basins and the different ages of the basins, must also be considered. The process of

chemical evolution in hydrologically-closed basins will be discussed in the context of the model outlined by Eugster and Hardie (1978) and Eugster and Jones (1979). Their model is reproduced in Figure 5.2 and has been descibed, briefly, in Chapter 3, section 1. Although these authors emphasise the importance of the initial chemical composition of the ground or spring water in determining the evolutionary pathway followed by a particular waterbody, variations in the mechanisms of chemical fractionation, in the level of biological activity and in sediment-water interactions, can also be important. Risacher (1978), in a study of the lakes of the Bolivian Altiplano, showed that whilst water chemistry in the region was largely dependent upon the lithology of the source area, the chemical evolution of these waters and the sediments deposited, were determined by the nature and quantity of sediments in the basins. Over time, the increasing sediment and sediment-water interaction can lead to a total change in the salts being deposited from the same initial water composition, independent of any climatic changes. It is to be expected then, that the waters of Central Mexico will show differences in their chemical composition due to the time which they have had to evolve; the geology of the catchments (itself often affected by recent volcanic activity); climate, especially the balance of P-E (precipitation - evaporation); biological factors and the impact of Man in this densely populated area.

A total of 70 water samples was collected between March and August 1982 from 47 sites in Central Mexico. These sites

included lakes, reservoirs, ponds, springs and irrigation ditches. In addition to surface samples from different parts of the waterbody, further samples were taken to yield a depth profile at lakes of particular interest (Laguna Zacapu, Michoacán; La Piscina de Yuriria and Hoya Rincón de Parangueo, Guanajuato). Field and laboratory procedures have been described in Chapter 4.

A series of analyses of samples collected in September 1973 by Dr. J.P.Bradbury of the U.S. Geological Survey, Denver, have been added to the results of the samples collected for this study (by S.E.M.). In some cases these provide additional wet-season samples from the same sites, but most are from different locations, thus broadening the sample area. Permission to use these data is gratefully acknowledged. Results of two analyses published by E.S.Deevey (1957) have also been included in the discussion. As a few of S.E.M.'s results were incomplete or from well outside the main study area, a total of 107 full analyses are presented here. Table 5.2 provides a complete list of the sample sites, the collector and the nature of the water bodies. The results for pH, E.C. (in $\mu S\ cm^{-1}$) and major ions are given in Table 5.3 (in pocket). Ions are expressed as meq/l, except where indicated otherwise. To facilitate the interpretation of the data and to highlight regional variations and patterns, the results have also been plotted on trilinear diagrams (Figures 5.3a to h). These show the relative percentages of the major cations ($Na^+ + K^+$ - Mg^{2+} -

Ca^{2+}) and anions ($CO_3^{2-}+HCO_3^- - Cl^- - SO_4^{2-}$). Different symbols have been used to indicate the type of waterbody from which the sample was taken. The numbers are as those given in the sample site list (Table 5.2).

5.2a East of the Basin of Mexico

Most of the sites in this grouping were in the Oriental Basin. The geology of this area has been described in Chapter 3, section 3b and sample sites are shown in Figure 5.4. The main characteristic of the lakes in this area is the low level of Ca^{2+} with Mg^{2+} or Na^+ and K^+ being the dominant cations (Figure 5.3a). Ca^{2+} appears to be being removed through the precipitation of calcium carbonate, although a pre-volcanic basement of Mesozoic calcareous rock in this area may be a good source of calcium through the deep circulation of groundwater (Garrels and Mackenzie, 1967). This precipitation is clearly seen in the form of reefs around the margins of Laguna de Alchichica (sample 10; Plate 6). The anions are dominated by $CO_3^{2-} + HCO_3^-$ and Cl^- (Figure 5.3b). High levels of SO_4^{2-} in Laguna de Totolcingo (sample 1) may reflect the influence of local sedimentary rocks. Where Ca^{2+} has been depleted, alkalinity is lowered, which probably accounts for the dominance of Cl^- in La. Alchichica. It is likely that the evolutionary pathway IIIA of Eugster and Hardie, from $Mg^{2+} - Ca^{2+} - HCO_3^-$ to $Na^+ - CO_3^{2-} - Cl^-$, is illustrated by the Oriental Basin. Other samples from this Eastern region show a rather different cationic composition, with a greater abundance of Ca^{2+}.

5.2b The Basin of Mexico

Unfortunately, only four full analyses are available from this large and complex basin (Figures 5.3c and d). It is possible, however, to identify a pathway of evaporative concentration from the $Na^+ - HCO_3^-$ composition of Lago de Zumpango (sample 18) to $Na^+ - Cl^-$ in Laguna Texcoco (sample 16). The Texcoco marsh plots intermediately. The depletion of Ca^{2+} and Mg^{2+} agrees well with the Eugster and Hardie model and is logically consistent with Texcoco's position as the lowest in elevation and most concentrated of the remnant lakes of the Basin of Mexico.

5.2c The Basin of Zacapu

As this basin has been the site of major coring and surface-sediment sampling work (see Chapter 6), a series of water and algal samples were collected from around the basin. The location of the sampling sites is shown in Figure 5.5 and the results of the analyses shown in Figures 5.3e and f. The present Laguna Zacapu is a small, remnant lake (Plate 7), fed by springs emerging from (?) Holocene basalt lavas west of the town of Zacapu. Water samples from the lake and its feeder springs (samples 20 to 29, 33, 35 to 36) plot in a compact field, with roughly equal proportions of Mg^{2+}, Ca^{2+} and $Na^+ + K^+$ (Figure 5.3e). Of the individual cations, Mg^{2+} is the most abundant. The anions are also clustered (Figure 5.3f), with high $CO_3^{2-} + HCO_3^-$ (> 60%), variable SO_4^{2-} and low Cl^- (generally < 10%). The overall water chemistry

appears to be closely related to the composition of the volcanic rocks which fringe this part of the basin (varying mainly from basalts to dacites with 62% silica). Laguna Zacapu and the various pools around the basin margin seem to be little-altered spring water. A depth profile taken from the coring site in La. Zacapu (Figure 5.6) shows a quite well-mixed lake, in which a marked characteristic is the high level of silica (SiO_2) at the base, declining up-profile. Whilst the presence of a very large diatom population (mainly Nitzschia palea) may have affected the accuracy of this profile, based only on field test kit results, it seems likely that this SiO_2-rich bottom water reflects groundwater/ spring input. Just west of the town of Zacapu is Cerro Capaxtiro, a recent andesitic cone the lava of which is distinguished by quite abundant glass-coated quartz crystals. An analysis of a sample of lava from this cone (Demant, 1981, sample 585) shows high silica levels (see Table 5.4).

The reservoirs and tanks around the basin, such as Presa Aristeo Mercado (sample 40), plot close together in terms of cations, all having low Mg^{2+} values. Unusually high levels of Na^+ and K^+ are shown by samples from Zacapu Celanese, a synthetic fibre plant (samples 30 and 31). Other sites with high levels of these cations are those into which this water feeds as it leaves the basin via the drainage network. El Angulo (sample 39) and Villa Jimenez (sample 47) are examples of this. The effect of the effluent from the Celanese plant is also clearly seen on the anion diagram, producing elevated SO_4^{2-} levels. It was noted in the field that the pipes

draining immediately from the works site were encrusted with sulphur. As the plant drains directly into the main artery of the basin's irrigation system, it is closely monitored by the local S.A.R.H. office (R. Bernal Sainz, pers. comm.), but is not deemed to cause major pollution problems.

The sample from the crater lake Hoya la Alberca or Alberca de Zipimeo (sample 49; Plate 8)) shows a higher percentage of Mg^{2+} and of $Na^{+} + K^{+}$ than the other Laguna Zacapu and spring sites. It also has higher than usual Cl^{-} levels which may be due to greater evaporative concentration. Such an interpretation is supported by the relatively high conductivity (3,600 $\mu S\ cm^{-1}$) of this lake.

5.2d West-Central Mexico, Other Sites

Although the samples represented on Figures 5.3g and h come from widely scattered sites in very different geological and hydrological settings, a clear evolutionary trend is evident, especially in the cation composition. There is a gradient from dilute lakes, such as Laguna Zirahuén (samples 71 to 73; Plate 9) which although closed by a lava flow probably loses water by groundwater seepage towards Lago de Pátzcuaro, to highly alkaline and saline lakes such as Hoya Rincón de Parangueo (samples 101 to 105; Plate 10), La Piscina de Yuriria (samples 93 to 95, 98 and 99; Plate 11) and Laguna Cuitzeo (samples 74 to 76). La Piscina de Yuriria and Hoya Rincón de Parangueo are both crater lakes situated in the state of Guanajuato, in the northern part of the

study area. Vertical profiles from these lakes are shown in Figures 5.7 and 5.8. This geochemical gradient towards the dominance of $Na^+ + K^+$ (Figure 5.3g) can be attributed to the loss of alkaline earths (Ca^{2+} and Mg^+) through evaporative concentration. Samples from Lago de Pátzcuaro suggest that it occupies an intermediate position along this gradient with moderately evolved waters. The composition of Pátzcuaro may, in part, be a result of active photosynthesis at the surface of this eutrophic lake, but out-seepage is a more likely cause for its relatively dilute chemistry.

The anion composition (Figure 5.3h) also shows a broad trend from $CO_3^{2-} + HCO_3^-$ to Cl^- dominant. It is interesting to note the evolution through time of Laguna Cuitzeo for which the two samples taken in 1973 (75 and 76) have a much lower percentage of Cl^- than sample 74, taken in 1982 when the lake was virtually dry.

Both cations and anions suggest a general trend of increasing evaporative concentration across the region from south to north. This is consistent with the climatic trend from the cool, humid highlands of Michoacán to the warm semi-arid climate of Guanajuato. Precipitation declines from > 1000 mm/annum to 500 to 600 mm and altitude decreases. A similar drying gradient also occurs southward into the state of Morelos, where Cl^- levels are again higher. The very high level of SO_4^{2-} in Laguna Tequesquitengo (sample 58) is probably indicative of local sedimentary rocks. A tendency for relatively high SO_4^{2-} contents in larger lakes is well illustrated by Lago de Yuriria (sample 63) and Laguna Cuitzeo

(74 to 76).

The samples from volcanic lakes in this area appear to provide a good example of pathway IIIa of Eugster and Hardie where waters of high initial $HCO_3/Ca^{2+} + Mg^{2+}$ ratio evolve into $Na^+-CO_3^{2-}-SO_4^{2-}-Cl^-$ or $Na^+-CO_3^{2-}-Cl^-(-SO_4^{2-})$ brines.

5.2e General Trends in Central Mexico

In order to remove some of the 'noise' introduced into the patterns of chemical types by the diversity of sampling sites, trilinear diagrams have been drawn up showing, firstly, the analyses from crater lakes and their associated springs (Figures 5.9a and b) and secondly, those from all lakes (Figures 5.9c and d).

The crater lakes and their associated springs (Figures 5.9 a and b) are relatively high in Mg^{2+} and low in SO_4^{2-}, regardless of region. It is interesting to note the differences, however, between the highly concentrated $Na^+ + K^+$ dominated Hoya Rincón de Parangueo and La Piscina de Yuriria and the relatively dilute Laguna Preciosa (sample 14), which is high in Mg^{2+}. The anions show a fairly consistent trend from high $CO_3^{2-} + HCO_3^-$ towards Cl^-, although the low alkalinity of Alchichica is noteable.

The figures showing all lake sites (Figures 5.9c and d) present a clear pattern of Ca^{2+} and Mg^{2+} depletion and $Na^+ + K^+$ enrichment. This gradient passes from the dilute, non-crater lakes of Michoacán, through the crater lakes to those of the Oriental Basin and, ultimately to the highly evolved

lakes of northern Michoacán and Guanujuato. Amongst the anions, most of the lakes have a very high percentage of $CO_3^{2-} + HCO_3^-$, which is as expected in a mainly volcanic region. The crater lakes, including Hoya la Alberca from the Basin of Zacapu as well as those further north, show, a trend from $CO_3^{2-} + HCO_3^-$ to higher Cl^-, although with low SO_4^{2-}.

5.2f Conclusions

It appears that in those parts of the study region receiving quite abundant rainfall and/or groundwater input, the chemical composition of the surface waters is mainly determined by the nature of the volcanic rocks which make up the Neovolcanic Axis. In the small, closed catchments of crater lakes and in the drier areas (north and east), it seems that the pathways of chemical evolution suggested by Eugster and Hardie (1978) and Eugster and Jones (1979) are applicable. That is, the depletion of Ca^{2+} and Mg^{2+} and enrichment of Na^+ and K^+, whilst $CO_3^{2-} + HCO_3^-$ are gradually superseded by Cl^- (see Figure 5.2). Although there are some samples which appear to be at variance with the expected pattern, these may often be explained by local circumstances.

5.3 Physical Characteristics of Central Mexican Freshwaters

As described in Chapter 4, physical characteristics of the waters sampled were recorded in the field. Where possible, the following features were noted: pH, E.C., temperature and transparency. In lakes where a series of samples were taken from different depths, pH, E.C. and

temperature were recorded down the profile. There was a great range in all these values, which might be expected in view of the variety of sample sites.

5.3a pH and electrical conductivity

Excluding some readings taken with pH papers, which are believed to have yielded unreliable results, almost all the pH values were greater than 7. The low (paper) values of 5, obtained for Laguna Zacapu were incompatible with both its CO_3^{2-} + HCO_3^- (alkalinity) levels and with pH values recorded on other occasions using a meter (8.8, 7.3, 8.15, 8.4). Although every attempt was made to minimize gaseous exchange (especially of carbon) after sampling, there were discrepancies between field pH results and laboratory determinations of CO_3^{2-}. In these cases pH values were retaken using the laboratory meter and showed values less than 8.3 (see Chapter 4, section 4a).

Electrical conductivity (E.C.) ranged from 72.0 to >50,000 $\mu S\ cm^{-1}$. Particularly high values were recorded from the highly concentrated waters of the crater lakes Hoya Rincón de Parangueo and La Piscina de Yuriria, and a fairly high value from Hoya la Alberca. The sample from a small, remnant pool of the almost dry L. Cuitzeo (sample 74) went off-scale on both pH and E.C. meters. In some cases, E.C. appears low relative to pH and T.D.S. (total dissolved solids), but this may be due to interference with the meter readings by organic matter (Forester, pers. comm.).

5.3b Temperature

Whilst none of the waters were really cold (none < 15°C), many were warm. Excluding the high temperatures (31° and 32°C) recorded at the outlet of the Zacapu Celanese factory, a number of the closed lakes recorded high temperatures, often equalling air temperature. While this was not too surprising with small, shallow water bodies at the end of the dry (and hot) season, it was quite striking with deep lakes. Hoya Rincón de Parangueo, for example, is more than 50 m deep, but the temperature at the surface in mid-lake was 28°C. The depth profiles presented above for three lakes: Hoya Rincón de Parangueo, La Piscina de Yuriria and La. Zacapu (Figures 5.8, 5.7 and 5.6) show that in all cases, temperature declined with depth. The low temperature of Zacapu, probably reflects the strong spring input into the lake. With the possible exception of the two very deep crater lakes sampled (Hoya la Alberca and Hoya Rincón de Parangueo) and, possibly of La. Zirahuén, the lake waters in Central Mexico are probably not thermally stratified throughout the year.

5.3c Transparency

Most of the water bodies sampled, apart from the spring-fed pools, had quite low secchi-disc transparency. In some cases this was due to a dense algal flora (as in La Alberca) and in others to suspended sediments. Abundant suspended sediment was a feature in a number of reservoirs,

for example Presa Cointzio (sample 67) and Presa Aristeo Mercado (sample 40). There were, however, two exceptionally clear lakes, one being the crater lake Hoya la Alberca (Alberca de Zipimeo) and the other Laguna Zirahuén. Both of these are deep, unproductive lakes in volcanic terrain.

5.4 Silica

Following convention, dissolved silica has been expressed as SiO_2 (Table 5.2). Although the results are only from field test kits, they probably indicate relative abundance fairly accurately. The values range from 0.5 ppm in the reservoir Villa Victoria, to 300 ppm in a sample from La Piscina de Yuriria, with an average of 42.5 ppm. Deevey (1957) found some of the highest SiO_2 values in his study area in the more turbid, shallow Mexican lakes such as Chapala (50 mg/1). A comparison of SiO_2 values from various studies of L. Pátzcuaro indicates that the test kit results may not be too inaccurate. Results from this study produce values for Pátzcuaro of 11 and 5 ppm, De Buen (1944) recorded 12 to 13 mg/1 and Deevey (1957), 14 mg/1.

The fairly high levels of silica in most of the Mexican samples are probably due to the availability of aluminosilicates in the volcanic rocks (Garrels and Mackenzie, 1967) with solubility increased under the relatively high temperatures and pH levels above 7. Many of the highest SiO_2 values in this study were found in crater lakes (such as La Alberca) and in springs and associated pools fed directly by groundwater emerging from lava flows

(e.g. Queréndaro, Tarejero, Santa Fe de la Labor). Some values of SiO_2 in African volcanic lakes of similar chemistry are given below:

Site	Area	SiO_2 mg/l	Source
L.Ziway	Ethiopian Rift	47.0	Gasse et al, 1983
L.Abiyata	"	55-130.0	"
L.Shala	"	130.0	Richardson & Richardson, 1972
L.Naivasha	Kenya Rift (E)	31.5	Gasse et al 1983
L.Elmenteita	"	295.0	

Factors affecting silica solubility have been discussed by Iler (1979) and the relationship between increasing pH, silica solubility and diatoms by Hecky and Kilham (1973). It seems unlikely that SiO_2 availability would be a limiting factor for diatom growth in this region on an annual time scale, although blooms may cause a marked depletion of SiO_2 on a seasonal basis. Variations in the ratio of nitrogen to phosphate may, however, favour forms of algae other than diatoms (Stumm and Baccini, 1978).

5.5 Discussion

Samples from a wide variety of freshwater sites in Central Mexico show that in most cases Na^+ or Ca^{2+} are the most abundant cations and that $CO_3^{2-} + HCO_3^-$ dominate the anions. In a dilute lake such as La. Zirahuén, the chemical composition is $Ca^{2+} > Mg^{2+} > Na^+ > K^+$, whilst $HCO_3^- > SO_4^{2-}$. Locally, as in La. Zacapu, Mg^{2+} may be the dominant cation. In more concentrated lakes, Na^+ is the major cation and CO_3^{2-} or Cl^-, the major anion. A comparison of Bradbury's 1973

results for Cuitzeo: $Na^+ > K^+ > Ca^{2+} > Mg^{2+}$, $CO_3^{2-} + HCO_3^- > Cl^- > SO_4^{2-}$ with those obtained in 1982: $Na^+ > K^+ > Mg^{2+}$, $Cl^- > CO_3^{2-} > SO_4^{2-}$, illustrates the final stages of evaporative concentration with the complete loss of Ca^{2+} and Cl^- exceeding CO_3^{2-}.

In order to examine whether there is a consistent relationship between the behaviour of particular pairs of ions or between related factors such as E.C. and pH, a series of linear correlations and regressions were run. In most of these, Na^{2+} was used as the fixed variable since it is a fairly conservative element. The data used here are those collected specifically for this study. The weakest correlation, which was not statistically significant at the 0.01 level, was that between Na^+ and Mg^{2+} ($r=0.20$) and the strongest, significant at 0.001, that between Na^+ and Cl^- ($r=0.95$). Some of the more interesting relationships are plotted on a log-log scale in Figures 5.10a to 5.10g.

The strong positive relationship between Na^+ and Cl^- (Figure 5.10a) is predictable in terms of the Eugster and Hardie model and from a consideration of the data. La Piscina de Yuriria, Hoya Rincón de Parangueo and Cuitzeo cluster together as the end members of this relationship. The highly evaporated sample from Cuitzeo has the highest Cl^- value. In general, La Piscina de Yuriria records lower Cl^- values than Hoya Rincón de Parangueo. A highly concentrated 'red' sample, from the margin of La Piscina de Yuriria (sample 98) is the exception to this. The same cluster of sites, with a rather disjunct distribution, marks the Na^+ vs

CO_3^{2-} + HCO_3^- relationship (r=0.90, significant at the 0.001 level) (Figure 5.10b). As might be expected La Piscina de Yuriria, even the `red' sample, is richer in CO_3^{2-}/HCO_3^- relative to Na^+ than Hoya Rincón de Parangueo. In the latter lake and L. Cuitzeo, Cl^- has clearly superseded CO_3^{2-}/HCO_3^- as the dominant anion. A number of sites in the Zacapu basin record high levels of Na^+ relative to their alkalinity. These are the sites affected by effluent from Zacapu Celanese: El Angulo and Villa Jimenez, where SO_4^{2-} from the fibre plant is important (see section 2c).

The regression of K^+ on Na^+ (r=0.84) (Figure 5.10d) again shows the cluster of high values from La Piscina de Yuriria, Hoya Rincón de Parangueo and Cuitzeo. The `red' sample from La Piscina de Yuriria shows particularly marked K^+ enrichment. The sites affected by the output from the Zacapu Celanese plant again fall well below expected K^+ values. The scarcity of K^+ in Laguna Zacapu and its feeder springs may be the cause of this.

Consideration of the relationship between Na^+ and SO_4^{2-} (r=0.62, significant at 0.001) (Figure 5.10f) indicates a breakdown in the clustering of La Piscina de Yuriria, Hoya Rincón de Parangueo and Cuitzeo shown with the other anions. Hoya Rincón de Parangueo contains relatively little SO_4^{2-}, whereas La Piscina de Yuriria has quite high values except for the `red' sample. Cuitzeo is the most SO_4^{2-} rich. The high SO_4^{2-} content of the samples from Zacapu Celanese and the Tanque Elevado (also in the Basin of Zacapu) are noteworthy.

The only inverse relationship was that between Na^+ and Ca^{2+} (r=-0.34) (Figure 5.10g). This correlation was significant at the 0.01 level, but not at 0.001. The general trend of the relationship is, however, as predicted by the Eugster and Hardie model, with the early loss of Ca^{2+} and its replacement by Na^+. The graph shows a very distinct clustering of samples with no, or very little, remaining Ca^{2+}. These are the group of very concentrated waters from La Piscina de Yuriria, Hoya Rincón de Parangueo and Cuitzeo which has been discussed in relation to a number of the other figures.

The correlation of E.C. with alkalinity (r=0.85) (Figure 5.10c) supports the shift from carbonate alkalinity to Cl^- under highly concentrated conditions. The correlation of laboratory pH with CO_3^{2-}/HCO_3^-, however, yielded a statistically significant, yet weaker linear relationship (r=0.48). In highly alkaline waters (> 100 meq/l) there tends to be more scatter in the pH/alkalinity relationship (Talling and Talling, 1965).

The correlation between E.C. and field pH (r=0.69) (Figure 5.10e), was statistically significant at the 0.001 level. Hoya Rincón de Parangueo is notable in having a relatively low pH for its E.C. as is the `red' sample from La Piscina de Yuriria. The possibility of Cl^- enrichment leading to a combination of high E.C. and salinity with comparatively low alkalinity and pH values was noted by Talling and Talling (1965). The distribution of values seems rather more continuous for these characteristics than for

those discussed above. Hoya la Alberca plots as one of the intermediate values between the highly concentrated group and the rest.

In general terms, the lakes of Central Mexico fall into the $Na^+ - CO_3^{2-}/HCO_3^- - Cl^-$ category. Volcanic lakes of similar composition occur particularly in East Africa and in the northern part of the Great Basin (especially Oregon) in the U.S.A.. Table 5.5 presents a summary of the characteristics of a number of African lakes of this type (Gasse et al, 1980). More detailed analyses from African lakes are given in Talling and Talling (1965), Hecky and Kilham (1973) and Street (1979). Analyses of Oregon lakes in the $Na^+ - CO_3^{2-}$ category are given for lakes Abert and Harney by Philips and Van Denburgh (1971) and for Summer Lake and Alkali Lake by Eugster and Hardie (1978). A limnological survey of the Warner Valley, Oregon conducted by S.P.Harrison and S.E.Metcalfe in the summer of 1984 confirmed that $Na^+ - CO_3^{2-}/HCO_3^-$ waters occur in that basin too. Lakes of similar chemistry are also found on the southern Altiplano of Bolivia (Risacher, 1978) and in Nicaragua (Swain, 1966).

In view of the scarcity of information on both the modern diatom flora of Mexico and its ecology, data from these other areas of similar water chemistry have been used to assist in the interpretation of Mexican assemblages. In the following section the results of samples of the present day flora will be discussed. An attempt has been made to relate changes in assemblages to differences in habitat and

in the chemistry of the water bodies from which they were taken. As indicated in the introduction to this chapter, the concentration of work of this type in East Africa means that most comparative examples have been drawn from there.

5.6 Diatoms

Present-day diatom populations were sampled at all the sites from which water samples were taken, and from a few additional places. Bottom sediments from the sediment/water interface were also collected. Field sampling techniques and sample treatment procedures have been described in Chapter 4. Counts of these samples were mainly carried out using an Olympus BH-2 or VANOX microscope at magnification x1000 and x1250 respectively. Only 67 of the samples produced full counts (i.e. $\geqslant$400 valves), which included 354 taxa. The results of these counts are listed in Appendix 3. All the identified taxa are included in the taxonomic check list (Appendix 2). As stated in section 1, the collection of these modern samples was viewed as an important piece of background work for this study of fossil assemblages. Clearly, the collection could have been more extensive and ideally re-sampling of sites should have been carried out on a regular basis to identify seasonal, or shorter term, population changes. Unfortunately, it was not possible to undertake such a sampling programme due to constraints on the length of time which could be spent in Mexico.

To assist with the interpretation of the results of these counts, it was decided to apply both a classification

(or clustering) and an ordination technique. The basic purposes of such techniques are: 1) to summarise large and complex data sets . 2) to aid in the environmental interpretation of community variation and in the generation of hypotheses concerning these variations, and 3) to help to refine models of community structure (Gauch, 1982). The results of applying both classification and ordination methods are believed to be complementary and to assist in the interpretation of the groupings or communities and environmental gradients represented by the raw data.

A number of different clustering techniques and computer programs are available (see the discussion in Gauch, 1982). The method selected was an hierarchical clustering technique used in the program TWINSPAN. TWINSPAN (TWo-way INdicator SPecies ANalysis) was written by M.Hill as part of the Cornell Ecology Series (1979a). It appears to be generally effective in representing data structure and in indicating community gradients, is robust to the vagaries of ecological data and makes relatively small demands upon computer time for large data sets. In a comparison of five hierarchical clustering techniques Gauch and Whitaker (1981) concluded that 'TWINSPAN (is) the best general purpose method, especially when the data set is complex, noisy, large or unfamiliar'.

TWINSPAN is based upon the divisions of ordinations, not the selection of indicator species. It consists of two main steps: the classification of the samples and then the

classification of the species based on that of the samples, i.e. upon the fidelity of species to a particular group of samples. The two classifications are then used together to obtain an ordered two-way table, in which groups of alike species and alike samples are put togther. The construction of the ordered, two-way table is based upon the identification of differential species. That is, those which have a clear ecological preference, as reflected by their occurrence in only a particular group of samples. The steps in the procedure may be summarised as follows:

1) The sample data are ordinated by reciprocal averaging to identify a direction of variation in the data (primary ordination).

2) This ordination (or axis) is then divided to split the samples into two groups.

3) Differential species are identified, which are preferential to one side or other of the dichotomy.

4) An improved ordination is constructed based upon the differential species (refined ordination).

5) This ordination is then used to pin-point where the dichotomy should be.

A third ordination (the indicator ordination) is also applied using a few, highly preferential species. This is mainly a process for checking the refined ordination.

In this study, all samples were entered during the course of the analysis. Eight cut levels of pseudo-species abundance (see Hill, 1979a for definition) were used: 1=0.0%, 2=2.0%, 3=5.0%, 4=10.0%, 5=25.0%, 6=50.0%, 7=75.0% and

8=90.0%. Within the ordered two-way table or matrix, therefore, the cut levels are used to define levels of abundance from the original species percentage input data (e.g. a 3 in the table represents 5-9%). All cut levels were weighted equally as the presence or absence of an individual species may be important in determining a particular assemblage (Gasse and Tekaia, 1982). In addition, all species were included as potential indicators and in the final tabulation. Other input parameters were set to default values.

The ordination technique chosen was detrended correspondence analysis (D.C.A.), using the DECORANA PROGRAM (HILL, 1979b). The aim of the ordination is to summarise community patterns by placing similar entities (either samples or species) close together in low dimensional space. The community structure indicated by the ordination may then be interpreted in terms of environmental factors. According to Gauch (1982) D.C.A. provides `a relatively objective community-centered ordination'. In addition, the D.C.A. ordination positions may help in understanding the divisions of the TWINSPAN hierarchical classification. D.C.A. is an eigenvector ordination technique, based on reciprocal averaging (as in TWINSPAN). It is an improvement upon reciprocal averaging (R.A.), however, as it removes any systematic relationship between the first and any higher axes (due to the `arch' effect (Hill, 1979b)). By means of rescaling, it also ensures that equal distances in ordination

space correspond to equal differences in species or sample composition.

The DECORANA output presented here has Axis 1 as the x axis and Axis 2 as the y axis. The length of each axis (or gradient) is equal to the length of the ordination in terms of units of 'standard deviation' (see Hill, 1979b). The figures along the axes have been multiplied by 100, therefore a score of 350 on the axis should be interpreted as 3.50 s.d. The species ordination may be 3 - 4 s.d. in length without there being any real variation in the data. For samples, however, a separation of 4 s.d. will generally mean that two samples will have no species in common. These sample scores are weighted mean species scores.

In order to reduce both the quantity of data to enter and the volume of output to interpret, the modern diatom data were run through TWINSPAN and DECORANA in three sets. These were: Laguna Zacapu and adjoining sites (20 samples); other sites in the Zacapu Basin (12 samples) and all other sites (35 samples). As TWINSPAN carries out first the sample classification and then the species classification, the results for each set will be presented in the same order. These will be followed by a discussion of the output from DECORANA.

5.7 Laguna Zacapu and adjoining sites

Input data consisted of the results from 20 samples ('Z' series) taken in and around Laguna Zacapu in Michoacán. The location of the sampling sites is shown in the field sketch

in Figure 5.11. Sampling around the outlet from the Zacapu Celanese plant is shown in more detail in Figure 5.12. The chemistry of this lake is given in Table 5.3 and shown on trilinear diagrams in Figures 5.3e and f. Diatom sampling sites and their associated water analysis numbers are given in Table 5.6. A total of 137 species were recorded. The ordered two-way table is presented in Figure 5.13a and the resulting dendrogram in 5.13b. The results of the DECORANA ordination for samples and species are shown in Figures 13c and 13d.

5.7a TWINSPAN Classification of Samples

The first division of the samples produced two groupings: ***0**, samples Z:2,3,4,5,8,9,10,11,12,13,14,15,16 and 17 and ***1**, samples Z:1,6,7,18,19 and 20 (Table 5.7). The indicator species identified were both for the ***1** group and were the planktonic diatoms Melosira granulata var angustissima (at abundance 2-4%) and M. ambigua (at 0-1%). The two groups represent samples from the lake itself and its outflow channel (***0**) and from a feeder pool La Zarcita, a tributary area and three bottom sediment samples from part of the drainage network (***1**). This ***1** group only underwent one further division which brought out the two sample clusters: ***10** (Z1,6,7) and ***11** (Z18,19,20). ***10** represented samples from La Zarcita and two from an area of gardens between this water body and the main lake. The ***11** cluster was the sediment samples for which the indicator species identified

was Cyclotella stelligera in low abundance.

The division of the *01 group separated samples from the surfaces of vegetation on the margin of the main lake and bottom sediment samples (Z3,4,12,13,14 (group *011)) from the rest (Z5,8,9,10,11,16, group *010). The final division of the *011 group placed the sediment samples in a different cluster (*0111) from the vegetation samples (*0110). The division of the *010 group proved less straight forward. A group of three samples (Z5,8,9) taken in a channel leading from a spring-fed pool into the main lake (site 4) and a sample taken in the main channel leading out from the lake, upstream of the outlet from the Zacapu Celanese plant (Z16), were put together (*0101). Another sample (Z10) from site 4, however, was placed on the other side of the dichotomy with sample Z11 from the margin of the main lake (*0100). The indicator species for this division, both related to *0100, were Gomphonema subclavatum var. mexicanum (0-1%) and Nitzschia palea var. debilis (2-4%). Sample Z11, however, was recorded as a misclassified negative, indicating that although the overall composition of the assemblage placed it to the left (or negative) side of the dichotomy, its indicator species score would assign it to the right (or positive) side. This provides a useful illustration of the subsiduary role of indicator species in this classsification technique. Although the indicator species for divisions will be given in this discussion, they do not necessarily determine where a sample is located at a dichotomy.

