THE POTENTIAL OF DIATOMS AND OTHER PALAEOLIMNOLOGICAL INDICATORS FOR HOLOCENE PALAEOCLIMATE RECONSTRUCTION FROM SPANISH SALT LAKES, WITH SPECIAL REFERENCE TO THE LAGUNA DE MEDINA (CADIZ, SOUTHWEST SPAIN)

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ABSTRACT

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A diatom-salinity transfer function is developed for quantitative palaeosalinity reconstruction, from a data-set of 74 modern diatom samples and limnological data from Spanish salt lakes. Relationships between species and environmental data are explored using principal components analysis (PCA), detrended correspondence analysis (DCA) and canonical correspondence analysis (CCA) with variance partitioning, and a conductivity transfer function is derived by weighted averaging (apparent $r^2 = 0.91$).

A model for direct lake-level reconstruction is developed using TWINSPAN to explore the relationship between diatom species distribution and lake permanence.

A survey is made of diatom preservation in the recent sediments of >50 lakes throughout Spain, and of the overall potential for Holocene reconstruction of a selected group of lakes. Diatoms are best preserved (least dissolved) in systems of southern Spain, and the Laguna de Medina is selected for analysis as a result. It is established by PCA that the correlated variables water depth and lake permanence, and salinity, are the most important factors influencing preservation.

The diatom record preserved in the lower 6m of a 10.3m core from the Laguna de Medina is analysed. Application of the transfer function is shown to be unreliable due to the effects of fossil diatom dissolution and a lack of modern analogues. A modified transfer function is derived which includes partially-dissolved assemblages and improves the match with the surface set, but remains unreliable. Palaeosalinity reconstruction therefore relies on traditional palaeoecological techniques. Lake-level change is also reconstructed independently from changes in the relative abundance of taxa.

Separate palaeosalinity and lake-level reconstructions are derived from lithological and ostracod shell-chemistry analysis, and the palaeoecology of ostracods, foraminifera, molluscs and plant macrofossils. The influence of human impact is assessed by comparison with the pollen and charcoal record.

The diatom record is strong despite dissolution effects, and a consistent interpretation of lake-level change can be made based on different indicators. Lakes were high prior to c. 7860 yr BP; following a phase of low, fluctuating lake levels, maximum lake level was attained around 6000 yr BP, after which it declined gradually. The record shows affinities with African and Mediterranean lake-level data and makes an important contribution to an understanding of Holocene climate change in these regions.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The use of palaeoenvironmental techniques to infer climate history has gained a special significance with concerns over global warming. In 1990 the IPCC Working Group advocated the use of palaeoclimatic data as a record of past natural variability for General Circulation Models ("GCM's") of climate change, and as an important means of validating climate-model simulations (Houghton, 1991). A reliable, continuous palaeoclimatic record is vital for validation of GCM's (Gates *et al.*, 1992).

Most techniques for continuous time-series analysis of Quaternary environments rely on the analysis of sediment cores from marine and continental environments (Bradley *et al.*, 1993). On a Holocene timescale, continental data is vital for the high resolution spatial and temporal coverage necessary to elucidate the regional and relatively short-term variability of Holocene climate change (Gates *et al.*, 1992).

It has been argued that salt lakes in hydrologically-closed basins can be highly sensitive to climate change and can provide excellent palaeoclimate records (Street-Perrott & Harrison, 1985). Changes in effective moisture result in fluctuations in lake level and corresponding changes in salinity, biota, mineralogy and geochemistry (Hammer, 1986), and evidence for past climate can be derived from analysis of biotic and abiotic remains preserved in sediment cores. With an adequate knowledge of modern environments to act as analogues, it is possible to infer past salinity, lake-level and climate change from these data.

To date, Holocene palaeoclimate data-sets for Europe have been based either on pollen data (e.g. Huntley, 1990) or on combined pollen and lake-level data (e.g. Harrison & Digerfeldt, 1993). The latter approach is probably more reliable, but the emphasis of both has been on freshwater systems rather than on the more responsive saline-lake systems. Whilst this is partly a result of the restricted distribution of salt lakes within Europe (Battarbee, 1991), the spatial coverage of Holocene data-sets is most sparse for Mediterranean Europe, and it is in this region where salt lakes are found. Salt lakes are exceptionally abundant in Spain, but the extent of Holocene palaeoenvironmental research there has been very limited until now.

Diatoms are excellent palaeoclimate indicators owing to their abundance, diversity and sensitivity to salinity (Battarbee, 1991). Most importantly, the development of quantitative transfer function techniques has greatly enhanced their potential for continuous, high resolution palaeosalinity reconstruction (Fritz & Battarbee, 1986, Fritz, 1990, Fritz *et al.*, 1991, 1993a, Cumming & Smol, 1993, Juggins *et al.*, 1994, Gasse *et al.*, in press).

As with other techniques, various taphonomic processes can affect the reliability of diatom-based palaeoclimate reconstruction. Of these, the effects of diatom dissolution on the quality of fossil assemblages are often the most important (Fritz, 1990, Barker, 1992, Ryves, 1994). In addition, the relationships between salinity, lake level and climate can be complex and palaeoclimate reconstruction from palaeosalinity data alone may not always be straightforward.

Interpretation can be strengthened by the use of multiple proxy data. Ostracods are of particular value since they are often abundant and well-preserved, and can provide two independent sources of data. Continuous palaeosalinity and/or palaeotemperature data can be derived from ostracod shell chemistry (Chivas *et al.*, 1983, 1985), and palaeosalinity and other palaeoecological data from an understanding of modern ostracod species ecology (Holmes, 1992a).

The main aim of this thesis is to assess for the first time the potential of diatoms in Spanish salt lake sediments as indicators of Holocene salinity, lake-level and climate change. This involves the development of a salinity transfer function, a survey of diatom preservation in Spanish salt lakes, and analysis of a Holocene core from a selected study site, the Laguna de Medina, Cádiz, southwestern Spain. For the additional steps from palaeosalinity to lake-level and palaeoclimate reconstruction, multiple proxy indicators, of which ostracods are the most important, are used to strengthen interpretation of the Laguna de Medina record.

To provide a context for the study, the limnological characteristics of inland salt lakes are described and defined in the next section of this chapter. The rationale for the thesis is developed in detail thereafter, through a discussion of the relative merits of different techniques for palaeoclimate reconstruction. The focus is on pollen and lake sediments, which are the main sources of data for testing Holocene GCM's. An outline of the structure of the thesis is provided at the end of the chapter.

1.2 CHARACTERISTICS OF SALINE LAKES

1.2.1 Definition of inland salt lakes

The present study concerns inland salt lakes, which have no connection to the sea. These closed-basin lakes, lacking a surface outflow, are found in *endorheic* regions, where precipitation is insufficient to cause major stream flow (De Martonne, 1928), and may be contrasted with *exorheic* regions in more humid climates where there is significant runoff and surface outflow from lakes to the sea.

Whilst inland salt lakes and marine water bodies are both saline, and can be inhabited by similar species, they are fundamentally different. These differences have been masked in the past by the use of the ill-defined term, 'brackish', to describe waters of salinity intermediate between marine and fresh water, since this also encompasses estuaries and coastal lagoons which are supplied by sea water (Hammer, 1986).

There is large body of literature, summarised by Hammer (1986), which deals with the problems of how best to classify inland salt lakes. The term *athalassic* (Bayly, 1967) has become a widely-accepted definition. It translates as 'non-marine', and was proposed to encompass all inland waters, regardless of salinity, which have not been connected to the sea in the recent geological past. This excludes some lakes such as the Caspian Sea which were connected to the sea in the earlier Pleistocene (Williams, 1986) but clearly separates inland from marine environments. Within this class, fresh water environments can be easily dealt with separately.

Salt lakes vary in their permanence, from permanent (perennially wet) to ephemeral. Ephemeral lakes dry out every year, and are known also as *playas*, *sebkhas* or *chotts*. Between these two categories there is a continuum of lakes which retain water all year for a varying number of years at a time, but which can dry out in years of drought, and other lakes which do not dry out completely in the summer, and in which groundwater levels are maintained at the surface due to the formation of a salt crust. In this study these lakes are termed 'semi-permanent'.

1.2.2 Distribution of salt lakes

Inland salt lakes occur in all continents, and their water volume approaches that of fresh waters (Williams, 1986). Their distribution is restricted to endorheic regions of semi-arid to semi-humid climate where there is a net annual moisture deficit.

In the Northern Hemisphere their main distribution is from 30-53° N in a broad band swathing northern Africa (the Sahara, Sahel and East Africa) and eastwards to the Near and Middle East and the continental interior of the former USSR, Tibet and northern India. They are also widespread in the interior of western North America (the Great Plains) and Canada (British Columbia), but their distribution within Europe is largely restricted to Spain. In the Southern Hemisphere they occur between 3° N and 42° S, in western South America, Australia, South Africa and the Antarctic (Hammer, 1986).

1.2.3 Lake origins

In addition to climatic factors, the origins of salt lakes can often be linked to a variety of geological processes, which operate at present or have done in the past, or to topographic factors, and they are difficult to define precisely (Timms, 1992).

The main origins of lake basins were classified by Hutchinson (1957). Most salt lakes are principally of tectonic origin (related to mountain building, block faulting or downwarping, for example), and/or volcanic or glacial origin. Tectonic and volcanic basins are widespread, whereas glacial lakes are restricted to areas of past glaciation and are most numerous in North America, in regions such as the northern Great Plains and British Columbia. On a global scale, other types of lake: solution, fluviatile, deflation, interdunal and meteorite basins, are relatively rare (Hammer, 1986), although the processes involved, such as wind deflation, are often of added significance in modifying the structure of others whose principal origin is linked more to volcanic, tectonic or glacial processes (Torgersen, 1984).

The occurrence of shallow, ephemeral salt lakes often depends also on flat topography, as in Spain, where the hydrological network is poorly-defined and the proximity of groundwater levels to the surface promotes the retention of water in lake basins (Montes & Martino, 1987).

1.2.4 Morphometry

Salt lakes vary considerably in size, partly as a function of their different origins, from shallow pools with a surface area of a few m^2 to large, deep lakes several thousand km^2 in area (Evans, 1993). Large, deep lakes, of depth >15m and surface area >100 km^2, are rare, however, and tend to be of tectonic or mixed tectonic-volcanic origin, such as Mono Lake and Walker Lake in the Great Plains, North America, or Lake Shala in the Rift Valley of East Africa (Melack, 1983). Lake Issyk-Kul in the former USSR has the largest volume (c. 2000 km^3), but this is extreme. Hammer (1986) lists only 26 lakes worldwide with a volume of >0.5 km^3; these do not include any lakes in Spain or Antarctica, which are smaller than those of other salt lake regions.

Lake morphometry can vary widely within a given region. 39 lakes in morainal depressions and glacially-dammed valleys of the northern Great Plains, for example, range in area from <1 to >200 km^2, and in depth from 0.1 to 28m (Fritz *et al.*, 1993).

Ephemeral lakes vary enormously in surface area but their shallowness is a consistent feature. Playa lakes of South America, for example, range in surface area from <0.1 to c. 100 km^2, but maximum water depth does not exceed 1m. The largest is Lake Eyre in Australia; in rare events it attains a surface area of 8806 km^2, but a maximum depth of only 6m (Hammer, 1986).

A relationship between lake origins and shape has also been demonstrated in a study of Spanish salt lakes (Florín *et al.*, 1993), which is alluded to in Chapter 2.

1.2.5 Hydrochemistry

1.2.5.1 Water salinity classification system

In a similar vein to diatom ecology classification systems, there has been considerable discussion as to the suitable definition of an ecologically significant water-salinity classification system for salt lakes. The history of the debate is discussed in Hammer (1986). The exact definition of the important ecological threshold between fresh and saline waters, and a second threshold at around 3-5 gl^{-1}, has received particular attention.

The modified Venice Symposium classification system (Societas Internationalis Limnologiae, 1959) defined by Gasse *et al.* (1987) for waters of North Africa is used here. Major water salinity boundaries correspond to the Venice System, but the terminology has been altered. The term 'saline', for example, has replaced 'haline' as a more suitable description of inland waters of varying brine composition, where total salinity is more important than chloride concentration in influencing species distribution.

Table 1.1 **Summary of the Gasse *et al.* (1987) water salinity classification system, and the approximate relationship of total dissolved solids ('TDS') with conductivity (based on Heurteaux, 1988).**

	TDS range (gl^{-1})	Conductivity range (mS cm^{-1})
Metasaline-hypersaline	40 - >300	>50
Eusaline	30 - 40	40 - 50
Polysaline	20 - 30	25 - 40
Mesosaline	5 - 20	7.5 - 25
Oligosaline	0.5 - 5	0.5 - 7.5
Freshwater	<0.5	<0.5

The system is summarised in Table 1.1. Waters of a salinity approaching that of seawater (c. 35 gl^{-1}) fall into the *eusaline* class. In this study conductivity (in $mS\ cm^{-1}$) is also used to represent salinity. The approximate relationship with total dissolved solids ('TDS' in gl^{-1}) is also given in Table 1.1. It is derived from chloride waters of the Camargue (Heurteaux, 1988) and may not be accurate for waters of a different brine composition, but provides a useful yardstick for comparison of the two.

1.2.5.2 Brine composition

Whereas dilute, freshwater systems tend to be dominated by carbonates, the anion dominance of saline lakes varies between carbonate, sulphate and chloride, or a mixture of these; major cations comprise Na^+, Mg^{2+} and Ca^{2+}.

This is partly due to the effects of evaporative concentration. Brine evolutuion follows predictable pathways with increasing concentration depending on initial brine composition, as salts precipitate out according to their relative solubility in a series from carbonates (least soluble) to sulphates to chlorides (Hardie & Eugster, 1970, Eugster & Hardie, 1978, Eugster & Jones, 1979). Above c. 3 gl^{-1} (the 'calcite branchpoint'), carbonates precipitate out and other ions attain dominance. The brine of hypersaline systems tends to be dominated by the most soluble chloride salts.

Brine composition also varies significantly between different salt lake regions according to regional bedrock geology. This is due to the influence of the local or regional geology on the chemistry of groundwater inflow and catchment runoff, which, together with direct precipitation, are the main sources of hydrological input (Wood & Sanford, 1990). Thus, salt lakes in the continental interior of Sasketchewan, the northern Great Plains tend to be sulphate-dominated (Last, 1989), lakes in East Africa are carbonate-dominated (Wood & Talling, 1988) and lakes in the arid interior of Australia, which are often located within ancient marine evaporites, are overwhelmingly dominated by chlorides (Geddes *et al.*, 1981).

In the absence of other influences on groundwater hydrochemistry, the length and residence time of groundwater flow can be significant; groundwater alkalinity increases with distance and flow time from the upper reaches of a drainage basin, and lake water chemistry in a given region can vary accordingly (González Bernáldez, 1992).

1.3 PALYNOLOGICAL TECHNIQUES FOR HOLOCENE PALAEOCLIMATE RECONSTRUCTION

Pollen is the main source of data on vegetation change, and is widely preserved in lake and peat sequences of temperate and arid regions. Data from a number of European pollen studies have been collated in the European Pollen Database (Guiot *et al.*, 1993a). On the assumption that they are in equilibrium with the climate, various 'modern analogue' approaches have been developed to relate modern plant or pollen distributions quantitatively to individual climatic variables. Temperature and precipitation reconstructions have been made from the fossil record both for individual sites (eg Guiot 1987, Guiot *et al.*, 1993b, Vincens *et al.*, 1993) and on a broad continental scale (Bartlein *et al.*, 1985, Harrison & Digerfeldt, 1993, Huntley & Prentice, 1988, COHMAP Members, 1988).

Pollen analysis has the disadvantage that Holocene precipitation estimates for Europe are not very reliable and reconstructions on a continental scale based on pollen data alone (e.g. Huntley & Prentice, 1988, Huntley, 1990) show a poorly-defined response (Guiot *et al.*, 1993a).

This is exacerbated by other factors which can reduce the reliability of pollen-based reconstructions. Vegetation responds relatively slowly to climate change and minor climatic fluctuations may not be registered (Lowe, 1991). Reliability can also be reduced by the difficulties of identifying some genera containing taxa of differing ecological tolerances, such as *Quercus* (oak), to species level. Human impact masks the climate signal, reduces the match between fossil and modern assemblages, and has been extensive in the later Holocene of Europe (Guiot *et al.*, 1993a, Reille & Lowe, 1993). The quality of data-sets also suffers from the number of studies not intended specifically for palaeoclimatic reconstruction (Harrison & Digerfeldt, 1993). The problem is most acute for Mediterranean Europe, where few studies have been made and regional data are sparse.

In recent studies, reconstructions have been improved by constraining the results with lake-level data, which show greater sensitivity to precipitation (e.g. Prentice *et al.*, 1992, Guiot *et al.*, 1993a, Harrison *et al.*, 1991). Guiot *et al.* (1993a) produced spatially coherent precipitation maps from Holocene sites across Europe where pollen analogues alone covered widely differing precipitation values.

In summary, pollen analysis is an important source of palaeoclimatic data but has its limitations. Pollen analysis is included in this study, but the emphasis is instead on the reconstruction of palaeosalinity and lake-level change as an independent source of palaeoclimate data.

1.4 RECONSTRUCTION OF HOLOCENE LAKE-LEVEL CHANGE IN FRESHWATER SYSTEMS

1.4.1 Background

Lake-level research has been crucial in overcoming an overemphasis on temperature change which arose out of pollen and glacial research (Street-Perrott & Harrison, 1985). Lake levels fluctuate in response to changes in the water balance, which in turn affects the distribution and character of sediments and biota. The limnological effects of climate change on freshwater lakes are less marked than on hydrologically-closed, saline lakes and techniques for lake-level reconstruction differ accordingly. Techniques for palaeoclimate reconstruction in freshwater systems are contrasted below with those for saline systems. The main value of the former is as an adjunct to pollen analysis, but lake-level data from saline lake regions are sufficiently sensitive to be used as palaeoclimate data-sets in their own right (Street & Grove, 1979).

Lake-level data for a number of freshwater lakes of temperate Europe have been collated in the European Lake-Level Database (Guiot *et al.*, 1993a, Harrison *et al.*, 1991, Harrison & Digerfeldt 1993).

1.4.2 Techniques for lake-level reconstruction

The reduced sensitivity of freshwater lakes in humid regions to changes in effective moisture is due to the existence of an outflow, but they have shown a regionally consistent response on annual to millenial timescales (Harrison & Digerfeldt, 1993). Lake-level change is recorded most clearly by changes in the sedimentary characteristics of the littoral zone. The most unequivocal method involves lithological and plant macrofossil analysis of core transects in the near-shore zone to identify its physical displacement through time, a technique advocated by Digerfeldt (1986) for palaeoclimatic reconstruction in freshwater lakes of Sweden and refined in recent studies by the inclusion of other data such as aquatic pollen (Harrison & Digerfeldt 1993).

Other techniques are less decisive (Battarbee, 1991). Lake levels have been reconstructed from changes in the ratio of littoral to offshore diatoms or invertebrates in deep-water cores, but interpretation is complicated by other factors such as the dependence of the distribution of lake habitats on individual lake morphometry (Battarbee, 1991) or the complexity of changes in the distribution and abundance of zooplankton with changing lake volume (Patalas & Salki, 1994). The deep-water sediments of large lakes may show no response at all due to limited transport of littoral assemblages.

Direct ecological relationships between biotic assemblages and individual climatic variables are also uncertain. Temperature reconstruction has been attempted on the basis of changes in chironomid (Walker *et al.*, 1991) and ostracod (Delorme *et al.*, 1977, 1989) species abundance. Indirect, diatom-based temperature reconstructions have been based on a correlation between species shifts, altitudinal or pH change, and climate in mountain lakes (Servant-Vildary & Roux, 1990, Psenner & Schmidt, 1992). Although significant relationships have been established, ecosystem relationships are complex and further work needs to be done to establish whether observed changes are more a function of other limnological processes whose relationship with climate is more complex (Walker *et al.*, 1992).

Other techniques include oxygen isotope analysis of biogenic carbonates (Siegenthaler & Eicher, 1986). ^{18}O:^{16}O-ratios show characteristic variation in line with long-term temperature fluctuations but, again, the relationship with Holocene climates is as yet poorly understood (Eicher, 1991).

In summary, lake-level and other limnological changes occur in freshwater lakes as a result of climate change, but the response is subtle. Lake levels can be reconstructed from evidence for the physical displacement of the littoral zone, but palaeoclimate proxies from a single, deep-water core are difficult to interpret.

1.5 RECONSTRUCTION OF HOLOCENE LAKE-LEVEL CHANGE IN SALINE SYSTEMS

1.5.1 Background

Closed-basin lakes occur in arid to semi-humid regions where annual evapotranspiration exceeds precipitation. Due to the lack of a surface outflow lake levels are highly responsive to changes in the ratio of precipitation to potential evapotranspiration ('P-PET') and minor climatic fluctuation can cause major changes in water level compared to freshwater systems (Harrison *et al.*, 1988). Salts tend to be conserved in the system and fluctuations in lake level are accompanied by significant changes in water salinity and ionic composition (Hardie & Eugster, 1970, Blinn, 1971, Eugster & Jones, 1979).

Global data on closed, saline lakes are held in the Oxford Lake-Level Database (Street & Grove, 1979, Harrison *et. al.*, 1988), and lake-level reconstruction forms the focus for major regional saline lake projects such as PALHYDAF (Palaeohydrology in Africa; Fontes & Gasse, 1991a), IDEAL (An International Decade for the East African Lakes; Johnson *et al.* 1990) and CASPIA (Juggins *et al.*, 1994).

1.5.2 Techniques for lake-level reconstruction

Salinity is an important ecological limiting factor so lake-level change can lead to shifts in species assemblage composition which far outweigh their response in open systems (Hammer, 1986). Sediment mineralogy and geochemistry vary not only with the physical displacement of the littoral zone, but also with salt precipitation and redissolution (Teller & Last, 1990).

In contrast to freshwater systems, detailed palaeoclimate reconstructions can be derived from a range of biotic and abiotic indicators preserved in deep-water sediment cores, and past lake levels and climate change can be inferred where a clear relationship exists between salinity and lake level. Since the relationship between salinity and lake level is not necessarily straightforward (Eugster & Jones, 1979, Street-Perrott & Harrison, 1985, Kilham & Cloke, 1990), interpretation is strengthened by the use of multiple lines of evidence.

The importance of saline lakes for palaeoclimate reconstruction stems also from their relative abundance in these regions, where other palaeoclimate data are scarce. Apart from a number of central valley mire systems, the peat and glacial records of more humid or colder climes are absent in lowland Mediterranean Europe, and tree-ring data are confined to mountainous areas over 1000m in altitude (Serre-Bachet, 1991, 1994, Till & Guiot, 1990).

This study is aimed at Holocene palaeoclimate reconstruction from the sediments of Spanish salt lakes, a region of Europe for which palaeoclimate data are sparse and where salt lakes are abundant but little-studied. The rationale for the choice of analytical techniques is developed below through a review of the techniques adopted, wherein others not included in the thesis are alluded to briefly. The discussion centres on diatom analysis, which forms the focus for this work, and ostracod analysis, which provides the most important source of data to strengthen interpretation.

1.5.3 Diatoms as palaeosalinity indicators

1.5.3.1 Background

Diatoms are single-celled, siliceous algae and are excellent palaeosalinity indicators because of their ubiquity, diversity and rapid response to salinity change. Their potential for high-resolution palaeosalinity reconstruction was recognised in palaeolimnological studies of salt-lake sequences in Africa and the America's (e.g. Richardson *et al.*, 1978, Bradbury *et al.*, 1981, 1989, Fritz & Battarbee, 1986, Gasse *et al.*, 1987, Radle *et al.*, 1989).

These early palaeosalinity studies were at best semi-quantitative. Since continuous palaeoclimatic data are necessary for climate modelling, the development of quantitative transfer function techniques to reconstruct past water quality from microfossil assemblages (Imbrie & Kipp, 1971, Birks *et al.*, 1990, ter Braak, 1987, ter Braak & Juggins, 1993) has been extremely important. Successful diatom-salinity transfer functions have now been developed in North America (Fritz & Battarbee, 1986, Fritz, 1990, Fritz *et al.*, 1991, 1993a, Cumming & Smol, 1993) and Africa (Gasse *et al.*, in press).

1.5.3.2 Diatom-salinity ecology and classification systems

The halobian classification system devised by Kolbe (1927) and modified by Hustedt (1953, 1957) was one of the first attempts to formalise the observed ecological relationships between diatoms and water salinity, and was based upon work in estuarine and marine littoral waters of Germany. In the Hustedt system, four characteristic groups of diatom taxa were recognised according to the water salinity at their observed maximum abundance, which are summarised in Table 1.2 below.

Many diatoms of saline waters are *euryhaline*, that is, they are found abundantly in waters of widely differing salinities and without a well-defined optimum, as is to be expected of non-equilibrium species in fluctuating environments (Krebs, 1985). The need to include overall tolerance ranges was proposed in a second system devised by Simonsen (1962) for the Baltic and extended by Ehrlich (1975) for hypersaline lagoons in Sinai. Similarly, Carpelan (1978) devised a system based on tolerance ranges alone for the diatoms of Californian lagoons, where the instability of waters was such that the diatom flora consisted entirely of highly opportunistic species whose densities within the limits of their tolerance ranges were independent of salinity.

Table 1.2 Summary of the halobian diatom classification system

Polyhalobous taxa:	stenohaline marine taxa with an optimum of >30 g l^{-1} salinity, plus more euryhaline taxa	
Mesohalobous taxa:	*euryhaline mesohalobous*: brackish water taxa with their optimum and lower tolerance limit within the range 30-0.2 g l^{-1} salinity	
	α-mesohalobous:	optimum of >10 g l^{-1}
	β-mesohalobous:	optimum of 0.2-10 g l^{-1}
Oligohalobous taxa:	taxa living in both brackish and fresh water	
	halophilous taxa:	optimum in slightly brackish water
	indifferent taxa:	optimum in fresh water
Halophobous taxa:	exclusively freshwater taxa (<0.2 g l^{-1}).	

Although these classification systems are still used in some palaeolimnological studies (e.g. Espinosa, 1994), their global applicability is questionable. In particular, they are based upon chloride-dominated waters, whereas inland waters are dominated variously by chloride, sulphate or carbonate anions and the biota can vary accordingly.

In addition, the classification of diatoms of different optima and tolerances into a limited number of groups reduces the accuracy and precision of the results. Additional information can be gleaned from autecological data, but a reliance on 'indicator species' can lead to an overemphasis on stenohaline taxa (ter Braak, 1987). When based upon a good modern data-set, the 'transfer function' approach for continuous, quantitative palaeosalinity reconstruction has proved far more powerful.

1.5.3.3 The transfer function approach

Following pioneering work by Imbrie & Kipp (1971) on marine foraminifera, the application of weighted averaging transfer function techniques to diatom-based palaeolimnological research in inland lakes was popularised by ter Braak & Van Dam (1989) and was developed principally in research aimed at investigating the effects of acid rain on lake-water pH in Scotland, Scandinavia and North America (e.g. Birks *et al.*, 1990). Its potential for palaeosalinity reconstruction has been established in more recent research in North America and Africa (e.g. Fritz *et al.*, 1993a, Cumming & Smol, 1993, Gasse *et al.*, in press). Diatoms have also been found to exhibit sensitivity to specific brine composition, in addition to the total salinity of lake waters (Gasse *et al.*, 1983), and in the most recent work (Gasse *et al.*, in press) transfer functions have also been developed for the reconstruction of ionic composition.

Modern palaeolimnological transfer functions are based upon principles of weighted averaging, and relate modern diatom surface sediment species assemblage composition to water quality in a 'training set' of samples spanning the ecological gradient of interest (in this study, salinity). Quantitative inferences of past salinity can then be made, with error estimates, based upon the whole assemblage.

Diatom data are noisy and comprise many species with widely-differing abundances and many zero values. Weighted averaging techniques are thought to be better-suited to species-rich data than modern analogue techniques used in pollen analysis (ter Braak & Juggins, 1993). In comparative tests against other transfer function techniques (e.g. Flower, 1986), they have proved more robust and have replaced multiple linear regression as the most appropriate technique. They have the advantage of simplicity over maximum likelihood regression and calibration procedures, which produce similar results but are computer-intensive (Birks *et al.*, 1990), and have a satisfying basis in ecological theory (ter Braak & van Dam, 1989).

1.5.3.4 Factors affecting palaeosalinity interpretation

As in all palaeoecological studies, the transfer function approach is based on uniformitarian principles and relies on the occurrence in the training set of good modern analogues for fossil assemblages. Interpretation can also be affected by a variety of taphonomic processes which reduce the representativity of diatom samples and can cause significant error in quantitative palaeosalinity reconstruction (Barker *et al.*, 1990). In saline lakes, the most important taphonomic processes are those which lead to the breakage and dissolution of diatom frustules, either in the water column or after deposition (Fritz, 1990, Barker, 1992). This can cause gaps in the fossil record or a bias in favour of more robust species which can seriously affect the reliability of both the fossil and modern diatom data (Barker, 1992, Ryves, 1994). Processes causing dissolution are poorly understood and may result from a combination of factors including salinity, ionic composition, pH, temperature, turbidity, sediment mixing or desiccation (Meriläinen, 1973, Flower, 1993, Ryves, 1994).

The primary aim of this study is to assess the potential of diatoms in Spanish salt lake sediments as quantitative palaeosalinity indicators, by the development and application to a Holocene fossil diatom sequence of a diatom-salinity transfer function based on a data-set, or 'training set' of modern diatom and limnological data. Diatom dissolution is a major theme throughout; its potential effects are taken into account at every stage of the study and it forms the focus for a comprehensive survey of diatom preservation in Spanish salt lakes.

1.5.4 Diatoms as direct indicators of water depth

A technique for direct, qualitative reconstruction of water depth based on the ratio of littoral to offshore fossil biota was alluded to in reference to freshwater lakes (Section 1.4.2). Although relationships with water depth are not necessarily simple, the approach is equally applicable to saline lakes and, in the case of diatoms, can provide complementary data against which to assess the results of palaeosalinity analysis.