The sample dichotomies have been summarised in Table

5.7. It can be seen that the clusters *00, *10 and *11 were differentiated after only two divisions, indicative of quite distinct assemblages. The *01 group, however, included a number of species clusters of similar composition which were only separated after further divisions. The classification of the samples appears to produce clusters taken from particular types of habitat (e.g. *0110 samples Z3 and Z4 from lake-margin vegetation) or from particular areas of the lake drainage system, such as the samples upstream of the main lake (*10, samples Z1,6,7). The significance of these groupings will be discussed further in section 7c.

5.7b TWINSPAN Classification of Species

The classification of the species in the samples from Laguna Zacapu and associated sites, went through the full six divisions provided for by the default option on the TWINSPAN program (Figures 5.13a and b). Even after this, a number of quite large species clusters still remained. In view of the size of some of these clusters, the final, smallest clusters will be described first and then put into their larger groups, beginning from the left.

The species at the extreme negative end of the species ordering (*00000 and *000010) fell into clear groups related to samples. The second of these two species clusters included Navicula pygmaea, Nitzschia hantzschiana, N. af. ignorata, N. pusilla, N. recta, N. sigma var. diminuta and Synedra rumpens var. familiaris. The two clusters occurred

mainly in sample group *00 (Z2,15,17). The other species common in these samples were Navicula pupula var. rectangularis and Nitzschia palea var. debilis (cluster *000011). The samples in which these were found were of the mid-lake plankton (Z2) and from the water and stone scraping collected in the main irrigation channel leading from the lake at the Celanese outlet (Z15,17), Celanese A. The most abundant species in these samples (Z2,15,17), however, were Nitzschia palea with Stephanodiscus subtilis and Synedra acus var. neogena. Species in the cluster *000011 also occurred in the sample group *010 (Z5,8,9,10,11,16), which came from the lake margin, from Zacapu site 4 and from the irrigation channel upstream of the Celanese outlet (Celanese B).

The species cluster *000100 also remained after six divisions. The species included were: Achnanthes lanceolata, Fragilaria construens var. binodis, Gyrosigma spencerii, Melosira granulata, Navicula capitata var. hungarica, N. damasii, Nitzschia rostellata, Pinnularia sp. 1, Stephanodiscus tenuis, S. tenuis fo. minor, S. transylvanicus, Surirella tenera and Synedra delicatissima var. angustissima. These species were found in low abundance (usually < 2%) in the sample group *011 (Z3,4,12,13,14) from lake-margin vegetation and basal sediment samples.

Melosira italica subsp. subarctica and Stephanodiscus/ Cyclostephanos sp. (*000110) formed a small species cluster found in sample group *01 (Z3,4,5,8,9,10,11,12,13,14,16). These were samples from the lake margin and its vegetation, Site 4 samples, bottom sediment samples and from Celanese B.

The species cluster formed part of a larger species group, with species from ***000111** (Achnanthes affinis, A. hungarica, A. linearis, A. minutissima, Cocconeis placentula, C. placentula var. euglypta, Diploneis elliptica, Gomphonema clevei, G. intricatum var. pumila, G. parvulum var. micropus, Gomphonema sp., Navicula canalis, N. cincta, N. cryptocephala, N. gottlandica, N. grimmei, N. halophila, N. radiosa var. parva, N. radiosa var. tenella, Nitzschia paleacea and Synedra ulna). This large species cluster was distinctive mainly of the sample group ***010** (Z5,8,9,10,11,16), being more abundant in samples Z10 (Site 4 vegetation) and Z11 (lake margin site 2).

The large species grouping ***001** exhibited a broad distribution across all samples. The particularly abundant and ubiquitous species were: Cocconeis placentula var. lineata, Stephanodiscus subtilis, Synedra acus var. neogena, S. goulardi and Nitzschia palea. Also widespread, but in smaller numbers were Gomphonema angustatum, Navicula heufleri var. leptocephala and Rhoicosphenia curvata. Within this ***001** group, smaller species clusters of interest were ***001011, *00110** and ***00111.** The first of these comprised the epiphytic species C. placentula var. lineata and R. curvata, with N. cryptocephala var. veneta. These occurred mainly in the sample grouping ***01** and in greatest abundance in samples from floating vegetation at Site 4 and from Celanese B (Z5,8,9,16 = ***0101**).

The second cluster (***00110**) by contrast, consisted of

planktonic species: Stephanodiscus subtilis, Synedra acus var. neogena and S. goulardi. These were more numerous in the sample group *011 and were particularly abundant in the mid-lake bottom sediment samples (Z12,13,14). S. subtilis was dominant in these assemblages with 25 to 49% of the count.

The final species cluster (*00111) was of Nitzschia ignorata, N. microcephala and N. palea. N. palea occurred in almost all the samples which is probably indicative of anthropogenic influence. It did, however, display an abundance gradient. It was most abundant (> 25%) in samples Z2,15 and 17 (from the middle of the lake and its outlet channel at Celanese A), then in two other sample clusters: samples Z3 and Z4 (*0110) from lake-margin vegetation and from Z5,8,9 and 16 (*0101) from Site 4 vegetation and Celanese B.

The next major species grouping was *01 which emerged at the second tier of species division. Nitzschia amphibia (at < 2%) was the indicator species in this group. N. amphibia occurred in all sample groups except *00 (Z2,15,17). The species cluster *011, within this group, was quite distinct (Cymbella mexicana, Nitzschia dissipata, N. intermedia and Stephanodiscus hantzschii var. pusilla). N. intermedia was the indicator species for the sample group *011 (Z3,4,12,13,14) from lake-margin vegetation and bottom sediments. This species cluster occurred in quite low abundance on both sides of the principal dichotomy of the samples.

On the positive side of the principal dichotomy of the species, the first cluster, distinguished at the third division, was ***1000.** The species in this cluster were Cyclotella stelligera, Fragilaria brevistriata var. inflata, Gomphonema ventricosum and Stephanodiscus hantzschii. C. stelligera was the indicator species for the sample group ***11** (Z18,19,20) from sediment samples associated with the Zacapu Celanese outlet. All the species in this cluster were found principally in this sample group.

The next two species clusters, part of the larger group ***1001**, included a number of epiphytic/littoral species such as Cymbella muelleri and Cocconeis fluviatalis. Stephanodiscus minutus was also part of this group, but was very widely distributed amongst the samples as might be expected in view of its position near the main species dichotomy.

Associated with the above groups at the ***10** level were two species clusters including a number of Nitzschia species: N. inconspicua, N. parvula, N. acicularis and N. gracilis (with Stephanodiscus carconensis and Navicula pupula). These occurred mainly in sample groups ***00** (Z2,15,17) from mid-lake and Celanese A and ***10** (Z1,6,7) from La Zarcita and Zacapu Gardens.

The species group ***110** had a quite distinctive distribution. Within it, the species cluster ***11000** of Fragilaria construens var. venter, F. pinnata, F. pinnata var. lancettula and Melosira granulata var. angustissima was important. F. pinnata var. lancettula and M. granulata var.

angustissima occurred in high abundance (10 to 74%) in samples Z1,6 and 7 (***10**) from La Zarcita and the gardens. The cluster as a whole was quite widely distributed, but concentrated in samples Z1,6,7 and Z18,19,20 (***11**), the Celanese sediment samples. M. granulata var. angustissima was the main (positive group) indicator at the first division of the samples. In the larger species group (***110**), there were several planktonic species: Cyclotella meneghiniana, Stephanodiscus niagarae and S. novaezelandiae. The two Stephanodiscus species were most abundant in samples Z18,19 and 20.

The next large group of species (***1110**), also occurred mainly in the Celanese sediment samples (Z18,19,20). There was a small cluster (***11100**) of Fragilaria brevistriata, F. construens and Stephanodiscus astraea var. minutula. ***111010** was a large cluster of co-occurring species, also in this group. Three planktonic species occurred at higher abundances (> 10%): Melosira ambigua, Stephanodiscus asteroides var. intermedia and S. astraea var. intermedia. These were particularly prominent in samples Z18, 19 and 20, referred to above. M. ambigua was an indicator species, with M. granulata var. angustissima, for samples on the positive side of the first sample division. This was a rather mixed cluster, including a number of species found in only one sample and at low abundance (e.g. Campylodiscus clypeus, Pinnularia maior and Rhopalodia gibberula var. Van Heurck). Melosira italica was grouped with this cluster at the fifth

level of species division.

The final species group (*1111) also comprised species found in small numbers in individual samples. All the species in this cluster occurred only in sample group *10 (Z1,6,7) from La Zarcita and the Zacapu gardens. They were the less common species in the samples dominated by the species group *110 and especially by cluster *11000 (M. granulata var. angustissima etc.).

To summarise the information in the ordered two-way table, the species group *00 occurred mainly in samples on the negative side of the sample dichotomy (samples Z:2,15,17,10,11,5,8,9,16,3,4,12,13,14). The most abundant species in these assemblages were from the species group *001. The *01 group of species, although mainly negative re the sample dichotomy, were actually present across the spectrum of samples, but at low abundance. The species group *10 had a similar distribution. This is as expected for species near the main species dichotomy. The *11 species group was present mainly in samples on the positive side of that dichotomy (samples Z1,6,7,18,19,20). The most abundant species in these samples were in the species group *110.

5.7c DECORANA results for Laguna Zacapu

The results for the 1st and 2nd axes for samples and species ordinations are shown in Figures 5.13c and 5.13d respectively. On Figure 5.13c, the type of sample (water, vegetation etc.) is distinguished by colour and some of the TWINSPAN clusters are marked. Samples Z1,6,7,18,19 and 20

are clearly isolated by the first axis (Figure 5.13c), with a distinct break in distribution along this gradient. Species occurring in these samples may not be found in the others in this set of samples. These same samples were also separated at the first level of the TWINSPAN sample division, to form group ***1.** Within this, the clustering of samples Z1, 6 and 7 and Z18, 19 and 20 (TWINSPAN clusters ***10** and ***11**) is also brought out by the ordination procedure.

The other samples appear to be arranged along the gradient represented by the 2nd axis. Although sample Z2, from the middle of the lake, and sample Z11, from the lake margin, fall at either end of this gradient, examination of the intervening samples shows that this gradient is not simply reflecting a change in water depth. The proximity of the bottom sediment samples (Z12 - 14) is interesting and was, also, confirmed by the TWINSPAN results. The length of the gradient of the 2nd axis is, however, such that all the samples are likely to have species in common. One feature of this gradient is the decrease in the percentage of N. palea from the lowest to the highest scoring samples. The gradient may, therefore, represent some sort of degree of anthropogenic influence as reflected by this species.

The species ordination (Figure 5.13d) is rather confused, with a large grouping of species between 4 and 5 s.d., on the 1st axis gradient. This group of high scoring species includes many (e.g. S. asteroides, S. astraea, S. subtransylvanicus, M. ambigua and C. clypeus) thought to be

derived from older fossil material (see below). Amongst the highest scoring species on this axis are a number indicative of higher Cl^- or more brackish-water conditions such as C. clypeus, F. brevistriata var. elliptica and Anomoeoneis costata. This does not, however, seem to be a consistent feature of the high scoring species as these include a number of Pinnularia spp. It is possible that this first axis mainly reflects the variation between past and present floras of the lake. In general, the species are widely scattered through the ordination space and trends are difficult to distinguish.

5.7d Groupings and Their Environmental Significance

The primary TWINSPAN sample dichotomy produced two sample groupings, ***1** (samples Z:1,6,7,18,19,20) and ***0** (Z:2,3,4,5,8,9,10,11,12,13,14,15,16,17). This division was also brought out by the DECORANA ordination, on the 1st axis (Figure 5.13c). The water-chemistry analyses related to these groups are numbers 32, 34, 30 and 31 for ***1** and 20, 21, 23-29, 30 and 35 for ***0** (see Figures 5.3e and f).

The samples in the TWINSPAN ***1** group were divided into those from La Zarcita (Z1) and the Zacapu gardens (Z6,7) (group ***10**) and those of sediment samples from the drainage channel from the Celanese plant (Z20) and from the irrigation channel into which this drained (Z18,19) (group ***11**). The DECORANA results produced the same groupings. The water samples from La Zarcita (32) and Zacapu Celanese (30 and 31) were relatively high in Na^+ and K^+ (especially Na^+), compared

with other water samples from the lake system. The sample from the Zacapu Gardens (34) was quite high in Ca^{2+}. In terms of anions, La Zarcita and the Gardens had more Cl^- than other samples, whilst the Celanese samples had high SO_4^{2-} levels due to industrial effluent.

The sample group ***10** (Z1,6,7) had a cluster of species (***11111**) unique to it. The species in this group formed a distinct block in the DECORANA species ordination, all scoring 4.52 or 4.53 on the first axis. Unfortunately, this group is almost impossible to distinguish on the species diagram (Figure 5.13d). It is possible that the occurrence of these species was due to the higher Cl^- levels in these waters. M. granulata var. angustissima has also shown to be tolerant of higher Na^+ levels than other Melosira species (Gasse et al, 1983). The rather unusual and diverse flora from the Celanese sediments probably reflected the presence of much reworked, fossil material. Valve preservation in these samples was not good. Fossil diatomites underlie much of this part of the Zacapu Basin and the Celanese drainage channel and the irrigation channel leading from the lake past the works, were probably excavated into these deposits. Fossil material may also have contributed to the assemblage recorded from the Zacapu Gardens, especially sample Z6. Sampling was carried out during a heavy rainstorm when rapid surface runoff was probably carrying material eroded from upslope. A number of the planktonic forms recorded in samples Z18, Z19 and Z20 (and to some extent

sample Z6), were very abundant in outcrops of diatomite exposed above the present-day lake level on the basin slopes to the west of the lake. The ^{14}C dates available suggest that much of this material is Pleistocene in age (see Chapter 6 for a detailed description of the sections, assemblages and ^{14}C dating). These samples highlight the problems that may be involved in trying to relate sediment samples to modern aquatic conditions, especially where diatomite is widespread and there is active erosion. Fortunately, it does seem possible to identify samples with a large fossil component in their assemblage.

The water samples related to the *0 sample division of TWINSPAN clustered very close together in terms of both major anions and cations. Only samples 30 and 31, affected by Zacapu Celanese were different, being enriched in $Na^+ + K^+$ and SO_4^{2-} (Figures 5.3e and f). In view of this, sample groupings were more likely to be indicative of habitat variations, or of some factor not revealed by the chemical analyses performed. The sample group *00 came from the mid-lake plankton (Z2) and the irrigation channel fed by the lake (Z15, Z17). There were no sediment samples in this group and Nitzschia palea dominated the assemblages. These samples appear to reflect the outflow of water mainly from mid-lake. The channel samples, taken at the Celanese outlet, showed no marked changes in the flora in response to inputs from the textile plant. The possible significance of the changes in the percentage of N. palea in determining the species groupings of the DECORANA ordination (Axis 2) has been

suggested above.

The TWINSPAN sample group ***011** comprised samples Z3,4,12,13 and 14. Z3 and Z4 were from vegetation around the margin of Laguna Zacapu and Z12, Z13 and Z14 were bottom sediment samples. (A further sample from the lake margin (Z11) was included with these until the third level sample divisions). The grouping of these two clusters indicates that large quantities of epiphytic and littoral species are entering the sediments, well away from the lake shore. Such an abundance of periphytic species may be due to sediment focussing or to greater diatom productivity in the littoral and is of considerable importance for the interpretation of core material if an over-representation of such species has been a consistent feature of sedimentation in the lake.

The remaining samples (Z5,8,9,10,11 and 16) formed TWINSPAN group ***010.** The first four of these came from a spring-fed channel leading into the main lake (Site 4). Samples Z8, Z9 and Z10 were scrapings from aquatic plants floating in about 1 m of water. The epiphytic Cocconeis placentula var. lineata (Jørgensen, 1948) was the most abundant taxon in all the Site 4 samples, although Nitzschia palea was also common. Unfortunately, no water sample was collected from this site, but the difference between samples from Site 4 and from the main lake probably reflect the more abundant aquatic vegetation at the former.

5.8 Basin of Zacapu, Other Sites

This data set included twelve sample counts with 157 taxa. The input parameters for the TWINSPAN program were the same as those used for the Zacapu lake sites. The sample sites, scattered around the basin floor and in nearby reservoirs or tanks, are shown in Figure 5.15. A list of the sites and their types, is given in Table 5.8. Complete diatom sample counts are numbered ('ZB' series) and these numbers are referred to in the text. The TWINSPAN ordered two-way table and species dendrogram for these data are given in Figures 5.16a and b and the DECORANA output in Figures 5.16c and d.

5.8a TWINSPAN Classification of Samples

Samples were collected from 12 sites around the basin, but full counts were only obtained from 8, often from just one of the variety of samples taken at each location. As a result of this problem, a number of sites are represented by only one assemblage. This was reflected by the sample classification. A summary diagram of the sample division is given in Table 5.9.

The first dichotomy of the samples separated samples ZB:1, 2, 3 and 12 (***1**), from the rest. The indicator species for this ***1** group was Navicula seminuloides at 2 to 4% abundance. These samples came from a spring-fed pool at Tarejero (ZB1 to 3) and from the crater lake Hoya la Alberca (ZB12). This group was not subdivided any further under the

default group size.

Subsequent divisions of ***0**, isolated samples ZB8 (Loma el Cementerio), ZB7 (B. la Laguna) and ZB11 (Bellas Fuentes). These were examples of single counts from sites. The sample group ***0110**, however, included several samples from El Angulo (ZB4, 5 and 6). El Angulo is the main drainage channel leading from the lake outflow, across the basin to its outlet in the northwest near Villa Jimenez. Also in this sample group were a Villa Jimenez sample (ZB10) and one from a spring-fed pool at Sta. Fe de la Labor (ZB9). The sample of bottom sediment from El Angulo was separated from the others at the fourth level of divisions. Achnanthes affinis (at < 2%) was the indicator species identified at this dichotomy.

5.8b TWINSPAN Classification of Species

Many different species were represented in the samples from the Basin of Zacapu, although taxa were often present in only one sample and at low abundance (< 2%).

The species group ***0000** (Figure 5.16b) consisted mainly of species from sample ZB8 (Loma el Cementerio). This sample was notable for its very wide range of taxa, many of which were unique to it. The smaller species cluster ***000000**, within this group, was more widely distributed, occurring in sample ZB8 and in the sample group ***011** (ZB:4,5,6,9,10,11) from El Angulo, Sta. Fe de la Labor, Villa Jimenez and Bellas Fuentes. The species cluster ***0001** (Cymbella minuta var. silesiaca, Eunotia curvata, Navicula confervacea and Navicula pupula var. rectangularis) had a similar low abundance

distribution in sample ZB8 and sample group ***001**, although the species were all present in sample ZB6 (El Angulo sediment).

The next major species grouping was ***001**. Within it, the cluster ***001000** consisted of species dominant in sample ZB7 (B. la Laguna). These species included a number of planktonic forms Melosira granulata var. angustissima, Stephanodiscus minutus and S. tenuis fo. minor, as well as a number of Navicula species (e.g. N. cuspidata). These species also occurred in the sample group ***011** (ZB:4,5,6,9,10,11). The next species cluster ***001001**, occurred in both samples ZB7 and ZB8 and in sample group ***011**. These species were quite widely distributed, but usually present in small numbers. The taxa in this cluster were Cyclotella meneghiniana, Melosira italica, Nitzschia gracilis, N. intermedia and N. palea var. tenuirostris, which may be part of the plankton at these sites.

Two species clusters in the species group ***00101** were also found mainly in the sample group ***011** (see above). Only Stephanodiscus subtilis, of these species, occurred in sample ZB7. The most abundant species in the two clusters were S. subtilis (***001010**) and Synedra acus var. neogena (***001011**). The ***001011** cluster contained many taxa, although with the exception of S. acus and Stephanodiscus tenuis they were recorded for only one or two samples, in low numbers (< 2%).

Species in the group ***0011** occurred in all samples. The group was formed of two clusters: ***00110** (Fragilaria

brevistriata, F. construens, Nitzschia acicularis and N. palea) and *00111 (Fragilaria construens var. venter, F. pinnata and Synedra goulardi). These two clusters were most important in the sample group *011 (ZB4,5,9,10,11,6). N. palea was particularly abundant in samples ZB4, ZB5, ZB9 and ZB10 (cluster *01100). These were samples from El Angulo, Sta Fe de la Labor and Villa Jimenez. The species group *010 was again widely distributed, but generally less abundant than the species in *0011. Of the *010 group, only Cocconeis placentula var. lineata occurred in considerable numbers, especially in sample ZB6, the El Angulo sediment. It is interesting to note that the El Angulo pattern of N. palea dominating the plankton and C. placentula var. lineata and S. subtilis being more important in the basal sediments, is very similar to the situation in the main Laguna Zacapu.

The next species group, *011, was divided into three clusters. Cluster *01100, including Fragilaria leptostauron var. dubia, Nitzschia amphibia and N. palea var. debilis, was widely distributed, with quite high abundances especially in sample ZB6 and the sample group *1 (ZB1,2,3 and 12) from Tarejero and Hoya la Alberca. Amphora veneta and Cymbella lanceolata formed a small cluster (*01101) occurring in samples ZB:4, 5, 10, 6, 1, 3 and 12. These were grouped with the *01100 cluster at higher levels in the division. The cluster *0111 comprised the taxa Achnanthes lanceolata and Fragilaria pinnata var. lancettula. F. pinnata var. lancettula occurred in quite large numbers (> 25%) in samples ZB11 (Bellas Fuentes) and ZB1 and ZB3 (Tarejero).

On the positive side of the principal species dichotomy, the species group ***10** occurred in many samples, but in low numbers. This was a distinct grouping, separated out early in the species divisions. It included three clusters: ***100** (Gomphonema angustatum, Nitzschia dissipata and Rhoicosphenia curvata), ***1010** (Fragilaria africana, Gomphonema affine, Navicula seminulum var. intermedia and Nitzschia microcephala) and ***1011** (G. parvulum). Species in these last two clusters did not occur in samples ZB7 or ZB8.

The next species group, ***1100**, was found in sample ZB8 (Loma el Cementerio) and sample group ***1** from Tarejero and Hoya la Alberca (ZB1,2,3,12). Species in this group included Navicula pygmaea, N. mutica and Nitzschia inconspicua. Joined with this group as ***110**, at the third level of division, was the group ***1101**. This was again made up of two clusters. The cluster ***11011** occurred across the board, but were most abundant in samples ZB1, 2, 3 and 12 (***1**). Species in this cluster were Achnanthes lanceolata var. dubia, Navicula heufleri var. leptocephala, N. seminuloides and Nitzschia romana. The final large species grouping (***111**) was restricted mainly to samples ZB1, 2, 3 and 12 (***1**). Two one-species clusters were included in this group for Navicula minima and Achnanthes affinis. A. affinis was particularly abundant (> 50%) in sample ZB2, a stone scraping from Tarejero.

The patterns of distribution from this ordered two-way table are less clear than those for the lake sites. This is probably due both to the low number of samples and to the

single occurrences of a number of species. Samples ZB7 (B. la laguna) and ZB8 (Loma el Cementerio) seem to have had little in common with the others. Species in the group ***0000** were mainly confined to sample ZB8. Nitzschia palea was the most abundant species in this sample, but still represented less than 20% of the count.

Nitzschia palea, Stephanodiscus subtilis, Synedra goulardi and Fragilaria species from cluster ***00111**, with Nitzschia palea var. debilis and N. amphibia, were the most abundant species in samples ZB4, 5, 9 and 10. These samples included species from both sides of the main species dichotomy, in small numbers. Fragilaria leptostauron var. dubia, F. pinnata var. lancettula (***011**) and Achnanthes affinis (***111101**) were most abundant in samples ZB1, 2 and 3. Sample ZB12 again had more Nitzschia palea and N. amphibia, as did samples ZB4, 5, 9 and 10. Navicula seminuloides and Nitzschia romana were quite abundant in these samples. Many species in the group ***111** were limited to this group of samples. Samples ZB1, 2, 3 and 12 also straddled the main species dichotomy.

5.8c DECORANA results for the Zacapu Basin

Results of the sample ordination are shown on Figure 5.15c, where sample types are distinguished by colour (as in Figure 5.13c), and TWINSPAN clusters indicated. The sample ordination revealed a greater disparity in the species composition of the samples (`ZB' series) than was the case

for the samples from within and around the lake ('Z' series). This might be expected in view of the wider variety of sampling sites. The first ordination axis serves mainly to highlight the difference between sample ZB2 (Tarejero stone scraping) and ZB7 (from B. la Laguna). The scores for these samples, having a difference of more than 4 s.d., reflects the fact that they have few species in common. The 2nd axis may have less environmental significance, as the scores are close enough together for there to be little real variation in species composition. Sample ZB8 (Loma el Cementerio) is quite isolated and both this and sample ZB7 were also separated out by the TWINSPAN classification. It is interesting to note the differences between the samples classed as similar by the two techniques. Samples ZB4, 5, 9 and 10 were also clustered together (***01100**) by TWINSPAN. In contrast, samples ZB2 and ZB12, which were placed at some distance in environmental space by DECORANA, were grouped together by TWINSPAN.

The species ordination (Figure 5.16d) again reflects the distinctiveness of sample ZB7 on the first axis. Species predominant in this sample, such as M. granulata var. angustissima and S. minutus, lie at the extreme of this first axis. The three highest scoring species on the first axis (Navicula accomoda, N. capitata and N. halophila) were found only in this sample. Eight of the eleven highest scoring species (> 5.36 s.d.), forming TWINSPAN cluster ***001000**, were also confined mainly to this sample. The occurrence of species such as N. halophila and Thalassiosira rudolfii may

reflect the relatively high SO_4^{2-} content of the waters from B. la Laguna. The species scoring between 4.83 and 5.93 s.d. on this axis (gradient), although most abundant in sample ZB7, display a wider distribution.

The highest scoring species on the 2nd axis (a total of 30 scoring 3.66 s.d.) all belong to the TWINSPAN cluster *000010 and are those species occurring only in sample ZB8 from Loma el Cementerio. The species with negative scores on this axis form a rather heterogeneous group, generally occurring in low numbers in the samples represented. Species scoring < 1.22 s.d. were found only in to the left of the TWINSPAN sample dichotomy (group *0). The ecological significance of this second axis is not immediately apparent. Although the water of Loma el Cementerio was relatively high in Ca^{2+}, this axis appears to be reflecting the large number of species found only in this sample, but at low abundance.

5.8d Groupings and their Environmental Significance

The water samples associated with particular diatom sampling sites are listed below and shown on Figures 5.3e and f.

Diatom Sample (ZB)	Water Sample	Minimum sample cluster (TWINSPAN)
1, 2, 3	37, 38	*1
12	49	
8	45	*00
7	43	*010
11	42	*0111
4, 5	39	
9	46	*01100
10	47	
6	39	*01101

The grouping of Tarejero (ZB1,2,3) and Hoya la Alberca (ZB12) by the TWINSPAN classification was unexpected in view of the rather different water chemistry of the crater lake, which was relatively enriched in Cl^- and $Na^+ + K^+$. These samples were, however, distanced by the DECORANA ordination (Figure 5.15c) The sample from Hoya la Alberca was not, however, collected from the plankton (this sample contained very few diatoms), but from a scraping of a stone at the lake margin. Sample ZB2 from Tarejero was also a stone scraping and these two samples have similar scores on the 2nd axis (gradient) of DECORANA. The other two samples from Tarejero (ZB1 and 3) lie close together in environmental space and at some distance from sample ZB2. Hoya la Alberca can be distinguished from Tarejero by its more abundant Nitzschia palea and N. amphibia. This may be due to the greater evaporative concentration of the crater lake.

The flora from Loma el Cementerio (ZB8) was extremely diverse, with no one taxon dominant. The cation composition of this water was rather unusual for the basin as a whole being high in Ca^{2+} and low in Mg^{2+} (cf Laguna Zacapu). This sample was distinguished by its high scores on the 2nd DECORANA axis, with a group of species unique to it having the highest scores along this gradient. High Ca^{2+} levels were a feature of reservoirs and tanks in the basin, as shown by water analyses 40 (Presa Aristeo Mercado), 43 (B. la Laguna) and 44 (Tunguitiro) (Figures 5.3e and f). In spite of this, sample ZB8 was separated from these other sites early in the sample classification. The anions from Loma el

Cementerio were much like the rest of the basin.

As indicated above, B. la Laguna (diatom sample ZB7) was relatively high in Ca^{2+} and also in SO_4^{2-} (Figure 5.3f, sample 43). This site was an artificial tank which was again separated out quite early on. A considerable number of planktonic species were recorded in this assemblage, coming from the species cluster *001000 (Melosira granulata var. angustissima and Stephanodiscus minutus).

Bellas Fuentes (sample ZB11), a spring-fed pool, had a cationic composition slightly enriched in in $Na^+ + K^+$, with an anion content much like Laguna Zacapu. Fragilaria pinnata var. lancettula was abundant (> 25%), with Nitzschia palea (> 10%). This was also the case with the water and sediment from Tarejero and the El Angulo sediment. Sample ZB11 was grouped with samples ZB4, 5, 6, 9 and 10 as far as the third sample division, although Tarejero was separated from these at the first division.

The samples from El Angulo (water and vegetation, ZB4 and 5), Sta. Fe de la Labor (ZB9) and Villa Jimenez (ZB10) (sample cluster ***01100**) were united with the El Angulo sediment sample (ZB6) higher in the sample divisions. The water samples from El Angulo (39) and from Villa Jimenez (47) were enriched in $Na^+ + K^+$. Anions were not very different from the main cluster in spite of the big input of SO_4^{2-} from the Zacapu Celanese plant, upstream from these later sampling points. Following the findings from the Laguna Zacapu sites, the distinction of the sediment sample is not surprising. In

samples ZB4, 5, 9 and 10 Nitzschia palea was important (> 10%) as was the case in the lake plankton and the Zacapu Celanese irrigation channel. As these sites are on the upstream part of the basin drainage network leading via the El Angulo channel out of the basin at Villa Jimenez, this floral similarity was to be expected. The samples contained quite a wide variety of species. Numerically important taxa were Stephanodiscus subtilis, Fragilaria construens var. venter, F. pinnata var. lancettula, Synedra goulardi, S. acus var. neogena Cocconeis placentula var. lineata and Nitzschia amphibia, which accurred in abundances > 2 to 3%.

5.9 Conclusions from the Zacapu Basin

The TWINSPAN classification and DECORANA ordination of 32 diatom counts from sites around the Basin of Zacapu in Michoacán, have been described. As the water chemistry of many of the sample sites was rather similar, it has proven difficult to distinguish a floral response to any particular chemical gradient. This task has been made more difficult by the apparent influx of older fossil diatoms into some of the samples. The clustering of samples has, however, grouped samples from similar habitats. This was particularly clear for the samples from in and around the lake. Differences between sediment samples and samples of living diatoms from water, stone and plant surfaces, have been highlighted. The importance of different substrates in producing different assemblages, and the variations between 'live' and sediment samples have been stressed by Jørgensen (1948).

The potential value of the samples collected around the basin (section 5.8) was reduced by the failure of a number of samples to yield large enough counts to be included in the analysis. Of these, a sample taken from the margin of Presa Aristeo Mercado had a flora with similarities to that in species group ***001**, especially samples ZB4, 5, 9, 10, 6 and 11. A deep-water plankton sample from the same location had a species assemblage similar to cluster ***0101**, but with Melosira ambigua(?) present in much greater numbers. Samples from the Tanque Elevado were like species group ***0011**, with Nitzschia palea abundant, plus the species cluster ***01100**, which included Nitzschia amphibia and N. palea var. debilis.

A comparison of the species groupings for the lake itself and for the rest of the basin, suggests considerable differences in co-occurring species, although particular species may be found in many different locations. Nitzschia palea is commonly abundant in water samples throughout the basin. In view of the relative scarcity of this species in sediments, it may be that sampling took place at the time of a seasonal peak in N. palea. It is probably also suggestive of the heavy human impact on the water resources of the basin (Patrick and Reimer, 1966; Lowe, 1974). There is not, however, any direct relationship between the abundance of N. palea and the amount of phosphate (P_2O_5) or nitrate (NO_3) in the water. N. palea attained its greatest numbers in the plankton of Laguna Zacapu where P_2O_5 was 1 mg/l (recorded as ppm) and NO_3, 0.13 meq/l. Other sites, such as Bellas Fuentes, although having higher phosphate had less abundant

N. palea. El Angulo was one example where high P_2O_5 (6.75 mg/l) did occur with large numbers of N. palea, but the flora collected there was probably affected by receiving outflow directly from the N.palea-rich lake. Human impact on present day water bodies may greatly reduce the value of collecting modern diatom samples to provide analogues for the interpretation of pre-disturbance fossil material.