The changing ratio of planktonic to benthic diatom taxa has been widely applied to reconstruct lake levels directly from fossil diatom assemblages in salt lake sequences from Africa (e.g. Gasse & Street, 1978, Gasse *et al.*, 1987, Haberyan & Hecky, 1987, Gasse & Fontes, 1989, El Hamouti, 1989, Lamb *et al.*, 1995) and the America's (e.g. Bradbury *et al.*, 1981, Metcalfe *et al.*, 1991, Hickman & Schweger, 1993). Metcalfe *et al.* (1991) attempted to reconstruct water depth in more detail, by classifying taxa according to five categories: aerophilous (tolerant of exposure to air), epiphytic (on plants), periphytic (on lake-bed substrate) and unclassifiable. Where inferred water depth shows a clear inverse relationship with inferred water salinity (e.g. El Hamouti, 1989), the technique provides a means of validating lake-level reconstruction from palaeosalinity data. In other cases (e.g. Gasse *et al.*, 1987) it can provide a useful indicator that the relationships are more complex.

In this study, the use of diatoms as direct indicators of water-level change is explored in addition to their use as quantitative palaeosalinity indicators. The validity of the approach is tested by analysis of the modern diatom training set, and it is applied in analysis of the Laguna de Medina sequence.

A range of other techniques used to assess and strengthen the reliability of Holocene palaeoclimate reconstruction is described below.

1.5.5 Ostracod shell chemistry as an indicator of palaeosalinity and/or palaeotemperature

1.5.5.1 The distribution function ('K_D value') approach

Ostracods are microcrustacea with bivalved shells ('carapaces') of low-Mg calcite, and they are abundant in waters of widely differing salinity. The analysis of Mg/Ca and Sr/Ca ratios of ostracod shells has been used to produce continuous palaeosalinity and/or palaeotemperature records on the basis of a relationship between ostracod shell chemistry and that of the host waters. It therefore has the potential to provide an ideal test of the reliability of a diatom-inferred palaeosalinity record.

Ostracods moult up to nine times during their life-cycle, at approximately one-weekly intervals during growth (De Deckker *et al.*, 1988). Each stage (an 'instar') is formed rapidly from calcium carbonate secreted from the host waters (Turpen & Angell, 1971). Any relationship between ostracod shell chemistry and the aquatic environment therefore relates to water quality over a short period of time rather than an average of prevailing conditions. In addition to Ca, the trace metals Mg and Sr are laid down, along with other elements such as P, Mn, Fe and K (Bodergat, 1985).

The most rigorous approach has been developed in work on Australian, chloride-dominated salt lakes (Chivas *et al.*, 1983, 1985, 1986a). A significant, genus-dependent relationship has been found between the Mg/Ca content of ostracod shells and the Mg content of host waters, which relates to both salinity and temperature of the host waters (Chivas *et al.*, 1983, 1986a), and between the Sr/Ca content of ostracod shells and the salinity of the host waters (Chivas *et al.*, 1983, 1985). Since Mg is laid down preferentially in juvenile instars, analysis is restricted to fully-calcified adults or the largest instar.

In a similar vein to the development of diatom transfer functions, Chivas and co-workers have developed methods for quantitative reconstruction by establishing the relationships between modern ostracod shell chemistry and water quality. Genus-dependent 'distribution coefficients', or 'K_D' values for Mg and Sr are derived as follows:-

$$K_D[M] = \frac{(M/Ca)_{CaCO_3}}{(M/Ca)_{H_2O}}$$

where K_D is the distribution coefficient, and M is the trace element (Mg or Sr), expressed as a molar ratio with calcium in the ostracod valve and host water respectively.

The distribution coefficient is applied in calibration of fossil ostracod sequences, to calculate the unknown molar ratio of the host waters. Since the Mg/Ca profile reflects both palaeosalinity and/or palaeotemperature change and the Sr/Ca profile reflects palaeosalinity only, their combined analysis can be used to uncouple palaeosalinity and palaeotemperature profiles.

1.5.5.2 Factors affecting interpretation

Various factors can affect the reliability of the ostracod shell chemistry record. In particular, the results of recent laboratory experiments suggest that distribution coefficients are a complex function of a much wider range of parameters than previously thought (Palacios-Fest *et al.*, 1994).

The most important of these is probably the influence of brine composition. Ostracod shell chemistry research has been extended in recent studies from chloride to sulphate and carbonate systems, where the relationships between shell chemistry and salinity can be more complex than in chloride systems. Sr is readily precipitated with aragonite since $SrCO_3$ and aragonite crystals are isomorphic (Chivas *et al.*, 1986b); as a result the Sr/Ca profile can vary according to different carbonate phases and is truncated during aragonite precipitation (Anadón & Julià, 1990, Engstrom & Nelson, 1991, Fritz *et al.*, 1994, Chivas *et al.*, 1993). As a result there has been a trend in recent studies towards abandoning the use of quantitative distribution coefficients (e.g. Bridgwater, 1995).

The reliability of the results can be assessed using a variety of techniques (Chivas *et al.*, 1993). The most effective is analysis of ostracod ^{18}O:^{16}O stable isotope content, which is related to the isotopic composition of the host waters; the oxygen isotope composition of the host waters is a function of evaporation, temperature and also the origin of the water (groundwater versus surface input). It provides both an independent palaeotemperature record for uncoupling of the Mg/Ca signal (Chivas *et al.*, 1993, Curtis & Hodell, 1993) and a means of assessing the influence of non-climatic factors in lakes of complex hydrology (Gasse *et al.*, 1987). Different mineral phases in the sediment record can be identified using X-ray diffraction (e.g. Martinez & Plana, 1987), which provides another means of assessing where the ostracod shell-chemistry profile may be driven by changes independent of climate

(Fritz *et al.*, 1994).

Ostracod shell-chemistry analysis is carried out in this study to provide a second, continuous palaeosalinity record against which to test the diatom reconstruction. The assumptions on which it rests are less certain than those of diatom analysis, and the aim is to derive a relative salinity curve from fossil ostracod trace-metal ratios, rather than to quantify the relationship with the salinity of host waters. Ideally the study would be combined with oxygen isotope and X-ray diffraction analysis, but this was not feasible given the time constraints of this study.

1.5.6 Other palaeoecological indicators

A range of biotic remains other than pollen and diatoms is often preserved in salt lake sediments. The most commonly-studied organisms comprise the calcareous microfossils: ostracods (e.g. De Deckker, 1982, Forester *et al.*, 1987) and foraminifera (e.g. Cann & De Deckker, 1981). The palaeoecological value of other biota which occur in both fresh and saline lakes is more well-researched in freshwater systems, but they are increasingly being employed in saline lake studies.

In respect to the reconstruction of past salinity (or brine composition), the value of different indicators depends on a range of ecological factors including their abundance, diversity and sensitivity to salinity, and on their ease of identification to species level. Although ostracods are less diverse than diatoms, they satisfy these criteria and are arguably the most useful palaeosalinity indicators after diatoms (Holmes, 1992a). Salinity tolerance ranges vary from euryhaline to stenohaline, and useful 'indicator species' are known with relatively narrow, well-defined salinity preferences (Neale, 1988). Salinity tolerance is thought to relate more to brine composition than to salinity *per se* (Forester, 1987, De Deckker & Forester, 1988).

As with diatoms, ostracods can also be used as direct indicators of lake level based on a knowledge of their modern distribution according to water depth but, again, this is probably a function of a range of factors such as water temperature or substrate texture (Palacios-Fest *et al.*, 1994) and a simple relationship with climate cannot be assumed. Ostracod techniques are reviewed in De Deckker (1988a), De Deckker & Forester (1988), Holmes (1992a) and Palacios-Fest *et al.* (1994), by which a range of other relevant limnological parameters such as lake permanence can be reconstructed.

In respect to other indicators, the use of chrysophyte cysts (non-diatom siliceous algae) as palaeoclimate indicators has been investigated in taxonomic and palaeoecological studies of North American saline lakes (Pienitz *et al.*, 1992, Cumming *et al.*, 1993). Other fossil remains have been analysed mainly as a component of multidisciplinary research. These include plant macrofossils (e.g. Digerfeldt *et al.*, 1992), charophyte oospores (green algae, e.g. Burne *et al.*, 1980, Gasse *et al.*, 1987, García, 1994a), molluscs (e.g. Gasse *et al.*, 1987, Plaziat, 1993), Cladocera ephippia (zooplanktonic and benthic arthropods, e.g. Kokkinn & Williams, 1987, Davis, 1994), chironomid head capsules (midge larvae, e.g. Davis, 1994) and *Artemia* cysts (brine shrimp, Last & Schweyen, 1985).

A full discussion of the relative merits of other indicators is beyond the scope of this chapter. In this study, ostracod palaeoecology provides the main tool for Holocene palaeoclimate reconstruction to complement diatom and ostracod shell chemistry analysis of the Laguna de Medina record. Interpretation is strengthened by deriving a concensus palaeoecological interpretation of palaeosalinity and lake-level change based also on a range of other indicators (foraminifera, molluscs and plant macrofossils). The choice of indicators is dictated in part by their preservation in the sediments. In the case of chrysophtes, charophytes and Cladocera, their potential is limited by the difficulty of identifying remains to species level (Cumming *et al.*, 1993, García, 1994b, Kokkinn & Williams, 1987), and they are not included in the study.

1.5.7 Sediment mineralogy and geochemistry

The mineralogy and geochemistry of salt lake sediments can provide data on palaeohydrology. As noted above (Section 1.2.5.2), the evolution of brine composition and precipitation of different salts follows a predictable pattern which depends on initial brine composition (Hardie & Eugster, 1978). In simple systems, mineralogical sequences can be interpreted in terms of past brine composition, salinity, lake level and climate (Teller & Last, 1990).

Lithostratigraphic description of sediment cores can be used to give an indication of changes in the abundance and morphology of large salt crystals such as gypsum ($CaSO_4.2H_2O$), and of fluctuations in sediment texture and structure. In addition to providing some data on mineralogy, this can be used to distinguish characteristic 'salt-lake facies' described by Hardie *et al.* (1978) and Eugster & Kelts (1983) and indicative of changes between an ephemeral 'salt-pan' environment (massive lenticular gypsum) and a perennial salt lake (preservation of laminated sediments).

Other rapid techniques for description of basic sediment properties comprise wet density and loss-on-ignition, which provide a coarse estimate of organic and carbonate content (Stevenson *et al.*, 1987, Digerfeldt *et al.*, 1992). Different mineral phases can be identified in detail using direct methods (X-ray diffraction, optical microscope, scanning or transmission electron microscopy), or indirectly by bulk and extractive chemical techniques.

Ideally, both the mineralogical and chemical aspects of sediment sequences should be analysed for a full understanding of lake sedimentation processes, including the possible influence of detrital input on the record (Jones & Bowser, 1978). The interpretation of lake-level change from such data is rarely straightforward, since it is complicated by processes such as diagenesis (Teller & Last, 1990). In this study, emphasis is given instead to the palaeoecological techniques described above, and lithological analysis is restricted to simple, rapid methods.

1.6 THESIS OUTLINE

The primary aim of the thesis is to assess the potential of diatoms in Spanish salt lakes for Holocene palaeoclimate reconstruction. The emphasis is on the development of a diatom-salinity transfer function and its application to the fossil diatom sequence of a selected study site (the Laguna de Medina, Cádiz, southern Spain), in order to derive a quantitative Holocene palaeosalinity record. The potential of diatoms as direct, qualitative indicators of lake-level is also assessed.

In the light of the potential effects of diatom dissolution on the quality of fossil diatom assemblages, a number of studies of diatom preservation in salt lakes throughout Spain are carried out as part of the procedures used for selection of the study site, and in order to assess the predictability of diatom preservation in different types of lake. Diatom dissolution is an important theme throughout, and analysis of the Laguna de Medina sequence includes the derivation of a modified transfer function which takes diatom dissolution into account and is a departure from standard techniques used previously.

Multiple proxy indicators, of which ostracod shell-chemistry analysis and palaeoecology are the most important, are used to strengthen interpretation of palaeosalinity and lake-level change in the Laguna de Medina, and the pollen and charcoal records are used as indicators of the influence on the system of human impact rather than climate. As adjunct to the studies of diatom preservation, the overall palaeolimnological potential of sites is also taken into account in the process of site selection.

There are effectively three separate stages to the study. These comprise the analysis of the modern diatom training set (Chapter 4), studies of diatom preservation and the broader palaeolimnological potential of Spanish salt lakes (Chapter 5), and a study of Holocene palaeoclimate change in the Laguna de Medina (Chapters 6-8).

CHAPTER TWO

THE STUDY REGION

2.1 INTRODUCTION

This chapter provides a description of the physical geography, geology and climate of Spain as a whole, with an emphasis on the geographic regions in which salt lakes occur, a description of the limnological characteristics of Spanish salt lakes, and a summary of previous palaeolimnological research in Spain. This provides a context for studies of the modern diatom training set in Chapter 4, and of diatom preservation in Spanish salt lakes in Chapter 5.

In the final section of the chapter, detailed descriptions are given of the local climate, geology, geography, geomorphology and limnology of the study site selected for Holocene palaeoenvironmental analysis, the Laguna de Medina, Cádiz, Andalucía, southwestern Spain.

2.2 REGIONAL PHYSICAL GEOGRAPHY AND GEOLOGY

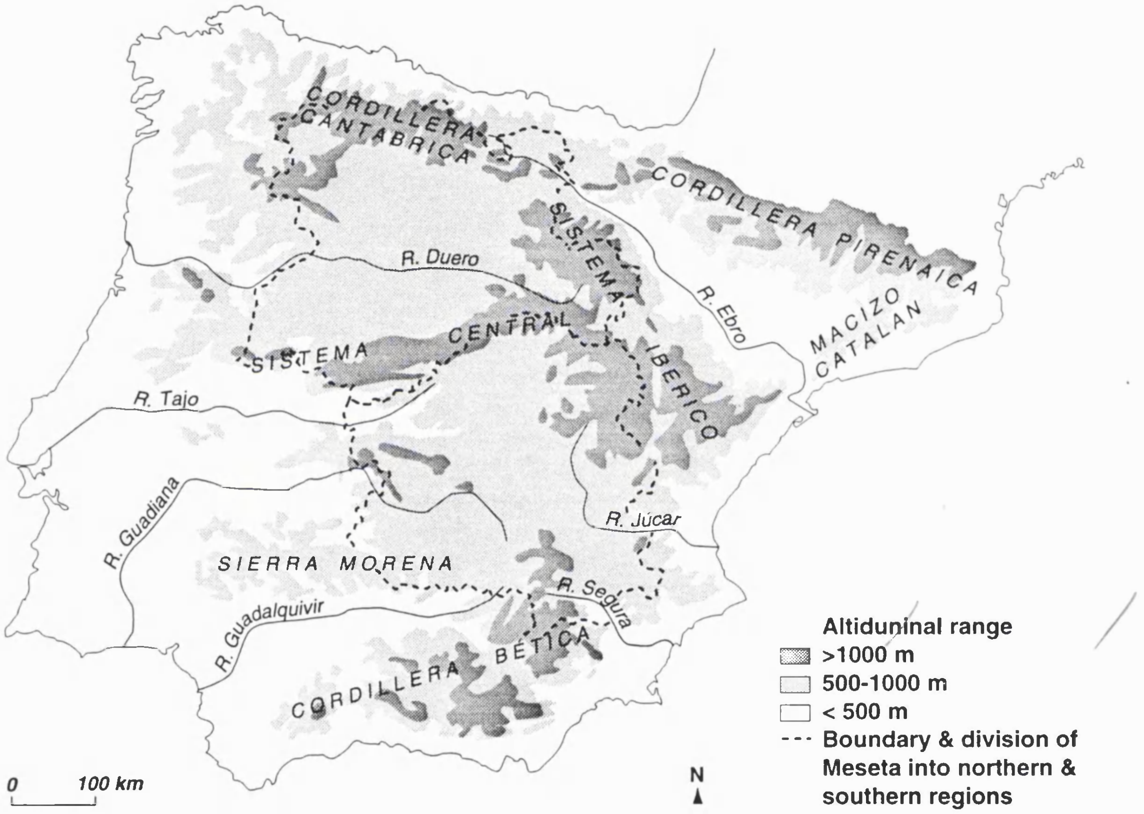
2.2.1 Description of major geographic regions

The physical geography and geology of Spain are summarised in De Teran *et al.* (1978a, 1978b) and Ager (1980). Maps showing the major geographic regions and relief are given in Figures 2.1 and 2.2. Although the Iberian Peninsula is one of the most mountainous regions of Europe, much of it is dominated by the extensive flat plains which intervene between mountain ranges. These plains form four separate geographic regions in which salt lakes are concentrated, namely, the northern and southern parts of a large central plateau, the *Meseta*, the basin of the Ebro river in Aragón, northeastern Spain, and the basin of the Guadalquivir in Andalucía, southern Spain.