5.10 Other Sites from Central Mexico

Samples collected from a wide variety of sites across Central Mexico provided the data for a third TWINSPAN classification. The data set consisted of 35 counts (`OS' series), which included 296 taxa. A summary of sites, samples and related water analyses is given in Table 5.10. Related water analyses are shown on Figures 5.3g and h, except those for Alchichica (East of the Basin of Mexico, Figure 5.3a and b) and Xochimilco (Basin of Mexico (Figures 5.3c and d). The TWINSPAN ordered two-way table is shown in Figure 5.16a and the species dendrogram in Figure 5.16b. DECORANA results are shown in Figures 5.16c and d.

5.10a TWINASPAN Classification of Samples

The primary sample dichotomy separated samples from Laguna Zirahuén (OS13,14,15) and from the reservoirs Villa Victoria and Presa del Bosque (OS27,28,29) from the rest (Table 5.11). The indicator species for this sample group (*1) was Melosira distans var. alpigena at 2 to 4% abundance.

Within the *0 group, sample OS2, a stone scraping from Rodeo was borderline and sample OS30, a stone scraping from Presa del Bosque was misclassified in the sense described above.

Subsequent division of the *1 group isolated the Zirahuén samples (*10) from the others (*11). The indicator species identified for the Zirahuén cluster was Amphora ovalis var. affinis at < 2%.

The large sample group *0 underwent several divisions to produce closely related clusters. The *00 group included samples from the crater lakes La Alberca and La Piscina de Yuriria and samples from Lago de Yuriria and Cuto de la Esperanza. The indicator species for ~~for~~ this side of the dichotomy were Nitzschia gandersheimiensis (2 to 4%), Achnanthes hungarica (< 2%) and Nitzschia palea (5 to 9%). The indicators for the large sample group *01 were Cocconeis placentula var. lineata (2 to 4%), which was the most important indicator species overall, Cyclotella meneghiniana (< 2%) and Rhoicosphenia curvata (< 2%).

Division of the sample group *00 produced a cluster of samples OS7, 8, 9 and 11 (*000). These were all the samples from La Piscina de Yuriria plus the water sample from Lago de Yuriria. The indicator species for this cluster was Nitzschia romana at < 2%. Samples in the *001 group (indicator species Achnanthes hungarica, 2 to 4%), were divided into two clusters. These represented the samples from Cuto de la Esperanza (OS25, 26) in cluster *0010 and from La Alberca (*0011). The indicator species for the *0010

cluster was Achnanthes affinis (< 2%).

The sample group ***01** was divided into two, still quite heterogeneous sample groups: ***010** and ***011.** The ***010** group included a number of samples from pools and irrigations channels, whilst ***011** was mainly of lake and reservoir samples. Sample OS24 (Campo Hermoso) was a misclassified positive, being placed in *011, at this dichotomy. The indicator species for the positive group was Navicula radiosa var. tenella (< 2%) and for the negative group (***010**) Cyclotella meneghiniana (< 2%).

Division of the ***010** group isolated the samples from Rodeo (OS1 and 2, ***0100**) from the rest (***0101**). The indicator for the larger group (***0101**) was Cocconeis placentula var. lineata (< 2%). Subsequent dichotomies of this group isolated first sample OS21 from Queréndaro (***01010**) (indicator species Cyclotella glomerata < 2%) and then samples OS23 and 31 (***010111**). The final clusters produced, therefore, were ***010111** of samples from Ixtlahuaca and the Río Lerma, and ***010110** (OS20,32,33,34,35). The latter cluster comprised of a deep water sediment sample from L. Pátzcuaro (OS20) and a series of samples from Xochimilco and Mixquic, chinampa areas in the Basin of Mexico. The indicator species for ***010110** was Amphora veneta (< 2%).

The sample group ***0110** underwent two further divisions. Sample OS30 (a stone scraping from the Presa del Bosque) was isolated as cluster ***01101,** with Achnanthes lanceolata at < 2%, the indicator species. The remaining samples in ***01100**

were divided into ***011000** (OS12 and 24) and ***011001** (OS16,17,18,19,22). As sample OS24 was indicated to be misclassified at the division of the *01 sample group, the significance of this small, final cluster is rather questionable. Samples in the ***011001** cluster included all those from Lago de Pátzcuaro except the deep-water sediment (OS16,17,18,19). and a vegetation sample from Valle de Bravo (OS22).

5.10b TWINSPAN Classification of Species

The classification of the 296 taxa has produced a large and quite complex hierarchy (Figure 5.16b). As with the other sets of data, the results will be discussed in order, through the species groups from top to bottom of the table.

The species group ***000** was widely distributed across the sample classification. Navicula mutica occurred in all samples in the sample group ***001** (OS25 and 26 from Cuto de la Esperanza, OS3, 4, 5 and 6 from La Alberca). Nitzschia ignorata was very abundant (> 50%) in sample OS8, the stone scraping from La Piscina de Yuriria. Synedra ulna formed > 5% of the assemblage in the bottom sediments from La Alberca. This species group was quite distinct and was separated out at the third level of species division.

The species group ***0010** contained many species, including those dominant in the sample group *001. The two species clusters ***001000** and ***001001** were particularly widely distributed. Nitzschia romana and N. palea occurred in the greatest numbers. N. palea, N. gandersheimiensis and N.

romana from these two clusters, were all indicator species for the sample classification. N. palea at 5 to 9% and N. gandersheimiensis at 2 to 4%, were indicator species for the sample group *00 and N.romana for the group *000. N. palea was most abundant in the sample groups *000 (OS7,8,9,11) from La Piscina de Yuriria and Lago de Yuriria; *001 and the clusters *010111 (OS23,31) from Ixtlahuaca and the Rio Lerma and *011000 (OS12,24) from L. de Yuriria vegetation and Campo Hermoso. The very large species cluster *001010 also formed part of the species group *0010. Within this cluster of species Achnanthes hungarica was an indicator species, at < 2%, for the sample group *00 and at 2 to 4% for the samples in *001. Species in this cluster were not found in samples in the *1 group (Zirahuén, Villa Victoria, Presa del Bosque). Gomphonema angustatum and G. parvulum were particularly important in samples from La Alberca (OS3,4,5,6). Navicula elkab and Navicula halophila represented > 10% of the assemblages in counts from vegetation and sediment samples from La Piscina de Yuriria (OS7,9). The final cluster in this group, *001011, consisted of species occurring in low abundance, more widely distributed than the species in *001010, but still not in the sample group *1. Cocconeis placentula, however, did make up 31% of the count in sample OS22 (Valle de Bravo vegetation).

The species group *00110 was a rather unusual grouping. It included forms which are normally periphytic (e.g. Fragilaria leptostauron var. dubia), aerophilous or

periphytic (e.g. Navicula confervacea), epiphytic (e.g. Cymbella lanceolata and Gomphonema species) and the planktonic Stephanodiscus subtilis. In this grouping, it is possible that all the species actually represented shallow water, vegetated sites, possibly quite eutrophic although no measurements of nutrients were made which might confirm this. These species were most common in the sample grouping *01011 for which A. lanceolata was an indicator species. Samples in this group included Pátzcuaro sediment and those from Xochimilco, Mixquic, Ixtlahuaca and Río Lerma. Amphora veneta as well as being an indicator species for the sample cluster *010110 (OS20,32,33,34,35) also occurred in low abundance (< 5%) in the sample group *01100 (samples OS12,16,17,18,19,22 and 24). Other species in this species group were fairly widespread, in low abundance, outside the sample group *1.

Species in the group *00111 occurred more commonly in samples in the group *011. The species cluster *001110 was again quite varied, including Achnanthes affinis, Navicula spp., Nitzschia spp. (including N. palea var. debilis and N. paleacea) and Stephanodiscus spp.. These species were probably in the plankton at these sites. Nitzschia inconspicua was found in large numbers (10 to 24%) in samples OS18 (Pátzcuaro vegetation) and OS30 (Presa del Bosque stone scraping) and made up more than 55% of the count from L. Alchichica (OS10). Stephanodiscus minutus formed 10 to 24% of the assemblages from L. de Yuriria vegetation and Campo Hermoso (OS12 and 24). Also in the species group *00111 was

the large species cluster ***001111.** This included a number of species occurring in only one sample, such as Amphora bullatoides (sample OS30), Gomphonema clevei var. javanica (sample OS22), Nitzschia recta (sample OS21) and Synedra goulardi (sample OS24). Most of the species were only minor components (< 4%) in the counts. Exceptions to this were Fragilaria crotonensis which was 23.2% of the assemblage in sample OS22 from Valle de Bravo, Melosira granulata var. angustissima 51.25% in sample OS21 from Queréndaro and Navicula adamantiformis which was 31.7% of the count from Campo Hermoso (OS24). The cluster of species were recorded mainly from the sample group ***011** (as was the cluster ***001110**) but were less abundant. The cluster also included Rhoicosphenia curvata an indicator species for the sample group ***01.**

Species in the clusters ***01000** and ***010010** were the subsiduary species (< 5%) in samples from the group ***01011** (OS20,23,31,32,33,34 and 35). Species in the ***010010** cluster were confined only to this sample group. Species in the clusters ***010011** and ***0101** (which formed the species group ***010** with the two previous clusters) had a widespread distribution, but were particularly common in the sample group ***010** (OS1,2,20,21,23,31,32,33,34,35). The cluster ***010011** (Cyclotella meneghiniana and Fragilaria construens var. venter) were found mainly in this sample group and especially in samples OS20, 32, 33, 34 and 35 (cluster ***010110**). They occurred in quite large numbers in these

samples. C. meneghiniana was most abundant (31.5%) in sample OS32 from Xochimilco. The occurrence of this species at < 2% was an indicator for sample group ***010**. The species cluster ***0101** had a more widespread distribution, especially the species Cocconeis placentula var lineata and Nitzschia amphibia. C. placentula var. lineata was found in large numbers in the sample cluster ***011001** (OS16,17,18,19,22). In sample OS19 (L. Pátzcuaro vegetation), it made up 86.75% of the count. The occurrence of C. placentula var lineata at < 2% was also an indicator species for the sample group ***0101.** N. amphibia was abundant (25 to 49%) in the samples from Rodeo (OS1 and 2). The two clusters ***010011** and ***0101** were the dominant species in samples OS20, 32, 33, 34 and 35 (***010110**) from Pátzcuaro sediment, Xochimilco and Mixquic. They seem to represent, therefore, fairly shallow eutrophic environments.

The high-level species group ***011** was composed of a series of small clusters of widely occurring species at low to moderate abundance. Epithemia sorex (at < 2%) was an indicator species for the sample cluster ***011001** (OS16,17,18,19,22) in which C. placentula var. lineata was an important species. Navicula radiosa var. tenella was also an indicator species for the sample group ***011** and was recorded mainly in this group. Amphora ovalis var. affinis, also in this species group, was an indicator species for the sample group ***10**, samples OS13, 14 and 15 from Zirahuén. The planktonic Melosira ambigua belongs in this species group, but occurred in large numbers in only one sample (OS12) from

Queréndaro (45%) where it was co-dominant with M. granulata var. angustissima. Although the water at Queréndaro was quite shallow, it was very turbid and high in SiO_2. The occurrence of large numbers of M. granulata var. angustissima in very turbid waters was noted by Gasse et al (1983). This whole group of species occurred more commonly on the positive side of the principal sample dichotomy (i.e. OS13,14,15,27,28,29), although at abundances of less than 5%

The species grouping ***100**, on the other side of the principal species dichotomy, was also quite broadly distributed. Only Achnanthes minutissima was present in large numbers, especially in samples OS1 and 2 from Rodeo (33 and 54%) and in sample OS28 from Villa Victoria.

The quite small species grouping ***101** was found mainly in sample groups ***011** and ***1**. Only Achnanthes affinis and A. linearis fo. curta were present as more than 5% of counts. Both taxa were present in sample OS17, a stone scraping from Pátzcuaro. The species in this group appear to represent the periphyton.

Only four species made up the species group ***110**. These four occurred at a wide variety of sites across the sample classification. All were present in small numbers except for Melosira granulata which was recorded in all samples in cluster ***11** and was most abundant (ca. 18%) in sample OS29 (Presa del Bosque).

Species in the group ***1110** again fell mainly in the ***1** sample group, but were also present in low numbers (< 2%) in

the sample group ***0101.** Cyclotella glomerata was an indicator species (at < 2%) for the separation of sample OS21 (Queréndaro) from the other samples in the group ***0101.** This Cyclotella was also recorded in two of the three samples from Zirahuén. the most abundant species in this species group was Melosira distans var. alpigena. It was found mainly in the ***1** samples, but was also present in large numbers in sample OS30 (Presa del Bosque stone scraping). In ***1**, it was most abundant in samples OS13 and 15 (Zirahuén deep water vegetation and sediment), OS27 (Villa Victoria) and OS29 (Presa del Bosque), where its values ranged between 27.6 and 65.0%. the presence of M. distans var. alpigena at 2 to 4% abundance was an indicator for the ***1** group at the first sample dichotomy.

As might be expected, the species group ***1111** comprised species from the ***1** sample group and, in particular, the cluster of samples from Zirahuén (OS13, 14, 15). This is suggestive of distinctive assemblages from this lake. Cyclotella stelligera, however, also occurred in samples OS1 and 2 from Rodeo. With the exception of Synedra rumpens var. fragilariodes the whole of the species cluster ***111101** was found only in the Zirahuén samples. The species group as a whole included a number of Cymbella, Gomphonema and Synedra species.

5.10c DECORANA results for Other Sites, Central Mexico

The much longer ordination gradient for this data set reflects the diversity of sample sites (Figure 5.16c).

Samples are coloured as in previous sample ordination diagrams. The first axis eigenvector (0.879) is particularly high, but seems to be due mainly to the influence of one species assemblage from sample OS21 (Queréndaro pool). This sample is clearly isolated from all the rest (Figure 5.16c). The other samples seem to fall along the 2nd axis, with the lowest score for L. Alchichica (sample OS10) and the highest for a sample from vegetation in Valle de Bravo (sample OS22). The possible chemical gradient suggested by these two extreme samples is not, however, supported by the intervening samples. The samples from L. Zirahuén and Villa Victoria, for example, have scores between those for Alchichica and La Alberca and Lago de Yuriria. The ordination places bottom sediment samples from a number of sites close to vegetation samples (e.g. samples OS20 (sediment), OS18 and 19 from Pátzcuaro and OS7 and 9, from La Piscina de Yuriria). In the case of the Pátzcuaro samples, the similarity between these two types of samples was not brought out by the TWINSPAN classification. The importance of epiphytic and lake-margin species in the sediments and the resulting similarities in assemblages were, however, indicated by the TWINSPAN classification for the samples from Laguna Zacapu and its associated samples.

The species ordination (Figure 5.16d), isolates three species with high scores on the first axis. Melosira ambigua and M. granulata var. angustissima are the dominant species in sample OS21 (Queréndaro). Achnanthes lanceolata is the

indicator species for the TWINSPAN species group ***01100**, but as it occurs in only three samples, at very low abundance, it may possibly be aberrant. The remaining species lie along the second axis. The species lying at either end of this axis, tend to come from the TWINSPAN cluster ***001111**, which are generally present in low numbers in samples lying close to the first sample division.

The first axis may reflect an increase in suspended solids or turbidity at the site. The absence of epiphytic species from sample OS21 was also noteworthy. As stated above, no particular chemical gradient could be identified for the 2nd axis. It is possible, however, that distinct habitats (plant or stone surfaces, the difference between sediment and water samples) are important. The chemical variations between these microhabitats would not be reflected by the 'gross' water samples. In a number of cases, samples from stone scrapings were placed at some 'distance' from the vegetation and sediment samples (e.g. La Piscina de Yuriria sample OS8 (stone sraping) compared with samples OS7 (vegetation) and OS9 (sediment)). Sensitivity to such small scale habitat variations tends to be overlooked, or seems to become less significant, when studying fossil assemblages, especially from mid-lake cores. This variation appears to have been brought out more clearly by the DECORANA ordination than by the TWINSPAN classification for this data set.

5.10d Groupings and Their Environmental Significance

A comparison of the results of TWINSPAN with the tri-

linear plots of the associated water samples indicates that changes in species assemblages may be a response to changes in chemical composition and the degree of evaporative concentration. Overall, there appears to be a gradient from the most dilute (Zirahuén) to the most concentrated waters (La Piscina de Yuriria and Lago de Yuriria). Such changes in the diatoms may be particularly indicative of variations in alkalinity and in Cl^- content of the water. Unfortunately, such an environmental gradient does not appear to be suggested by the DECORANA output, which seems to emphasise physical and microhabitat variations. It is , however, worth describing the possible relationship of species assemblages to chemistry, indicated by TWINSPAN, in more detail.

In the TWINSPAN classification, the samples from La Piscina de Yuriria and Lago de Yuriria (***000**) are dominated by Nitzschia species. In La Piscina de Yuriria, Navicula elkab and N. halophila are the most abundant individual species in vegetation and sediment samples (OS7,9). The stone scraping from the lake (OS8) had a rather different flora with Nitzschia ignorata and N. palea dominant. N. palea and N. longissima var. reversa were the main species in Lago de Yuriria (OS11 and 12), whilst the vegetation sample from this site (OS12) also had abundant N. palea, but with Stephanodiscus minutus and a wide variety of other species. The water samples from these sites (93 to 95, 98 and 63), show them to be enriched in $Na^+ + K^+$, with high alkalinity and with Cl^- forming a higher proportion of the anions than

for most of the waters. The sites also had quite high levels of NO_3^- (> 1.2 meq/1).

Samples from Cuto de la Esperanza (OS25, 26) and La Alberca (OS3 to 6) were grouped together in ***001.** In all these samples, except OS26, Achnanthes and Gomphonema species (especially G. parvulum and G. angustatum) were most abundant. In OS26, N. palea was most abundant and it also occurred in other samples in considerable numbers. Nitzschia amphibia was often common. Related water samples (64, 92, 91) suggest that these are high bicarbonate (HCO_3^-) waters, lying approximately mid-way along the evolutionary pathway outlined for the cations. Both sites, and especially Cuto de la Esperanza, supported abundant aquatic vegetation and had high phosphorous content (more than 3.75 mg/1).

Samples grouped together as ***010** have assemblages dominated by a number of different species. The samples from Rodeo (OS1,2) have a flora dominated by N. amphibia and Achnanthes minutissima with species of Navicula, other Nitzschia and Gomphonema common. The flora from Querétaro (OS21) was dominated by M. granulata var. angustissima and M. ambigua. The turbulence and high SiO_2 levels at this site have been referred to above. The cluster of samples from Pátzcuaro (OS20), Xochimilco (OS32) and Mixquic (OS33, 34, 35) all include large numbers of Fragilaria species. In Pátzcuaro, Nitzschia amphibia occurs in the greatest numbers of any individual species, but the flora is nevertheless, very diverse and no one species really dominates. At Xochimilco and Mixquic, Cyclotella meneghiniana and Cocconeis

placentula are important components of the assemblages, accompanied by Nitzschia gracilis at Xochimilco and by Melosira italica at Mixquic. Water samples taken at Xochimilco and Mixquic showed quite high levels of phosphate (> 2.5 mg/1). The small sample cluster of Ixtlahuaca (OS23) and Río Lerma (OS31) both have N. palea in great abundance (51 and 25%), although the Río Lerma flora is more diverse. Levels of phosphate were also quite high at these sites, 2.5 and 5.0 mg/1 respectively. In general terms, the water analyses from these locations (55, 70, 51, (19), 61, 77) indicate that CO_3^{2-}/HCO_3^- alkalinity was lower than at the sample sites in the group ***001.** The Río Lerma is high in Ca^{2+} and SO_4^{2-}, but the effects of the chemistry are difficult to identify. Sample OS24 from Campo Hermoso (water number 62) probably has more in common with this group than its TWINSPAN classification suggests.

The grouping of the sample clusters ***011000** (OS12 and 24) and ***011001** (OS16,17,18,19,22) does not appear to be particularly significant. The samples from L. de Yuriria vegetation (OS12) and Campo Hermoso (OS24), do both have N. palea and Stephanodiscus minutus present in quite high abundance. The flora of OS24 is, however, dominated by Navicula adamantiformis. The difficulties of classifying this sample have already been referred to. The cluster of samples from Pátzcuaro and Valle de Bravo vegetation is more floristically consistent. Cocconeis placentula var. lineata forms more than 40% of counts from samples OS16, 18 and 19 from Pátzcuaro, and C. placentula is the most abundant

species in sample OS22. The stone-scraping sample from Pátzcuaro has Achnanthes species dominant, as was the case with sample OS2 a stone scraping from Rodeo. The deep-water sediment sample from Pátzcuaro (OS20) fell into a different species group at the division of the sample group ***01**. The Cocconeis and Achnanthes flora of the samples in ***011001** probably reflects the provenance of the samples (plant and stone surfaces) rather than chemical differences, although Patzcuaro and Valle de Bravo are low in SiO_2 (< 30 ppm) compared with other sites.

The presence of abundant M. distans var. alpigena has already been cited as being characteristic of samples in the ***1** group (OS13,14,15,27,28,28) and in sample OS30, another sample from Presa del Bosque. It is the most numerous species in deep water samples from Zirahuén (OS13 and 15), in the water sample from Villa Victoria (OS27) and in the two samples from Presa del Bosque (OS29 and 30). Water samples from Zirahuén deep water (71), and Villa Victoria (65) had relatively low alkalinities (< 1.7 meq/1). In these lakes, the presence of Cl^- was not detected. Overall, the most distinctive feature of the waters was their low T.D.S (total dissolved solids), being the most dilute waters sampled. Villa Victoria and Presa del Bosque were also Ca^{2+} rich, although in Zirahuén Ca^{2+} and Mg^{2+} were present in roughly equal abundance, but much more than $Na^+ + K^+$. Villa Victoria and Zirahuén also had low silica levels (< 15 ppm). The chemistry of Presa del Bosque (water number 66) was rather

different from the other sites, being more alkaline and with higher T.D.S. As low Cl^- is a more consistent feature than the others, M. distans var. alpigena is probably responding to this, but may be encouraged by the fairly abundant Ca^{2+}, typical of more dilute waters. Samples from shallow-water vegetation however, were dominated by other species. The Zirahuén sample (OS14) contained many Synedra species and at Villa Victoria (OS28) Gomphonema intricatum var. pumilla and Achnanthes minutissima were more abundant than M. distans var. alpigena. Cyclotella stelligera was the second most abundant species in the Zirahuén deep-water samples. In an early limnological study of Zirahuén, De Buen (1943) found that the lake was not rich in plankton, although diatoms were abundant in the samples collected for this study.

The sample from L. Alchichica (OS10) was quite distinct. The water analysis from this lake (10) shows it to contain very little Ca^{2+} (being high in $Na^+ + K^+$) and to have a high proportion of Cl^-. Its low alkalinity was noted previously. In common with the other Cl^--rich samples in group *000, Nitzschia species are important, mainly N. inconspicua with N. romana. There was little vegetation present in L. Alchichica and it is probably much less eutrophic than lakes such as La Piscina de Yuriria and Lago de Yuriria. This absence of vegetation and the lack of settlement and human use of the basin at Alchichica may account for the very small numbers of N. palea recorded from this lake.

It does seem, therefore, that the changes in diatom assemblages recorded for the samples discussed here and

ordered by TWINSPAN, can be interpreted in terms of changes in chemical composition and concentration. As might be expected, changes in response to chemistry are most clear at the extremes of the spectrum, whilst for samples and species near the middle of the classification, habitat variations are emphasised, as they were in the samples from the Zacapu Basin. This was also the case for the 2nd DECORANA axis where initial examination suggested a gradient of chemical concentration, but which in more detail, stressed the importance of habitat.

It is interesting to note that the application of both TWINSPAN and DECORANA to these data has suggested different ways in which the samples may be grouped and apparently different factors to which they are responding. Both techniques have highlighted the major role of specific habitats in determining species assemblages which may overide the effects of chemical differences in the water bodies taken as a whole.

5.11 General Comments on the Central Mexican Samples

The use of TWINSPAN and DECORANA to classify and group samples and species collected across Central Mexico has highlighted a number of features important for the interpretation of fossil material. The assemblages of diatoms collected live (from water, plants and rocks) are often very different from those found in bottom sediments. These sediments frequently have a large component of

periphytic and epiphytic species, even if collected from deep-water sites. As all the sampled lakes are well mixed, this is probably not surprising. The importance of overturning and sediment focussing in bringing species from the littoral zone into the deep-water sediments and in mixing organisms sinking at different times, has been pointed out by Carney (1982). In some cases, reworked fossil diatoms form an important part of the sediment assemblage. Large Stephanodiscus species, such as S. niagarae and S. astraea (S. rotula) are not believed to be living currently in the sites which were sampled. Only smaller Stephanodiscus species, such as S. minutus and S. subtilis, appear to be present in large populations. The importance of specific habitats in determining the species present has been stressed for all the groups of samples discussed above. In general, this might be expected to have more implications for cores or sediment samples collected from near-shore or shallow-water locations. It is to be hoped that taking a core from mid-lake avoids the problems for palaeoenvironmental interpretation posed by the variation between microhabitats.

The species Nitzschia palea is very common and very abundant throughout Central Mexico at the present day. It is, however, rarely present in large numbers in sediments and can probably be taken as a true indicator of anthropogenic influence. This species is generally a eutrophic indicator (Cholnoky, 1968). In large numbers, it is believed to be a good indicator of organic pollution (Lowe, 1974). In a study of the impact of European on lakes in Michigan, Schuette and

Bailey (1980) found *N. palea* only in their post-settlement samples. Other *Nitzschia* species appear to be found mainly in environments with elevated alkalinities, where Cl^- becomes more important amongst the anions. Under such conditions, *Nitzschia* species may dominate the plankton. *N. amphibia* appears quite frequently in samples from vegetation and *N. ignorata* from stone scrapings. It is not clear how these species are related to these substrates. The association of a *Nitzschia*-dominated flora with elevated alkalinities was first suggested by Hustedt (1949). Richardson (1968) extended this idea. He pointed out that *Nitzschia* usually dominates the plankton of shallow, turbid lakes only where blue-green algae are not dominant. High nitrogen and phosphate availability also appear to be important for this genus. In alkaline lakes where blue-green algae are important, *Navicula elkab* and *Nitzschia frustulum* may occur frequently (Richardson *et al*, 1978). This competitive factor may be contributing to the floral variations in the samples from La Piscina de Yuriria.

Fragilaria species are common in the Mexican samples, especially in fairly shallow spring-fed environments such as Xochimilco, Zacapu Gardens and Tarejero, where the pH ranges from 7.5 to 8.5. Relatively abundant Mg^{2+} may encourage this genus. Richardson (1968) has questioned the value of *Fragilaria* as an indicator of chemical variation, although Round (1957) believes that it is indicative of slightly alkaline water, declining in neutral or slightly acidic

conditions. Achnanthes species appear to be important on stone surfaces (epilithic) and in shallow water in fairly chemically dilute environments such as Villa Victoria, Zirahuén and Tarejero. Cocconeis placentula var. lineata is a very common epiphytic species, often occurring in large numbers.

The study by Gasse et al (1983) of the diatom assemblages of Africa, provides some useful points for comparison with the Mexican results. The genera which the authors classify as Group II (Achnanthes, Amphora, Cocconeis, Cymbella, Gomphonema, Navicula and Nitzschia abundant (i.e. $\geqslant$ 33%) are also widespread in the Mexican samples. Their summary of Group II as representing 'the periphytic assemblages of numerous freshwater biotopes', many with abundant aquatic macrophytes, also seems applicable to the sample results presented here. As was suggested at the end of section 5.9c, Gasse et al (1983) also found that diatom communities under such low to medium pH, low to medium alkalinity, mainly sodium carbonate/bicarbonate water conditions, were very dependent upon the particular substrate. Assemblage composition and diversity is thus largely the result of local, microhabitat.

Other assemblages identified in the 1983 paper that appear relevant to the Mexican context are IIIC (Melosira, Fragilaria, Synedra) and IIID (Melosira, Stephanodiscus, Nitzschia). Melosira distans var. alpigena was identified as a possible component of the IIIC assemblage. The low to very low E.C., medium pH and very low to low alkalinity conditions

outlined for this IIIC assemblage, suggest that Villa Victoria and Zirahuén could belong in this category. The IIID assemblage, in which the Nitzschia species included N. amphibia, N. gracilis and N. palea, may be applicable to the more chemically concentrated water bodies, especially those which are shallow, well mixed and rather turbid. Samples from La Zarcita, B. la Laguna and possibly Presa del Bosque may fall into this category.

Nitzschia-dominated lakes (with Stephanodiscus or Fragilaria construens var. venter in more dilute conditions) (assemblage IVA), may also occur in Mexico. The predominance of N. palea at many Mexican sites, however, rather complicates the chemical interpretation of this species grouping. The IVD assemblage, which includes Navicula elkab as a possible dominant, may be comparable with the samples from La Piscina de Yuriria. In the African examples, this assemblage was found in the plankton in shallow, well mixed closed lakes and in the benthos of larger lakes. The Group IV assemblages were collected from weakly to strongly alkaline, silica-rich waters of the Na - CO_3-Cl type. La Piscina de Yuriria falls into this category. Unfortunately, no diatom counts were available from the most highly concentrated Mexican waters to test whether other groupings were also applicable.

As suggested at the beginning of this chapter, the chemical and floristic similarities of East Africa and Central Mexico appear to support the validity of making

comparisons between them. The more abundant species-ecology information from Africa may also be of value in the interpretation of fossil assemblages for which no modern analogues were found in Mexico. Such a transfer of ecological and/or habitat information must, however, be carried out with caution. In general though, it appears that environmental gradient/species relationships, such as those outlined for alkalinity by Hecky and Kilham (1973) and Richardson et al (1978) are of some value. The use of ecological information from outside the tropics (e.g. Lund, 1954, 1955; Round, 1957) and from areas with waters of different chemical composition (e.g. Grimes et al, 1984), should not be forgotten, although even greater care is needed in its application. A summary of the apparent ecology of the species recorded in this study is given in Appendix 4. The information for this appendix was derived from both published data and from the results of this investigation.

Chapter 6

THE ZACAPU BASIN

'Abajo de este cerro (Hoya la Alberca/Zipimeo) cae la cienega de Tzacapo donde hay lagunas profundisimas con infinito pescado'

(Below this peak.... lies Zacapu Marsh where there are very deep lakes with infinite numbers of fish)

Fr. Alonso de la Rea, 1643

6.1 Introduction

The Zacapu Basin, Michoacán (19° 51'N, 101° 40'W) is one of the series of lake basins in Central Mexico created by the disruption of the Río Lerma drainage system by Pleistocene volcanic activity (Waitz, 1943; Barbour, 1973). Reconnaissance in the basin showed that lacustrine diatomites known as tizates, from the Nahuatl tizatl meaning white earth (Correa Perez, 1974), were exposed in the southwestern part, near the town of Zacapu. These indicate that the level of the present Laguna Zacapu has fluctuated markedly in the past. The results from two of these surface sections and from a core taken in the present day lake, are presented here.

6.2 Geology

The background to the geology and evolution of the Neovolcanic Axis has been described in Chapter 3. The Zacapu Basin (volcanic zone III, see Figure 3.5) is a broad alluvial- and lacustrine- sediment filled basin at

approximately 1,980 m a.s.l.. It is surrounded by andesitic and basaltic volcanic highlands (Demant, 1981) which reach an elevation of 3,365 m a.s.l.(Plate 12). A simplified geology map of the basin is given in Figure 6.1. Lacustrine sediments occupy an area of about 261 km^2, within a total drainage basin area of 335 km^2 (Correa Perez, 1974). The DETENAL 1:50,000 surface geology maps for Zacapu indicate strong faulting with a NE - SW trend, particularly to the north and east of the basin. To the west are extensive basaltic lava flows. The absence of faulting within these suggests that they post-date the last episode of fracturing in this region. West of the town of Zacapu, the lava flows are blocky and have a fresh appearance. Demant (1981) suggests that they may be Holocene in age. The local name for these blocky flows is malpaís (Ordoñez and Prado y Tapia, 1902). This feature probably accounts for the name Zacapu (or Tzacapo) which means the place of stones or pedregal. The basin floor displays some relief with small 'islands' or 'peninsulas' and lower raised areas (<10 m relief) called lomas (Arnauld et al, (1) unpublished). Apart from the samples collected by Demant for his thesis no detailed work has, apparently, been carried out on the geology of this basin.

6.3 Climate

The Zacapu basin experiences a climate of the Cwa type in Köeppen's classification. The causes of this type of climate have been described in Chapter 2. Annual

precipitation and moisture deficit/surplus data for the town of Zacapu were shown in Figure 3.9. Average monthly temperatures are moderate for the latitude, but mask wide diurnal variations. In January, for example, temperatures usually exceed 20 °C in the daytime, but often fall to below freezing at night (S.A.R.H., unpublished data). June is the warmest month. There are seven meteorological stations in the western part of the basin, maintained by the S.A.R.H.. These are located at Tirindaro, Tarejero, Zacapu, Villa Jimenez, Copándaro, Yerbabuena and Tariacuri (Figure 6.2). Data from three of the stations (Zacapu, Villa Jimenez and Copándaro) for the first seven months of 1982 (the main period of sampling) are presented in Table 6.1 and illustrate some of the intra-basin variability.