The *Meseta* occupies most of the interior at altitudes of 638-880m asl. The 'northern Meseta' is separated from the 'southern Meseta' by a range of Palaeozoic granites, the Sistema Central (Central Sierras) which bissects it diagonally. It is bounded by the Carboniferous limestone Cordillera Cantabrica (Cantabrian Mountains) and the Sistema Ibérico (Iberian Mountains) to the north and east respectively, and the Sierra Morena to the south. It is open to the west. The Meseta as a whole has been dissected in the west by downcutting of the high energy Duero (Douro) and Tajo (Tagus) rivers following uplift at the end of the Tertiary. In the southern Meseta, known also as *La Mancha*, sedimentary deposits are more intact since over much of the region the hydrology forms an open

Figure 2.1 Map showing the major geographic regions of Spain

Figure 2.2 Map showing the relief of the Iberian Peninsula



network with little capacity to erode and dissection has not been pronounced. Continental evaporites derived from former inland lakes mainly of the Tertiary Period are widely preserved as intercalated clays, marls, limestone and gypsum.

To the northeast of the Peninsula, in the region of Aragón, the Ebro Basin is a flat depression 150-410m asl in the forelands of the Pyrenees whose origin has been linked with subsidence prior to the Tertiary (De Teran *et al.*, 1978a). It is separated from the sea by the Macizo Catalan (Catalan Mountains). Thick continental Tertiary evaporites and detritic sediments which overlie Mesozoic evaporites are remnants of a large interior drainage basin which was present throughout the later Tertiary (Oligocene and Miocene epochs). Non-evaporitic lacustrine deposits to the south of the Basin once considered of marine origin (Ortí, 1984) are thought also to be continental (Anadón, 1992).

The regions of southern Spain known collectively as Andalucía (Andalusia) were affected by the Alpine orogeny which led to the formation of the Cordillera Bética (Baetic Cordillera) complex of ranges and internal depressions towards the end of the Tertiary. Outside this complex the Guadalquivir Basin forms a large depression to the west at 20-460m asl which is bounded to the north by a major fault of the Sierra Morena. It is open to the Atlantic and was once a gulf connecting the Atlantic with the Mediterranean, formed after subsidence and a major marine transgression during the Miocene. Uplift of the western Peninsula took place at the end of the Pliocene and overall marine regression followed during the Pleistocene (Siljeström *et al.*, 1994). Thick, fine-grained marine evaporites are preserved. Older strata such as Triassic Keuper marls outcrop in the interior and, in contrast to the characteristic flatness of La Mancha and much of the Ebro Basin, the relief is gently undulating.

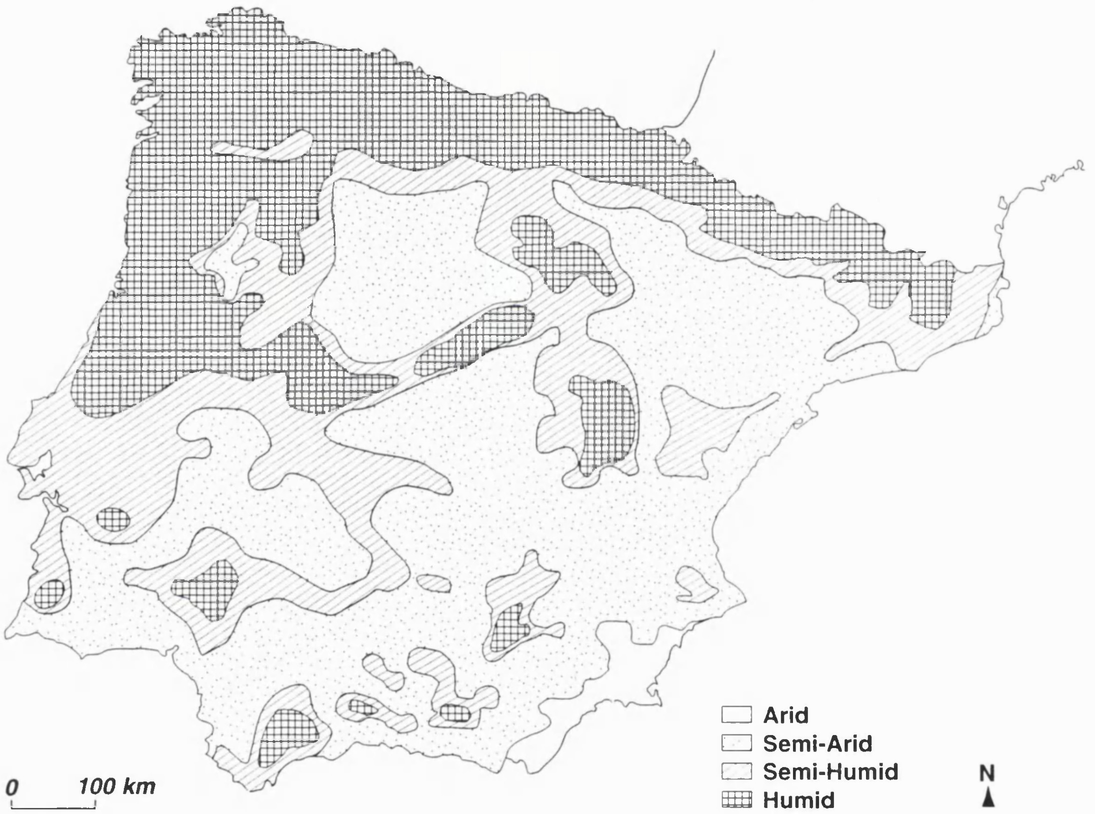
2.2.2 Regional climate

The climate of the Iberian Peninsula is highly variable due to the combined influence of Atlantic, continental and subtropical weather systems. In addition, the varied relief and the rainshadow effect of the mountains which virtually surround the interior cause a marked contrast between mountain and lowland and between coastal and interior climate regimes (De Terán *et al.*, 1978b).

The distribution of different climate zones is usefully described in terms of humidity, that is, differences in the ratio of annual precipitation ('P') to evaporation ('E') estimated by Font Tullot (1983) based on Thornthwaite's humidity indices, which incorporate an estimate of annual evapotranspiration to provide a realistic estimate of net water balance. Major humidity zones are given in Figure 2.3. Apart from the northern humid zone and high mountains, most of Spain is arid or semi-arid (P:E <0.7).

The northern humid zone is outside the influence of subtropical pressure belts and has an oceanic

Figure 2.3 **Map showing the major humidity zones of the Iberian Peninsula (reproduced from Font Tullot [1983]). [Zonation is based on estimated mean annual precipitation:evaporation ('P:E'), as follows. Arid: P:E <0.3; Semi-arid: 0.3 <P:E <0.7; Semi-humid: 0.7 <P:E <1.0; Humid: P:E >1.0.]**



climate similar to other regions of northwest Europe, with mild winters, cool summers and frequent rain throughout the year; mean annual precipitation often exceeds 1000mm yr^{-1} (Font Tullot, 1983). Potential evapotranspiration ('PET') is at a minimum (<600mm yr^{-1}) and there is an excess of effective moisture (P-PET) throughout the year.

In contrast, the rest of the Peninsula apart from the high mountains is more arid. PET is high and reaches a maximum of up to 1300mm yr^{-1} in the Bay of Cádiz (southwest Spain), in the province of Córdoba (central southern Spain) and in the lower Segura (southeast Spain) (Font Tullot, 1983). There is marked seasonality throughout, due mainly to the influence of subtropical high pressure belts. Seasonality is also enhanced by Atlantic depressions; the polar jet stream is deflected to the north or south of the Peninsula for much of the year, but is an important source of spring and autumn storms in the interior (Linés Escardo, 1970).

The climate of the Iberian Peninsula is Mediterranean in character towards the coast, including the Atlantic seaboard of southwest Spain, and continental in the interior. Summers are hot and dry throughout; water reserves are exhausted by May or earlier and summer is a period of marked moisture deficit which lasts for up to seven months. Winters are mild in the Mediterranean zone and colder in the continental interior. The seasons of maximum precipitation vary according to region between winter, spring or autumn. In winter much of the northern Peninsula is removed from the influence of Atlantic depressions and spring or autumn precipitation maxima dominate, whereas winter precipitation maxima more typical of Mediterranean climates characterise the southern Peninsula.

The aridity of La Mancha and the Ebro Basin is enhanced by the rainshadow effect of the northern mountains; the effect is accentuated in the southern Meseta by the additional influence of the Sistema Central (De Terán *et al.*, 1978b). Mean annual precipitation is 300-400mm yr^{-1} in La Mancha and the Ebro Basin, and up to 500mm yr^{-1} in the northern Meseta; this is very low compared to the PET values of around 1000mm yr^{-1}. Winters are relatively cold (mean January temperatures 2-6°C) and summers hot (mean August temperatures >22°C).

The openness of Andalucía to the Atlantic allows penetration of moist airstreams in winter, spring and autumn (Font Tullot, 1983). Mean annual precipitation in the Guadalquivir Basin is 300-800mm yr^{-1}. Effective moisture is low over much of the Basin, however, since winters are mild (mean January temperatures >6°C) and summers very hot. The lower and middle Guadalquivir, where PET is at a maximum for the Peninsula, is the hottest region of Spain and August daily temperatures often exceed 40°C.

Aragón is affected by a strong northwesterly wind, the *cierzo*. In comparison wind speeds are lower in the Guadiana and Guadalquivir basins and the upper Tajo (Linés Escardo, 1970).

2.3 SPANISH SALT LAKES

2.3.1 Distribution

The distribution of endorheic salt lakes (>3 gl^{-1} total dissolved solids) is shown in Figure 2.4. A catalogue compiled by Pardo (1948) listed 240 salt lakes, a significant number of which have now disappeared through drainage or been altered by input of fresh water or urban waste (Montes & Martino, 1987). The majority are located in the Ebro Basin of Aragón, the Guadiana Basin of La Mancha and the Guadalquivir Basin of Andalucía. Smaller clusters occur in the Segura and Júcar basins of Albacete, La Mancha and between the Duero and Tajo basins in the northern Meseta.

Other saline water bodies comprise artificial salt pans and coastal lagoons which are located intermittently along all but the northwestern Spanish coastline.

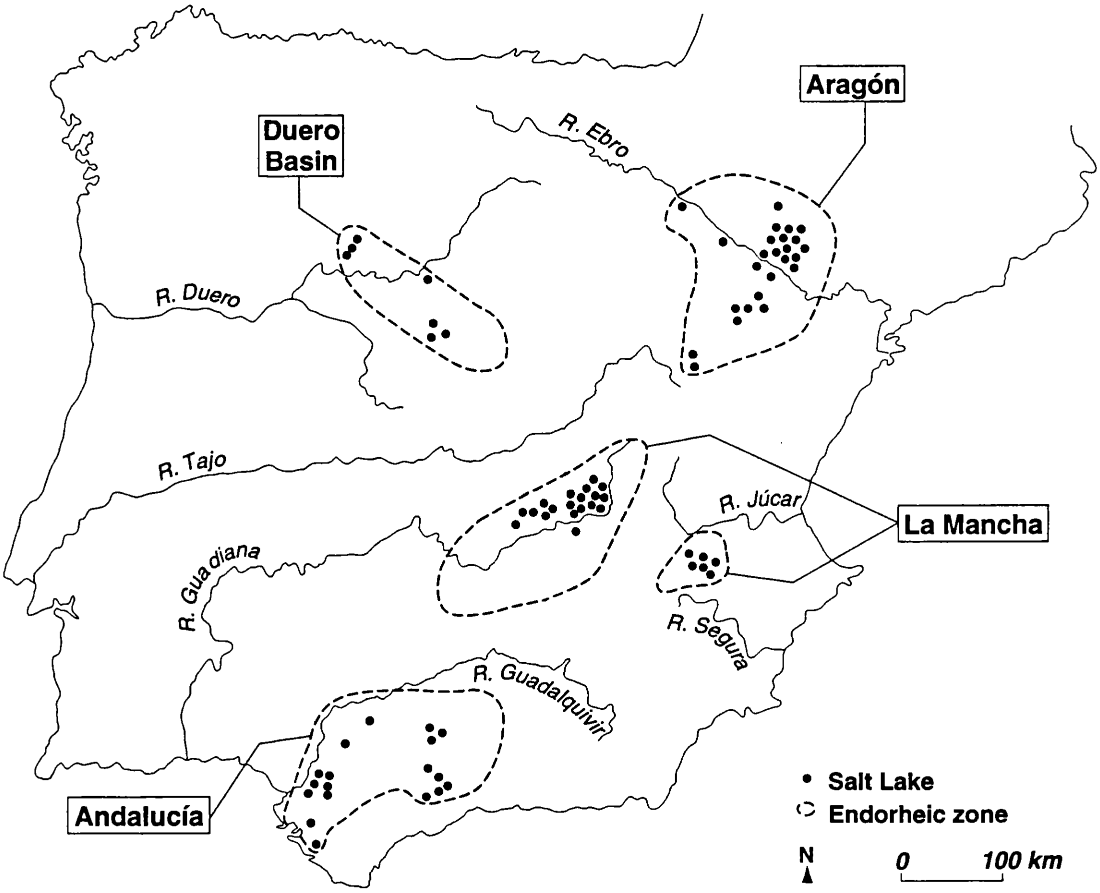
2.3.2 Lake origins

Endorheic lakes occur within semi-arid or semi-humid climate zones where annual evapotranspiration exceeds precipitation. Their distribution in Spain is further restricted to regions of flat topography where endorheism is favoured by a poorly developed drainage network and by the proximity of groundwater levels to the surface (Alonso, 1985). Spanish salt lakes are unusual in that the origins of most are related to processes of limestone and evaporite dissolution and subsidence, in regions where Tertiary or earlier continental and marine deposits are preserved at or beneath the surface.