6.4 Vegetation

The natural vegetation of the basin slopes would probably be the mixed oak (*Quercus ruber*) and pine forest which dominates the Tarascan Sierra (West, 1948). West, however, described the vegetation around Zacapu as being rather 'scrubby'. At Zacapu, as in other lacustrine basins in Central Mexico, the natural vegetation is rather difficult to determine due to long-term clearance. An analogue for the vegetation of the *malpaís* may be provided by the *pedregal* vegetation described by Leavenworth (1946), which is rich in shrubs and oak (Plate 13).

6.5 Hydrology and Limnology

The basin and lake of Zacapu were artificially drained at the end of the 19th century with the creation of the hacienda of Cantabria (Freddolino, 1973) by the excavation of a short canal through the natural outlet in the northwest at Villa Jimenez (Tricart and Rios, unpublished) (Plate 14). Even prior to this, however, much of the basin floor was occupied by marshland and the name Cienega (marsh) de Zacapu (or Zipimeo) was commonly applied (for example Velasco, 1890). Before drainage, the whole of the basin floor was covered by rushes, reed grass and aquatic plants, which rendered the basin navigable only via canals across the marsh (Freddolino, 1973). Lakes within the basin at this time were called Laguna de Garcia, Lago de Urumbecuaro, La Patera, La Zoromuta, Laguna de los Puercos and Laguna de Zacapu. In spite of these drainage works, the whole basin floor flooded in 1966 (Ing. M. Ramirez Chavolla, pers. comm.) and stimulated the execution of a new drainage scheme. A small remnant lake (Laguna Zacapu) now lies near the town of Zacapu (Plate 7) , with a feeder pool called La Zarcita.

The western part of the basin (excluding Laguna Zacapu) forms irrigation district 22 of the S.A.R.H. and maize is intensively cultivated. Springs, at the base of the surrounding volcanics, are a major source of water to the basin. The main feeder springs for the Zacapu irrigation district are shown on Figure 6.2. The two most important are

at Tarejero and Zacapu, both providing >1.5 m^3/s. The present-day water chemistry and diatom flora of the basin have been described in Chapter 5, sections 2c, 7 and 8.

6.6 Archaeology

Zacapu was an important Tarascan ceremonial centre (see Chapter 3) and there were annual pilgrimages to the town and to the temple of Curicaueri (the principal Tarascan deity) from the original Tarascan capital at Tzintzuntzan (Freddolino, 1973). The founder of the Tarascan royal line, Hireti-ticatame, apparently arrived near Zacapu ca. 1200 A.D. and married a woman from the royal house of Naranja before moving on to Tzintzuntzan. Post-classic settlement in the basin was dense (Arnauld *et al*, unpublished (1)) which has tended to obscure evidence for pre-Tarascan occupation, although Freddolino (1973) believes that the Tarascans settled into an already densely populated area.

The first systematic excavations in the basin were carried out by Alfonso Caso (Caso, 1930). He excavated three sites: Potrero de la Isla and Potrera de la Aldea (subsequently covered by the expansion of Zacapu) and El Palacio in the *malpaís*. Unfortunately, Caso's site map is rather diagramatic (Figure 6.3). Pyramids (*yucatas*), burial grounds and large quantities of ceramics have been discovered, some of which may be pre-Tarascan.

Investigation of the pre-classic to conquest occupation of the basin is now being carried out by the Centro de Estudios Mexicanos y Centro Americanos (CEMCA), under the

direction of Claude Bataillon. One of the features of the post-classic sites in the basin is the use of retaining walls or terraces. These seem to have had three functions: to mark out residential areas, to delimit open spaces and for cultivation (Arnauld et al, unpublished(1)). The use of terracing may have reduced soil erosion resulting from the cultivation of slopes above the basin floor. Occupation appears to have been concentrated around the basin margins, on small islands or peninsulas within the lake area, or on the lomas. Arnauld and his co-authors believe that the period of occupation at the basin-floor sites was different from that of the basin margin and probably reflected variations in lake level. The CEMCA group carried out an intensive reconnaissance of the malpaís and part of the lomas (Arnauld et al, unpublished (3)). In the malpaís they found a number of quite large sites (ranging in size from 3 ha. to $3.3\ km^2$) indicative of a fairly large population. In the surveyed area of lomas, between Jauja and Cantabria, one hundred sites were found, with traces of old canals and ditches along the northern edge. The authors suggest that intensive agriculture, employing artificial drainage was the major activity, although exploitation of the marsh flora and fauna was also important. Unfortunately, no ^{14}C dates are currently available from these excavations.

The basin of Zacapu has, therefore, supported a high density of population for at least the last 1000 years, although settlement may have been concentrated in the western

part of the basin. Any attempt at reconstructing environmental change over this period must consider the effects of this anthropogenic influence.

6.7 Sedimentary records from the Zacapu Basin

Sequences of lacustrine sediments were sampled at seven locations across the basin floor (Figure 6.6). The sediments at all of these, except for the pit at site 7, were highly diatomaceous. Sites 1 to 4 were exposed sections through diatomite, abutting onto the malpaís west of the town of Zacapu. The elevations of the sections relative to present lake level were recorded (see Chapter 4, section 2c). No systematic study of these diatomites has previously been undertaken, although Ehrenberg made some species identifications in 1869 (Diaz Lozano, 1917). J.P.Bradbury (pers. comm.) has sampled the diatomites along the western margin of the present lake and has a 15 m core from the lake itself, but has published no results. Rico-Montiel et al (1980) published an abstract in the proceedings of the IVth Coloquium on Palaeobotany and Palynology, describing two diatomaceous deposits in the Zacapu basin. One was a 10 m section of diatomite near Zacapu and the other, a lacustrine 'soil' near Cantabria, towards the middle of the basin. The flora in the diatomite apparently indicated variations in water depth and salinity pre-dating the deposition of the most recent lavas. The soil assemblages had a high proportion of benthic species and were thought to represent the most recent period of the lakes history. The full

details of these sequences remain unpublished.

6.8a The Brickpit Section

A 5 m section was exposed by quarrying west of the town of Zacapu (19° 49'N, 101° 48'W), on the north side of the road to Zamora and Guadalajara (Figure 6.5). Lying 15.82 m above the present lake, the section consisted of diatomites intercalated with lake-margin (silts, well-sorted sands and marsh soils) and colluvial deposits (Plate 15). The beds were somewhat contorted, possibly due to slumping as the level of the water table at the site, fluctuated. Slumping of this type was recorded at Tlapacoya in the Basin of Mexico (Limbrey, 1976). However, by examining a number of profiles in the Brickpit Section and tracing beds across these, it was possible to sample a complete sequence. An urn burial was found in the upper part of the section (Figure 6.6) and was entrusted to the Departamento de Prehistoría, Mexico City, for identification.

Analyses for grain-size, loss-on-ignition (L.O.I.) and sediment chemistry were undertaken by S.P.Harrison and are described in Metcalfe and Harrison (in press). The stratigraphy is shown in Figure 6.7; grain-size, sorting and L.O.I. in Figure 6.8 and sediment chemistry in Figure 6.9.

6.8b Stratigraphy

The basal unit of the profile was a diatomite (bed 1) with low L.O.I. and a high proportion of fine-grained (finer than 4.75 Ø) material. Ca, Mg, Fe and Mn were low, but Na

and K were high. Bed 2 was one of a series of well sorted, black beach sands, with low organic content and few fines. There was a marked increase in Ca and Mg content and a lesser increase in Fe and Mn. Bed 3 was composed of diatomaceous sandy clay loam which fined and increased in L.O.I. upward. Bed 4 was interpreted as an organic marsh soil, with a L.O.I. of about 10%. Above this was an abrupt transition to another black sand (bed 5). This was marked by sharp peaks in a number of elements and particularly Na and Ca. This was overlain by a thin bed of diatomite (bed 6) in which fines again predominated. The sediment chemistry indicates that water conditions were much fresher than during the deposition of bed 5. Bed 7, another diatomaceous sandy clay loam unit, was similar to bed 3, although of a coarser texture. This was overlain by another marsh soil (bed 8), which had a higher L.O.I. and more Fe and Mn than bed 7. The 'poddy' diatomite forming bed 9 had a very high proportion of fines (about 95%) and Fe and Mn content was low. This was overlain by another marsh soil (bed 10), similar to bed 8. A bed of yellow/brown clay (bed 11) overlay the marsh soil. In this unit, the % fines increased and L.O.I. decreased relative to the bed below. L.O.I. continued to decline in bed 12 (silty and sandy clay) and the sediment became coarser. Bed 13, a diatomite, was much finer-grained although chemically fairly similar except for a reduction in Ca and Mg content. Another unit of organic marsh soil formed bed 14 which was overlain by another silt and sandy clay unit (bed 15). Bed 16, a

diatomite, showed a marked increase in the percentage fines and a slight fall in L.O.I.. Low levels of Fe and Mn were recorded. The yellow-brown clay of bed 17 displayed a reverse trend in fines and L.O.I. and a sharp increase in Mg and Fe. This was overlain by a thick unit of black sand (bed 18) which was similar to the other black sand beds in the profile. The sandy clay loam in bed 19 fined upwards, but was still quite coarse (35% < 4.75ϕ). The sediment chemistry indicates quite concentrated conditions during the deposition of this unit. Bed 20 was the uppermost organic marsh soil, with an increase in fines, organic matter (L.O.I.), Fe and Mn. The transition between this bed and the overlying diatomite (bed 21) was quite abrupt. The diatomite contained 99% fines and the sediment chemistry indicates fresher water conditions, or less clastic input, although Na showed little decline. The uppermost unit was classified as colluvium (bed 22). In this bed, the sediments were coarser and Ca and Mn showed particularly distinct increases.

The predominance of fine-grained sediments in this section probably reflects both the basaltic geology of the catchment and the importance of diatom valves as autochthonous input. The minima of fines in the black sands are quite distinct. Particle size analysis of the coarser sediment fraction (> 4.75ϕ) probably reflects sorting under different environmental conditions (Figure 6.8) (Solohub and Klovan, 1970). The black sands, for example, are well sorted, which would be expected of a beach deposit. L.O.I. is roughly parallel with clay content, except in the

diatomites and especially the deeper-water facies where there would be little input of organic matter from lake-margin vegetation or from slope material. The high levels of manganese and iron in some of the marsh soils may indicate periods of significant input of soil material from the catchment (Elder et al, 1976).

6.8c Radiocarbon Dating

The marsh soils in the section (average L.O.I. 10.3%) were sufficiently organic for dating. ^{14}C age determinations were carried out on beds 4, 10, 14 and 20. Three radiocarbon dates were provided by the Radiocarbon Accelerator Unit in Oxford. These were from bed 4: 26,600 ± 590 yr BP (OxA-159), bed 10: 28,100 ± 680 yr BP (OxA-158) and bed 14: 25,200 ± 530 yr BP (OxA-160). Two additional radiocarbon dates were obtained from the Carbon-14/Tritium Measurements Laboratory Harwell, on beds 4 and 20. The age for bed 4 was determined to be 27,660 ± 1400 yr BP (HAR-5896). Bed 20 was dated to 26,780 ± 2660 (HAR-5898) which suggests that the urn burial was emplaced in the sediments quite a long time after their deposition. In view of the considerable age of these sediments, their sensitivity to even very small inputs of modern carbon and the large errors on the dates from the Harwell Laboratory, the exact age of this sequence is unclear. It would appear to have a minimum age of 28,000 years. Bacterial attack on the ~~the~~ organic matter may account for some of the intersample variation. Examination

of the lipid fraction of the sediments (see section 6.8d) shows that the soils from beds 10 and 14 retained indications of higher plants as a source of organic matter, whereas in bed 4 algal and bacterial forms dominated. This may suggest that the dates from beds 10 and 14 may have been less affected by younger contamination.

6.8d Lipids

Analysis of the sedimentary lipids was undertaken by A.J.Fowler (R.L.A.H.A., Oxford) as part of her D.Phil project (Fowler, 1985). It was hoped that lipid analysis would enable the different beds to be classified according to their major source of organic matter.

The environmental interpretation of lipids is based upon the existence of marker molecules for different biological communities. The most abundant molecular classes are straight chain fatty acids and hydrocarbons (n-alkanes). Long-chain fatty acids ($> C20$) indicate higher-plant material, while short-chain fatty acids ($< C20$) mark aquatic (algal or bacterial) input. The ratio of long to short chain molecules (E.I.) indicates the relative proportion of each in the sediment. This ratio may, however, be affected by bacterial activity. Specific n-alkanes indicate particular plant types. The Carbon Preference Index (C.P.I.) is used to express the relationship between odd and even chain lengths. High values of this index reflect terrestrial lipids and low values aquatic lipids.

The value of lipid analysis in the interpretation of

the Brickpit sediments was, unfortunately, diminished due to their low organic carbon content and considerable age. All the beds contained some algal or bacterial material, with no beds having only higher plant material (whether from terrestrial or aquatic plants). The interpretation of the lipid record is complicated by the fact that early diagenesis of the fatty acids (producing shorter chain lengths) may lead to an overestimation of the 'lacustrine' (algal and bacterial) component. As conditions in the Brickpit sediments were not suitable for good preservation, being mainly freely draining, the significance of the lipid results alone is unclear. They will, however, be referred to when of interest.

6.8e Diatoms

Samples for diatom analysis were collected from each of the beds described in section 6.8c, with two from the diatomite bed 3. Slides were prepared using the methods outlined in Chapter 4, section 5b. The relative frequencies of species recorded ($\geqslant$ 2%) are shown in Figure 6.10. In spite of the heterogeneous nature of the stratigraphy of this section, a series of diatom zones may be distinguished, although the transitional nature of the zone boundaries must be stressed. The zones (I - V), with their dominant and common species (*sensu* Gasse *et al*, 1983), are illustrated in Table 6.2. When these counts were carried out *F. pinnata* and *F. pinnata* var.*lancettula* were clumped together; where the

proportion of the two varieties appears ecologically significant it will be given.

Zone 1 - Melosira ambigua is the dominant species in this zone (> 68%) with M.granulata var. angustissima and Fragilaria pinnata . M. ambigua is a euplanktonic diatom (Lowe, 1974) and suggests deep water at the site. No analogue for this assemblage was found in my modern collection of modern Mexican diatoms. It does, however, seem similar to the assemblage IIIc of Gasse et al (1983) which is typical of the plankton of large East African lakes. If this is so, then conditions of low to very low electrical conductivity (E.C.), medium pH and low to very low alkalinity may be indicated. In East Africa lakes with this association are usually of the CO_3-HCO_3 type. The chemical similarities between many East African and Central Mexican lakes have been discussed in Chapter 5. Street (1980) suggested that in lakes of this type (IIIC) precipitation and evaporation over the lake surface are important components in the water budget (atmosphere-controlled lakes). In contrast to the present day remnant Laguna Zacapu, in which spring input is very important, a large lake filling the whole basin would be more of the type described by Street. Gasse et al (1983) indicate that in the IIIC assemblage, Melosira spp. dominate in open water environments (plankton) whilst Fragilaria spp. are most important in shallow, marginal areas. A possible intermediate situation may be exemplified by La Zarcita, a pool about 1 - 2 m deep, feeding into Laguna Zacapu, in which M. granulata var. angustissima and F. pinnata are dominant.

Zone II - F. pinnata is clearly dominant in this zone, exceeding 78% of the counts in samples from bed 2 (a black sand) and bed 3 (a sandy clay loam). F. pinnata var. lancettula forms only a small percentage of the F. pinnata group. F. pinnata appears to develop optimally at pH 7.6 to 7.8 (Cholnoky, 1968), in shallow standing water (Bradbury, 1971; Haworth, 1977). The interpretation of the ecology of this species, which has been the subject of some debate, is discussed more fully in Chapter 7, section 5ci. Bradbury (1979) points out that Fragilaria spp. are quite likely to become detached from their substrate and enter the plankton. The assemblage in this zone is, therefore, interpreted as representing a fairly shallow (1 - 2 m) lake, with open water at the site. The appearance of C. placentula var. lineata in bed 3, sample 3T, may indicate shallowing of the water and more abundant aquatic vegetation as this species is usually epiphytic on higher plants (Jørgensen, 1948; Bradbury, 1979). F. pinnata var. pinnata was only recorded in low abundances in the modern samples. The predominance of F. pinnata var. lancettula in a number of shallow pools around the Zacapu basin at the present day (e.g. Bellas Fuentes, Tarejero) may indicate more brackish conditions than in the past (Patrick and Reimer, 1966).

Zone III - The assemblages from beds 4 - 13 have been included in this zone which is believed to represent a period of fairly shallow, but fluctuating,water levels at this site. The fall in lake level suggested by sample 3T seems to

have continued. The assemblage in bed 4 (an organic marsh soil) includes F. pinnata and C. placentula var. lineata, as well as Melosira italica, which is usually regarded as a periphytic species (Hustedt, 1930b) and the soil or aerophilous diatoms Hantzschia amphioxys and Navicula mutica (Lowe, 1974). The pH may have increased as the water shallowed. H. amphioxys has an optimum pH between 7.8 and 8.0 (Cholnoky, 1968) and C. placentula var. lineata between 7 and 9 (Lowe, 1974).

A deepening and slight freshening of the lake is indicated by the diatomite bed 6. Fragilaria leptostauron var. dubia is dominant, with F. construens var. venter and F. pinnata common. F. leptostauron var. dubia is periphytic, but according to Patrick and Reimer (1966) usually needs a substrate. This may indicate that although fluctuating, the water did not become as deep as during the deposition of zone II. The assemblages in beds 7 - 13 indicate a return to shallower conditions with abundant macrophytes. At times, organic marsh soils developed (beds 8 and 10). Inputs of terrestrial material are suggested by the sediment analyses, especially in bed 8 where there are large peaks in Fe and Mn. The age range for the marsh soils in this zone is 27,660 ± 1400 yr BP (HAR-5896) for bed 4, to 28,100 ± 680 yr BP (OxA-158) for bed 10. In view of the large standard errors on these dates, they are not significantly different.

Zone IV - The organic marsh soil at bed 14 marks the base of zone IV. The measured age of this bed was 25,200 ± 530 (OxA-

160). In this zone C. placentula var. lineata is the most abundant species, although only exceeding 33% (dominant) in bed 17. F. pinnata and F. leptostauron var. dubia are common, as is F. construens var. venter in bed 16. At present, C. placentula var. lineata is very abundant in assemblages from the margins of Laguna Zacapu and from lake-margin aquatic vegetation. In samples of this type, it exceeds 50% of the count (sample numbers Z5 and Z9). It also accounts for >10% in four other samples, including one of bottom sediments from the middle of Laguna Zacapu. As some of the aquatic plants supporting large populations of C.placentula var. lineata were collected in water about 1 m deep, an increasing abundance of vegetation at the site, rather than an actual fall in water level, may have caused the floral variations in this zone. The marsh soil (bed 14), however, probably does indicate shallower water. In bed 16 (a diatomite) Fragilaria spp. are more abundant than C. placentula var. lineata.The water may have deepened, therefore, or become less well vegetated during this period. A slight deepening and freshening may also be indicated by the absence of Epithemia turgida (optimum pH >8 according to Cholnoky, 1968), Rhopalodia gibberula var. Van Heurckii and H. amphioxys from this bed (cf beds 14 and 15).

Zone V - In the uppermost zone (beds 18 - 22), Fragilaria spp. are again dominant, although F. pinnata and F. pinnata var. lancettula are more important in beds 18 and 19 and F. leptostauron var. dubia in beds 20 - 22. Bed 20 was dated to

26,780 ± 2660 yr BP (HAR-5898). Common (5 - <33%) species in this zone include C. placentula var. lineata and F. construens var. venter. In bed 18 (a black sand), Stephanodiscus astraea var. intermedia also came into this category. The diatomite (bed 21) is again dominated by Fragilaria spp., as was the case for bed 6 in zone III. This may indicate less aquatic vegetation at this time. The return of C. placentula var. lineata in considerable numbers (9.7%) in bed 22 suggests that fringing vegetation was again nearer at hand.

6.8f Diatom Abundance and Preservation

Diatom abundance (valves/g sediment) varied from 7.58×10^6 in bed 18, to 2.01×10^{10} in bed 3T (Figure 6.11). Diatoms were generally most abundant in the diatomite beds (6, (9), 13, 16 and 21) although bed 1 was an exception. The high diatom content of bed 3 (sandy clay loam) was reflected in the more diatomite-like appearance of this bed up the profile. The peaks in abundance were marked by a predominance of Fragilaria spp., a phenomenon also noted by Gasse (1978) from Mt. Badda in Ethiopia.

Preservation in the diatomites was generally acceptable for counting and good in bed 3. Lowest diatom numbers were recorded in the black sands (2, 5 and 18) although only in bed 5 was preservation poor. Preservation was worst in the organic marsh soils/clays (beds 4, 8, 10, 14 and 20) although numbers consistently exceeded 10^8 valves/g.

6.8g Summary and Conclusions

The Brickpit sequence appears to record one major change in lake level (above bed 1), followed by a series of minor fluctuations, occurring prior to 25,000 yr BP. An attempt to summarise this information has been made by using published ecological data to plot the total percentage in each level falling into particular habitat categories (euplanktonic, epiphytic, aerophilous/soil and others (Figure 6.12). The peak in planktonic forms in bed 1 clearly reflects the dominance of *M. ambigua* in this level. The ^{14}C dates available suggest that this deep water episode occurred prior to 28,100 $\pm$ 680 yr BP (OxA-158) and possibly before 30,000 yr BP (A.J.Fowler, pers. comm.). It is interesting to note that *M. ambigua* and *M. granulata* var. *angustissima* were indicator species for the first division of the samples in the TWINSPAN analysis of samples from Laguna Zacapu. The samples containing these species were sediment samples from Zacapu Celanese, collected from channels apparently cut into old fossil diatomite, and samples believed to be influenced by inwashing of older material by surface runoff.

Calculation of the total % of *Melosira*, *Fragilaria* and *Cocconeis* spp. (Figure 6.13) clarifies the dominance of zone II by *Fragilaria* spp.. This episode has been interpreted as one of moderately deep to shallow water, in which *F. pinnata* (and var. *lancettula*) may have entered the plankton. In zone III *Fragilaria* spp. and *C. placentula* var. *lineata* were the most abundant. The importance of terrestrial input and very

shallow water conditions are indicated for the organic marsh soils by the peaks in aerophilous/soil spp. in these levels (beds 4, 8, 10 and 14). In beds 10 and 14,the lipid data indicate that most of the organic material came from higher plants. The diminution in the numbers of aerophilous and soil spp. in zone IV, with an increase in epiphytic species (including C. placentula var. lineata) may support the idea that very abundant aquatic vegetation, rather than shallow water, produced these assemblages (see comments in 6.8e). The possibility of a stabilization of the basin slopes relative to conditions during zone III cannot, however, be discounted. The age of the uppermost sediments poses some problems. The urn was originally thought to be Tarascan due to the proximity of a cemetery up-slope from this site and the use of urn burials by this culture (Freddolino, 1973). The colluvium at the top of the section may, therefore, be Holocene in age, separated from the Late Pleistocene sediments by an unconformity.

The site of the Brickpit appears to have been close to the edge of the lake during the deposition of most of this exposure. However, if topographic relationships have remained constant, the occurrence of a marginal embayment at this site implies that between ca. 28,000 and 25,000 yr BP, a lake with a surface level >16 m above that of the present lake occupied the basin of Zacapu. The deep-water phase recorded at the base of this sequence, is also suggested by exposures of diatomite at higher elevations than that of the Brickpit. The danger of making this higher=older assumption,

however, will be shown in section 6.9. The effects of the eruption of the lava flows on this west side of the town (which may be Holocene in age) on the elevation and bedding structures of the older sediments, are not clear from this section. The possibility of this kind of disturbance cannot be ruled out, but seemed unlikely in the field as the site lay in a small valley leading between separate lava flows.

6.9a Zacapu Section 1

The site of Zacapu Section 1 is situated approximately 500 m west of the Brickpit section, adjacent to the Zamora/Guadalajara road (19° 49'N, 101° 49'W). The section was almost 2 m thick and consisted of a sequence of diatomites, diatomaceous silts, sandy silts and sands. A bifurcated marsh soil was recorded at 80 cm from the base. The elevation of the base of the section was 34.4 m above present lake level.

6.9b Stratigraphy

The sequence of sediments in Zacapu Section 1 is shown in Figure 6.14. The percentage fines ($< 4.75\phi$) and L.O.I. are illustrated in Figure 6.15. The basal unit was 27 cm of silty diatomite with some small 'pods' of diatomite. Occasional fish bone fragments were noted. Both the percentage fines and L.O.I. increased upwards through this unit. Above this unit lay 9 cm with lenses of silty diatomite and black sand. The lateral extension of this unit included

a lens of (?) marsh soil from which a sample for dating was collected. Only 26% fines were recorded from this unit. The next unit, a clayey silt, occurred between 36 and 45 cm from the base of the section. L.O.I. and % fines remained relatively low in these sediments. 15 cm of diatomaceous sandy silt formed the next unit. L.O.I. increased, although still less than 5%, as did percentage fines. The overlying unit was 9 cm (61 - 50 cm) of diatomaceous silt. The trends in L.O.I. and % fines continued from the unit below. A bed of light, powdery diatomite, 9 cm thick, formed the next unit. % fines showed a sharp increase, to 58% at 65 cm, while L.O.I. declined. These features are typical of a diatomite and were also noted in the Brickpit sediments. Between 69 and 80 cm lay diatomaceous silt with occasional sand grains. The % fines declined up the profile. The upper boundary of the diatomaceous silt (at 80 cm) was marked by a thin band of black, organic sand, believed to be a marsh soil. This layer bifurcated along the profile, with an intercalated lens of colluvium. The lower band of the marsh soil (black sand) was sampled for ^{14}C dating. Above the marsh soil lay 42 cm (82 - 124 cm) of diatomite, becoming more silty upwards. Occasional fish bones were recorded in this unit. The very low L.O.I. and high percentage fines (62%) at 90 cm are indicative of a fairly pure diatomite and the reduction in fines (30% at 120 cm) and general increase in L.O.I. up the profile reflect the increasing silt content of the sediments. The prismatic structure of the top 20 cmof this unit suggests that the sediments underwent exposure and

desiccation. The next unit (124 - 140 cm) was another diatomite, with lenses of black sand at 130 cm. Fines increased to >55% and L.O.I. also increased to more than 10% in the top 10 cm of the unit. The top of the unit, however, appeared weathered and organic material may have been introduced from above. 10 cm of slightly weathered diatomaceous silt formed the next unit (140 - 150 cm). L.O.I. increased sharply in this unit, probably reflecting soil development in the uppermost 25+ cm of the profile (150 - 175+ cm), a loamy soil.

6.9c Radiocarbon Dating

Samples from the marsh soil at 27 -36 cm and from the sandy, marsh soil at 80 cm were submitted for dating at East Kilbride. Unfortunately, only the upper sample contained sufficient organic carbon for dating by conventional means. An age of 7,330 ± 70 yr BP (SRR-2256) was obtained (D.D.Harkness, pers. comm.).

6.9d Diatoms

Samples for diatom analysis were collected at 10 cm intervals with an additional sample from 65 cm, so that the diatomite at that level was represented. The relative abundances of species (≥2%) are shown in Figure 6.16. Five zones have been identified between the base of the profile and 150 cm (Table 6.3).

Zone 1 - This zone (lying within the silty diatomite with

pods of diatomite) included samples from 0 - 20 cm. Cyclotella meneghiniana is dominant, but declines in abundance up the profile, with Stephanodiscus niagarae, S. astraea var. intermedia and S. astraea var. minutula (S. minutula) and Melosira ambigua becoming more numerous. Although C. meneghiniana may spend time in the littoral (Bradbury, 1979), it is more usually planktonic (Hustedt, 1949; Javakul et al, 1983). The increasing abundances of euplanktonic species (Figure 6.17) such as S. niagarae and M. ambigua suggest that, overall, the lake was becoming deeper over this period. Conditions at the base of the profile may have been slightly saline (Rushforth et al, 1981) with quite high levels of chemical concentration in the water (Evenson et al, 1981). The flora suggests eutrophic conditions. The occurrence of a number of epiphytic species (e.g. Epithemia turgida and Cymbella mexicana) and Navicula halophila, a saline-water species (Hammer et al, 1983) in the association from 10 cm may indicate lake level actually fell, before rising again.

Zone II - Three subzones have been identified in this zone. M. ambigua is most common in IIa and IIc and C. meneghiniana in IIb. Assemblage IIa includes S. astraea var. intermedia, S. niagarae and Melosira monospina as common (5 - <33%) species. A fairly deep, slightly alkaline lake, possibly with relatively low silica content (Kilham, 1971; Gasse, 1977b) may have occupied the site. A fall in lake level is suggested by the dominance of C. meneghiniana at 40 cm. A

unit of clayey silt at this level provides support for this interpretation. Lake level apparently rose again during the deposition of the assemblage at 50 cm.

Zone III - Fluctuations between C. meneghiniana and Cyclotella stelligera as most abundant species typify this zone. The sediment sequence progresses diatomaceous silt to diatomite (61 - 70 cm), to diatomaceous silt and then sand and marsh soil (80 cm). Like C. meneghiniana, C. stelligera may be part of the plankton or the periphyton (Huber-Pestalozzi, 1942). Bradbury (1978), however, has suggested that it may be planktonic in eutrophic lakes. The assemblages in Zone III may indicate that this was the case here. A rise in lake level is suggested by the powdery diatomite and at 65 cm C. stelligera is dominant (60.3%) and S. niagarae and M. monospina common. Up the profile the increasing abundance of C. meneghiniana, the occurrence of Fragilaria and Nitzschia spp. , together with the silty, then sandy nature of the sediments marks renewed shallowing and slight evaporative concentration, of the lake. The organic sandy marsh soil at 80 cm was ^{14}C dated at 7,330 $\pm$ 70 yr BP (SRR-2256).

Zone IV - A marked change in assemblage occurs above the marsh soil. Although rather varied, the zone shows a general upwards decrease in abundance of S. niagarae and C. stelligera, with a corresponding increase in Campylodiscus clypeus, Cymbella spp. and C. placentula var. lineata.

S. niagarae reaches a peak of abundance (31.9%) in the

diatomite at 90 cm. This species has been described by Gasse (1977b) as being in the process of extinction. It is, however, abundant in lakes and rivers throughout North America, where it flourishes in meso- to eutrophic waters with salinities from 3 - 30‰. (Theriot and Stoermer, 1981; Hammer et al, 1983). Extant material has also been reported from Russia and West Java (Theriot and Stoermer, 1981). The water of Laguna Zacapu may have been quite cool and calm (Gasse, 1977b) during this period. In sediments from L. Texcoco in the Basin of Mexico, the earliest assemblage, which was dominated by S. niagarae was interpreted by Bradbury (1971) as indicating a large, cool, possibly deep, low salinity lake.

The occurrence and increasing abundance of C. clypeus in Zacapu (reaching a maximum at 110 cm) suggests a marked change in the physical and chemical character of the lake. The sediment, however, was still diatomite. C. clypeus is a benthic, mesohalobous (2 - 16‰) species (Servant-Vildary and Blanco, 1984). Round (1973) records it as epipelic and non-motile. Gasse and Tekaia (1983) propose C. clypeus as an indicator diatom for pH 8 - 8.6. In Zacapu section 1, its occurrence with Anomoeoneis costata (pH >8.6, Gasse and Tekaia, 1983) indicates distinctly brackish water conditions. Bradbury (1971) reported an assemblage with C. clypeus and A. costata as indicating a brackish, shallow-water episode in L. Texcoco. One of the phases recorded by Rico-Monteil et al, (1980) was apparently also based upon the occurrence of C.

clypeus and A. costata var. sculpta (Bradbury, pers. comm.). In collections of modern Mexican diatoms made for this study, C. clypeus was found only in the crater lake L. Alchichica, in the Oriental basin (see Chapter 5, section 2a). The water in this lake is of the $Na^{+} - Cl^{-}$ type. The former abundance of this species in Laguna Zacapu (now an $Mg^{2+} - HCO_3^{-} - CO_3^{3-}$ lake) indicates a considerable degree of evaporative concentration, following the Hardie and Eugster (1970) model. As the present-day freshwater lake is open, the palaeolake was, presumably, closed at this stage, allowing much greater evaporative concentration to occur. The input of spring water to the basin may also have been markedly reduced at this time. The assemblage at 120 cm is rather mixed, although the structure of the sediments suggested desiccation at the top of the diatomite.

Zone V - This uppermost zone shows strong similarities to Zone III, with the alternation of C. stelligera and C. meneghiniana as the dominant species. Like Zone III, Zone V has been subdivided. C. stelligera is dominant in Va, with Fragilaria pinnata common and lesser numbers of other Fragilaria spp. and Stephanodiscus spp. The abundance of the oligohalobous (< 2.2 ‰ salinity) C. stelligera (Servant-Vildary and Blanco, 1984) indicates a dramatic change in water chemistry conditions from that prevailing during the deposition of the upper part of the underlying diatomite. At 140 cm (Vb) C. meneghiniana is dominant, which may again indicate more alkaline, organic matter-rich conditions. The

assemblage in Vc (150 cm) shows a reversion to C. stelligera as the dominant species (58.56%). The presence of S. niagarae and M. monospina as common species may indicate that the lake was again deepening, although the occurrence of Fragilaria spp. and C. placentula var. lineata suggests that only the beginnings of a transgression may be represented.

6.9e Summary and Conclusions

The ^{14}C date obtained from 80 cm assigns Zacapu Section 1 to the Holocene. Hence, no overlap with the sequence from the lower-lying Brickpit Section is suggested. Presumably, the upper, Holocene sediments at the latter locality have been eroded away. Zacapu Section 1 records a number of quite distinct fluctuations in lacustrine conditions, particularly depth and salinity. Figures 6.17 and 6.18 show curves representing variations in habitat and salinity indicated by the species included in the diatom diagram (Figure 6.16). Prior to 7,330 ± 70 yr BP, the lake appears to have deepened (from Zones I to II) before receding to below the level of the site by 7,330 yr BP (the top of diatom Zone III). The progress of this rise and fall was, however, rather erratic.

The episode of deepest water in the basin apparently occurred soon after 7,330 yr BP. This is rather masked on the habitat graph (Figure 6.17) by the classification of C. stelligera as facultatively planktonic. The lake then apparently shallowed and became considerably more saline. An enrichment in Na and Cl is suggested. The upper part of the profile indicates a return to less saline water conditions of

intermediate (?deepening) depth.

6.10a Zacapu Core 1

A 14.3 m core was recovered from the present Laguna Zacapu using a modified Livingstone corer (see Chapter 4, section 2a). As the upper portions of a number of the core segments had become compressed during recovery and extrusion, the core depths have been recalculated to allow for this. As a result, although sub-sampling was carried out at 5 and 10 cm intervals, the corrected depths distort the distance between samples. The discussion below uses the corrected depths.

6.10b Stratigraphy

The core consisted of soft, diatomaceous gyttja ranging in colour from dark, chocolatey brown (10YR 2/1) to grey and khaki (10YR 2/2 or 3/2). The consistency of the mud varied from fine and structureless to that with a structure described as strong or medium 'curdy'. Laminae were present throughout the core, but overall, the stratigraphy appeared to be rather monotonous. Plant remains and root hairs were noted in the top 12 cm. As had been the case with the Brickpit sediments, organic carbon content was generally low (1 - 3.6%) except at 266 - 276 cm where it reached 5.6%. Reed macrofossils were found at this last level. Based on lipid analysis, most of the organic matter in the core sediments apparently came from higher-plant material.

Aquatic organic matter (short-chain molecules) was probably lost through early and preferential diagenesis in the water column, before reaching the sediments (Fowler, 1985).

In the bottom core segment, a wedge of black (10YR 2/1) mud, believed to be contaminant from the surface, was noted and avoided for sampling and dating purposes.

Chemical analysis of the sediments was undertaken by P.E.Hales as part of his own D.Phil research. Results relating to the diatom counts (see section 6.10c) are shown in Figure 6.19. The main feature of all the curves is the major increase recorded in the top 150 cm. The clastic content was generally very low. All elements except Ca reach their peak in this portion of the core. Parallelism in the trends of the elements is fairly general (cf Lewis and Weibezahn, 1981), but is particularly clear here for Ca, Mg and Al. Fe shows a very similar pattern, but in a rather dampened manner. Al is the most abundant of the cations analysed.

Moving up from the base of the core, the first major peak, especially marked in Ca and Al, occurs at 1189 cm (Ca=8.99 mg/g). Fe, Mg, Na and K all increase to a lesser extent. Between 900-700 cm, there is a quite distinctive pattern of variations. Above 900 cm, all the elements become less abundant recording low levels at 877 cm and then increasing to display double peaks at 814 cm and 775.5 cm. Again, these are particularly pronounced in Al and Ca. A further peak occurs at 623 cm.

Na displays a slightly different trend. Having been at

very low levels between 600 and 400 cm, it shows a step-like increase. Except for Na, all the other elements display a marked increase above 150 cm. Na, however, 'takes off' above 100 cm, increasing from 2.71 mg/g at 102 cm to 15.23 mg/g at 93 cm.

In the topmost metre, all the elements have a double peak, although its position is somewhat staggered. These peaks are shown very clearly in the curves for Al (34.3 mg/g at 93 cm and 53.1 mg/g at 47 cm) and Fe (17.5 mg/g at 93 cm and 16.8 mg/g at 47 cm). Between the top two samples,only Na continues to show an increasing trend.

The interpretation of the significance of the sediment chemistry from this core is not a simple matter. Diatom valves formed a major component of the sediment (see section 6.10e) and most of the core material became distinctivly pale and powdery upon drying. Such diatom-dominated sediments have also been recorded from Lake Kivu (Degens et al, 1973), Lake Naivasha (Richardson and Richardson, 1972) and from eutrophic Minnesotan lakes (Bradbury, 1975). It is interesting to note that Richardson and Richardson (1972) also refer to the occurrence of a number of whitish flocculent zones in their core, which may be similar to the 'curdy' layers identified in Zacapu core 1. Such layers may be typical of rapidly deposited diatomite (K.Kelts, pers. comm.). Only in the top 150 cm of the core do the elements suggest dramatic changes in the environment. The increases in Na and Al at this level may indicate an influx of

allochthonous, clastic material (Dean et al, 1984), probably due to accelerated erosion of the basin slopes. The concurrent increase in Ca may also reflect allochthonous input of unweathered silicates from the basaltic rocks in the catchment (Jones and Bowser, 1978) or may be due to evaporative concentration of the lake water itself (Eugster and Hardie, 1978). Overall, the higher concentrations of cations in the top of the core probably indicates the combined effects of a shallower, more chemically concentrated lake than that which existed earlier in the Holocene (Richardson and Richardson, 1972) and greater inputs of allochthonous material due to increased rates of erosion in the catchment (Engstrom and Wright, 1984). The generally smaller, variations in Ca and Mg through the core, may reflect the more ready precipitation of the alkaline earths as minor evaporative concentration occurred. Ca reaches its highest level at 1189 cm. The abundance of Al in the sediments is probably due to the Al-rich basalts on the west side of the lake. As Al is usually conserved in solid phases (Eugster and Hardie, 1978) its abundance in the sediments and scarcity in the lake water is to be expected. The reasons for the lack of convergence between the behaviour of Na and other elements, especially Al and K, which might be expected to show similar trends (Engstrom and Wright, 1984), remain unclear.

6.10c Radiocarbon Dating

Radiocarbon determinations have currently been obtained

from twelve levels in the core, between 64.6 - 74.6 and 1247.8 - 1257.8 cm. Dating was carried out at the Oxford Radiocarbon Accelerator unit as part of A.J.Fowler's D.Phil project. Dates were run on different fractions of the sediment (conventional preparation; lipid fraction; macrofossil cellulose). The results obtained are given in Table 6.4 and displayed on an age/depth plot in Figure 6.20. 10cm blocks of core material were taken, the central 1 cm being used for conventional preparations and the remainder of the material bulked for lipid and macrofossil extractions.

The core dates range from 1,100 ± 90 ^{14}C yr BP (OxA-226) to 5,200 ± 160 ^{14}C yr BP (OxA-282), with the lipid dates being consistently older (by 400 - 500 years) than those derived from conventional preparations. Samples 3 - 7 show statistically significant differences in the dates from conventional and lipid material (Figure 6.20). The ages converge at sample 8, diverge at 9 (862 - 872 cm) and converge once more at 10. Samples 11 and 12 again diverge. Fowler suggests that where the dates converge there has been a significant input of higher-plant material (samples 1, 8 and 10). Sample 8 showed a particularly large input of higher plant material, based upon its n-fatty acid CPI (see section 6.8d). The major difference between lipid and conventional ages in sample 9 is probably due to the major algal/bacterial content of the lipid fraction (see below). In sample 10, terrestrial input was again important.

Due to the problems discussed below, the conventional

or bulk preparations are believed to be the more reliable. A bulk sample from level 12 was prepared by conventional methods, and yielded an age of 3,970 ± 120 yr BP. In order to provide a comparison with the dates from the Accelerator, a sample from 1370 - 1380 cm (uncorrected depth) was sent to the N.E.R.C. Radiocarbon laboratory at East Kilbride. However, this proved to be impossible to date due to the very low organic carbon content (0.7%) (D.D.Harkness, pers.comm.). A sample from this part of the core has now been submitted to the Accelerator unit for dating.

The age determinations obtained from the core pose considerable problems of interpretation. There are a number of reversals in age going up the core, for example between samples 3 and 1. Such reversals cannot be explained simply in terms of disturbance of the sediments as examination of the core had shown that laminations were preserved. In fact, there is no statistical difference between the dates from conventional preparations for the sample groups 1, 2 and 3; 4, 5, 6, and 7 and 9 and 10 (R.Gillespie, pers. comm.). In part, the similarity in the ages from different levels may be explained by the very rapid sedimentation rate in the core. Based upon regression analysis of the ^{14}C ages from the conventional preparations, the sedimentation rate is 0.42 cm/year. This is probably due, in large measure, to the high diatom productivity of the lake (see section 6.10e). Up the core, the sedimentation rate is fairly constant to sample 4 (conventional preparation age 2,230 ± 150 yr BP), but suddenly decreases up to sample 3 (conventional preparation

age 1,100 ± 90 yr BP). If the calculated average sedimentation rate is extrapolated, this would yield an age of 3,400 yr BP for the base of the core. However, if the date from the bulk sample 12 (3,970 ± 120 yr BP) is accepted, then the rate of sedimentation was slower during the deposition of the sediments at the bottom of the core, than it was subsequently. A comparison of the diatom assemblage at the base of the core with that from the top of Zacapu Section 1 (thought to post-date 7,330 yr BP), indicates no overlap. The age of the core, therefore, is probably considerably less than 7000 years. A 15 m core obtained from Laguna Zacapu by J.P.Bradbury had a basal date of about 8,000 yr BP.

The most problematic aspect of the dating of Zacapu Core 1, is the apparent age of the surface sediments. Linear regression of the dates from conventional preparations, against depth, suggests that the top of the core is approximately 990 years old. If this is the case (there being no ^{14}C dating of the surface sediment), then either all the sediment deposited during nearly the last 1,000 years has been eroded away, or there is 'dead' carbon affecting the apparent age of the sediments. The former possibility seems most unlikely in such a highly productive lake. If the latter is true, then the dates must be subject to some hardwater error. Such dating problems were not anticipated in volcanic terrain. One possible explanation is that the spring waters feeding the lake actually circulate more deeply

and have a longer residence time, than was originally thought and bring ^{14}C-poor carbon into the lake. Old diatomites, underlying the fresh-looking basalts are a possible source of this carbon. Surface mud having an apparent age of about 1,000 years was reported by Deevey and Stuiver (1964) for Linsley Pond, Connecticut. These authors also showed that even small inputs of ^{14}C-poor groundwater can account for considerable ^{14}C depletion in deep waters and bottom sediments.

The presence of such 'dead' carbon (unequilibrated with the atmosphere) would have the most influence on the dates from those samples containing little higher-plant (presumably equilibrated) material. This might account for the convergence of the lipid and conventional preparation dates in those levels where higher plants contributed more to the lipid fraction.

Incorporation of old or 'dead' carbon currently appears to be the simplest explanation for the apparent age of the surface sediments. If this is accepted, then 990 years must be deducted from all the laboratory dates to yield an estimated age. As will be described below, the chronology which results from this step seems to be logical with respect to the environmental trends recorded in the core. In the following discussion, therefore, the laboratory dates on conventional preparations, minus 990 years are given in parentheses or cited specifically. Figures 6.20 and 6.21 and Tables 6.4 and 6.6 show the uncorrected dates.

Zacapu Core 1 may, therefore, be expected to retain a

very detailed record of variations in the environment over the later Holocene.

6.10d Diatoms

Samples for diatom analysis were prepared at 5 cm intervals from the core material remaining after the removal of the sediment blocks for ^{14}C and lipid analyses. Counts were carried out at 10 cm intervals, except where examination of the intermediate levels indicated a significant change in assemblage, when every 5 cm was counted. The variations in species present in abundances $\geq 2\%$ are shown in Figure 6.21. A series of 14 diatom zones have been distinguished, primarily on the basis of changes in the dominant ($\geq 33\%$) and common (5-$<33\%$) species (Gasse *et al*, 1983). These zones have also been marked on the core diatom diagram (Figure 6.21). In view of the complexity of the record between 1250 - 1350 cm, this interval is shown using a different vertical scale in Figure 6.22. The detail of zonation in this part of the core is shown there. As diatom preservation appears to be particularly significant in assessing the palaeolimnological changes indicated by the diatom assemblages in this core, this will be discussed with the characteristics of the zones. A summary of diatom preservation is given in Appendix 5, based upon a subjective assessment made at the time of counting. The core will be described from the base upwards and depths of individual samples refer to the mid-point of that 1 cm sample.

Zone I (1427 - 1400cm) - This zone comprises the bottom three samples from the core and has assemblages consisting mainly of Melosira, Cyclotella and Nitzschia spp. Diatom preservation in the samples was rather poor, so the relative abundances of some of the species may be rather suspect. Except in the bottom sample, where C. stelligera is most abundant, M. granulata is most numerous. Other common species include Cyclotella glomerata, Nitzschia tropica, N. paleacea, M. italica subsp. subarctica and C. placentula var. lineata. The ecology suggested by these species seems rather mixed and the possibility of reworking must be considered. In the tropics, Nitzschia spp. are generally indicative of warm ($>23^{o}$ C, (Gasse, 1977b)), alkaline lakes (Talling and Talling, 1965; Richardson, 1968), rich in nutrients. In contrast, C. stelligera and C. glomerata are usually associated with more dilute, less alkaline waters (Brugam, 1983). Bradbury (1978) discusses the problems of separating these two Cyclotella spp. and feels that misidentification may be the cause of some confusion concerning their ecological preferences. Bradbury feels that both species may be planktonic in eutrophic conditions which was probably the case in Laguna Zacapu. The presence of well preserved Melosira valves in the top of this zone may indicate that this genus was predominant in the lake's plankton at this time, whilst the poor preservation of the other species may indicate reworking.

Zone II (1386 - 1387 cm) - A single sample has been placed

into this zone, both on the basis of species assemblage and preservation. Synedra acus var. neogena (comb. nov.) is dominant and preservation good, unlike the samples on either side. The occurrence of a Synedra plankton appears to be a feature of tropical lakes (Hustedt, 1949; Richardson and Richardson, 1972). The greater abundance of S. acus var. neogena, relative to M. granulata, may indicate higher SiO_2 concentrations than previously, possibly >15 mg/l (Richardson and Richardson, 1972). This level of SiO_2 would be in keeping with the very high present day silica content of the lake (>44 ppm (=mg/l)).

Zone III (1373 - 911.5 cm) - The predominance of Nitzschia paleacea and N. gracilis typifies this zone. Subzones a - k have been identified on the basis of changes in the overall species assemblage and in preservation. The abundance of Nitzschia spp. suggests that the lake remained quite alkaline, productive and warm over this long period. N. paleacea is particularly suggestive of warm water conditions, being euthermal, but it does tolerate wide temperature variations (>15 ^{o}C) (Gasse, 1980). The optimum pH for this species may lie between 7.8 - 8.2 (Cholnoky, 1968).

Preservation in subzone IIIa (1373 - 1327 cm) worsened up core, to the sample from 1365.5 cm. Well preserved valves in this section were of Epithemia, Cymbella and Gomphonema spp. which may indicate shallow water conditions, possibly with abundant aquatic vegetation. The sample from 1365.5 cm was too badly preserved for the count to have much validity and may reflect reworking of the valves under very shallow

water, high energy conditions. N. gracilis became more abundant up through this subzone. The exact taxonomic status of this species seems rather confused (see Lange-Bertalot 1976 and 1980a), but the forms recorded in the Zacapu core seemed quite distinct (Plate 47, figures 12 and 13).

Subzone IIIb (1322 - 1301.5 cm) comprises three samples. In this subzone, Synedra goulardi and S. acus var. neogena are common. S. goulardi is another warm water species (Patrick and Reimer, 1966) and these assemblages may, therefore, indicate consistently warmer, more alkaline (Hustedt, 1949) and silica-rich conditions than had existed previously. The valves of S. goulardi were particularly well preserved and heavily silicified in this subzone.

A quite distinct assemblage occurs at 1297.5 cm (subzone IIIc), with M. granulata dominant (>43%). Common species are N. paleacea, Stephanodiscus/Cyclostephanos sp.1 (possibly S.minutula) and Synedra rumpens var. familiaris. The valves of Nitzschia spp. are mainly broken at this level which may indicate that they were not actually growing at the site during this period. A Melosira plankton probably indicates a brief episode of less alkaline conditions (<1.5 meq/l, according to Richardson, 1968). Although silica probably still exceeded 7 mg/l (Richardson et al, 1978) it may have been less abundant than previously. A freshening and possible deepening of the lake may be indicated.

In subzone IIId (1291 - 1282 cm), although N. paleacea is numerically dominant, the preservation of the diatom

valves may indicate that conditions were not particularly favourable for it. Synedra acus, S. acus var. neogena and S. goulardi are all common in this subzone (5 - <33%). Long valves of these species were intact when long Nitzschia spp. were broken. At the top of this subzone Melosira spp. were also well preserved. Moderately alkaline, fairly nutrient rich conditions appear to have persisted. The increase in M. granulata var. angustissima up core may indicate a slight increase in salinity (Gasse et al, 1983; Grimes et al, 1984).

A sharp decline in Nitzschia spp. has been used to identifiy subzone IIIe (1276 - 1277 cm). M. granulata is most abundant and other common species are M. italica subsp. subarctica, M. af. granulata, N. paleacea, Stephanodiscus minutus and M. granulata var. angustissima. Apart from any relationship to changes in alkalinity, the increase in Melosira spp. may indicate more turbid conditions, needed to keep the valves in suspension. Muddy, turbid conditions are apparently inimical to a Nitzschia phytoplankton (Gasse, 1977b). The occurrence of M. italica subsp. subarctica and S. minutus may reflect rather cool water temperatures (Lund, 1954; Bradbury, 1975). A return to a Nitzschia flora, however, occurs in subzone IIIf (1272 - 1261 cm). S. goulardi is again common and well preserved in this subzone. Between this subzone and the overlying subzone IIIg, two radiocarbon ages are available. These are of 3,590 ± 100 yr BP (OxA-275) (2,600 BP) and 3,970 ± 120 yr BP (2,980 BP), from a small conventional and bulk conventional sample, respectively.

Subzone IIIg, from 1240 - 1182.5 cm, is marked by a numerical predominance of N. paleacea and N. gracilis, but rather poor preservation of these species. Overall, preservation was rather variable, but generally poor at 1220 cm. Some valves of M. granulata, Cymbella and Epithemia spp. and C. placentula var. lineata were, however, well preserved at this level and may indicate shallow turbid, ? well vegetated conditions. S. acus var. neogena was not common in this subzone, although S. goulardi was, in certain levels. A ^{14}C date of 3,800 $\pm$ 100 yr BP (OxA-274) (2,810 BP) was obtained just above this subzone from a conventional preparation.

In subzone IIIh (1172.5 - 1112.5 cm), N. paleacea is dominant reaching 71.85% in the sample from 1132.5 cm. Unlike subzone IIIg, S. acus var. neogena is common. If the ecology of this new combination is more like that of S. rumpens var. neogena than of S. acus var. acus, fairly high pH (>8) (Gasse and Tekaia, 1983), silica rich conditions may be implicated. Towards the top of this subzone (1122.5 cm) few Melosira spp. were recorded, which may also indicate elevated alkalinities (Hustedt, 1949) corresponding to class II of Talling and Talling (1965), with an E.C. from 600 to 6000 $\mu S\ cm^{-1}$. The boundary with subzone IIIi is transitional, with Melosira spp. becoming more abundant. In the sample from 1097.5 cm, at the top of IIIi, valves of N. paleacea and N. gracilis were rather broken, whilst Melosira spp. were well preserved and heavily silicified.

N.paleacea continues to form a major percentage of the assemblages in subzone IIIj (1086 - 1033 cm), although often poorly preserved. A ^{14}C age of 3,040 ± 100 yr BP (OxA-273) (2,050 BP) was obtained within this subzone from 1086 - 1078 cm. Just above this dating sample, Melosira spp. were few. At 1054.5 cm only the long S. acus var. neogena were well preserved, although N. paleacea formed 61.95% of the count. Up core from this, Synedra spp. and some long chains of M. granulata were well preserved. A slightly less alkaline, more turbid lake may be indicated.

In subzone IIIk (1022.5 - 911.5 cm) the preservation of the different species was very variable between samples. This may reflect short term fluctuations in alkalinity, silica abundance, turbidity etc. The preservation of all species in the sample 1002.5 cm was generally poor. At 980 cm, only Melosira spp. were well preserved, with M. italica subsp. subarctica, M. granulata var. angustissima and M. granulata all common. M. italica subsp. subarctica is generally more abundant than it was in previous subzones. Within the period represented by this subzone, there is a brief episode when Melosira spp. decline and N. paleacea and N. gracilis are dominant (934.5 and 923 cm). Preservation of the Nitzschia spp. is good in these levels and suggests conditions favourable to them.

Zone IV (901 - 877 cm) - is marked by a change to assemblages in which Melosira spp. are most abundant (mainly M. granulata and M. italica subsp. subarctica). Preservation amongst many

of the other species was rather poor. This shift may have been caused by a change to less alkaline, cooler conditions. A conventionally prepared sample, between the top of this zone and the bottom of zone V was dated at 2,820 ± 80 ^{14}C yr BP (OxA-272) (1,830 BP).

Zone V (852 - 801.5 cm) - In the lower part of this zone, N.paleacea is again the most abundant species, although Melosira spp., Cyclostephanos sp. and other Nitzschia spp. are also common. Heavily silicified valves of Melosira spp. occur from 839.5 cm to the top of the zone. Preservation was good in the top two samples from this zone although their assemblages were rather different. In the lower sample (814.5 cm), M. italica subsp. subarctica is most abundant, with quite a diverse assemblage. The upper sample, however, (802 cm) has N. paleacea and N. gracilis as dominants (both >33%) with S. acus var. neogena common. Heavily silicified Melosira spp. are still present.

Zone VI (797.5 - 586.5 cm) - The lower boundary of this zone is again gradual, marked by the establishment of assemblages with low species diversity. In subzone VIa (797 - 654.5 cm) N. paleacea is dominant and M. granulata, Cyclostephanos sp., M. italica subsp. subarctica, N. gracilis and Nitzschia tropica common. A ^{14}C age of 2,590 ± 80 yr BP (OxA-237) (1,600 BP) was obtained from 775.7 - 776.7 cm. The low species diversity in this subzone may indicate more chemically-concentrated conditions (Hecky and Kilham, 1973; Hammer et al, 1983). Preservation of the Melosira spp. was

particularly variable. At 701.5 cm, for example, M. granulata was very broken up whilst there were heavily silicifed valves of M. italica subsp. subarctica. The presence of the latter species in what otherwise appears to be a warm water, alkaline environment, is rather puzzling. It may have survived in the bottom sediments when conditions were unfavourable for it to be in the phytoplankton (Lund, 1954). Cyclostephanos sp. becomes more abundant through this subzone. Unfortunately, the absence of this species from the collection of modern Mexican diatoms and the dearth of ecological information on others in this genus, handicap any attempt at palaeoecological reconstruction. At the top of the subzone, M. granulata becomes the dominant species which may indicate that the lake became less alkaline.

The boundary between subzones VIa and VIb has a ^{14}C date of 2,350 ± 100 (OxA-235, conventional preparation) (1,360 BP). Preservation in the lower part of subzone VIb (633.5 - 586.5 cm) was generally poor. Cyclostephanos sp. is most abundant at 623.5 cm and again at 602.5 cm. Variable preservation and species assemblages may indicate lacustrine conditions which were fluctuating both chemically and physically. The high degree of breakage may have resulted from relatively high energy conditions during this period. Breakages became particularly pronounced at the base of Zone VII.

Zone VII (566 - 491 cm) - The boundary between zones VI and VII is marked by a ^{14}C date (conventional sample) of 2,460 ±

150 yr BP (OxA-233) (1,470 BP). In Zone VII M. granulata is often the most common diatom. However, the very poor preservation in the middle of this zone (523.5 - 513 cm) makes the validity of the counts questionable. At the top of the zone, preservation improves, especially of S. acus var. neogena. The valves of Melosira spp., however, were very broken. The assemblages of species in this zone were much as those occurring further down the core, but no clear environmental trend is apparent.

Zone VIII - The sample from 480.5 cm has been placed in a separate zone due to the marked peak in N. palea var. tenuirostris. Valve preservation was also much better in this level.

Zone IX (457.5 - 280 cm) - The base of this zone has been

dated to 2,240 ± 150 ^{14}C yr BP (OxA-231) (1,250 BP) and two subzones were identified within it. Preservation in the lower part of subzone IXa (457.5 - 397 cm) was again poor and the significance of the percentages of species questionable. Above 424 cm, however, M. italica subsp. subarctica becomes the dominant species, often being heavily silicified. Other Melosira spp. (M. granulata and M. granulata var. angustissima) are also more abundant.

The predominance of Melosira spp. is probably a good indication that the lake was less alkaline than previously, with lower pH conditions than previously. M. italica subsp. subarctica continues to dominate in subzone IXb (386 - 280

cm). The abundance of this species, usually found in cool water (Lund, 1954 and 1955; Battarbee, 1984), in this tropical lake is quite surprising, although silica-rich, moderately eutrophic conditions would be favourable to it. In IXb, S. minutus is also common; this species may, again, be indicative of rather cooler conditions. The segment 368 - 378 cm was dated at 2,230 ± 150 ^{14}C yr BP (OxA-229) (1,240 BP). Preservation worsened up the core, with the result that the validity of the count from 323 cm is extremely doubtful. An increasingly turbid, (?) high energy environment may be suggested, especially by the increase in M. granulata var. angustissima (Gasse et al, 1983). The abundance of this variety and of M. granulata var. angustissima fo. curvata (for example at 344 cm) may indicate conditions similar to those for the IIID assemblage of Gasse et al (1983) viz: medium to high E.C. and alkalinity, medium to high pH and varying silica content, in CO_3 - HCO_3 waters. In East Africa, this IIID assemblage is characteristic of closed lakes with low salinity and daily mixing. The present Laguna Zacapu would fit this description well, although N. palea dominates the present-day flora.

Zone X - This zone includes only one sample (258.0 cm) and is distinguished by an abrupt change in flora from that in Zone IX. Unfortunately, the sampling interval here is rather wide due to the removal of the ^{14}C sample from 266- 276 cm. This sample yielded a date of 1,100 ± 90 yr BP (OxA-226) (110 BP). S. acus var. neogena is dominant (>33%) in this zone, with N.

gracilis, M. italica subsp. subarctica, C. placentula var. lineata and Rhoicosphenia curvata common (5 - <33%). The valves of M. italica subsp. subarctica were rather broken up. Increased silica levels or water temperatures may be implicated.

Zone XI (246 - 164 cm) - Two subzones were distinguished within this zone. In subzone XIa (246 - 201 cm), M. italica subsp. subarctica and S. acus var. neogena are generally the most abundant species. C. placentula var. lineata is common at the bottom of the subzone and may indicate aquatic vegetation at the site, although not necessarily shallow water (Jørgensen, 1948; this study). A flora of M. italica subsp. subarctica and S. acus was recorded by Serieyssol (1984) from Lake Pavan, a crater lake in the Massif Central with bicarbonate waters. Seyrieyssol reports surface waters with a pH of 7 - 9, a temperature of 17 ^{o}C in summer and silica values between 7.5 and 24.3 mg/l. This assemblage may also be like the IIIB type of Gasse et al (1983) which they collected from waters of medium alkalinity and pH, of Na - HCO_3 - CO_3 type, with water temperatures reduced by altitude.

The base of subzone XIb (197 cm) seems to indicate a temporary return to more alkaline conditions (N. paleacea being the most common species), although S. acus var. neogena is again most abundant in the next sample.

Zone XII (163.5 - 113.5 cm) - The base of this zone is marked by a ^{14}C date of 1,180 ± 150 yr BP (OxA-224) (190 BP). M. italica subsp. subarctica, S. acus var. neogena and

Cyclostephanos sp. are most abundant in this zone, with Cyclostephanos sp. becoming more important up core. Melosira spp. were generally well preserved in this zone and often occurred in chains. Until the ecology of this Cyclostephanos can be established, it can only be assumed that conditions were similar to those during XIa.

Zone XIII (109 - 93cm) - The assemblages in this zone show a gradual shift up the core. M. granulata var. angustissima becomes dominant by the top of this zone (93.5 cm) with Stephanodiscus subtilis, Synedra goulardi and Stephanodiscus tenuis common, in addition to Cyclostephanos sp. and M. italica subsp. subarctica. As mentioned above, the increase in M. granulata var. angustissima may indicate higher levels of Na in the water, resulting either from surface runoff or from evaporative concentration of the lake waters themselves. S. tenuis (S. hantzschii fo. tenuis of Håkansson and Stoermer, 1984) is also tolerant of relatively high total dissolved solids (T.D.S) and is a diatom favoured by anthropogenic eutrophication (Theriot and Stoermer, 1982). The flora in this zone may indicate a shallowing of the lake. At present, M. granulata var. angustissima is dominant (49%) in La Zarcita, a 1 - 2 m deep pool which feeds into Laguna Zacapu. Both S. tenuis and S. subtilis may occur in shallow/littoral environments (Stoermer and Yang, 1969; Stoermer and Ladewski, 1976).

Zone XIV (82.5 - 5 cm) - The uppermost diatom zone was

distinguished mainly by the abundance of S. subtilis, with S. goulardi (dominant at 15 cm), S. tenuis, Synedra acus var. neogena and M. granulata var. angustissima amongst the common species. A ^{14}C age of 1,190 ± 150 yr BP (OxA-222) (200 BP) was obtained from 64.6 - 74.6 cm. The abundance of small Stephanodiscus species in this zone is probably a clear indication of anthropogenic disturbance, with increased nutrient loadings (Bradbury, 1975; Håkansson, 1976; Carney, 1982; Battarbee, 1984). M. granulata var. angustissima has also been identified as a post-disturbance planktonic diatom by Bradbury (1975). The presence of littoral (Fragilaria pinnata var. lancettula) and epiphytic species (C. placentula var. lineata) indicates the proximity of the lake margin to the coring site. The assemblages from this zone are very similar to those recorded from modern bottom sediment samples and from nearshore aquatic macrophytes (see Table 5.5 and Chapter 5, section 7 for discussion). This would indicate that the lake has been fairly shallow, well mixed, eutrophic and quite alkaline (pH ca 8.3) for at least the last 1000 ^{14}C years (corrected age, 200 years).

6.10e Diatom Abundance

Diatoms were very abundant in the sediments of Zacapu Core 1, ranging from 4.15×10^{8} valves/g (322 - 323 cm) to 2.61×10^{11} valves/g (196 - 197 cm). Figure 6.23 shows the variation in diatom abundance through the core. In view of the role played by valve preservation in determining assessments of abundance, samples where preservation was

classified as poor or unacceptable (see Appendix 5) are shown. The sample from 322 - 323 cm, for example, was in the unacceptable category, so that the estimated diatom content (valves/g), must be treated with considerable caution.

The main feature of the abundance curve is the sudden and enormous peak in diatom numbers occurring between 200 - 100 cm (diatom zones XIb, XII and XIII). Unfortunately, the ^{14}C dates from the conventional preparations (thought to be the most reliable) are rather confused in this part of the core, but suggest that the episode occurred between 1,040 - 1,190 ^{14}C yr BP (about 200 years ago). The uncorrected bracketting lipid dates for the same depth span are 1,080 - 1,640 yr BP. The decline in diatom numbers in the top metre of the core may be less a reflection of falling nutrient levels than of competition from blue-green algae, which can both successfully compete for nutrients and shade out diatoms. Under such circumstances, small diatoms, tolerant of low-light intensities, such as small Stephanodiscus species may be the best effective competitors (Bradbury, 1975). Although M. italica subsp. subarctica is also tolerant of low light levels (Lund, 1954, 1955), its decline in numbers during the period of peak diatom abundance, suggests that other conditions became less suitable for it. In general, Laguna Zacapu seems to have been a favourable environment for diatoms, probably encouraged by the silica-rich waters issuing from the base of the neighbouring basalts. There were few signs of corroded valves in the

samples examined and preservation was probably more dependent upon the amount of mechanical breakage than on chemical processes.