Most salt lakes of the Ebro Basin, Aragón, are ephemeral dolines formed either by gradual dissolution of gypsum after infiltration of rainwater through dissolution cracks in the upper limestone crust (Sánchez Navarro *et al.*, 1989), or by less structured dissolution and subsidence of limestone or gypsum-rich evaporites. Aeolian erosion is particularly significant here; many basins are elongated due to deflation and this is the main mechanism by which salts are removed when lakes are dry (Pueyo Mur, 1978). Wind deflation is the most important variable in the formation of lakes to the south of the region, in lake basins whose geomorphology is constrained by the structure of sandstone palaeocanals (Sánchez Navarro *et al.*, 1991).

The southern Meseta lakes of La Mancha are in a karstic zone where, in addition to both limestone and evaporite dissolution (carbonate-rich marls or gypsum), origins are often also linked to geological factors such as structural faulting, as is the case with the lakes of Alcázar de San Juan, Ciudad Real

Figure 2.4 Map showing the distribution of Spanish salt lakes (closed circles). (Modified from Comín & Alonso [1988].)



(Tello Ripa & López Bermúdez, 1988, Florín *et al.*, 1993).

The solution lakes of Córdoba and some others in Andalucía were formed after limestone dissolution by meteoric water and groundwater (Torres Esquivias *et al.*, 1990). The origins of others such as the Fuente de Piedra, Málaga and the lakes of Cádiz are related to the dissolution of either Triassic or Tertiary gypsum- or halite-rich evaporites (Bernués Sanz, 1990, Fernández-Palacios, 1990).

Deep freshwater karstic lakes occur outside the main salt lake regions in Albacete (the Ruidera System; González Martín *et al.*, 1987), Cuenca (e.g. Vicente & Miracle, 1988) and to the north of Barcelona, northeast Spain (e.g. the Laguna de Banyoles; Pérez-Obiol & Julía, 1994).

Some salt lakes originated independently of dissolution. Small volcanic crater lakes southwest of Ciudad Real in La Mancha were formed in the Pliocene (Hernández-Pacheco, 1932); many have now been drained for agriculture (Montes & Martino, 1987). The main origin of others such as the Laguna de Gallocanta, Teruel (Comín *et al.*, 1983) and the Laguna de Pétrola, Albacete (Ordoñez *et al.*, 1973) is tectonic, related to either faults or fractures. The lakes of the northern Meseta are of ancient fluvial origin and were isolated within Tertiary detritic sediments in endorheic areas at the centre of large interfluves (González Bernáldez, 1992); some lakes in La Mancha such as El Hito, Cuenca are also of fluvial origin (Florín *et al.*, 1993).

2.3.3 Hydrology

Most Spanish salt lakes are ephemeral and dry out every summer. The majority of permanent or semi-permanent lakes, which dry out every few years, are located in Andalucía. With the probable exception of the few crater lakes, which often have small, well-defined drainage areas, patterns of groundwater flow in Spanish salt lakes are complex and vary considerably between lakes, from minor flow through sediments of low permeability, shallow aquifers or springs, to major aquifer flow in lakes connected to the regional groundwater table (Montes & Martino, 1987). Groundwater outflow can occur through internal seepage or aquifer flow; a lake-bed can exhibit groundwater inflow and seepage simultaneously in different areas and net input/output alternates over time in a complex relationship with lake level (González Bernáldez, 1992).

Most of the ephemeral lakes are 'groundwater windows', or areas of local or regional groundwater discharge where inflow is enhanced by capillary action (Sánchez Navarro *et al.*, 1991) such that water levels are maintained into the season of water deficit (González Bernáldez, 1992). Water retention is enhanced by an impermeable substrate (marl or deflocculated clay) which prevents loss of surface waters by infiltration (Recio Espejo & Tirado Coello, 1982a).

Other ephemeral lakes, such as the Laguna de la Ballestera, Sevilla, are in recharge areas where shallow water levels are maintained by the proximity of groundwater levels to the surface. This impedes infiltration of meteoric waters and water is retained in the basins for some part of the year even though groundwater makes a negligible contribution to the net water balance. Small (<20m diameter) lakes in recharge areas of the northern Meseta are thought to be unconnected to groundwaters and water retention is a product of substrate impermeability alone (González Bernáldez, 1992).

In addition to freshwater karstic lakes, the relatively high water depth (>2m) of a small number of Spanish salt lakes is mainly due to their connection to major aquifers. Unlike other lakes of the Ebro Basin, the Laguna Salada de Chiprana is 5m deep and permanent due to its connection to steady regional groundwater flows (González Bernáldez, 1992), although its current permanence is mainly a function of recent human impact (Davis, 1994). Estimates for aquifer input exceeded total surface input (direct precipitation + runoff) for three permanent lakes in southern Córdoba, Andalucía (Torres Esquivias *et al.*, 1989).

Few detailed studies have been made of groundwater outflow. The models of lake function proposed by Sánchez Navarro *et al* (1989 and 1991) assume no outflow for both solution and deflation basins in Aragón. This is not necessarily the case, however. Significant groundwater outflow to the nearby river has been demonstrated for the Laguna de Gallocanta, a semi-permanent tectonic basin in Teruel, northeast Spain, for example (González Monterrubio *et al.*, 1982 in Montes & Martino 1987). Major aquifer outflow is an important characteristic of the freshwater karstic system of Ruidera, where a series of lakes located along a gentle gradient are linked by subterranean flow (González Martín *et al.*, 1987).

2.3.4 Physical lake characteristics

Compared to salt lakes globally, most Spanish salt lakes are small (mean lake area <0.5km^2) and shallow (mean water depth <1m). Notable exceptions are the Fuente de Piedra, Málaga (12.2km^2), the Laguna de Medina (12.1km^2) and the Laguna de Gallocanta, Teruel (13.3km^2). The Laguna Salada de Chiprana, Aragón (Balsa *et al.*, 1991) and some of the lakes of Andalucía are 5-10m deep.

Many of the shallow, ephemeral lakes which predominate in Spain are typical *playa* lakes with characteristically flat lake-beds and, where wind deflation is significant, small lunettes on the lake shore (Sánchez Navarro *et al.*, 1989). The morphometry of both small recharge lakes and ephemeral solution lakes is often circular or subcircular; deflation basins are more elongated. Lakes with an origin related to structural faulting are more irregular in shape. Deeper, karstic lakes in relatively pure limestone or carbonate-rich marl areas such as the Laguna Chica, Villafranca de los Caballeros, tend to be circular or subcircular with conical lake basins (Florín *et al.*, 1993).

2.3.5 Hydrochemistry

Carbonate-rich salt lakes are rare in Spain, and are restricted largely to the northern Meseta. In this region, the salinity of lakes such as the Lagunas de Coca is due to the input of alkaline groundwaters, whose mineralisation is a consequence of long groundwater flow time in siliceous aquifers (González Bernáldez, 1992).

In most other lakes groundwater input has an overriding significance in determining lake salinity and brine composition since it is charged with dissolved evaporite salts, and lake waters are saline even with short groundwater flow and residence time (González Bernáldez, 1992). Runoff tends to make a relatively small contribution to total inflow but may also be charged with salts from evaporite outcrops (Torres Esquivias *et al.*, 1989). As a result the ionic composition of lake waters varies with local or regional geology. Almost without exception the dominant ions are Na^+, Mg^{2+}, Cl^- and SO_4^{2-}. Na-Cl or mixed $Na\text{-}Mg\text{-}Cl\text{-}SO_4$ lakes are associated with marine evaporites in Andalucía and, with lower Mg^+ content, with continental evaporites in the Ebro Basin; lakes of La Mancha are within continental evaporites and are mainly $Mg\text{-}SO_4$ type. Apart from freshwater karstic lakes, carbonates are significant (>25% of the anion sum) only in the lakes of the northern Meseta (Comín & Alonso, 1988).

2.4 PREVIOUS PALAEOENVIRONMENTAL RESEARCH

The view has tended to prevail that the Peninsula south of the Pyrenees and Cantabrians has not undergone any large-scale Holocene climate change compared to the rest of western Europe (Lamb, 1977, Gilman & Thornes, 1985, Huntley & Prentice, 1988, Turner & Hannon, 1988). This may have been due in part, however, to a reliance on fragmented documentary data and a paucity of palaeoenvironmental data. Based on documentary data Font Tullot (1986) suggested there was evidence for a phase of general climate deterioration from the start of the 16th Century which followed a relatively warm, wet phase which might be equated with the western European 'Little Ice Age' and 'Little Climatic Optimum' respectively, but which differed in their timing and were not as extreme or well-defined.

Research in the natural sciences has expanded considerably over the last ten to twenty years (Casado & Montes, 1992). There is now a large body of data on the ecology and mineralogy of salt lakes, but Holocene palaeoenvironmental research has been virtually restricted to the palynology of upland and coastal mires. It is only very recently that the semi-arid interior has become a focus for research or that other techniques for palaeoclimate reconstruction have been employed.

Pollen studies in humid upland sites were often of coarse spatial and temporal resolution and poor chronological control, and provide no clear evidence for regional climate change within the last 5,000 years (Davis, 1994). More recently, evidence from humid, lower altitude sites inland has been interpreted either in terms of the anthropogenic effects of forest clearance (e.g. Pérez-Obiol *et al.*, 1986, Van den Brink & Janssen, 1981) or, in Quaternary studies aimed at climate reconstruction on a longer timescale such as that on the karstic Laguna de Banyoles (Pérez-Obiol & Julía, 1994), as a general period of climate amelioration following the Late Glacial.

Forest clearance appears to have been the major influence on vegetation over the past 6,000 years on the coastal plains of both humid and semi-arid zones (Menéndez Amor & Florschütz, 1961, 1964, Stevenson, 1985, Stevenson & Moore, 1988, Stevenson & Harrison, 1992, Riera-Mora & Esteban-Amat, 1994). The same conclusion has been reached in studies of coastal lagoons, and their evolution otherwise is linked more to sea-level change (e.g. Dupré *et al.*, 1988).

The semi-arid interior has been largely ignored. Until very recently research consisted almost entirely of geomorphological studies of hillslope erosion and accumulation, the interpretation of which may have been biased by an underlying assumption of little climate change. Gilman & Thornes (1985) argued that patterns of erosion and accumulation in the badlands of arid southeast Spain could be interpreted only in terms of human impact due to its localised pattern. Burillo Mozota *et al.* (1986), however, argued in a similar study in Aragón that the influence of climate was difficult to distinguish from anthropogenic or tectonic influences, and patterns of erosion may have been linked to the combined effects of storm frequency and human occupation.

The long lacustrine-peat bog sequence at Padul, Granada has been the object of several pollen studies concerning the last interglacial-glacial cycle (e.g. Menéndez Amor & Florshütz, 1962, 1964, Florschütz *et al.*, 1971, Pons & Reille, 1986a, 1986b). Pons & Reille (1986a, 1986b) considered the Holocene part of the sequence in some detail, but it is truncated at c. 4450 BP and shows little evidence for climate change other than a warm phase around 8,000 years ago.

In a review of evidence for lake-level and climate change in the Mediterranean, Harrison & Digerfeldt (1993) summarised current palynological and lithostratigraphic data from the Iberian Peninsula. On the basis of two coastal mire studies in southwest and northwest Spain (Stevenson, 1985, Menéndez Amor & Florschütz, 1961), a mountain lake study in Portugal (Janssen & Woldringh, 1985) and the research at Padul, he concluded there was strong evidence for the postulated early Holocene wet phase in the western Mediterranean from around 12,000 BP, and also for an abrupt drop in lake levels after c. 5000 BP across the region. The sequences of one of these sites (the Laguna de las Madres, Huelva; Stevenson, 1985) does not extend back to 5000 BP, however, and that of Padul is truncated at c. 4450 BP, and the conclusions are perhaps premature.

More recently, stronger evidence for climate change has been furnished in the northeastern Peninsula by the pollen analyses of Stevenson *et al.* (1991), Macklin *et al.* (1994) and Davis (1994) on salt lakes of the Ebro Basin. This is the first detailed, dated palaeoenvironmental research of these systems to have been made. Davis (1994) extended the study to the semi-quantitative reconstruction of past lake levels using data derived mainly from macrofossil and mineralogical analyses, and presents evidence for significant climate change over the past 9,300 years.

The work of Comín and colleagues (Comín *et al.*, 1990) on the Laguna de Gallocanta, Teruel is the only other Holocene core-based research outside the sphere of palynology. They compared a 15-year record of water level and salinity fluctuations with the mineralogy of a 100cm core from the lake but the core was not dated and showed significant evidence for diagenetic change, such that lake-level fluctuations were not recorded.

In spite of their value as palaeosalinity indicators, the potential of diatoms and ostracods for palaeoclimate reconstruction has not been assessed. Diatom and ostracod palaeoecology has been confined to evaporite sequences of the Lower Pleistocene epoch or earlier (Servant-Vildary *et al.*, 1990, De Deckker *et al.*, 1979, Anadón, 1989, 1992). A study of ostracod shell chemistry has been made in a freshwater system mentioned above, the Laguna de Banyoles (Wansard & Julía, 1993), but it was aimed at palaeotemperature reconstruction on a long timescale and was at a relatively coarse resolution.

2.5 DESCRIPTION OF THE STUDY SITE

2.5.1 Introduction

The second part of the thesis (Chapters 6-8) is concerned with the reconstruction of Holocene lake-level change from analysis of a sediment-core collected from a study site chosen as a result of palaeolimnological surveys described in Chapter 5. The geographical and limnological characteristics of this site, the Laguna de Medina, Cádiz, Andalucía, are described in this section.