6.10f Summary and Conclusions

Using the dates corrected for the apparent age of the surface sediments, Zacapu Core 1 provides a record of changes in the lake over at least the last 3,000 years. The record is rather complex and apparently 'noisy', in part because of the very high rate of sedimentation. The possibility that some of the species' peaks reflect seasonal pulses, must be considered. The high sedimentation rate is probably largely due to the massive production of diatoms, which is illustrated by the calculation of diatom valves/g sediment (Figure 6.23).

The compilation of summary diagrams helps us to make some generalisations about the changes recorded in the core. As the major genera in the core (Nitzschia, Synedra, Melosira and Stephanodiscus) were probably all planktonic in this tropical lake (Hustedt, 1949; Richardson, 1968; Gasse, 1980) plotting changes in the percentages of species by habitat is not very revealing. Fluctuations in the total percentages of these major genera (Figure 6.24) are, however felt to be significant in view of their known sensitivity to changes in alkalinity (Talling and Talling, 1965; Richardson, 1968), silica availability (Richardson et al, 1978) and turbidity (Gasse, 1977b). In general terms, the periods with Nitzschia spp. dominant are felt to be the most alkaline, possibly warm

and less turbid than others. Melosira spp. probably indicate less alkaline, more turbid conditions, with high levels of available silica. Peaks in Synedra spp. may correspond to the periods of highest silica availability (Richardson et al, 1978).

None of the species represented would suggest oligotrophic conditions in the lake, but the peak in Stephanodiscus spp. (mainly the small species S. subtilis and S. tenuis) is believed to reflect the recent cultural eutrophication of the lake. The earlier Stephanodiscus peak (300 - 400 cm) is due to S. minutus and may indicate a eutrophic, but less enriched lake than the later episode (Bradbury, 1975).

Although there is some controversy over the value of freshwater diatoms as palaeotemperature indicators, plotting the species (occurring at $\geq$2%) by their apparent temperature preferences produces some interesting results (Figure 6.25). The base of the core shows a majority of mesothermal species (temperatures 15 - 30 ^{o}C), particularly Cyclotella stelligera and C. glomerata. The bulk of the core, however, is dominated by euthermal species (warm water, usually >30 ^{o}C) of the genus Nitzschia and M. granulata and varieties. Oligothermal species (cool water, 0 - 15 ^{o}C) show a series of peaks in abundance between about 400 and 140 cm, which overlaps with the beginnings of the 'take-off' in diatom abundance (Figure 6.23). The cool-water diatom curve principally reflects the importance of M. italica subsp.

subarctica in this part of the core.

Drawing together the evidence from sediment chemistry, lipids and diatoms it is possible to attempt to reconstruct the environmental changes recorded in the core. A summary, using dates uncorrected for possible hardwater error, is given in Table 6.5. The base of the core (diatom zone I) may indicate a lake less alkaline than that exisiting subsequently. Gasse et al (1983) suggest that C. stelligera is favoured by Mg^{2+} rich waters. The water issuing from the foot of the basalt lava flows today is high in Mg^{2+} and Ca^{2+} (see Chapter 5) and the inferred persistence of the alkaline earth in the lake waters indicates that there was little evaporative concentration occurring (Eugster and Hardie, 1978). Conditions may have been cooler than at present, or rainfall more evenly distributed through the year. Cyclotella was found to be important in the pre-settlement plankton of Frains Lake, Michigan by Carney (1982).

A long period of more alkaline (probably >1.5 meq/l) and warm conditions ensued (diatom zone III). The predominance of Nitzschia spp. may indicate relatively low turbidity. A possible low stand of the lake is recorded at 1365.5 cm, which, calculated from the average sedimentation rate would correspond to 3,250 yr BP. Periods of Melosira domination during this zone probably indicate less alkaline, more turbid conditions, possibly due to increased surface runoff. The divergent lipid and conventional preparation ^{14}C dates from level 12 (1248 - 1258 cm) are interpreted by Fowler (pers. comm.) as indicating less runoff and low lake

level, with reduced higher-plant input. The diatoms in subzone IIIg would support this interpretation, as would the peak in a number of elements in the sediments at 1189 cm. A further possible episode of low lake level may be recorded at 1002.5 cm.

The lake apparently became fresher and possibly cooler (diatom zone IV), prior to 2,820 ^{14}C yr BP (1,830 BP). Chemical concentration in the sediments also fell in this part of the core to a low at 877 cm (top of diatom zone IV).

A considerable change is indicated by diatom zone VI (*N. paleacea* dominant), where the species diversity was very low. An alkaline, chemically concentrated lake appears to be implicated. The occurrence of peaks in sediment chemistry (e.g. at 775.5 cm) may support this inferrence. Drainage from the lake may have been substantially reduced during this period, enhancing evaporative concentration. This may be the longest sustained low stand represented in the record. A ^{14}C date of 2,590 $\pm$ 80 yr BP (OxA-237) (1,600 BP) was obtained from a conventional preparation in this interval and a greater higher plant contribution is believed to have reduced the divergence between this and the lipid date. Fowler thinks that this higher plant material represents more terrestrial vegetation, more runoff and hence, higher lake level. The diatoms, however, suggest a low lake level and in this subhumid climatic regime a reduction in precipitation, with a lessening of plant cover, would lead to an increase in surface runoff. The latter interpretation, of drier

conditions, is proposed here. The upper part of this diatom zone indicates fluctuating aquatic conditions, although a peak in sediment chemistry may suggest fairly shallow, concentrated waters. The bracketting dates for subzone VIb derived from lipid and conventional preparations show reversals up core.

Less alkaline, and possibly cooler and deeper lacustrine conditions are suggested by the diatoms in zone IX. The date from a conventional preparation at the base of this zone was 2,240 ± 150 yr BP (OxA-231) (1,250 BP). Melosira spp., especially M. italica subsp. subarctica were dominant. Cooler water may have resulted either from increased spring flow or from increased precipitation over the lake during this period. A ^{14}C date of 2,230 ± 150 yr BP (OxA-229) (1,240 BP) was obtained from 368 - 378 cm, in the lower part of this zone. Towards the top of this zone, however, a change in assemblage and poor valve preservation suggest more chemically concentrated and turbid conditions. This interpretation is supported by a minor peak in sediment chemistry. The ^{14}C sample from 266 - 276 cm in this zone, included abundant reed macrofossils, indicating a very low lake level and possibly desiccation. The date from this sample (conventional preparation) was 1,100 ± 90 yr BP (OxA-226) (110 BP).

Above this level, the lake probably freshened again (subzone XIa) before becoming alkaline (? shallower) in subzone XIb. Diatom abundance increased rapidly during this period. The period of deposition of subzones XIb to XII was

also marked by a rapid increase in the levels of the elements determined in the sediments, although the increase in Na was lagged relative to the others. The ^{14}C date from the base of zone XII (166.6 - 176.6 cm) was 1,180 $\pm$ 50 yr BP (OxA-224) (190 BP).

The flora of zone XIII indicates a shallowing of the lake, with an increase in Na levels and greater eutrophication. Increased chemical concentration is also suggested by the sediment chemistry results. The increased rate of sedimentation in this part of the core probably reflects accelerated erosion of the basin slopes, possibly due to anthropogenic influence, although it may have been enhanced by a reduction in vegetation cover due to slightly drier conditions.

The abundance of small Stephanodiscus spp. at the top of the core (zone XIV) is felt to be a clear indication of anthropogenic enrichment of the lake. The decline in the abundance of most of the elements in the sediments, except Na, may indicate that there was less evaporative concentration than during the deposition of zone XIII. The continued washing in of eroded surface sediments may help to explain the sustained high sodium levels at the surface, but is not reflected by other elements thought to be indicative of erosion (Engstrom and Wright, 1984).

Thus, the diatom flora of Zacapu Core 1 provides a clear record of changes in the chemical and physical nature of the lake. These changes, in the lower and middle portions of the core, probably largely reflect the effects of

variations in the climate, through the balance of P - E. Up core, the influence of Man, in this quite densely populated basin becomes more apparent and the top metre appears to be a record of cultural eutrophication. If the age adjustment of -990 years is applied to the ^{14}C dates, this would fall within the post-Hispanic era. The availability of sediment chemistry and radiocarbon and lipid analyses, helps to interpret the diatom record. Considerable emphasis has also been placed upon the variable preservation of particular species, within and between assemblages.

6.11 Conclusions from the Zacapu Basin

It was hoped that by examining lacustrine sediments from both surface sections and from a core, that a broader spatial and temporal assessment of lake level fluctuations would be possible than from the study of a single site. In the event, the extremely rapid rate of sedimentation in the present lake and the erosion of parts of sequences from the basin slopes, meant that parts of the record were missing. The radiocarbon dates from the Brickpit and Zacapu Section 1 clearly show that these sequences are temporally distinct. Although no ^{14}C date is yet available from the bottom of the 14.3 m core, comparison of the fossil diatom assemblages from the top of Zacapu Section 1 (zone V) and the base of the core (zone I) do not suggest an overlap either. The presence of *C. stelligera* in these two zones may, however, indicate that there is only a short period separating the two records.

The Brickpit sequence provides a record of Late Pleistocene conditions in the basin. A deep water episode (M. ambigua dominant) is recorded, prior to 28,100 and possibly before 30,000 yr BP. After this, conditions at the site were of shallow, fluctuating water levels, often with quite abundant aquatic vegetation. The fossil assemblages suggest moderately alkaline waters, pH probably about 8 and are similar to those found today in spring-fed pools and on aquatic vegetation in the basin. Even during the later, shallow water conditions at the Brickpit site, the lake must have stood 15 - 20 m above its present level.

Further evidence for this Late Pleistocene lacustrine phase is available from two sections elsewhere in the basin. At a site near the cemetery, west of the town of Zacapu, an organic clay layer, presumably representing a low lake level, has been dated to 26,100 ± 560 yr BP (OxA-161). The lower part of this section clearly underlies the young-looking basalt flow, although the upper part appears to be plastered on to the front of the lava. A preliminary examination of the diatom species in this section has been carried out. Diatom analyses from here would be extremely interesting and may be undertaken in the future. A peat deposit, overlying lacustrine deposits in a railway cutting north of the town has a ^{14}C date of 28,409 ± 3026 yr BP (Tricart and Rios, unpublished). This peat is believed to have slid downslope to its current position and to indicate a lake level several metres above the present marsh. Tricart and Rios suggest that 28,000 yr BP marks the end of a transgression peaking

before this. Such an interpretation would be consistent with that given for the Brickpit. These authors believe that a col, north of the crater lake Hoya la Alberca (Hoya de Zipimeo) acted as the outlet for the lake during this period. Lake level probably reached about 2,000 m a.s.l., that is about 20 m above present. A lake of this depth would have filled the entire basin, assuming that the topography of the basin was as present. Lacustrine diatomites found through the col are thought to be the result of the pre-28,000 yr BP transgression.

Zacapu Section 1, although at an higher elevation than the Brickpit (34.4 m above present lake level) apparently records part of the Holocene history of Laguna Zacapu. Unfortunately, only one ^{14}C date was obtainable, of 7,330 $\pm$ 70 yr BP (SRR-2256) from 80 cm. The diatom assemblages in this section indicate marked variations in lake depth and salinity. Prior to 7,330, two cycles of lake level rise and fall are recorded. Even though the marsh soil at 80 cm indicates that the lake had receded below the site, this still reflects a lake 35.2 m above present. The S. niagarae assemblage may record the phase of maximum lake depth, just after 7,330 $\pm$ 70 yr BP. The abundance of this species may suggest a quite deep, calm, cool lake, with lower silica content than generally suggested by the diatoms in this basin (Gasse, 1977b). At the elevations implied by a lake with a planktonic flora at this site (probably >2020 m a.s.l.) the palaeolake Zacapu would have occupied an enormous area,

relative to the modern lake . A near neutral pH in the large lake may have led to less silica being in solution and more liable to depletion by diatoms. Silica-rich groundwater may also have played a less important role at this time. A lake of rather different chemical composition from the present and indeed, Late Pleistocene, lakes is also suggested by the shallow water assemblage following the S. niagarae peak. The saline, Cl rich conditions indicated by C. clypeus were not repeated during shallow water episodes represented in the core or Brickpit Section. Tricart and Rios also noted the existence of diatomites at about +40 m relative to the present lake level, but assumed that they were evidence for an ancient palaeolake. If reliable, the Holocene age for Zacapu Section 1 could indicate otherwise.

There appear to be grounds for doubting the validity of the date from Zacapu Section 1. The dating sample itself had a low carbon content and was associated with soil material, so that some contamination may have occurred. With the present-day topography of the basin, a lake at + 20 m above Laguna Zacapu would overflow at several points, in addition to Villa Jimenez. Zacapu Section 1 repesents a lake at at least 34.4 m above present. Such a lake would cover an area extending well beyond the modern drainage basin. In addition, the Cl-rich conditions represented in the upper part of the section, suggest that evaporative concentration of the lake waters occurred, probably due to the closure of the basin. This would be impossible, under current conditions, for a lake at this elevation. Another factor, is

the distinctive flora of this section, which was not found in either the Brickpit or the core. The only other location at which similar assemblages were identified was the Cemetery profile, where the samples predated 26,100 ± 560 yr BP. Whilst it is possible that considerably wetter conditions, during the Holocene, could have resulted in such a large lake (with a flora of large Stephanodiscus spp. and Cyclotella spp.), there does seem reason to doubt it. There is no other evidence, currently available from Zacapu, for such a large Holocene lake; nor does the evidence for this period from other sites in Central Mexico suggest the widespread occurrence of markedly wetter conditions. There are, however, clear indications of a much larger lake, probably dating from before 28,000 yr BP. Work on other surface sections around the basin, may help to clarify the chronology of the events recorded in Zacapu Section 1. In the absence of any firm evidence, however, the ^{14}C date assigning the section to the Holocene, must be accepted for the time being. If this date proves to be accurate, then the most likely explanation for the present elevation of the section is tectonic uplift. Such movement may have been associated with the extrusion of the basalt lava flows (malpaís) on this side of the basin.

As was noted above, there is no obvious overlap between Zacapu Section 1 (assuming it to be Holocene) and the base of the Zacapu core. During the period represented by the core, the lake appears not to have reached the levels indicated by

the surface sections discussed. The abundance of Nitzschia spp. was distinctive of the core. The widespread occurrence, after 3,000 yr BP, of Nitzschia floras in East African lakes earlier dominated by Melosira or Stephanodiscus spp. has been noted by Curtis Stager (1984). Lakes in this category include Victoria, George, Mobutu Sese Seko (Albert) and Naivasha. This change is seen as a response to increasing aridity in the most recent Holocene.

The phase of deepest and coolest water, recorded in the core, seems to have occurred between 1,240 and 110 yr BP (dates corrected for apparent hardwater effect). Unfortunately, the conflicting results from the dating of different organic fractions in the sediments, and the variable degree of influence of 'dead' carbon on these, confuses the establishment of an exact chronology. Lake level seems to have been low on a number of occasions, mainly between 3,000 and 2,000 yr BP; 1,600 and 1,360 yr BP (lowest ?) and at about 210 to 110 yr BP (corrected ages). The earliest period probably reflects a general drying trend over the second half of the Holocene, but the effects of Man and specifically of accelerated erosion leading to increased sedimentation rates and basin infilling, render a simple climatic interpretation of the more recent shallow-water episodes unwise.

In conclusion, therefore, analyses of lacustrine sediments from the Zacapu basin indicate two major lacustrine transgressions: one prior to 28,000 yr BP and, accepting the date from Zacapu Section 1, a second soon after 7,330 $\pm$ 70 yr

BP. Generally low lake levels and presumably fairly dry conditions, seem to have prevailed since the mid-Holocene. The most recent sediments in the basin record the effects of human impact on the lake ecosystem.

Chapter 7

THE UPPER LERMA BASIN

The second lacustrine basin to be investigated was the Upper Lerma,or Toluca, basin lying between the Basin of Mexico and the area including the Zacapu Basin, discussed in Chapter 6. Sediment sequences from two pits dug into the basin floor yielded an environmental record covering the Holocene.

7.1 Geology

The background to the formation of the Upper Lerma basin has been outlined in Chapter 3, section 3b. It is an high altitude (2,575 m), flat-floored basin, surrounded by volcanic highlands (Figure 7.1). It lies between the strato-volcano Nevado de Toluca (Plate 16) and its associated deposits in the west and an extension of the Chichináutzin group in the east. The basin floor covers an area of about 30 km N-S x 10 km E-W, which may be divided into two zones: the eastern half lying at or below 2,600 m and the western half at 2,600 to 2,800 m. The DETENAL 1:50,000 surface geology maps for the area show that most of the basin is infilled with alluvium, but there (that) are extensive areas of lacustrine sediments, mainly in the eastern (lower) half. In the NW of the basin, near the current outlet, there are more clayey deposits.

The volcanic geology of the southern part of the basin has been studied in some detail. Bloomfield (1975) described

the area south and east of the basin i.e. those volcanoes associated with the Chichináutzin group. Bloomfield (1973) and Bloomfield and Valastro (1977) have published on the Tenango Basalt and the tephrochronology of the Nevado de Toluca. More recent work has been carried out by Robin et al (1980). In view of the potential of pumice and ash layers as marker horizons, the main episodes of activity will be outlined below.

The earliest volcanic activity associated with the Nevado de Toluca produced andesitic flows rich in silica. Although thought by Bloomfield (1973) to date from the mid-Tertiary, Robin et al (1980), have now dated this period of activity to 1.5 - 1.2 m.y. ago. This was followed by E - W faulting, with a throw to the north of >100 m which has left a major fault line south of the Tenango basalt. Following a period of dormancy, a series of paroxysmal explosions deposited pumice and ash and formed dacitic domes (63.4 - 66.7% silica). One of these dacite domes is the present summit of the Nevado de Toluca, the Pico del Fraile. Peléan eruptions produced lahars, the last phase of which occurred c. 28,000 yr BP and led to the partial destruction of the summit and the formation of a crater. A Plinean type eruption, dated c. 24,000 yr BP, produced the Lower Toluca Pumice (L.T.P.). A second major Plinean eruption produced the Upper Toluca Pumice (U.T.P.) which is chemically very similar to the dacite lava flows of the volcano. An analysis of the U.T.P. by Robin et al (1980), shows that the main constituents are SiO_2 (60.6%) and Al_2O_3 (17.7%). ^{14}C dating

of four samples of charcoal from beneath the U.T.P. have yielded an average date of 11,280 ± 70 yr BP The U.T.P. covers >2,000 km^2 (Bloomfield and Valastro, 1977) and is probably equivalent to the pomez tripartita de grano fino of the Basin of Mexico. In the Toluca basin itself, the lower member of the U.T.P. is more widely distributed than the upper member and is found as far south as the Sierra de Las Cruces, 50 km from the Nevado de Toluca (see Figure7.1). Bloomfield and Valastro (1977) have constructed an isopach map for this unit. Phreatomagmatic explosions marked the end of this period of activity. Although the main volcano has been dormant during the Holocene, the so-called Tenango `basalt' dates from this period. This `basalt' is actually an andesitic basalt (Bloomfield, 1973). The flows have produced a mesa-like landform which is a distinctive landscape feature in the south-west part of the basin. The archaeological site of Teotenango lies on the edge of this flow. Charcoal rich soil below the Tenango `basalt' has been ^{14}C dated to 8,440 ± 440 yr BP (Tx-1665) (Bloomfield, 1973).

On the east side of the Toluca basin, three volcanoes have produced large quantities (>0.75 km^3) of ash. From north to south these are: Cuauatl, Tres Cruces and Tezontle. Isopach maps for these and other important volcanoes are given in Bloomfield (1975). The lavas, dating from the Late Pleistocene through to the Holocene, all fall in the calc-alkaline field. They are mainly andesitic (52-64% SiO_2), but range from alkalic basalts to dacites. The Tres Cruces

tephra dates from about the same time as the Tenango 'basalt'. ^{14}C dates on palaeosols overlain by the Tres Cruces ash have yielded ages of 8,390 ± 100 yr BP (Tx-1606) and 8,490 ± 90 yr BP (Tx-1609). Bloomfield (1975) suggests an age of <8,440 ± 70 yr BP for the deposit, but as he points out:

> 'the paleosol ages give the maximum age of eruption of the overlying tephra; the actual age may perhaps be 200 years less than this figure'
>
> p.484

No significant volcanic activity has been recorded around the basin over the recent past. There has, however, been some tectonic activity associated with the settling of the basin. This has produced some step faults, near Tres Cruces, with a throw to the north of ca. 2.5 m (Bloomfield, 1975).

7.2 Drainage

The floor of the Upper Lerma (Toluca) basin was formerly the site of a number of lakes. Although standing water now occupies only a tiny area, there are extensive deposits of lacustrine sediments (see above). Former lakes were Chiconauhapan, near Almoloya del Río; Jajalpa; Lerma or Chignahuapan and Capulhuac. The spring-fed Río Lerma rises near Almoloya del Río in the south-east of the basin (Figure 7.1). The Lerma, known as Rombata or Patumbio in the local Matlatzinca language (Piña Chan, 1975) is now mainly canalised and drains out of the basin in the NW, via the Presa Antonio Alzate. The basin has been artificially

drained and there are hundreds of windpumps in the northern, densley populated, half. Some marshland remains, mainly in the south, in the area of L. Chiconahuapan. There is a large aqueduct system built around the eastern margin of the basin, which receives much of its water from wells and springs associated with the lavas to the east. This aqueduct also leaves the basin via the gap in the NW. Although this basin is not hydrologically closed at the present, it is believed to have been so for periods during the Holocene.

7.3 Climate

In general, the climate of the basin is as described in Chapter 3, section 3c. Temperatures are, however, considerably modified by the high altitude of the basin. Climatic data are available from three weather stations in the basin: Toluca (2,675 m), Lerma de Villada (2,578 m) and Almoloya del Río (2,600 m) (García, 1973). The coldest month is January, with average temperatures of 9.5 to 10.2°C. Monthly maximum temperatures range from 14.7 to 15.6°C, increasing with decreasing altitude, as might be expected. The warmest month, however, varies from May (Toluca) to June (Lerma and Almoloya del Río). Average annual rainfall ranges from 800.2 mm to 868.3 mm, falling mainly in the summer months (June - September). The month of maximum rainfall follows the same trend as temperature, being July in Toluca and a month later at the other two stations. Frosts are quite frequent. The summit of the Nevado de Toluca (4,685 m)

supports a permanent snow cap, the extent of which is probably controlled by moisture availability, rather than temperature (Heine, 1973a).

7.4 Archaeology

The abundance of springs and lakes, made the Upper Lerma basin an ideal place for settlement. The lakes, in particular, were an important source of food with fish (pescado blanco), frogs, water shrimp and aquatic birds (Piña Chan, 1975). Before the Spanish conquest, the Toluca Basin, or Valle de Matalcingo, was the most important area in what is now the Estado de México. The basin was particularly heavily populated during the Matlatzinca period and just prior to the Spanish Conquest. The Matlatzincas developed from Otomies who entered the basin in 650 - 750 A.D. (Piña Chan, 1975). The Otomies were a subculture in the final period at Teotihuacán and the Toltecs, Nahuas and Mexicas were part of the same group (see Chapter 3, section 3e). Teotenango, located in the southern part of the basin on the Cerro Tetepetl (the Tenango `basalt'), was built as a major ceremonial centre between 750 and 1162 A.D.. Originally, the occupants of the southern half of the basin were called Teotenancas and those of the northern half, Tolocas. These became known under the common name of Matlatzincas from about the middle of the 13th century (Piña Chan, 1975). From the mid 12th century, a militarisitic element was introduced by Chichimec groups entering the basin. Teotenango became a major centre of this new militarism. During the period of

Aztec military expansion (1474 - 1476 A.D.), Teotenango was made a subject settlement, although not all the Matlatzinca peoples were conquered. In contrast, the Matlatzincas were allies of the Tarascans in Michoacán and would send them extra troops in time of war.

7.5a Palaeoenvironmental Records from the Upper Lerma Basin

Two pits were dug in the floor of the former Lake Chiconahuapan near Almoloya del Río (19°08'N, 99°31'W) (Figure 7.2). This was the highest in elevation of the lakes that once occupied the valley floor. The swampy lake floor now occupies an area of about 23 km^2. The present small, remnant lake, with a pH of 8 and a conductivity of around 720 $\mu S\ cm^{-1}$, is of the $Na\text{-}CO_3\text{-}HCO_3$ type. The flora from this lake is listed in Appendix 3. In the surrounding area there are numerous archaeological sites (Piña Chan, 1975), the most spectacular of which are the pyramids at Teotenango (see section 4).

7.5b Stratigraphy and Sediment Chemistry

The sediments sampled consisted of organic lake muds and peats, with intercalated volcanic tephras. The stratigraphic sequence in the two pits is shown in Figure 7.3. The oldest unit was an 115 cm-thick grey pumice, at the base of Pit 2. This is believed to be the dacitic U.T.P. of Bloomfield and Valastro (1977), dated ca. 11,600 yr BP (see section 1). A petrographic comparison of a sample from 159-160 cm, with

the Cenzina Pumicite de Grano Fino from Tlapacoya in the Basin of Mexico, has confirmed this (Steen-McIntyre, pers. comm.). It had a low organic content and low magnetic susceptibility (Figure 7.4). This pumice was overlain by a thin bed of grey organic mud which marks the establishment of swampy conditions on the valley floor. A ^{14}C date of 8,160 ± 100 yr BP (SRR-2632) has been obtained from this unit suggesting that there may have been an hiatus between the deposition of the U.T.P. and that of this lacustrine unit. The mud is overlain by 65 cm of very dark grey ash. The ash fits the description of the andesitic Tres Cruces tephra (Bloomfield, pers. comm.). The reason for the difference between the ^{14}C age of the underlying grey mud and that suggested by Bloomfield for the Tres Cruces tephra has been given by that author and is cited in section 1. It is, therefore, believed that this unit is the Tres Cruces tephra. The magnetic susceptibility of the tephra was relatively high near the base, but decreases upwards which may be partly because the heavy Fe-bearing phenocrysts tend to settle out first (Steen-McIntyre, pers. comm.). The upper layers of the tephra also appear to have been weathered under subaerial conditions prior to the deposition of the overlying light grey, diatomaceous mud. This mud contained woody fragments, which have been identified as Coniferae (but not Pinus) by the Jodrell Laboratory, Royal Botanic Gardens, Kew. They may have been washed into the site from higher altitudes, a process seen to occur elsewhere in Mexico (Street-Perrott, pers. comm.) The wood fragments were dated to 6,010±70 yr BP

(SRR-2631).

A narrow unit of organic mud overlay the diatomaceous mud. This unit was interrupted at 60 cm by a fine grained yellowish vitric ash, which was marked by a secondary peak in magnetic susceptibility (Figure 7.4). Immediately above the ash, loss-on-ignition (L.O.I.) increased and the magnetic susceptibility declined. Up-profile, however, these trends were reversed and magnetic susceptibility reached 6×10^{-7} S.I. units at the 40-41 cm level. L.O.I. increased once more above 30-31 cm towards a layer of large plant macrofossils at 20-21 cm which resembled the root mat underlying the present day peat surface. Magnetic susceptibility fell to very low levels ($< 1 \times 10^{-7}$ S.I. units) in this macrofossil-rich unit. Charcoal from the peaty sediments at 25-26 cm has been identified as being of pine (Pinus) spp. (Jodrell Laboratory). The macrofossils from 20-21 cm were identified as being the underground stems of herbaceous monocotyledons.

The uppermost stratigraphic unit was peat, becoming fibrous and Sphagnum rich in the top 10-15 cm. In this Sphagnum peat, L.O.I. decreased (although still > 60% at the current ground surface) and magnetic susceptibility increased. These trends may indicate a recent influx of sediment from the basin slopes.

In Pit 1, the basal unit was a dark grey tephra (Figure 7.5) which showed signs of water sorting. Sediment chemistry analyses (undertaken by Dr. F.A.Street-Perrott) show the tephra to be high in Al, Mg, Ca, Fe, Ti, Mn and to a lesser

extent K (Figure 7.5). This ash fits the description of the andesitic Tres Cruces tephra (Bloomfield, pers. comm.). A radiocarbon date of 5,970 ± 180 yr BP (SRR-2255) was obtained from 170-171 cm. This date, however, was believed to be unreliable due to the very low organic content (see section 7.5c). Loss-on-ignition and magnetic susceptibility were high. The tephra was overlain by a thin, reddish layer and then by 22 cm of very dark grey diatomaceous mud. In contrast to the preceeding unit, L.O.I. was high and increased through the unit and magnetic susceptibility was low. Within this unit, Na and, to a lesser extent Fe, showed peaks. A date of 6,960 ± 50 yr BP (SRR-2630) was obtained from the middle of this unit (150-151 cm). A further date of 5,960 ± 60 yr BP (SRR-2254) was obtained from the upper boundary of this unit. These dates are discussed further in section 7.5c on the dating of the pits.

A black, organic mud overlay the grey mud and contained some shells of the snails Physa, Biomphalaria and Succinea. Today, these species are found living on aquatic macrophytes in residual ponds on the basin floor (Street-Perrott, pers. comm.). Magnetic susceptibility and inorganic content were very low at the base of the unit. Although these measurements might suggest stable environmental conditions, the sedimentation rate between the dated levels 140-141 and 130-131 cm (0.37 mm/yr) was nearly twice that recorded elsewhere (see discussion under dating section). Most of the chemical elements were fairly stable, except for Na which showed a marked decline from the previous unit. Above 120-

121 cm, a number of changes occurred which suggest a destabilisation of the environment. Ca, Na and Al increased which may indicate an input of detrital aluminosilicates such as plagioclase feldspar, from the volcanic rocks in the basin. Up-profile, L.O.I. decreased slightly and sand grains were present in the sample from 110-111 cm. This level was dated to 5,880 $\pm$ 50 yr BP (SRR-2629). A slight increase in magnetic susceptibility, Fe and Ti may indicate an influx of primary magnetite and/or ilmentite derived from the Tres Cruces tephra and related volcanics (Metcalfe *et al*, in press). This input of coarser grained material may have been due to an increase in soil erosion from the surrounding slopes.

The fine grained yellowish ash (recorded at 60 cm in Pit 2) was located at 90 cm in Pit 1, where it was marked by a very strong peak in magnetic susceptibility (ca. 11 x 10^{-7} S.I. units) (Figure 7.5). Frequency dependent susceptibility (formerly quadrature susceptibility (Oldfield, pers. comm.)), however, was relatively low suggesting that the ash was not very weathered (Oldfield, pers. comm.). Chemically, the ash showed peaks in Al, Na, Ti, K and Fe (slightly above the ash). A date of 4,570 $\pm$ 70 yr BP (SRR-2253) was obtained on the organic mud immediately below the yellow ash (Figure 7.3). The ash may correspond with the Upper Fine Pumice of the Basin of Mexico which is bracketted by dates of 4,880 $\pm$ 120 and 4,250 $\pm$ 110 yr BP (Limbrey, 1976; Watts and Bradbury 1982).

Lying above the ash was a unit of organic, lacustrine mud, in which L.O.I. increased and magnetic susceptibility decreased. The latter, however, increased markedly above 80-81 cm, as did frequency dependent susceptibility. An influx of mainly silt sized material may be indicated. The 60-61 cm level has been ^{14}C dated to 1,620 $\pm$ 50 yr BP (SRR-2628). At the top of this unit, the sediments became peaty. A ^{14}C date of 1,380 $\pm$ 50 yr BP (SRR-2627) was obtained at 40-41 cm.

The plant macrofossil layer (found at 20 cm in Pit 2) was at 35 cm in Pit 1. A peak in Na and in inorganic content occurred at and just above this layer. A date of 870 $\pm$ 50 yr BP (SRR-2252) from 30-31 cm provided a minimum age for the desiccation suggested by the macrofossils. Sand grains were observed at 25-26 cm and taken with the other evidence may indicate that relatively coarse-grained material was reaching the basin floor during this period of falling lake level. As in Pit2 peat, Sphagnum- rich at the top, formed the uppermost unit. L.O.I. generally increased through this unit except at the very top although as in Pit 2 it still exceeded 60% at the surface. A minor peak in Na was recorded at ca. 10 cm.

7.5c Radiocarbon Dating

A series of ten radiocarbon dates have been obtained from the two Upper Lerma pits to provide both a chronology for the sequences and to assist in their correlation. It was also hoped to obtain some support for the tentative identifications of the tephra layers. These age

determinations were carried out by Dr.D.D.Harkness of the N.E.R.C. Radiocarbon Laboratory, East Kilbride. The reference numbers for the determinations were SRR-2252 to SRR-2255 and SRR-2627 to SRR-2632.