2.5.2 Location and morphometry

The Laguna de Medina (36°37'18"N, 6°02'48"W) is located in southwest Spain in the municipality of Jerez de la Frontera, province of Cádiz, Andalucía (Figure 2.5). It is 8km to the southeast of Jerez and 16km from the Bay of Cádiz at an altitude of 30m asl and occupies an interfluvial position in gently undulating terrain between the río Guadalete, 3km to the north and the Arroyo Salado, 6km to the south. The lake has an area of 12.13 km^2 and a catchment area of 16 km^2, most of which extends to the south. The lake-bed is flat and Figure 2.5 gives an indication of its elongated, circular shape. A series of

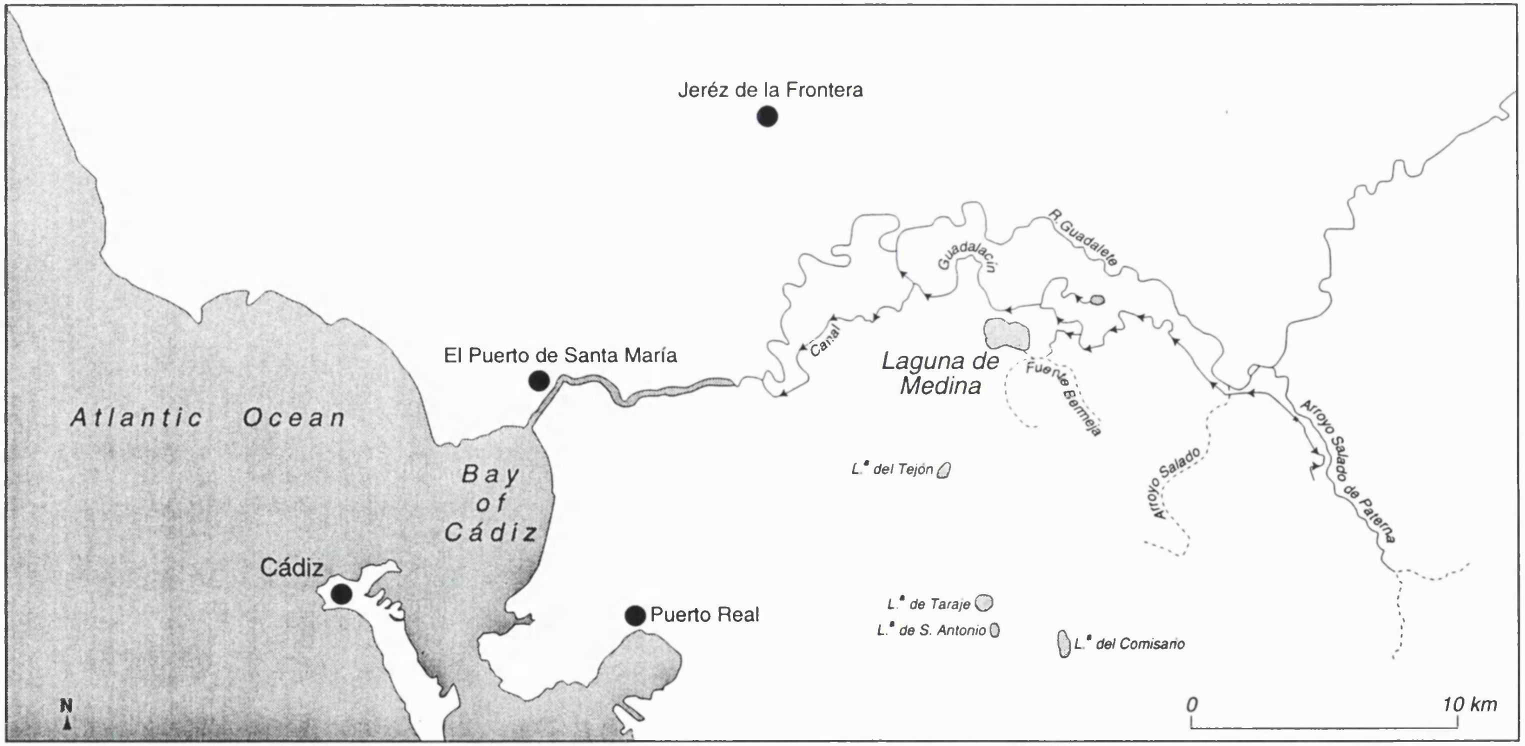
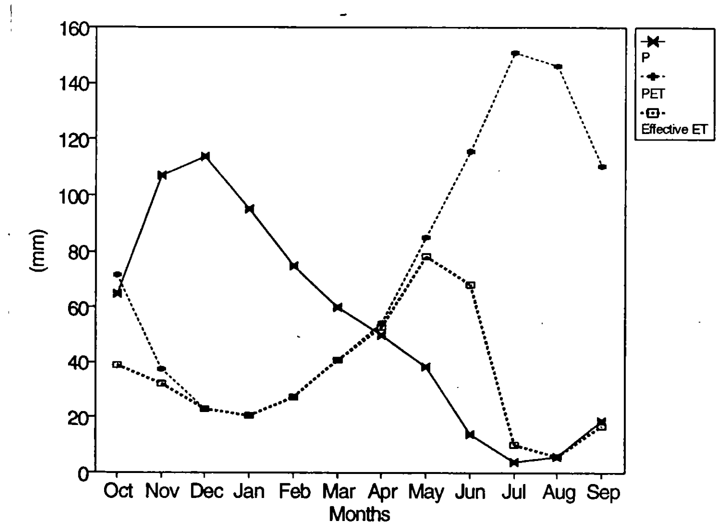


Figure 2.5 Location map of the Laguna de Medina.

Figure 2.6 **Diagram showing the water balance in the locality of the Laguna de Medina, based on monitoring data 5 km from the lake (reproduced from Páez, 1991).**



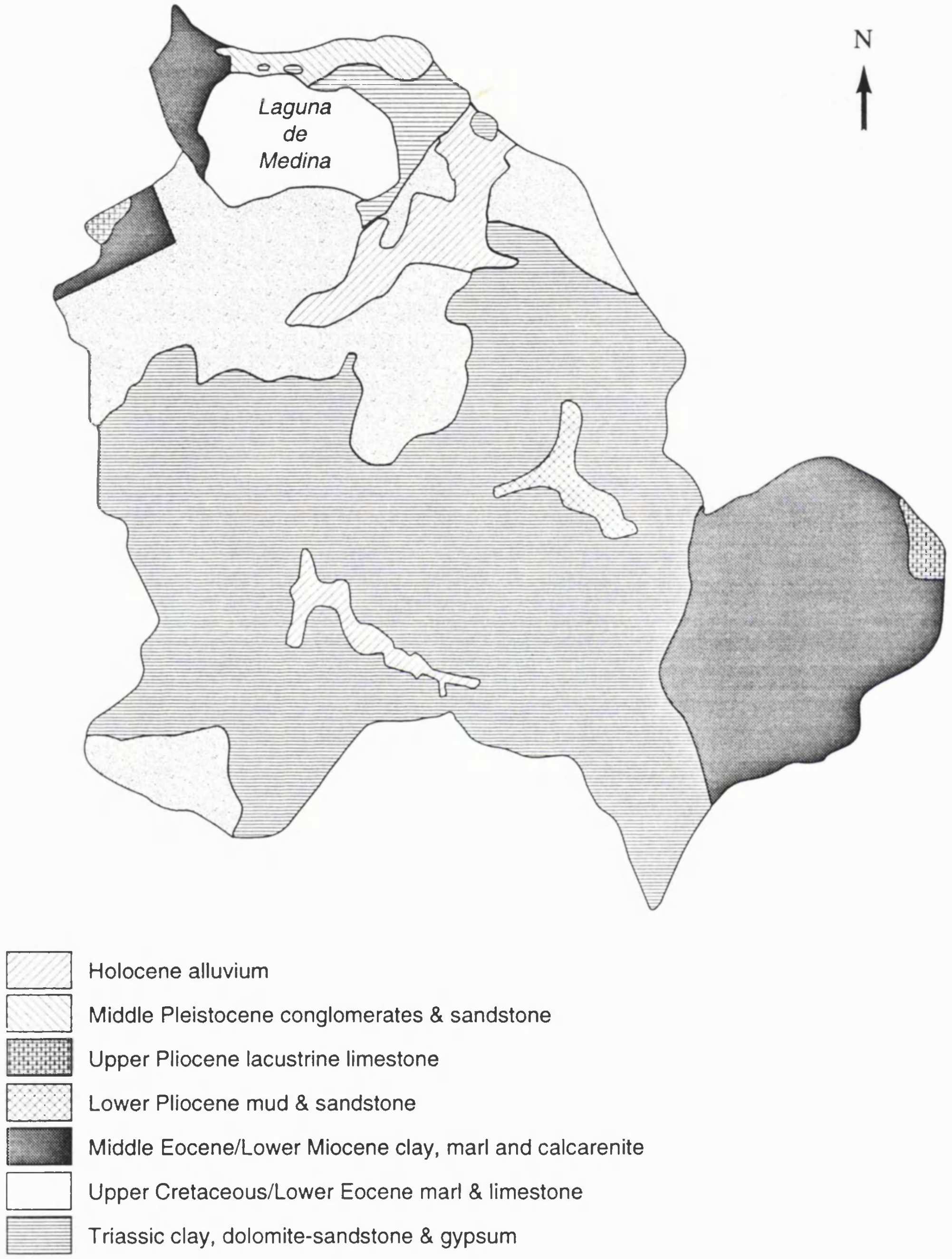
KEY: P = monthly precipitation, PET = potential evapotranspiration, ET = evapotranspiration.

Pleistocene terraces border the northern and part of the southern shores of the lake. The shoreline is relatively flat to the east, west and the southwest.

2.5.3 Climate

The province of Cádiz has a semi-humid, Mediterranean climate in which spring and autumn seasons are poorly-defined. A hot, dry summer extends from April to September and a mild, humid winter from October to April. Continentality is greater inland than on the coast. The pattern of mean annual precipitation in relation to evaporation for the closest monitoring station to the Laguna de Medina (c. 5km away) is given in Figure 2.6 and shows a 5-month summer period of water deficit. Local PET is estimated at around 850-1000 mm yr^{-1} according to different methods and effective evapotranspiration at around 300 mm yr^{-1} (Fernández-Palacios, 1990). 50% of rain falls between November and January;

Figure 2.7 **Map showing the catchment geology of the Laguna de Medina (reproduced from Páez, 1991).**



mean annual precipitation over the last 30 years is 525 mm yr^{-1}, but extremes of 250-975 mm yr^{-1} have been known (Páez, 1991). Mean annual temperature is 17.3°C, with extremes of 11.1°C and 23.5°C. Average minimum temperatures fall to around 6°C during December and January, the coldest months. July and August are the hottest months, during which average temperature is 32-33°C and daily temperatures often exceed 40°C.

Due to the proximity of Cádiz to the Straits of Gibralter and the north African coast, the region is subject to two dominant wind patterns. Atlantic westerlies (the *Poniente*) bring clouds and rain. Very dry winds of variable intensity and originating in the Sahara (the *Levante*) blow in an ESE direction and accentuate the summer water deficit (Páez, 1991).

2.5.4 Local geology, geomorphology and lake origins

The catchment geology of the Laguna de Medina is shown in Figure 2.7. It is more variable than other lakes of Cádiz (Páez, 1991). Much of the catchment is dominated by Triassic clays, gypsum-rich evaporites and Eocene marls; a low ridge of mid Pleistocene sandstone and conglomerates borders its northern shore and Holocene alluvial deposits are centred around an inflow to the southeast, away from the lake shore.

The system is unlikely to have been affected greatly by regional tectonic activity over the Holocene. In contrast to the active tectonism of eastern Andalucía, tectonism in the region of Cádiz is thought to be minimal and has been estimated at around 1cm subsidence per thousand years (Zazo *et al.*, 1993).

On a local scale, however, the results of recent geomorphological studies of the Pleistocene deposits of the river terraces of the río Guadalete (Giles Pacheco *et al.*, 1993a, 1993b, Rodríguez Vidal *et al.*, 1993) suggest considerable deformation in the area due to the plasticity of the underlying Triassic and Tertiary deposits. The origin of the Laguna de Medina itself is thought to be related to subsidence after subsurface dissolution of Triassic evaporites, prior to which the Fuente Bermeja, a temporary *arroyo* which feeds the lake on its southeastern shore, may have been a tributary of the río Guadalete (Fernández-Palacios, 1990).

The evolution of the modern lake basin has been only recently investigated. Rodríguez Vidal *et al.* (1993) propose a mechanism for the origins of the Laguna de Medina based on geomorphological studies of five terraces which form the ridge on the northern shore of the lake, a tentative chronology for which is provided by the inclusion of archaeological remains.

During the Middle Pleistocene, alluvial deposits were laid down which now form part of the highest terrace at +50m, and contain abundant lithic artefacts from the Lower Palaeolithic. They are overlain by a red vertisol of the late Middle Pleistocene. The drainage network then became endorheic for the first time, and lowering of the groundwater table promoted a phase of subsidence by dissolution of gypsiferous deposits, which led to the formation of the Laguna de Medina, following which the uplift of the highest terrace occurred due to diapiric mechanisms and the intrusion of underlying Triassic, marl-rich deposits. Red soils were eroded and deposited as a debris slope as a consequence. The authors suggest these processes triggered renewed small-scale diapiric activity which led to the minor deformation of the basal levels of this unit. At the end of this diapiric phase the 'red unit' continued to develop and extend laterally to form the fourth lowest terrace, at +15m, which contains Upper Achulean lithic artefacts (Middle-Upper Pleistocene).

It is thought that the modern configuration of the lake was established during the late Upper Pleistocene. Deposits of the fourth terrace were eroded laterally by the meandering of the río Guadalete, which led to the deposition of the lowest terrace at +5/10m, containing Middle Palaeolithic artefacts. Renewed karstic subsidence of Triassic gypsum was initiated at the same time, which led to the formation of an escarpment on the northern shore and the deposition of alluvial deposits as a consequence of renewed erosion of slope sediments.

In the context of this study, it is pertinent that the system is thought to have stabilised since the early Holocene, and is overlain by stable soils which contain *in situ* Copper and Bronze Age archaeological industries (c. 3900-2500 BP), but the detailed geomorphological evolution in the earlier Holocene, prior to c. 4000 BP, is yet to be determined.

2.5.5 Hydrology

Pardo (1948) described the Laguna de Medina as permanent rather than ephemeral. At present, it is 'semi-permanent' and dries in severe drought years (e.g. 1977/8, 1980/81 and 1992/1993). Maximum water depth is around 2.2m in the late winter and in wet years such as 1989/1990 it does not fall much below 2m even during the summer (Páez, 1991). Recorded salinity for high lake levels has varied from 1.5 gl^{-1} in March, 1965 (Marazanof, 1967) to c. 6.5 gl^{-1} in March, 1982 (Furest & Toja, 1984), although recent drainage may have increased mean salinity. The lake is eutrophic; nitrate levels are relatively low, but the waters are enriched in phosphorus (Furest & Toja, 1984).

The lake has no outlet and the only inflow other than runoff is through the Fuente Bermeja. Due to substrate impermeability, infiltration and groundwater circulation are reduced and major aquifer input is unlikely. The lake fluctuates considerably from year to year according to changes in effective moisture; direct precipitation and runoff are thought to be the most important inputs (Fernández-

Palacios, 1990), although significant groundwater influence is perhaps suggested by the retention of water in the basin into the summer months. A study is in progress to determine the extent to which local aquifers influence hydrology (Páez, 1991).

2.5.6 Lake vegetation

The natural woodland of the catchment has been reduced to patches of matorral where land is not cultivated. This includes species such as *Pistacia lentiscus*, *Quercus coccifera* and the wild olive, *Olea europaea* (Antuñez et al, 1980). The lakeside vegetation forms an almost continuous belt which varies in composition according to annual conditions. *Phragmites australis* is dominant, with patches of *Scirpus maritimus* and *Typha dominguensis*. *Juncus maritimus*, *Juncus acutus*, *Schoenoplectus lacustris* and *Scirpus holoschoenus* are less frequent. A small patch of *Tamarix africana* occurs on the northwest shore.

Salicornia ramossisima and *Cressa cretica* are abundant on the shoreline in dry years, especially on the flat shoreline to the southwest, with *Frankenia laevis* located at higher levels subject to periodic indundation.

The aquatic flora shows marked annual fluctuations and is dominated by the algae *Chara* and *Cladophora* and the plant macrophytes *Potamogeton pectinatus*, *Zannichelia obtusifolia*, *Myriophyllum spicatum* and *Ceratophyllum submersum* (Fernández-Palacios, 1990).

2.5.7 Land use and human impact

Concerns over wetland conservation in Spain arose only recently. The Laguna de Medina is the most highly protected of twelve lakes in Andalucía declared as Nature Reserves in 1987 and it is included in the list of the European Ramsar Convention for protection of wetlands (Fernández-Palacios, 1990). Hunting and the use of pesticides are controlled in a 254 ha zone surrounding the lake.