In Pit 2, the dated levels were 144-146 cm and 75-76 cm. The first of these, from lacustrine sediments between the (?) Upper Toluca Pumice and the (?)Tres Cruces Tephra, yielded an age of 8,160 $\pm$ 100 yr BP (SRR-2632). The dating sample from 75-76 cm in diatomaceous mud, was waterlogged wood fragments and was dated to 6,010 $\pm$ 70 yr BP (SRR-2631).

Seven samples have been dated from Pit 1, which were selected to provide a chronology for major environmental changes suggested both by the visible stratigraphy and by the results of other analytical techniques. Radiocarbon samples were submitted from 170-171 cm, 150-151 cm and 140-141 cm to date: the return of lacustrine conditions after the depositions of the (?) Tres Cruces tephra; the peak of the lacustrine transgression and the regression indicated by the diatom assemblages and the boundary between the diatomaceous mud and the overlying organic lake mud. The samples from 140-141cm and 150-151 cm yielded ages of 5,960 $\pm$ 60 yr BP (SRR-2254) and 6,960 $\pm$ 50 yr BP (SRR-2630) respectively. The lower sample underwent stringent decontamination (Harkness, pers. comm.). The date from 170-171 cm, however, was only 5,970 $\pm$ 180 yr BP (SRR-2255). The organic content of this lowest sample, which was taken from within the basal tephra, was very low (4.9%). Only 1.5 g of carbon was recovered and

vertical leaching from the horizons above is believed to have influenced the measured age, resulting in an anomolously young age (Harkness, pers. comm.). Within the black organic mud, an age of 5,580 ± 50 yr BP (SRR-2629) was obtained from 110-111 cm. The level was believed to mark an increase in soil erosion from the basin slopes. A maximum age for the Yellow ash of 4,570 ± 60 yr BP (SRR-2253) was indicated by a date on black mud with occasional macrofossils at 90-91 cm. The 60-61 cm level (black, organic mud) was dated to 1,629 ± 50 yr BP (SRR-2628). The base of the peaty layer and a marked peak in Na were dated at 40-41 cm. The age, of 1,380 ± 50 yr BP (SRR-2627), provided the younger bracketting date for the second lacustrine episode indicated by these sequences. An age of 870 ± 50 yr BP (SRR-2252) was obtained from the plant macrofossil layer at 30-31 cm, indicating complete desiccation at the site.

On the basis of the ^{14}C chronology, it was possible to investigate changes in the rate of sedimentation over time. Age/depth relationships for the two pits are shown in Figure 7.6. The calculated rates are listed in Table 7.1. In Pit 2, the scarcity of dates renders such calculations rather speculative, especially as the two dates available lie below and above the (?) Tres Cruces tephra. More reliable calculations may, however, be made for Pit 1. Calculated rates of sedimentation (excluding any allowance for breaks in the depositional record) range from 0.01 to 0.37 mm per year. The rate was low in the diatomaceous mud (0.01 mm/year) but showed a very rapid increase (0.37 mm/year)

between 140-141 and 110-111 cm. Whether this reflected a particularly accelerated rate above 120-121 cm or applied to the whole period, is unclear. The rate of sedimentation slowed considerably between 110-111 cm and the yellow ash at 90-91 cm (0.15 mm/year). The radiocarbon dates from 90-91 cm and 60-61 cm yield a sedimentation rate of only 0.01 mm/year. This appears to provide some support for the idea that there was an hiatus in lacustrine deposition at, or just after, the time of deposition of the yellow ash. Further dating will help to clarify this. The upper part of this unit had a calculated sedimentation rate of 0.08 mm/year. The rate increased rapidly, however, (0.2 mm/year) during the period of desiccation and input of coarse sediments. The sedimentation rate of 0.34 mm/year calculated for the top of the profile assumed that no sediment had been lost and may well be unrealistic.

7.5d Diatoms

Diatom samples were prepared at 5 cm (Pit 2, Figure 7.7) and 10 cm (Pit 1, Figure 7.8) intervals, by the method given in Chapter 4. The results for each level are expressed in percentage terms. Only diatoms occurring with an abundance $\geq$ 2% are shown on the diagrams. The diatom record from each pit will be presented by stratigraphic unit, in the framework of the diatom zones suggested in Tables 7.2 and 7.3. Reference to species as 'dominant' or 'common', follows the terminology of Gasse et al (1983), where dominant species $\geq$

33% of the count and common species 5 - < 33%.

7.5di Pit 2

Zone 1 -The stratigraphic unit at the base of Pit 2 is believed to be the oldest of those sampled in Upper Lerma. The preservation of the diatoms in the tephra , thought to be the Upper Toluca Pumice, was generally poor, with most of the valves being broken up. An attempt at environmental reconstruction may, however, be made although the possibility that the diatoms may have been reworked, must be considered. The two samples within this unit (159 - 160 and 155 - 156 cm) form Zone I (Table 7.2). Cocconeis placentula var. lineata is most abundant, with other common species being Melosira italica, Epithemia turgida, Hantzschia amphioxys, Nitzschia amphibia, Caloneis bacillum, Rhopalodia gibberula (type 2), Diploneis pseudovalis and Pinnularia viridis. These are mainly shallow water and epiphytic species. C. placentula var. lineata is usually epiphytic on higher plants (Jørgensen, 1948) as are species of Epithemia and Rhopalodia. H. amphioxys is an aerophilous diatom (Hustedt, 1930a). M. italica is mainly littoral (Gasse, 1980) as is N. amphibia (Hustedt, 1930a) although the latter species may also be found in the plankton of tropical lakes. The assemblage is indicative of shallow, fairly alkaline water, with a pH > 8 (Cholnoky, 1968) and abundant aquatic vegetation. Within the organic mud (150 - 151 and 145 - 146 cm) (Figure 7.7), M. italica becomes more abundant (Zone Ib). This taxa has been recorded as two forms, one of which may represent a marsh or

stress form (Bradbury, pers. comm.) (see Plate 17, figures 13 and 14 and Chapter 4, section 7b). The occurrence of this form and of many aerophilous and soil species, including H. amphioxys and Navicula mutica (Hustedt, 1930a; Hustedt, 1937-39) suggests very shallow water conditions. The upper part of this unit was dated to 8,160 ± 100 ^{14}C yr BP (SRR-2632).

Zone II -Melosira italica is dominant in the sample from 140 - 141 cm at the base of the dark grey ash (Tres Cruces Tephra). Eunotia bigibba var. pumila and E. naegeli are common. This assemblage may indicate very dilute waters (Gasse, 1980) and with the occurrence of Fragilaria species may suggest nutrient-poor conditions relative to the preceeding levels. This level has been classed as Zone II. No diatoms were present in the middle section of the tephra between 135 -136 and 95 - 96 cm. This is not surprising as the tephra is of the air-fall type.

Zone III - The diatom record resumes near the top of the tephra, where the assemblages are dominated by Fragilaria species (especially F. pinnata var. lancettula). The predominance of Fragilaria spp. within the tephra may reflect the ability of this genus to survive in a minerogenic environment, where nutrients are available only from inorganic sources (Haworth, 1976). At 85 - 86 cm (Figure 7.7), the valves are very broken up, with strong signs of dissolution and/or weathering. It is likely that this marks a brief hiatus in sedimentation with reworking of older

deposits. The upper part of Zone III includes the diatomaceous mud overlying the tephra. F. pinnata var. lancettula was dominant in the sample from 75 to 76 cm, with F. pinnata, F. construens var. venter and F. brevistriata common. At 70 to 71 cm, additional species present at 5 - < 33% were N. amphibia, Synedra fasciculata var. tabulata and Fragilaria construens. Reports on the ecology of Fragilaria spp. have been very varied, both in terms of its habitat (c.f. Stockner and Benson, 1967 and Haworth, 1976) and its nutrient significance (c.f. Jørgensen, 1948 and Patrick and Reimer, 1966). The association probably represents fairly shallow (1 to 3 m) water (Bradbury, 1979), slightly alkaline and possibly oligotrophic or mesotrophic (Gasse, 1980). In samples of the modern flora, F. pinnata var. lancettula was common at two sites in the Zacapu Basin, Tarejero and Bellas Fuentes. These are both spring-fed pools and would probably fall into the mesotrophic to eutrophic category. The upper part of Zone III probably marks a period of lake-level rise, although the water at the site of Pit 2 was not deep. A ^{14}C date of 6,010 $\pm$ 70 yr BP (SRR-2631) was obtained within this diatomaceous unit. Pieces of wood, originally thought to be from drowned shrubs, were found in this unit. These have now been identified as fragments of Coniferae (not Pinus) which may have been washed into the site.

Zone IV - In Pit 2, the black organic mud was extremely thin and was represented by only one sample (65 - 66 cm). The

assemblage from this level was unusual, hence its distinction as Zone IV. Melosira distans var. africana (see Plate 17, figures 18 and 19) was the most abundant species (31%) with F. construens var. venter common. This Melosira species was not found anywhere else in this profile, nor in Pit 1. It was not present in any of the samples from the modern diatom collection either. In tropical Africa (Gasse et al, 1983), M. distans var. africana is characteristic of warm, dilute, neutral to slightly acidic, riverine swamp environments. Such conditions would be consistent with an high precipitation regime which produced well vegetated conditions in the basin, with abundant surface runoff, but low sediment yields.

The deposition of the yellow ash, dated at 4,570 $\pm$ 60 yr BP (SRR-2253) in Pit 1, was probably followed by an hiatus in sedimentation. As this proposition is based upon ^{14}C dates obtained from Pit 1 sediments, it will be discussed more fully below. In Pit 2, the organic mud overlying the ash has been divided into diatom zones V (60 - 61 cm) and VI (55-56 to 24-25 cm). These may form part of a continuous sequence, but there appear to be sufficient floristic differences to justify the separation of 60 - 61 cm from the others.

Zone V -In this zone, the aerophilous species H. amphioxys is most abundant, with Achnanthes hungarica, N. amphibia and Eunotia curvata common. The assemblage is ecologically rather mixed, N. amphibia having an optimum development at pH > 8.5 and tolerating quite high, but variable, salinities,

whilst E. curvata develops best at pH below 7 (Cholnoky, 1968). The occurrence of a number of Gomphonema species (including G. angustatum, G. parvulum and G. gracile) may indicate intermediate pH values of ca. 7.5 (Cholnoky, 1968). This genus may be periphytic (Gasse, 1980) or epiphytic (Jørgensen, 1948). Overall, the assemblage suggests shallow or very shallow water conditions, possibly with considerable fluctuations in water chemistry on short spatial or temporal scales.

Zone VI - This is dominated in turn, by the species C. placentula var. lineata, Melosira ambigua and N. amphibia and appears to represent an upwardly transgressive sequence. In subzone VIa, in the sample from 55 - 56 cm, C. placentula var. lineata is dominant with C. placentula, Pinnularia viridis and Rhopalodia gibberula (type 2) common. As both Cocconeis species and Rhopalodia gibberula are epiphytic, this suggests that there was abundant aquatic vegetation at the site. P. viridis has a preferred habitat of very shallow water near springs or marshes (Hustedt, 1930a) but unlike many others of this genus will tolerate a wide range of pH, up to and above 8 (Cholnoky, 1968). At 50 - 51 cm, the common species occurring with C. placentula var. lineata are N. amphibia, M. ambigua and Amphora veneta. The occurrence of the planktonic M. ambigua (Lowe, 1974) probably suggests that the water was becoming deeper at the site.

The continuation of this deepening trend is indicated by the assemblages in subzone VIb where M. ambigua is the

most abundant species. M. ambigua is common in the plankton of East African lakes (Richardson, 1968; Richardson and Richardson, 1972; Gasse et al, 1983) where it is most abundant in lakes in Talling and Talling's (1965) class I type, with pH 7 to 8.7 and E.C < 600 µS cm^{-1}. pH may be a more important factor than alkalinity in determining whether this species, or Nitzschia species, dominate the plankton. The lake waters may also have been quite turbid to support M. ambigua in the plankton (Hutchinson, 1967; Bradbury, 1975). This turbidity may have been due to an influx of sediment from the basin slopes as indicated by the mineral-magnetic measurements and by the increase in the inorganic content of the sediment. An increase in abundance of M. ambigua when erosion due to land clearance increased nutrient loading was also reported from Minnesota by Bradbury (1975). N. amphibia which was common in this subzone (VIb), is known from plankton collections in tropical lakes (Huber-Pestalozzi, 1942). Cyclotella meneghiniana, which also occurs in all the samples from this zone, is facultatively planktonic (tychoplanktonic) (Hustedt, 1930b). Unlike most other Cyclotella species, C. meneghiniana is indicative of eutrophic conditions (N-heterotroph according to Cholnoky, 1968). High amounts of dissolved organic matter may also have contributed to the appearance of N. amphibia in the plankton (Bradbury, 1979). The episode of deepest water conditions was probably recorded at 40 - 41 cm.

In subzone VIc, N. amphibia is more common than M. ambigua. This may have been the result of increasing

alkalinity, possibly due to the evaporative concentration of the water as lake level fell. Richardson (1968), following Hustedt (1949), indicates a shift from a Melosira to a Nitzschia plankton at alkalinities > 1.5 meq/l. Nitzschia also predominates where E.C. lies between 600 and 6000 $\mu S\ cm^{-1}$ (Talling and Talling (1965), group II). However, in the uppermost sample of this zone (24 - 25 cm), N. amphibia, although dominant, is accompanied by F. construens var. venter and F. construens as common species (with M. ambigua). This indicates that the water was considerably shallower, less alkaline and less nutrient-rich than in subzone VIb. The increase in abundance of N. amphibia may, therefore, represent a fall in water level and the occurrence of this species in the littoral, rather than in the plankton. It appears that this drop in water level occurred during the period when coarser material was being washed down onto the basin floor. Using the ^{14}C dates from Pit 1, this episode of lacustrine expansion took place between ca. 4,500 and 1,400 yr BP.

Complete desiccation of the lake, occurring soon after 1,380 $\pm$ 50 yr BP (from Pit 1) seems to be indicated by plant macrofossil layers in both pits. Diatom preservation was poor in these layers. In Pit 2, diatom zone VII includes the two samples from just below (20 - 21 cm) and just above (10 - 11 cm) this layer. No countable diatoms were preserved in the sample from 15 - 16 cm. The shallowing of the lake does not appear to have resulted in more alkaline conditions as

F. construens was dominant and F. construens var. venter common. This may have been due to the removal of ions from the water by aquatic vegetation. Sphagnum is known to be particularly effective in this process (Richarson and Richardson, 1972) and Sphagnum peat forms the uppermost unit of both pit profiles. In this zone, the Fragilaria flora probably does indicate nutrient-poor conditions. The occurrence of species indicative of more alkaline conditions (N. amphibia, C. placentula var. lineata) below the macrofossil layer, probably reflects the last vestiges of the larger lake. In a study of an high altitude bog in Ethiopia, Gasse (1978) suggested a cycle from marshy, alkaline conditions, rich in aquatic plants to drier, more acid conditions through the growth of peat bog. The growth of the bog (Sphagnum) raises the habitat of the diatoms above the level influenced by surface runoff, leading to a flora of acidophilous and aerophilous diatoms. The oxidizing and acidic environment within the bog encourages the dissolution of the siliceous diatom valves. The upper part of Zone VII may represent an early stage in this process as peat developed at the site of the Pit. The completion of the cycle, with wetter conditions raising the local water table to reintroduce more alkaline, more nutrient-rich conditions seems to be indicated by the diatoms in Zone VIII at the top of the profile. Renewed flooding probably occurred.

Navicula heufleri var. leptocephala is most abundant at 5 - 6 cm and Rhopalodia gibberula (type 2) at 0 - 1 cm (although this species is also common at 5 - 6 cm).

Denticula elegans, a marsh diatom (Bradbury, 1979) and Hantzschia amphioxys are also common in both samples. In the uppermost sample Nitzschia palea, a diatom often associated with anthropogenic influence (Lowe, 1974), becomes quite abundant. This flora indicates a fairly shallow, possibly lake margin or pond environment, quite alkaline and rich in aquatic vegetation. A considerable seasonal variation in water depth may be indicated. The abundance of H. amphioxys may, however, indicate an influx of sediment onto the basin floor, in the recent past. The final, artificial, drainage of the lake does not appear to be recorded.

7.5dii Pit 1

The diatom record from Pit 1, although far better dated, is unfortunately more patchy than that from Pit 2. As for the second pit, a series of zones have been identified, but only have any real coherence above the yellow ash. The zones are identified in Table 7.3. No diatom record is preserved in the (?) Tres Cruces tephra at the base of the Pit (Figure 7.8), although it appears to be water sorted. The reddish layer at the top of this bed may represent an hiatus contemporaneous with that recorded at 85 - 86 cm in Pit 2, but could be a product of diagenesis. The ^{14}C dates currently available suggest that this episode occurred around 7,000 years ago. In Pit 1 the diatomaceous mud overlying the tephra provides a less condensed record of lake transgression and regression than that preserved in Pit 2. Although the

assemblages are very varied, the samples within this unit have been grouped together as Zone I.

Zone I -At 160 - 161 cm, Melosira italica and H. amphioxys are common. The abundance of Pinnularia and Eunotia spp. at this level may indicate a shallow marsh, with circum-neutral pH (Patrick and Reimer, 1966). H. amphioxys is a species which is found over a wide range of pH (5.5 to 9.2) with an optimum at about 7 (Cholnoky, 1968). The water was probably very dilute (Gasse, 1980) and the marsh may have been fed springs emerging from the volcanics around this part of the basin.

At 150 to 151 cm (dated to 6,960 ± 50 yr BP (SRR-2630)), a marked deepening and chemical concentration of the lake is indicated. Cyclotella meneghiniana, Melosira granulata var. angustissima and Gomphonema parvulum all become common. The planktonic Stephanodiscus niagarae and S. subtilis (Huber-Pestalozzi, 1942) also occur. The water was probably quite alkaline with a pH of 8 to 8.5 (Cholnoky, 1968). More alkaline conditions are also suggested by the decline in the percentage of Eunotia and Pinnularia species. The fluctuations in the percentage of taxa indicative of neutral to acidic pH values (from Gasse, 1978) are shown in Figure 7.9. A peak in Na in the sediments at this level may also indicate quite elevated salinities, possibly on a seasonal basis. Such fluctuations would be in keeping with the predominance of C. meneghiniana (Cholnoky, 1968). The association of M. granulata var. angustissima with Na rich

waters has been noted by Gasse et al (1983). The Fragilaria assemblage in Pit 2 (Zone III) at this time, indicates that Pit 1 was closer to the locus of deepest water. A possible analogue, but on a much larger scale, is provided by Lake Ziway-Shala, Ethiopia, where during the early and mid-Holocene Melosira-Stephanodiscus- Cyclotella assemblages in mid-lake corresponded to a Fragilaria dominated flora in the swampy, marginal embayments (Gasse, pers. comm., cited in Street, 1979).

A marked change, however, is indicated by the assemblage at 140 -141 cm (in Pit 1). H. amphioxys is most abundant and Rhopalodia gibberula (type 2), Navicula mutica, C. placentula var. lineata and Caloneis bacillum are common. The presence of aerophilous species such as H. amphioxys, N. mutica and Pinnularia spp. (Gasse, 1980) indicates a distinct fall in water levels and less alkaline conditions (Figure 7.9). The return of Pinnularia species may again be the result of spring input to the basin, which becomes more noticeable in the record during periods of low lake level. A similar pattern of high lake levels being alkaline and low lake levels fresh, has been recorded by Bradbury (1971) from L. Texcoco in the Basin of Mexico. This shallow water stage, in Upper Lerma, has been dated to 5,960 $\pm$ 60 yr BP (SRR-2254).

The diatomaceous mud passed up into black, organic mud (135-136 to 95-96 cm). Within this mud, no diatom record was preserved. Only a few valves were found and these were almost all broken and showing signs of dissolution. The reason for the very poor preservation of the valves in this

part of the section is, as yet, uncertain, but may be associated with a deficiency of silica, or with the very rapid sedimentation rate indicated for the lower part of the unit. Above 110 - 111 cm, however, (dated at 5,880 ± 50 yr BP) the first major input of clastic sediments from the basin slopes seems to be suggested. It is not yet possible to determine whether the cause was climatic or anthropogenic. Fragments of valves of Pinnularia spp., including the aerophilous P. borealis (Lowe, 1974) and H. amphioxys may be indicative of shallow water/swamp conditions at this time. Such an interpretation would be in keeping with that proposed for Zone IV in Pit 2 where this unit is represented by a M. distans var. africana and F. construens var. venter assemblage. The absence of a planktonic flora from both these records may indicate that L. Chiconahuapan was draining freely northwards and out of the basin as a whole at this time. It is possible that the drainage had been impeded by the deposition of the Tres Cruces tephra and that the wetter period recorded particularly in Pit 1, led to the breaching of this obstruction.

As in Pit 2, the diatoms above the yellow ash in Pit 1 also indicate a cycle of lake-level rise and fall. Zones II, III and IVa and b have been delimited, mainly on the basis of variations in the common (5 - <33%) species, although these boundaries are rather artificial.

Zone II - is the sample from 80 to 81 cm where C. placentula var. lineata is most abundant (24%) with H. amphioxys and M.

italica common. The occurrence of many other commonly epiphytic species such as G. parvulum, Achnanthes hungarica and Rhopalodia gibba var. ventricosa (Jørgensen, 1948) indicates shallow or marsh conditions with abundant vegetation.

Zone III - The assemblages in Zone III are very diverse. N. amphibia is most common in both the samples included, but forms only 9.8% of the count at 70 to 71 cm and 8.2% at 60 to 61 cm. Other common species at the lower level are C. placentula var. lineata, Eunotia flexuosa and G. parvulum. At 60 to 61 cm E. flexuosa is also common, with N. palea and R. gibba var. ventricosa. The occurrence of the planktonic M. ambigua and the tychoplanktonic C. meneghiniana may indicate deeper water conditions somewhere near this site. However, N. palea, Rhopalodia gibba var. ventricosa and Synedra ulna may all be epiphytic on higher plants (Jørgensen, 1948) and indicative of shallow (? lake margin) conditions (Gasse, 1980). The water was probably quite eutrophic as indicated by G. parvulum (Carney, 1982), N. palea (Lowe, 1974) and S. ulna (Gasse, 1980).

The decline in the number of sponge spicules per 100 diatoms from 80 - 81 cm , up the profile, may indicate increasing turbidity in the water, as suggested for M. ambigua in Pit 2. The 60 - 61 cm level, dated at 1,620 ± 50 yr BP, may correspond to the lacustrine peak recorded at 40 - 41 cm in Pit 2. It is interesting to note that during this episode Pit 2 was closer to the area of deepest water than

Pit 1 (cf. the record from the diatomaceous mud above the dark grey (? Tres Cruces) tephra). This suggests a basin configuration more like the present, with the Pit 1 site closer to the basin margin. The renewed ponding up of water may actually indicate a decrease in precipitation compared with the interval between about 6,000 yr BP and the deposition of the yellow ash, causing a reduction in outflow, or be due to tilting or downwarping of the basin floor.

Zone IV -Diatom subzone IVa appears to record the fall in water level after the lacustrine phase. C. placentula var. lineata is most abundant (22.7% in 50 - 51 cm and 30.4% at 40 - 41 cm) with Epithemia adnata var. proboscidea common in both samples. M. ambigua is also common in 50 - 51 cm, suggesting the final stages of higher water levels. At 40 - 41 cm, the other common species are Cymbella lanceolata and G. parvulum. These assemblages are dominated by epiphytic species (Jørgensen, 1948) which develop best in waters with a pH of about 8 (Cholnoky, 1968). The ^{14}C date of 1,380 $\pm$ 50 yr BP from this level provides an upper bracketting date for the second period of lake expansion recorded in the two pits.

In subzone IVb, C. placentula var. lineata continues to be abundant, although in the uppermost sample (10 - 11 cm) F. construens var. venter is dominant. A layer of macrofossils occurring at 30 - 31 cm indicates that the site was dry at that time. A Na peak was recorded at this level and is probably associated with a maximum of clastic input. This corresponds to the first appearance of N. palea in

significant numbers and is probably an indicator of human impact on the basin (Schuette and Bailey, 1980). Bracketting dates of 1,380 ± 50 and 870 ± 50 yr BP place this appearance of N. palea within the main period of temple construction at the site of Teotenango (see section 7.4). Such building and the associated expansion in farming activity around the basin would also account for the increase in clastic material reaching the basin floor. The presence of more Cymbella and Gomphonema species, such as C. minuta var. silesiaca and C. lanceolata may suggest a decline in the nutrient content of the water (Jørgensen, 1948). An increasing abundance of Fragilaria construens var. venter moving towards the topmost peat unit, would support this suggestion (Patrick and Reimer, 1966). The relationship of a F. construens + F. construens var. venter assemblage to trophic status and in particular to peat growth, has been discussed above.

The assemblage from 10 to 11 cm is very similar to that recorded from the present remnant lake (F. construens var. venter + C. placentula var. lineata = 45%). Unfortunately, no count was possible from 0 - 1 cm in this Pit and it seems likely that the upper part of the sequence (Zone VIII in Pit 2) has been lost, possibly through recent shrinkage and deflation of the peat following the drainage of the basin.

7.5d iii Diatom abundance and Preservation

As a known dry weight of sediment was used in the preparation of all samples (0.1 g), it was possible to

calculate the number of valves/gram sediment, using the number of diatoms recorded in a traverse average. The results for Pits 1 and 2 are plotted in Figure 7.10. Abundance in Pit 2 varied from 1.03×10^6 valves (10-11 cm) to 4.03×10^8 valves (75-76 cm). In Pit 1, the figures were 6.09×10^5 valves (90-91 cm) to 5.19×10^8 valves (20-21 cm). Clearly, the calculation of these figures was greatly affected by the state of preservation of the valves in a particular level. In Pit 2, preservation was relatively poor in the U.T.P. and in the shallow water deposit above. Diatoms were absent from much of the Tres Cruces tephra. Preservation was generally good from the diatomaceous mud at 80-81 cm up to the yellow ash, where most of the valves were broken. Above the ash, preservation was variable, but generally rather broken, to the top of the profile. 15-16 cm was almost devoid of diatoms. Preservation might have been more of a problem in Pit 1 where the valves were generally lightly silicified inspite of the silica rich volcanics in the catchment and rather broken. Only in 140-141 cm could preservation be described as good.

Inspite of the difficulties inherrent in such a subjective assessment of abundance, a comparison of the two graphs shows consistent trends. The diatomaceous muds above the Tres Cruces tephra are marked by peaks in abundance in both Pits. This may be associated with the silica made available from the tephra (52-64% SiO_2). Above the yellow ash, too, both profiles show an increase in abundance, although this is more marked in Pit 1 than in Pit 2. The

rather compressed nature of the upper part of Pit 2 makes it difficult to compare trends in abundance in this section of the profiles. Inspite of the very poor state of preservation of the valves in the peaty mud above the macrofossil layer in Pit 1, diatoms are clearly more numerous there than in Pit 2. The base of recent peat growth, however, is marked by an absence of countable valves in Pit 2 and by a sharp decline in the number preserved in Pit 1. This is probably due to increased dissolution with greater pore-water circulation. Preservation improves and abundance increases again in Pit 2 and it is possible that this very top part of the record is missing from Pit 1. This may have been the result of a more complete desiccation and erosion or deflation at the site of this Pit.

7.5e Comments on the Diatom Species

A wide variety of diatom species were found in these sediments, although preservation was often poor (see above). There are no modern analogues within the basin, at the present day, for the deeper water episodes. The modern diatom collection from Mexico has provided floras similar to those believed to indicate shallow, slightly alkaline conditions with both *Fragilaria* and epiphytic rich assemblages. No samples were collected, however, which were rich in *Pinnularia* spp or with *M. distans* var. *africana*. This presents something of a problem in interpreting assemblages that are thought to represent neutral to slightly

acidic water conditions.

7.5f Chrysophyte Cysts

Chrysophyte cysts, the siliceous resting spores of golden brown algae, occurred in considerable numbers in both Pits 1 and 2. In the course of carrying out the diatom counts, a record was also made of the number of cysts encountered per 100 diatom valves. These results have been plotted up in Figure 7.11. Two major morphological types were found: smooth spheres and with marked spines (see Plate 50). Collars were distinct in all cases. Although not identified any further, the relative abundance of cysts may provide an additional environmental indicator.

A comparison of the curves of number of cysts/100 diatoms with that for the total % of a number of neutral-slightly acidic indicator species (Eunotia spp, Pinnularia spp, Diploneis spp (excluding D. pseudovalis) and M. distans var. africana) (Figure 7.9) shows an interesting correspondence. Cysts appear to have been most abundant during periods when the diatom flora suggests marsh or shallow, lake margin conditions at the sites, with low to moderate pH. They were abundant, for example, at 65-66 cm and 55-56 cm in Pit 2. They were not common when shallow, but more alkaline conditions prevailed, as at 140-141 cm in Pit 1. Numbers also decline during deeper water phases. This would be in keeping with the finding of Adam and Mahood (1981). The authors also point out that some winter freezing also encourages cyst development. The high altitude of the

Upper Lerma (Toluca) basin, with >80 frosty days/year (Plan Lerma, S.A.R.H., 1966) may well account for the abundance of cysts in this record in comparison with that from the Zacapu basin. Zacapu, at the lower elevation of 1,988 m a.s.l. has only 30-40 frosty days/ year. In Upper Lerma, during the winter, even average temperatures are close to the 10°C optimum for vegetative growth and spine and collar development suggested by Sandgren (1983).

It is interesting to speculate whether the cysts may contain some palaeotemperature record. If the lower part of the black mud does indeed represent an high rainfall, stable environment at ca. 6,000 yr BP, with shallow, marshy conditions, then the absence of cysts might be the result of higher temperatures. Diatoms were not preserved between 135-136 and 90-91 cm in Pit 1 and no cysts were seen between 135-136 and 110-111 cm. Above this level, however, cysts became very abundant up to the yellow ash, inspite of the continuing scarcity of diatoms. In Pit 2, the cysts show a similar increase in numbers up to the yellow ash. A peak in temperature and precipitation at ca. 6,000 yr BP, followed by a decline, would not be at variants with current ideas concerning orbital parameter changes and variations in solar radiation (e.g. Kutzbach, 1983; Kutzbach and Guetter, 1984; Kutzbach and Street-Perrott, 1985).

7.6 CONCLUSIONS

Sediment sequences from two pits in the Upper Lerma

(Toluca) basin provide a record of environmental change over approximately 11,600 years, for an high altitude site in the tropics. A series of fluctuations in water levels and changes in water quality, are recorded. Some of these fluctuations have been presented in a simplified, graphical form in Figure 7.12 a and b. These graphs were constructed using published habitat (Figure 7.12a) and pH preference (Figure 7.12b) data. The curves represent the % of species within a sample falling into each category. Episodes of increased sediment influx onto the basin floor also appear to be indicated, possibly due to the impact of Man. The major events recorded in the pits are as follows:

1) A period of lacustrine deposition in shallow water, with abundant aquatic vegetation suggested by the presence of many epiphytic diatom species. This occurred after the fall of the Upper Toluca Pumice (ca. 11,600 yr BP) and has a ^{14}C date of8,160 $\pm$ 100 yr BP. After this date, the water may have become slightly deeper. This episode is recorded only in Pit2.

2) The deposition of the Tres Cruces tephra ca. 8,400 yr BP. At the site of Pit 2, this led to a reduction in epiphytic species and less alkaline water conditions. The upper part of the tephra is weathered. Shallow (1-2 m) water depth is indicated by a Fragilaria dominated flora with epiphytics such as C. placentula var. lineata and Cymbella lanceolata. No diatom record was preserved in what is, probably, the top of the Tres Cruces tephra at the base of Pit 1.

3) A possible hiatus at the top of the Tres Cruces tephra is suggested by the weathered nature of the tephra and broken up

valves in Pit 2. This may also be marked by the reddish stained layer in Pit 1.

4) Lacustrine deposition was resumed prior to 6,960 ± 50 yr BP, with a transgressive diatom sequence. Pit 1 was closer to deeper water at this time but the lake may have spread out to reach the site of Pit 2 by 6,010 ± 70 yr BP. Diatom abundance in Pit 2 reaches its peak during this period. Water levels probably fell again quite rapidly and this lake episode was over by 5,960 ± 60 yr BP.