Local human occupation is known from the Lower Palaeolithic and Chalcolithic on the Pleistocene ridge adjacent to the lake (Giles Pacheco *et al.*, 1989, 1993a), and there is evidence for continuous human presence in the region since at least 6000 BP (Stevenson & Harrison, 1992).

Although the lake was not protected until recently, the main impact is thought to have been restricted to hunting and fishing, collection of birds' eggs, cutting of reed-beds and the exploitation of the lake-margins, for which there are documentary records from the time of the Arab Conquest in the 10th Century to the present (Granados Corona, 1991). In the recent past, there was concern over the possible ecological impact of dust from a gravel-extraction plant in operation to the north of the lake since the 1960's, until its operations were directed away from the protected zone after 1987 (Nature Reserve Guard, pers. comm.).

Since advanced techniques for water extraction were not developed until recently, any past attempts to drain the lake are thought not to have had a major effect (Granados Corona, 1991). Irrigation has expanded significantly since 1948; a plan to turn the lake into a reservoir was abandoned, but a reduction in water levels has occurred since 1948 due to extraction of water for irrigation from the inflow and the lake itself (Tello Ripa & López Bermúdez, 1988).

The majority of the catchment is dedicated to dry farming of cereals and sunflower. Irrigated farming of cotton, sugar beet and sorghum is concentrated on the alluvial plains of the Guadalete, north of the irrigation canals marked in Figure 2.5.

CHAPTER THREE

METHODS

3.1 INTRODUCTION

This chapter provides a description of the methods used for selection of sampling sites, sample collection, and laboratory analytical techniques for each section of the thesis, which is effectively split into three parts. These comprise the development of a modern diatom training set and derivation of a salinity transfer function (Chapter 4), studies of diatom preservation and the palaeolimnological potential of recent and Holocene lake-sediment sequences (Chapter 5), and analysis of a Holocene sediment sequence from a selected study site, the Laguna de Medina, Cádiz (Chapters 6-8). Data analytical techniques are dealt with separately in the appropriate sections.

3.2 RATIONALE FOR SITE SELECTION

3.2.1 Transfer function: sites used for the modern diatom training set

For collection of a modern diatom data-set, or 'training set', by which to determine diatom response to water salinity, sites were selected along a salinity gradient from fresh (<0.5 gl^{-1} TDS) to hypersaline (>60 gl^{-1} TDS). To test whether there was a significant response to other environmental parameters, the sampling strategy covered the full range of lake-water chemistries, depth and permanence exhibited by salt lakes in this region. Spanish endorheic lakes do not include many fresh, oligosaline, carbonate-dominated or permanent waters. To provide analogues for possible former lake phases sampling was extended to include open karstic systems and permanent artificial water bodies such as reservoirs and coastal salt pans or lagoons.

Sampling sites were selected using data derived from the following:- general summaries (Plans, 1969, Montes & Martino, 1987, Martino, 1988, Comín & Alonso, 1988), regional ecological studies (Baltanás *et al.*, 1990, Torres Esquivias *et al.*, 1989, de Juana, 1990, Margalef, 1947, 1956, Armegnol *et al.*, 1975, Cirujano Bracamonte, 1990, Alonso, 1985, Furest & Toja, 1984, Marazanof, 1965, Bigot & Marazanof, 1967, Balsa *et al.*, 1991, various papers in Troya Panduro & Bernués, 1990) and individual lake studies (e.g. González Martín *et al.*, 1987, Hernández-Pacheco, 1932, Marfil *et al.*, 1975, Moya, 1986). 1:200 and 1:50 scale maps were also consulted. Up-to-date information on recent human impact (e.g. lake desiccation through irrigation) was furnished by Prof. Montes and colleagues of the Universidad Autónoma, Madrid prior to fieldwork in March, 1992 and by conversations with Nature Reserve guards in the field.

A small number of additional surface sediment samples from a range of sites, mainly in the Ebro Basin of northeast Spain, was selected from the data-archives of Newcastle and Durham Universities. These samples are included in the training set.

The resultant data-set is mapped and described in Chapter 4.

3.2.2 Sites used in studies of diatom preservation

3.2.2.1 Introduction

Diatom dissolution is common in saline lake sediments and the limnological factors affecting diatom preservation are poorly understood (Barker, 1992). Since diatom preservation in Spanish salt lakes has not been assessed previously, a comprehensive survey was made of diatom preservation in sediment cores from salt lakes throughout Spain to assess the potential of sites for Holocene palaeoenvironmental reconstruction and to select the study site for detailed analysis. The survey combined screening of short (<50cm) and longer sediment cores and was designed to maximise the number of sites studied while at the same time allowing for assessment of the quality of lake sediments at depth.

The processes of site selection and the range of cores used for each study are summarised below. Distribution maps of sampling sites for each study are given in Chapter 5.

3.2.2.2 Description of Preservation Studies

Preservation Study I: Regional Survey

The Regional Survey incorporated sites throughout Spain and was split into two parts. The first part (Part A) was a preliminary assessment of preservation in long cores from a variety of lakes in the Ebro Basin of northeast Spain and another in La Mancha, based on material selected from the data-archives of Newcastle and Durham Universities. Part B was a comprehensive regional survey of preservation in short cores from lakes throughout Spain other than in the northeast. The sampling strategy for Part B was designed on the basis of the results of Part A to give priority to sites of possible high potential.

Preservation Study II: Long-Core Survey

A limited number of sites was selected for the Long-Core Survey (Study II) as a result of Study I. The

Long-Core Survey involved a detailed assessment of both diatom preservation and overall sediment quality in longer sediment sequences to establish the palaeolimnological potential of these sites. The study site, the Laguna de Medina, Cádiz, was selected for detailed analysis as a result.

Preservation Study III: Factors Affecting Diatom Preservation

The ability to predict diatom preservation in different types of lake would be of value for research into palaeoclimate change. The sediment core data-set provided the basis for a third study to establish the usefulness of the measured lake parameters as predictors of diatom preservation.

The study was concerned with the predictability of preservation in the recent sedimentary environment, based on diatom preservation in a data-set of short cores. A data-set of long, Holocene cores was used to assess its predictability over the long term.

3.2.2.3 Lake basin characteristics as a criterion for site selection

The assessment of the suitability of sites for a Holocene palaeoclimate study took into account other factors likely to affect the reliability of lake-sediment records as indicators of past climate, which are outlined below. While Preservation Study I (the Regional Survey) incorporated a wide variety of lakes, an attempt was made to include in the data-set all those lakes whose basins were identified as of high potential on this basis, and the same factors were taken into account in selecting a sub-set of sites for Preservation Study II (the Long-Core Survey) and in selecting the study site itself.

- *Hydrology and lake origins.* Palaeoclimate reconstruction from palaeosalinity data assumes a simple relationship between water salinity, lake levels and effective moisture (Street-Perrott & Harrison, 1985). This can be affected by changes in salinity consequent upon other factors independent of climate such as groundwater inflow or outflow independent of climate, or by subsidence. Although some tectonic basins may exhibit significant groundwater outflow, basins of tectonic or volcanic origin were regarded in this study as more likely to be stable than karstic salt lakes undergoing continuous subsidence, and were given special emphasis. Karstic lakes known to be dominated by major aquifer flow were excluded.

- *Basin morphology.* Very few studies of Spanish salt lake sediments have been made previously. In the absence of published data on basin sediment depth and quality, those with moderately steep sides were regarded as more likely to provide a high-resolution stratigraphic record than flat-bottomed basins in which sediment focussing is reduced and changes in the volume of lake waters are less likely to result in major changes in lake-level (Street-Perrott & Harrison, 1985).

- *Human impact.* Lakes where human impact such as salt extraction or dyke-building had caused major sediment disturbance were excluded. The influence of recent human impact on current lake status was taken into account; lakes which had been artificially-desiccated through irrigation or drainage were retained as potential sources of high-quality sediments at depth.

3.3 FIELD METHODS

3.3.1 Access

Access to individual lakes in the nature reserves of Andalucía was granted by kind permission of the local environmental agencies through the assistance of Prof. Montes of the Universidad Autónoma, Madrid.

For other lakes with restricted access the local landowners or reserve guards were contacted at the time of sampling. In most cases access was granted to take at least a lake edge surface sample. Access was refused to visit volcanic lakes within bull-breeding grounds southwest of Madrid, and the hunting grounds on the site of the former Laguna de la Janda, Cádiz.

3.3.2 Collection of modern data for the diatom transfer function

3.3.2.1 Surface sediment samples

Other than surface sediment samples selected from the Newcastle and Durham University data-archives (sampling dates of 7/90, 4/91, 7/91 and 9/91), the majority of surface sediment samples was collected during fieldtrips in Spring, 1992. The data-set was expanded during the summers of 1992 and 1993. A small number of samples was collected during visits to Spain in December, 1991 and August, 1992.

Most samples were 0.5cm subsamples from sediment cores taken using methods described below (3.2.3). These were collected from the centre of lakes where possible to obtain a modern diatom assemblage most likely to be representative of the lake flora as a whole (Charles, 1990). Where coring with a boat on deeper lakes was prohibited or not feasible due to high winds, a core or c. 0.5cm depth epipelon sample (mud/clay habitat) was taken at the lake edge. Samples from Newcastle University comprised 0.5cm depth gravity corer surface samples or c. 0.5cm depth samples collected manually from the sediment surface; those from Durham University comprised 1cm depth gravity corer surface samples or c. 4cm depth samples collected manually.

3.3.2.2 Benthic samples

To obtain modern ecological data on diatoms of different habitats, used for interpretation of diatom species distribution according to habitat preference in Chapter 4, additional benthic samples were collected from each diatom habitat represented. Epipelon (mud/clay) samples were collected from below the water line at the lake edge. Others were collected from damp mud on the lake shore for information on aerophilous diatom communities. Rarer epiphyton (plant) or epipsammon (sand) communities were sampled, selecting relatively clay-free plant specimens and rinsing the sand several times to eliminate allochthonous diatoms.

3.3.2.3 Water chemistry and water quality

Conductivity was measured in the field using pHOX 52E and Jenway meters, and pH with a Beckman meter. 0.5 litre water samples were collected in acid-washed plastic bottles at the sediment sampling point for laboratory analysis of major ions and filtered through a 0.45µm mesh within 12 hours. ⑳ Two samples (ELLL1 4/92 and CGSQ3 8/93) were impossible to filter due to the content of suspended sediment and crystallised salts respectively.

An attempt was made to assess turbidity using a secchi disc. Most lakes were either shallow and clear enough for the lake-bed to be visible or were sufficiently wind-stressed that the disc would not remain vertical. A qualitative assessment of turbidity and water clarity was made instead.

3.3.3 Collection of modern ostracod samples

Modern ostracod samples were collected from permanent, accessible saline water bodies in Summer, 1993 to assess the variability of ostracod shell chemistry in a living population of the genus used for shell chemistry analysis. Multiple 0.5cm depth surface sediment samples were collected with the Glew corer (Glew, 1991), and combined with the residue collected after sieving a large volume of water through a 250µm mesh. To preserve body parts intact, samples were preserved in Lugol's iodine solution.

3.3.4 Collection of sediment cores for preservation studies

3.3.4.1 Coring techniques

Table 3.1 summarises the coring techniques which were used according to differences in sediment texture and water depth. Sediment texture was variable and within single cores alternated between soft and hard units with intermittent bands of solid salt crystals. Cores were taken from open water or the sediment surface (soft, recently wet or hard, dry) depending on the current state of the lake.

3.3.4.2 Cores for Preservation Study I (Regional Survey)

Long cores from Newcastle and Durham Universities were used for Preservation Study I, Part A (sampling dates of 7/90, 7/91 and 9/91), while the bulk of the data-set for the Regional Survey comprised short (<50cm depth) cores which were collected for Part B in Spring, 1992 (27 March to 12 April).

Table 3.1 Summary of coring techniques

CORING TECHNIQUE	SEDIMENT TYPE	LAKE TYPE	CORE LENGTH	CORE DIAMETER	EXTRUSION INTERVAL
Glew gravity corer (Hongve gravity corer) (Kajak gravity corer)	Soft surface sediment	Recently dry (soft sediment) or wet, any water depth	0.5m	5.5cm	0.5cm: surface 1cm: remainder
Modified Livingstone piston corer (perspex tube and piston bung)	Soft surface sediment	Wet, any water depth	1m	7.4cm	0.5cm: surface 1cm: remainder
Livingstone piston corer with Cobra leverage extraction	Soft sediment at depth	Dry or wet, any water depth	>10m	5cm	1cm
Cobra percussion corer with leverage extraction	Hard sediment	Dry or wet, <1m water for deep cores	c. 10m max	6cm	2cm
Hiller with manual extraction (back-up technique)	All	Dry	c. 5m max	4cm	2cm
Screw auger with manual extraction (back-up technique)	All	Dry	c. 2m	10cm	c. 2cm
Trowel hole 'section'	Hard surface sediment	Dry	c. 0.3m	N/A	2cm

Both the Glew gravity corer (Glew, 1991) and modified Livingstone corer (a 1m long perspex tube and piston bung designed by the laboratory at UCL for taking large-volume surface sediment samples, and operated on the same principles as the chamber described in Livingstone, 1955) take undisturbed samples of the sediment-water interface, important for obtaining a representative modern surface sample. The modified Livingstone corer provides more sediment but is cumbersome in shallow water. Since diatom analysis does not require much sediment, short cores were collected using the Glew corer for Preservation Study I, Part B and to provide the bulk of the modern diatom data-set. The Hongve (Wright, 1990) and Kajak gravity corers operate on similar principles and were used by Durham and Newcastle Universities respectively to sample surface sediment. Dry sites were sampled from a cleaned section of a small pit ('trowel samples').

Coring was conducted from an inflatable boat in waters >1m deep and the core tube was pushed manually into the sediments of shallow lakes, or lakes without a measurable water depth but in which surface sediments were soft, using the core bung to create a vacuum after insertion. Extrusion was carried out in the field; the top 1cm was subsampled at 0.5cm intervals to provide surface samples, and the remainder at 1cm.

3.3.4.3 Long cores for Preservation Study II

Long cores for Preservation Study II (Long-Core Survey) were collected in Summer, 1992 (1-15 July). Surface cores were taken with the modified Livingstone or Glew corers. Since the Hiller corer and screw auger provide small sediment samples with a high risk of contamination and are difficult to take deep cores with, the Livingstone lightweight piston corer (Livingstone, 1955) and Cobra 2-stroke percussion corer with 1m gouge attachment ('COBRA 148', Berema AB, Sweden) were used thereafter by preference. Coring techniques alternated according to sediment type; the Cobra percussion corer has an open chamber gouge and will penetrate very hard sediments but will not hold soft sediment; the closed chamber of the Livingstone corer passes easily through soft sediment but the chamber and alloy rods are easily damaged in hard sediment.

Cores were taken from a single borehole. The Cobra leverage system was used to extract both types of core to overcome difficulties of lifting them from deeper levels. For this a stable platform was necessary; a wooden platform with a hole at its centre was located on the lake bed in shallow (<1m deep) or dry lakes. A raft was used in deeper lakes, although this was insufficiently stable for use of the Cobra in sediments >2m below the sediment surface.