5) The interval between 5,960 ± 60 and 4,570 ± 60 yr BP may also have been wetter than present, but the absence, from Pit 1, of a diatom record for this episode, makes this interpretation somewhat speculative. In the upper part of the black mud there are signs of environmental disturbance and increased soil erosion. A sample, containing sand grains, from 110-111 cm has a ^{14}C age of 5,880 ± 50 yr BP. Fragments of diatoms at 100-101 cm suggest shallow, slightly alkaline pond conditions. Pit 2 has only one sample on this unit in which M. distans var. africana dominates. This assemblage may be more indicative of conditions early in the deposition of the black mud. It has been tentatively suggested that the crysophyte record might provide an indication of conditions warmer than present for the period 6,000 to 5,800 yr BP. If a warm and wet climatic regime (or one with rainfall throughout the year) predominated at this time, then a situation of the whole basin draining freely through a fluvial system out into the Río Lerma might be

envisaged. In view of the absence of any indications of major human activity in the basin at this time, the disturbance recorded in the upper part of the record (ca. 5,800 to 4,570 yr BP), was probably due to a change in climate, possibly to cooler and drier (or more seasonal) conditions.

6) The deposition of the yellow ash shortly after 4,570 ± 60 yr BP. This ash seems to match part of an ash-lapilli-ash unit found north of the summit of Popocatépetl in the Basin of Mexico by White (1962) (Steen-McIntyre, pers. comm.). It may also correspond to the pomez marcadora superior identified by Mooser (1967) from Tlapacoya in the Basin of Mexico. Unfortunately, no samples from this site are available for comparison. The yellow ash seems to occur in both pits.

7) Above the ash a further episode of lake-level rise and fall is indicated. Its date of initiation is unknown, as the radiocarbon dates available seem to suggest an hiatus in deposition after the fall of the yellow ash. During this episode, the locus of deepest water was closer to Pit 2 than to Pit 1. The peak of this transgression was probably ca. 1,600 years ago, after which water levels fell once more. This regression was accompanied by clear indications of an increase in sedimentation rate, probably due to an influx of silt-sized material, possibly top soil. Between 1,380 ± 50 and 870 ± 50 yr BP, the lake dried out completely and a layer of macrofossils was preserved at both sites. Although Man undoubtedly played a part in the disturbance of the basin

slopes during this period, it seems unlikely that this human impact is a sufficient explanation in itself for the increase in sedimentation rate and the shallowing of the lake. It is probable that the climate did become drier, which would have led to both a fall in water levels and to a reduction in natural vegetation cover, making the soils more vulnerable to disturbance.

The recent past has been marked by renewed peat growth at both sites. Some standing water seems to have persisted near Pit 2. The more alkaline nature of the flora there, may be due to the greater distance of this site from the springs at the base of the abutting lavas.

Whilst these two pits can only provide a preliminary indication of the water level and environmental fluctuations which have occurred in the Upper Lerma basin, they do suggest that this basin is a potentially valuable high-altitude site for further palaeoenvironmental study. Clearly further investigation of sites across the floor of the former Lake Chiconahuapan and of the sites of the other palaeolakes, are needed to provide a more detailed picture. This would be particularly important for establishing periods when these lakes might have been linked and created a system draining freely out of the basin.

Chapter 8

DISCUSSION

8.1 Techniques

This study of Late Quaternary environmental change in Central Mexico has been based upon the ecological interpretation of sub-fossil diatom assemblages preserved in lacustrine and marsh sediments. It was assumed that the sedimentary diatom assemblages would reflect the mean composition of the diatom communities in the lake at a given time. Diatoms have provided particularly valuable evidence for climatic changes in the tropics and subtropics, where such changes are often expressed in terms of variations in precipitation and evaporation (Richardson and Richardson, 1972; Gasse, 1975; Bradbury, 1979). The success of such an approach depends upon having a fairly accurate idea of the ecology of individual species, or groups of species, at present. In view of the recognised differences between the apparent environmental preferences of species in temperate and tropical latitudes (Hustedt, 1949; Gasse, 1977b) and the relative scarcity of ecological information for tropical diatoms (cf Gasse et al, 1983), a study of the present day limnology of Central Mexico and of the diatom flora, was undertaken (see Chapter 5). It was hoped that these two lines of investigation would be complementary.

Fossil material was collected from pits, surface sections and a core. Whilst the number of sampling sites within the two major basins (Upper Lerma and Zacapu) were

relatively few, it was hoped that the sampling design would enable the spatial variation in the observed changes to be appreciated. The problems encountered in the Zacapu basin have been discussed in Chapter 6 ,section 11. Although 'one core' studies have been criticised, Anderson's (1984) comparison of records from a series of cores indicated that all of them exhibited similar overall trends, but with differences in the percentages of individual species (see also Davis et al, 1984). Also, the logistical difficulties of carrying out multi-core studies overseas are considerable.

As Battarbee (1979b) has pointed out: 'The palaeolimnologist requires information from every quarter'. Where available, therefore, the diatom records have been supplemented by palaeoenvironmental information derived from studies of the sediments themselves and of the lipids within them. These have tended to indicate that the diatom record is the most sensitive, particularly in a lake such as Zacapu where diatoms dominate the sediments. Whilst pollen analysis would have provided very valuable information, especially in terms of palaeotemperatures and the timing of the beginnings of agriculture (through Zea mays), these results were not available at the time of writing. The problems with using pollen in this region, where pollen of Pinus and Quercus tends to dominate all other types, possibly obscuring significant fluctuations in other species (Palacios Chávez, 1977), must also be born in mind.

In the study of modern diatom assemblages, multi-

variate statistical techniques were applied to help to reduce the large data sets to more compact groupings (of species or samples) which might be easier to interpret in terms of variations in their environments. The two programs used were TWINSPAN, for hierarchical classification (or clustering) and DECORANA for ordination using detrended correspondence analysis. These, or similar programs, have been employed in a number of diatom studies (Gasse et al, 1983; Grimes and Rushforth, 1983; Merilainen and Huttunen, 1984) and have proved to be valuable tools in studying the ecology of assemblages of species. The results from the collection of modern Mexican diatoms (including basal sediment samples) were presented in Chapter 5, sections 6 - 11. Although the results from the broader Central Mexico data set appeared to indicate chemical gradients in the water bodies, those from the Zacapu basin highlighted the importance of substrate to particular species groupings, especially where water chemistry displays little variation between sites (see also Battarbee et al, 1985). It seems likely that more pronounced ecological gradients would have emerged had all the data sets been put together. Gasse et al (1983) for example, used a set of 210 samples from many East African sites, for their analyses. The postulated similarities between the East African and Mexican floras appeared to be upheld, both by the modern and subfossil material. It was also interesting to note that samples including a lot of reworked fossil material (e.g. L. Zacapu samples 18, 19 and 20) were isolated by the clustering program. The identification of this older,

allochthonous material was only possible as samples from the diatomaceous outcrops had also been investigated.

The main purpose of the modern limnological survey (Chapter 5) was to attempt to gather modern analogues which could then be applied to assemblages found in the sedimentary sequences. The difficulty of using the 'modern analogue' concept in a densely populated are was apparent. Although the modern samples were collected at only one time during the course of the year, a comparison with surface sediment samples indicated that many of these assemblages were not likely to be represented in the subfossil material. This was particularly true in the case of the Nitzschia palea-dominated samples. Surface sediment samples generally proved to be the most useful and should probably have been collected from a wider range of locations within the sampled water bodies. It may, therefore, be of greater value when working on a time scale of thousands of years to concentrate on modern surface sediment assemblages as possible analogues, rather than on samples of the plankton and periphyton which show seasonal variations.

In a number of cases, no modern analogue was found for assemblages recorded in the sediments. Both the pit sequences from Upper Lerma and the Zacapu sections (especially Zacapu section 1) had fossil assemblages with no counterpart in the modern diatom collection. This may be the result of a present day climate unlike anything recorded in the past and/or due to the effects of anthropogenic

disturbance. Changes in basin configuration and the influence of volcanic activity (e.g. ash falls and lava flows) may also play a part. Under these circumstances, the environmental interpretation of the fossil material has had to rely upon published ecological information.

In general, however, diatoms have proven to be sensitive indicators of environmental change in Central Mexico. The present-day flora of the region is extremely interesting and deserves further study. The potential value of diatoms to the study of Mexico's current environmental problems seems considerable.

8.2 Results - a palaeoenvironmental perspective

8.2a Central Mexico

The environmental changes which have been inferred from the sequences in the Upper Lerma and Zacapu basins, may be compared with those from other parts of Central Mexico. Using the lake-level coding system developed by Street and Grove (1979), Figure 8.1 has been compiled from published data. The rather complex picture from different areas in the Basin of Mexico (see Chapter 3, section 3d) is summarised in Table 8.1. Although scanty, the lake level evidence seems to indicate quite wet conditions prior to 22,000 - 23,000 yr BP, a relatively dry (but by no means arid) global glacial maximum and a moist early Holocene. Generally dry conditions seem to have prevailed between 3,500 and 4,500 yr BP (time period 5), becoming wetter again between ca 1,500 and 2,500yr

BP (time period 2).

The records from Tlapacoya (Limbrey, 1976), Texcoco and Chalco (Bradbury, 1971; Watts and Bradbury, 1982) of conditions drier than previously, but still wetter than present, at 27 - 24,000 yr BP, fit well with the evidence from the Zacapu Brickpit Section (Chapter 6, section 8). Unfortunately, neither of the basins investigated here provided information on conditions around 18,000 yr BP. Watts and Bradbury's (1982) interpretation of the pollen record from L. Pátzcuaro suggests a cool and possibly fairly dry climate. Evidence from the Basin of Mexico is rather vague for this period, but Bradbury (1971) concludes that the pluvial conditions of the southwest U.S.A. did not extend as far south as Central Mexico. Heine (1973a), assuming that glacial advances on the peaks of Central Mexico are controlled mainly by summer precipitation, believed that the period 32,000 - 12,000 yr BP was generally cold and dry. In a series of papers between 1971 and 1984 Heine developed a glacial chronology for Central Mexico composed of five periods of advance (see also White and Valastro, 1984). With the precipitation/glaciation relationship suggested above borne in mind, these glacial episodes are:

MI - 36,000 - >32,000 yr BP
MII - ca 12,000 yr BP
MIII - 10,000 - 8,500 yr BP
MIV - 3,000 - 2,000 yr BP
MV - Little Ice Age

A change to wetter conditions at the very end of the Pleistocene, or early Holocene, is indicated by a number of records from the Basin of Mexico (Niederberger, 1979;

Bradbury, 1982), L. Pátzcuaro (Watts and Bradbury, 1982) and L. Chapala (González Quintero et al, 1974) as well as by the glacial advances (Heine, 1973b and 1976). Niederberger (1979) suggests that a major lacustrine trangression occurred at Zohapilco between 7,970 ± 220 BC and 5,090 ± 115 BC (ca 10,000 - 7,000 BP). This may correspond to the transgression recorded in Zacapu Section 1, prior to 7,330 ± 70 ^{14}C yr BP (SRR-2256). A drying event seems to be indicated around 7,500 - 7,000 yr BP. This is recorded in the Chalco basin, in Zacapu Section 1 and, possibly, above the basal tephra in Upper Lerma pit 1. The brevity of this dry episode is indicated by the date of 6,960 ± 50 (SRR-2630) for the subsequent transgression in Upper Lerma pit 1 and by an age of 7,000 - 6,000 yr BP for a transgression at Zohapilco. Although undated, deep water conditions seem to have been established soon after 7,330 yr BP at the site of Zacapu Section 1.

The climate appears to have become drier again towards the middle Holocene, culminating about 4,500 - 4,000 yr BP. At 4,300 yr BP, Bradbury (1971) records L. Texcoco as very low, with spring water being the main determinant of the diatom flora. In the Upper Lerma sequences very shallow water conditions (? an hiatus) are indicated above the Yellow ash, which was deposited shortly after 4,570 ± 60 yr BP (SRR-2253).

The period 3,000 - 2,000 yr BP seems to have been generally wetter than present. The diatom sequence from Lago

de Pátzcuaro (Bradbury, unpublished data) shows F. pinnata declining and S. astraea (S. rotula) and M. granulata increasing, with M. granulata attaining maximum abundance at ca. 2,145 yr BP. Analysis of a 2.49 m section near Pátzcuaro, with a base 0.80 m above the present lake level (Street-Perrott et al, 1982) indicated that the lowest part of the section was deposited in standing water. The basal silty loam was dated to 2,300 ± 60 ^{14}C YR BP (SRR-1862). Wetter conditions sometime between 3,000 and 2,000 yr BP are also indicated by the MIV glacial advance of Heine (see above), and have been suggested by Sanders et al (1979) for the period of the establishment of Teotihuacan in the Basin of Mexico, at the end of the Formative or Preclassic period (see Chapter 2, section 5 and Chapter 3, section 3e). A pollen record from coastal Guerrero (Gonzalez Quintero, 1980) also indicates warm and wet conditions between 3,000 and 2,000 yr BP. Using the corrected dates for the Zacapu core (laboratory date - 990), the diatom record seems to reflect low, but oscillating lake levels. Around 2,000 yr BP, however, the lake seems to have deepened, culminating in the Melosira flora of zone IV (corrected age 1,830 yr BP). The sequences from Upper Lerma indicate a lacustrine transgression starting after the deposition of the Yellow Ash and culminating at about 1,600 yr BP.

Subsequent to this wetter period, there appears to have been a general increase in aridity (García, 1974; Bradbury, unpublished data; this study). González Quintero (1980) suggests that there was a reduction in precipitation from

2,000 to 1,500 yr BP, with temperature falling over the same period. The period of lowest lake level recorded by the Zacapu core seems to have occurred at about 1,360 yr BP. A return to wetter conditions is then indicated at both Zacapu and the Guerrero site. The diatom flora from the Zacapu core reflects a fairly deep and cool lake at about 1,000 yr BP (subzones XIa and XIb), although a rapid fall in lake level is recorded by the macrofossils found at 266 - 276 cm (top of subzone XIb). The pollen record from Guerrero (González Quintero, 1980) is also interpreted as reflecting an increase in precipitation towards 700 yr BP, before declining to a minimum at about 450 yr BP.

The Guerrero pollen and Zacapu diatom records may also provide some indication of palaeotemperature trends over the later Holocene. Both sequences record warm conditions for the period 3,000 to 2,000 yr BP, followed by a marked cooling. This cool episode, which González Quintero (1980) believes reached a peak at 750 - 450 yr BP, corresponds to period of the Little Ice Age in Europe and to a minor advance of the Mexican glaciers (see above).

Although it has been suggested in the past that the climate of Central Mexico has been largely stable over the Pleistocene and Holocene (see especially Barbour, 1973; Smith et al, 1975 and Alvarez, 1977, but also Bradbury, 1971 and Watts and Bradbury, 1982) there seems to be a considerable volume of evidence to the contrary. Whilst records from individual basins may be of little palaeoclimatic

significance, it appears that consistent fluctuations between wetter and drier conditions may be traced across Central Mexico. These fluctuations are, however, apparently less dramatic than those recorded by the lakes of the southwest U.S.A. (Smith and Street-Perrott, 1983) or the Rift Valley of East Africa (Gasse et al, 1980) for example. By examining the archaeological and historical evidence for variations in climate in Mexico (Chapter 2), and the possible meteorological mechanisms for these, the recognition and interpretation of such changes on a longer time scale acquires more validity.

As was discussed in Chapter 1 and emphasised in subsequent chapters, Man has played an important part in shaping the present day environment of Central Mexico. For recent sediments, the effects of human disturbance of the basin ecosystem may mask, or obliterate, any evidence of climatic changes. Brown (1984a) for example, declines to attribute any palaeoclimatic significance to records from small, closed-basin lakes in Guanajuato. The potential of the archaeological record as a source of palaeoclimatic information, however, has been indicated in Chapters 2 and 3. A knowledge of regional and local archaeology also assists in the interpretation of sediment sequences and may prevent the erroneous identification of 'climatic' changes. Episodes of vegetation clearance and enhanced sedimentation rates, especially when complemented by evidence of cultivation (e.g. through the presence of the pollen of Zea mays) provide valuable palaeoenvironmental information.

The long history and importance of sedentary agriculture in Mexico was described in Chapter 3. In Central Mexico, apart from the early evidence from the Basin of Mexico (Niederberger, 1979), Watts and Bradbury (1982) report maize cultivation around L. Pátzcuaro from about 3,500 yr BP and Heine (1976) attributes soil erosion to human impact from 800 B.C. (ca 2,700 - 2,800 BP). Bradbury's unpublished diatom record from Lago de Pátzcuaro shows a big peak in Stephanodiscus spp. since approximately 990 yr BP and probably indicates cultural eutrophication of the lake. A similar peak is recorded in the top metre of the Zacapu core (Zone XIV). The dating of both these episodes falls within the Post-Classic period of Tarascan expansion (Freddolino, 1973) and the corrected Zacapu dates places it in the post-Hispanic period. Thus, in terms of a palaeoenvironmental study, the record of Man plays a varying role depending upon the time interval involved. The earliest archaeological data and the most recent historical information mainly provide evidence about variations in climate and their possible effects on Man, whereas on an intermediate timescale (say the last 1,000 - 2,000 years) the role of Man as a causal factor in environmental change is dominant. It is of great value that diatoms are sensitive to the changes brought about by both climatic variations and by human disturbance and nutrient enrichment.

8.2b The Pan-American Context

In order to provide a broader framework for the evidence from Central Mexico, results from other parts of northern South America, Central America and the southern U.S.A. will be summarised. A broad review of Pleistocene changes in tropical South America is given in Van der Hammen (1974) (see references in this). He concludes that the full glacial in the high Andes was cold and dry. At Fuquene in the Colombian Andes, for example, precipitation may have been less than half of present. The coastal areas of Guyana and Surinam were occupied by real savanna at this time, indicating lower precipitation overall, or a far more seasonal distribution. The glacial fall in sea level is rejected as being sufficient explanation for the observed changes. Particularly in the highlands, the very late glacial (ca 13,000 - 11,000 yr BP) was considerably wetter and this period is called the Guantiva interstadial. In the Venezuelan Andes, Salgado Labouriau et al (1977) also record wetter conditions between 12,250 - 11,960 yr BP, equivalent to the Colombian Guantiva interstadial. The timing of the moist episode around 12,000 yr BP fits well with the Mexican evidence, although the difference in glacier response is interesting. Servant and Villaroel (1979) presenting evidence from the high Bolivian Andes, record lakes 5 - 10x larger than present at both pre 28,000 and ca 11,000 yr BP. These dates are again in agreement with the Mexican data. Further evidence for full to late glacial aridity (spanning

18,000 yr BP) is provided by Ochsenius (m.s., 1982) for Amazonia between 18,000 - 12,000 yr BP and by Colinvaux (1972) for the Galapagos Islands between >34,000 and 10,000 yr BP. Colinvaux also records a fairly deep lakes between 10,000 - 8,000 yr BP. In general, though, the Holocene history of the region is less clear. However, dry conditions are indicated from Laguna de Agua Sucia in the Llanos Orientales (Colombia) for the period 6/5,000 - ca 3,800 yr BP. A brief review of the Holocene climatic history of South America as a whole has been published by Markgraf and Bradbury (1982).

Lake Valencia in Venezuela has been the subject of quite intense study, with results published in a series of papers (e.g. Bradbury, 1979; Salgado Labouriau, 1980; Bradbury et al, 1981; Leyden, 1985). The environmental history of the lake records both the influences of climatic change and Man. In general, conditions were dry from 13,000 to ca 10,000 yr BP, becoming wetter towards 8,500 yr BP when the lake was overflowing. Two episodes of low lake level are indicated at $7,130 \pm 300$ and $5,480 \pm 300$ ^{14}C yr BP. The first of these, which probably lasted about 1,000 years, is in keeping with the short dry 'event' suggested by the Mexican data (e.g. Zacapu Section 1). Following the dry conditions of the mid-Holocene, the level of Lake Valencia then rose again to a maximum at ca 3,000 yr BP. The trend of increasing salinity, with greater clastic sediment input and turbulence, recorded in the uppermost part of the Valencia core, is interpreted as being due to the effects of Man. The

parallels with the Zacapu core are striking.

Studies within the core area of Central America have been plagued by the problems of the influence of sea level and by the lack, or unreliability, of radiocarbon dating. Some trends do, however, emerge although the predominance of pollen work emphasises temperature, rather than moisture changes (e.g. Martin, 1964). Bartlett and Barghorn's (1973) study from the Isthmus of Panama is mainly a sea level and temperature record of the type indicated above, but the period 7,300 - 4,200 yr BP is recorded as being probably drier than present.

The lakes of the Peten district of Guatemala have been the subject of a series of investigations by E.S.Deevey and his associates, although Cowgill *et al* (1966) worked on Laguna Petenxil. There have been major difficulties obtaining reliable ^{14}C dates in this limestone area, due to the 'hardwater' effect and to massive deposits of colluvium bringing carbon of many ages and from many sources, into the lakes. However, Deevey (1978) reported a credible date of 8,410 $\pm$ 180 yr BP, on wood, from close to the base of a core from L. Quexil. This core indicated that the early Holocene was moist, with precipitation probably close to present levels. Deevey *et al* (1983) were finally able to identify the Pleistocene/Holocene boundary in the bottom sections of long cores retrieved from L. Quexil and L. Salpeten, which indicated that Late Pleistocene aridity preceeded the Holocene moist interval. The implications of late glacial

aridity for the age of the tropical forest in this region, and the fact that the Peten was not a refugium for mesophytic taxa during the last glacial, have been discussed by Leyden (1984). The impact of the Classic Maya civilisation and later non-urban populations on the limnology and hydrology of the lakes in this areas was profound (Deevey et al, 1980). Whether the late Preclassic - early Classic was also a dry period, enhancing the impact of Mayan forest clearance, has been the subject of some debate. Vaughan (1979) believes that his L. Quexil core does indicate drying for the period 1,700 - 1,500 yr BP. Although the influence of Man in creating savanna conditions in the early Classic was probably paramount, Vaughan and Deevey (1985, in press) tend to feel that climatic drying did play a part. Covich and Stuiver's (1974) work on L. Chichancanab in the Yucatán, Mexico, again reflects the dry Late Pleistocene, although the early Holocene was also very arid, with total desiccation of the lake at ca 8,000 yr BP. The lake then became rapidly deeper, reaching a maximum at about 5,500 yr BP.

The scarcity of data for northern Mexico has been referred to in Chapter 1 and the evidence currently available discussed. North of the U.S. border and particularly in the southwest U.S.A., however, a considerable number of studies have been carried out. Results from different techniques have, however, often appeared to be conflicting, with differences probably partly attributable to variations with altitude and with the response rates of the various plants and animals used as sources of information. The evidence

from this region is currently being reviewed and synthesised by the COHMAP (Cooperative Holocene Mapping Project) group. A recent review of the lake-level records from the western United States has been published by Smith and Street-Perrott (1983). The concept of 'pluvial' conditions at the last global glacial maximum still holds good for this region. In the southeast U.S.A. however, the pattern of full glacial aridity, recorded by most sites in Central America and northern South America (with long enough records) is again repeated (Watts, 1975 and 1980; Watts and Stuiver, 1980). Shallow lakes in the southeast, such as Buck Lake, were mainly dry prior to 8,500 yr BP. The record from Sheelar Lake, near Gainsville, Florida (Watts and Stuiver, 1980) records cool, dry possibly windy conditions from 23,880 to 18,500 yr BP, followed by a possible hiatus in deposition until 14,600 yr BP. Mesic forest expanded between 14,000 and 13,000 BP but the terminal Pleistocene was either drier or subject to increased fire frequency. The early Holocene (9,500 - 7,500 yr BP) is recorded as drier and possibly warmer than today, with present climatic and vegetation conditions only established in the late Holocene. The absence of conditions wetter than present during the Holocene appears to be a feature of this southeast region.

Using data from a wide variety of sources (some of which have been presented above), a series of maps of moisture status for the region from approximately 35°N to 5°S have been compiled. The time periods shown are 18,000, 9,000

and 6,000 yr BP (Figures 8.2, 8.3 and 8.4). The different techniques employed at the recorded sites are shown in Figure 8.5. An earlier version of these composite maps and their possible significance, was discussed by Street-Perrott et al (1985). The map of moisture status at 18,000 yr BP clearly shows the broad swathe of wetter conditions extending from the southwest U.S.A. down into northern Mexico. A clutch of sites in the central volcanic highlands (Neovolcanic Axis) of Mexico indicate conditions slightly drier than present, whilst Florida, the Yucatan and northern South America suffered marked Late Pleistocene aridity. The map for 9,000 yr BP reveals a far less extreme pattern than that for 18,000 yr BP. The tropics were, generally, becoming wetter, whilst very dry conditions had not yet developed in the southwest U.S.A.. By 6,000 yr BP most of the areas north of 20°N seem to have been much as at present, except for Florida which was still drier. Central Mexico and northern Central America appear to record conditions slightly wetter than present, although this episode may have been of short duration. In spite of great variability in the precision and reliability of the data used in this compilation, broad regional trends do emerge. This provides some encouragement for trying to explain the observed changes in terms of variations in the atmospheric circulation.

Employing only the lake-level data, Harrison and Metcalfe (in press) have attempted to describe and explain the patterns in lake-level variations for the Americas north of the Equator in this manner. In some respects, this

exercise served only to highlight the complexity of tropical climates. For Central Mexico specifically, however, the data suggested that fluctuations in the strength of the monsoon circulation, bringing summer rainfall, and in the strength and position of the mid-latitude Westerlies, as a source of winter precipitation, were the major sources of variation.

At 18,000 yr BP, the mean position of the mid-latitude Westerlies apparently lay well south of present, bringing abundant rainfall to the southwest U.S.A. and across into northern Mexico. The presence of the vast Laurentide ice sheet over North America was probably the main reason for this displacement, deflecting the Westerlies equatorward. Kutzbach and Wright (unpublished ms.) suggest that the development of an intensified jet stream, south of the Laurentide ice sheet, was an important element in producing increased precipitation over the southwestern U.S.A. This area would have lain in the entrance region of the jet core in an area with upper level divergence, lower level convergence and upward vertical motion. Hence, it would be an area of storm and precipitation maxima.

Depressions and disturbances related to the Westerlies and their associated frontal zones, may have brought some rainfall to Central Mexico, especially to the higher areas, as they do in the present day. The combined effects of an equatorward shunting of the major circulation belts; cold, stable conditions over the North American continent and reduced sea-surface temperatures over the Gulf of Mexico,

seems to have led to a breakdown in the summer monsoon. This is reflected by the very dry conditions in places such as Florida, Yucatán and northern South America where the summer rainfall of the north-east Trades is the predominant source of precipitation. Although generally associated with meridional circulation conditions (see Chapter 2), it is possible that nortes brought some precipitation to the Mexican Gulf coast and central highlands as cold air, flowing outward from the very cold North American continental interior would still have been warmed and picked up some moisture traversing the Gulf of Mexico. The relatively small temperature drop of the Gulf waters was noted in Chapter 1.

The onset of wetter conditions at about 12,000 yr BP appears to have been a feature of the whole intertropical belt (Harrison et al, 1984; Street-Perrott and Harrison, 1984), although the episode was of short duration. It seems to have been associated with a brief warming of the Atlantic (Street and Grove, 1979) and of the Gulf of Mexico (Emiliani et al, 1975). The effect of this may have been to stimulate a return of some summer precipitation. Heine (1983 and 1984) points out that his MII glacier advance occurred only on the high volcanoes east of the Basin of Mexico, close to the Gulf.

The evidence for 9,000 yr BP suggests an atmospheric circulation pattern intermediate between the glacial and interglacial (present) types. Rising lake levels in the tropics indicate that the summer monsoon was becoming reestablished as the interior of North America slowly began

to warm up, ocean sea-surface temperatures increased and sea level rose. The persistence of relatively moist conditions in the southwest U.S.A. and probably in northern Mexico, may indicate that the Westerlies were still south of their present-day mean latitude . The trend towards 6,000 yr BP is one of the American tropics becoming gradually wetter, although there seems to have been a dry event sometime between 7,500 and 7,000 yr BP. A similar episode of low lake levels was recorded in Ethiopia between 7,800 and 7,200 yr BP (Gillespie et al, 1983). The increase in precipitation in the northern hemisphere tropics over the period 9,000 - 6,000 yr BP was probably related to a strengthening of the monsoonal circulations in response to an enhanced seasonal cycle of solar radiation associated with the Milankovitch mechanism (Kutzbach and Street-Perrott, 1985). During this period (9 - 6K) arid conditions were established in northern Mexico and the southwest U.S.A.. The mean latitude of the Westerlies at this time, may have been north of present. There is clear evidence from Central Mexico that conditions became drier towards ca 4,500 yr BP. A similar trend is indicated by falling lake levels in inter-tropical Africa. It has been suggested (see section 8.2a) that a period of wetter conditions is recorded in Central Mexico around 2,500 - 2,000 yr BP. Juillet (1984) in an isotopic study of cores from the Gulf of California suggests that strong north-west winds were established over the region at about 2,100 yr BP. It is proposed that the wetter conditions in Central Mexico

at this time, may have resulted from an increase in winter precipitation brought by mid-latitude depressions, reducing the seasonality of the climate in this area. It is interesting to note that Gasse et al (1980) also report transgressions of lakes in the southern Rift of East Africa starting between 2,700 - 2,500 yr BP. As indicated above, a climatic interpretation of the lacustrine sediment sequences over the last 1000 - 2000 years is rendered problematic by the increasing influence of Man, although generally Mexico seems to have followed the drying trend common to much of the tropics.

The availability, in Central Mexico, of moisture from both tropical and temperate weather systems appears to have dampened the response of this area to the global-scale changes in the atmospheric circulation which produced such dramatic results in other parts of the tropics and sub-tropics. The nature of this response might be predicted from the study of the climate of the region in the present day (Chapter 2). Under such circumstances, the palaeoclimatic patterns are likely to be complex and often difficult to interpret, and even to identify. Excluding the northern part of the country, however, the lake level record from Mexico appears more like the 'tropical' pattern originally described from East Africa (e.g. Gasse, 1975; Street and Grove, 1976 and 1979; Gasse, 1980) than the 'temperate' pattern of the southwest U.S.A. (see Chapter 1). The link between lake levels in the northern hemisphere tropics, the strength of the monsoon circulations and the forcing role of the

Milankovitch mechanism has been described by Kutzbach and Street-Perrott (1985).

8.3 Summary and Conclusions

In the introduction (Chapter 1), a number of questions were raised concerning environmental change and its causes in Central Mexico over the Late Quaternary. It was felt that such questions could only be tackled by first learning something of environmental conditions now and in the recent (archaeological and historical) past. In Chapter 2 the present-day climate of Mexico was described and evidence for fluctuations in this, and their possible causes, were discussed. Chapter 3 provided background information for the main study area in the Neovolcanic Axis and particular emphasis was placed upon the importance of Man in this region. As the study of subfossil diatom assemblages was chosen as a technique likely to produce interesting results, a limnological survey was undertaken. The results of the chemical analyses of the waters and some aspects of the modern diatom flora were presented in Chapter 5. It was hoped that this information would provide a sounder basis for the interpretation of fossil diatom assemblages than a reliance on published data alone. General aspects of the techniques used in this investigation were described in Chapter 4. Palaeoenvironmental records from two lake basins Zacapu, in Michoacán and Upper Lerma in the Estado de México, were presented in Chapters 6 and 7. The relationship and significance of these results in a wider geographical context

has been discussed above.

Unfortunately, the new evidence presented here provides little, or no, additional information about conditions in Central Mexico in the Late Pleistocene. Evidence from other sources, however, indicates that the moister conditions of the southwest U.S.A. at this time, did not reach as far south as 19°N. A climate slightly drier than present is suggested and towards the equator, this aridity intensified. The proposition that Central Mexico lay along a climatic 'hinge zone' seems to have received some support. The records from Zacapu and Upper Lerma do, however, provide clear evidence for a series of climatic fluctuations during the Holocene (cf. Brown, 1984b) which may be correlated with events in other parts of Central Mexico, Central America and northern South America. The archaeological evidence suggests that Man has responded to the changes in climate particularly since the mid-Holocene. The early adoption of a sedentary, agricultural way of life has been an important factor in causing this sensitivity to climatic fluctuations. Over the last 3,000 years the evidence of Man as an agent of environmental change has become increasingly clear. Although the climate has undoubtedly continued to vary, recent environmental change in Central Mexico may be largely the product of human impact.

In 1982, Bradbury stated that:'The Holocene has not been convincingly subdivided in any place in Mexico or Central America, partly because the climatic record... has

often been compromised by human activity and partly because there has been insufficient work and absolute age control in this region'. Whilst the problems of working in a region with a long record of high population density remain, it is proposed that the new data presented here, together with a closer examination of earlier studies, enables a series of climatic episodes during the Holocene, to be identified.

The recognition of the variability of climate over the Holocene appears to be one of the major thrusts of current palaeoclimatic research (Bartlein et al, 1984; Davis, 1984). It is hoped that this piece of work will be a contribution to this and to our knowledge of tropical diatom assemblages from a sadly neglected, yet potentially very rewarding part of the tropics.

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