Both corers may cause some compression when used on sediment with hard gypsum bands, so the depth of each section was calculated from the core base. Livingstone cores were extruded in their entirety into plastic drainpipe and wrapped in plastic film for storage. Following lithostratigraphic description modified Livingstone, Glew and Cobra cores were extruded in the field at 1cm, 1cm and 2cm intervals respectively, taking the top 0.5cm for surface sediment. The top c. 10cm of each Cobra gouge was highly unconsolidated; this was probably contaminated so was discarded along with a thin layer of sediment in contact with the chamber which was scraped off the consolidated sediment slices with a clean spatula. The base of the core was cleaned to remove any contaminated sediment which may have fallen down the borehole.

3.3.4.4 Long core for Holocene study (the Laguna de Medina)

Cores were collected from the selected study site, the Laguna de Medina, Cádiz, Andalucía, in Summer, 1993 (13-15 August). The coring strategy reflected the need for a continuous, uncontaminated sequence and an increased sediment volume for radiometric dating.

Parallel cores were collected from three boreholes located within 1m of each other (DMDN2, DMDN3 and DMDN4) at the centre of the dry lake-bed. Core sections from one of the boreholes were offset initially by 50cm to avoid core-breaks occurring at the same sediment depth across the three cores.

3.4 LABORATORY METHODS - TRANSFER FUNCTION

3.4.1 Water chemistry analysis

The anions Cl^-, SO_4^{2-} and NO_3^- were analysed on the Dionex Ion Chromatograph of the Geology Dept, UCL. A standard was run every 8 samples for drift correction (20ppm SO_4, 10ppm NO_3, 5ppm Cl and PO_4 and 1ppm F). Sulphate and chloride are two major anions contributing to lake-water salinity; in order that their concentrations fell within detection limits dilutions were made using deionised water according to sample salinity, ranging from x10 on fresh water to x20,000 on hypersaline. As a result nitrate concentrations were below detection in many samples. Facilities to analyse trace concentrations of phosphates separately were not available. Unfiltered samples (ELLL1 and CGSQ3) and hypersaline samples with extensive salt precipitation on the bottles (ETRZ1, EPNH1 and EQUE1) were not analysed.

Alkalinity titration was performed by the Department of Agriculture's Freshwater Fisheries Laboratory at Pitlochry, Scotland, using a Radiometer TTT88 Titration System with a remote reference electrode with a 40cm KCl head (HMSO, 1982).

Major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+ and Sr^+) were analysed on the inductively coupled plasma atomic emission spectrometer ('ICP-AES') of Kingston University. To calibrate the machine two standards (50ppm Ca, Na and Mg, 5ppm K and 0.5ppm Sr for one, and twice the dilution for the other) and an

HCl blank were used. The first standard was run every twelve samples during analysis to enable drift-correction. Molar anion and cation sums were calculated and used to check ionic balances.

3.4.2 Diatom analysis

3.4.2.1 Slide preparation

Slides were prepared from all surface sediment collected, including those which were dry at the time of sampling. Diatom slides were prepared by standard methods (Battarbee, 1986) from c. 0.2g of wet sediment. Hot H_2O_2 followed by HCl were used to remove organics and carbonates. Samples were cleaned by centrifuging up to eight times for four minutes at 1200 rpm with distilled water, a method which allows clay particles in suspension to be decanted off and is unlikely to cause significant loss or breakage of diatom frustules (Juggins, 1988). Naphrax was used as a mountant in slide preparation.

Several different concentrations were prepared to attain maximum diatom concentration without their being obscured by mineral particles.

3.4.2.2 Counts

All slides were counted using a Leitz Ortholux light microscope at a magnification of x1000. 500 valves were counted where possible, or 300 valves in well-preserved samples dominated by 3 species or less. For some poorly-preserved assemblages only 100-250 valves were counted. Diatoms were classed as 'present' in poorly-preserved assemblages when it was not feasible to count 100 valves; many of these consisted almost entirely of dissolved fragments of *Campylodiscus clypeus.*

3.4.2.3 Nomenclature and taxonomy

The main diatom floras consulted were Krammer & Lange-Bertalot (1986, 1988, 1991a, 1991b), Gasse (1986), Archibald (1983) and Germain (1981). Other key references included Ben Khelifa (1989), Ubierna León & Sánchez Castillo (1992), Noël (1984), Sabater *et al.* (1990) and Schoeman & Archibald (1988), together with individual papers mentioned in the text.

Diatom nomenclature follows Krammer & Lange-Bertalot (1986-1991) ('KLB' hereafter) for most taxa. Taxa not included in these volumes are named according to individual taxonomic references. Diatom nomenclature also follows imperatives set up within the CASPIA Project (Juggins *et al.*, 1994), which aims to harmonise the taxonomy of salt lake diatoms worldwide. Some common taxa regarded as a single species by CASPIA have distinct forms in the Spanish data-set and have been separated into varieties.

For difficult taxa, diatoms are described as 'cf.' where the species differs only slightly in size or shape from published descriptions, or where taxa notoriously difficult to distinguish from closely-related taxa are not present in sufficient abundance in the data-set to confirm the identification, but which match the published description.

Diatoms are described as 'sp.', followed by a number and sometimes a description in brackets, where identification to species level is more uncertain. These comprise unidentifiable but distinct taxa, fragmented valves for which the features necessary to distinguish between two possible species were missing, and taxa of variable morphology which did not match any single description of related taxa closely enough to assign a specific name. Unidentifiable taxa which were rare are grouped into a general 'sp.' category for the genus.

Taxonomic descriptions are given below for common taxa which are taxonomically difficult or whose nomenclature diverges from KLB or CASPIA guidelines.

GENUS *ACHNANTHES*

Achnanthes fogedii Håkansson 1978

Achnanthes fogedii was described from Holocene fossil assemblages in estuarine sediments of southern Sweden and no reference to its presence in modern diatom assemblages has been found by the author. Valves are elliptical, c. 7-9μm x 4.5-5μm, striae 22-25/10μm. Under the light microscope the rapheless valve appears almost as a hyaline plate since the very short striae are indistinct. The valve face is undulating and striae on the raphe valve are interrupted; this characteristic separates it from the similar species *A. holsatica* Hust. (Hustedt 1936 Tab. 407) (Håkansson, 1978).

GENUS *AMPHORA*

Amphora arcus var. *sulcata* (A. Smith) Cleve

The morphology of this taxon (Kaczmarska & Rushforth, 1983) was confirmed by reference to archive material from Tunisia, housed in the Laboratoire d'Hydrologie, Université de Paris-Sud, France and published in Ben Khelifa (1989).

Amphora coffeaeformis/acutiuscula group:-

- *Amphora coffeaeformis* (Agardh) Kützing. 1844

(Syn. *Frustulia coffeaeformis* Agardh 1827, *Amphora salina* W. Smith 1853)

- *Amphora acutiuscula* Kützing. 1844

(Syn. *A. coffeaeformis* var. *acutiuscula* (Kützing) Rabenhorst 1864)

- *Amphora* sp. 1 [cf. *acutiuscula*]

KLB (1986) regards *Amphora acutiuscula* as a variety of *A. coffeaeformis*. In the Spanish data-set valves of *A. coffeaeformis* have well-defined lineate striae and a gap in the striae at the centre of the ventral margin; the raphe is straight, filiform and close to the ventral edge as described in Archibald & Schoeman (1983). Valves of *A. acutiuscula* have more robust, punctate striae and a gap in the ventral striae is not always present; the raphe is filiform but curves upwards towards the valve centre. Gasse (1986) found the two species to differ in their ecological tolerances and they have been maintained as separate species here.

Valves of *A.* sp. 1 were of length 20-33µm, valve width 5-6 µm and had weakly punctate dorsal striae of density (18) 22-30/10µm. There was no gap in the ventral striae and the filiform raphe was strongly arched. The valve dimensions fall within those of *A. coffeaeformis* described in Archibald & Schoeman (1983) (length 13-60µm, valve width 4-9µm, striae (16) 17-24 (26)/10µm at the centre and (20) 22-30/10µm at the ends), but the raphe and ventral area of Spanish specimens differ from the type description. The latter characteristics show closer affinities with *A. acutiuscula*, but this species is more robust (striae density in descriptions by various authors of '*A. coffeaeformis* var. *acutiuscula* are given in KLB (1986 p. 348) and range from 10-21/10µm.

Valves of *A. acutiuscula* were separated from valves of a similar robust, punctate species, *A. holsatica*, by their smaller size (*A. holsatica* length 25-48µm) and by the coarse, punctate girdle bands of the latter (KLB, 1986, Tab. 152, Figure 1).

<u>*Amphora libyca* Ehrenberg 1840</u>

(Syn. *Amphora affinis* Kützing 1844; *Amphora ovalis* var. *affinis* (Kützing) Van Heurck 1880; *Amphora ovalis* var. *libyca* (Ehrenberg) Cleve 1985; *Amphora ovalis* var. *pediculus* (Kützing) Cleve 1895, non (Kützing) Van Heurck 1885)

Two forms of *Amphora libyca* were found in the Spanish data-set which differed in size and robustness and were distinct:- *A. libyca* var. 1 [large] (length 35-55µm, width 6-8µm, cf. KLB, 1986, Tab. 149, Figure 4) and *A. libyca* var. 2 [small] (length 20-30µm, width 5-8µm, cf. KLB, Tab. 149, Figure 6).

Since the central area of the large variety only was preserved in the most poorly-preserved fossil assemblages, as inflated central raphe terminals with some dorsal striae, the two forms were maintained as separate entities.

In dissolved assemblages there was a possibility of confusion with centres of a species of similar morphology, *A. ovalis* (Kutzing) Kutzing 1844, but since all valves which were sufficiently preserved had the gap in the dorsal striae characteristic of *A. libyca*, all were assigned to this species. It was separated from dissolved centres of *A. commutata* Grunow 1880 by the heavily silicified, sharply-curved central raphe terminals and lineate striae of the latter.

Amphora margalefi var. lacustris Sánchez 1993

This diatom was described from the waters of two lakes in the Spanish data-set in Málaga, Andalucía (the Lagunas Chica and Grande, Archidona, BCCA and BGDE) and the species and its variety are known only from Spain at present (Sánchez Castillo, 1993).

From the type description, frustules are linear-elliptical with rounded or +/- rostrate ends (length 18-27µm, valve width 3.1-4.9µm, dorsal striae 18-20/10µm). The ventral margin is distinctly convex and the straight, filiform raphe is located at the centre of the valve. The dorsal striae are variable, and there are none on the ventral side of the valve.

Specimens in the Spanish data-set were found both in these lakes and in others such as the Laguna Amarga, Córdoba (AAMA). Valve dimensions were more variable than in the published description:- length 12.1-22µm, width c. 3µm and dorsal striae 18-28/10µm. These dimensions overlap the description of *A. margalefi* Tómas from the Cape of Creus Peninsular, northeastern Spain (length 6.7-15.8µm, valve width 2.4-3.4µm, dorsal striae 25/10µm) (Sabater *et al.*, 1990). Its variability is poorly-known at present and the two varieties may be synonymous, although they have been separated under the SEM also on the basis of the number of puncta per row in the striae (1-3 in the type species and 3-7 in the variety). The variety *lacustris* has been adopted here to be in accord with its description from the same lakes.

Amphora sp. 2 [cf. tenarescens/tenerrima]

Small *Amphora* species of similar morphology to the *A. coffeaeformis/acutiuscula* group (min. length <13µm, dorsal striae 22-30µm) occurred at low frequency (5% max. abun.) in the Spanish data-set. Small *Amphoras* are poorly-described at present and they were therefore assigned to an indeterminate category.

Amphora veneta Kützing 1844

This species is highly variable and characterised by a zone of more widely-spaced, more coarsely punctate striae at the centre of the dorsal valve (length 5-60µm, valve width 3-8µm, dorsal striae 19-30/10µm within central striae). Two distinct forms were recognised in the data-set. *Amphora veneta* var. 1 [large] (length 26.5-59µm, width 6.6-10µm, dorsal striae 12-20/10µm at centre cf. KLB, 1986, Tab. 151, Figure 13) had rostrate poles and in some valves dorsal striae coarser than the type description. *A. veneta* var. 2 [small] (length 15-30µm, width 4.5-5.5µm, dorsal striae 24-28/10µm at centre, cf. KLB, 1986, Tab. 151, Figures 9, 14-16) had blunt poles and matched closely the type description. Some specimens of *A. veneta* var. 1 [large] opened to a semi-circular central area on the dorsal side of the valve, whereas the dorsal axial area was consistently narrow in *A. veneta* var. 2 [small].

There may be some confusion between *A. veneta* var. 1 and *A. subcapitata* (Kisselev) Hustedt 1959, length 45-80µm, valve width 9-13µm, dorsal striae 10-12/10µm at centre. Some valves combined a rounded dorsal central area around which the striae were most widely-spaced (12/10µm) and poles drawn out as in *A. subcapitata*, but the size range of a single population in HLCA ranged from length 26.4-43µm and was therefore too small for *A. subcapitata*. Valves which overlap characteristics of both species were found also in the British Columbian salt lake data-set (Cumming *et al.*, 1995) and were denoted 'sp.'. The characteristics were not constant enough in the Spanish data-set to separate another variety.

GENUS *BRACHYSIRA*

Brachysira vitrea/aponina group:-

- *Brachysira vitrea* fo. *lanceolata* (Mayer) Schoeman & Archibald 1988
(Syn. *Anomoeoneis exilis* fo. *lanceolata* Mayer; *Anomoeoneis vitrea* (Grunow) Ross)
- *Brachysira aponina* Kützing 1836
(Syn. *Navicula aponina* (Kützing) Kützing 1844)

In contrast to the generic structure proposed by KLB (1986), Schoeman & Archibald (1988) follow Round & Mann (1981) in separating *Brachysira vitrea* from members of the genus *Anomoeoneis* and suggest it has strong affinities with *B. aponina*. In addition to specimens which match well the species *B. vitrea*, some populations in the Spanish data-set are lanceolate and lack the capitate poles of *B. vitrea*, and are separated here as fo. *lanceolata*. Their morphology is less variable than the specimens depicted in Schoeman & Archibald (1988); all have dense striae and the poles are blunt rather than slightly rostrate (cf. Schoeman & Archibald, 1988, Figures 58 & 60). Striae density in the Spanish data-set ranged from 30 to >35/10µm (uncountable).

The valve dimensions of *B. vitrea* fo. *lanceolata* (length 12.5-32µm, width 4-5.5µm, striae (32) 34-37/10µm) overlap those given in KLB (1986) for *B. aponina* Kützing 1836 (length 14-35µm, width 4-5.5µm, striae 35-42/10µm, KLB, 1986, Tab. 93, Figures 8-9). The main difference is in striae density and no other morphological traits appear to distinguish it under the light microscope; Patrick & Reimer (1966, p. 380) suggest the criteria which separate *B. aponina* from similar *Brachysira/Anomoeoneis* taxa are unclear. Specimens of *B. aponina* were found in the Laguna Salada de Chiprana (HSAL) and their identification was confirmed by comparison with material from North America (Fritz, unpubl. material). The valve striae were so dense as to appear 'black' under the light microscope. They were therefore separated from those designated *B. vitrea* fo. *lanceolata* in which the striae were discernible. Sites in which the latter were found included lakes in Málaga from which *B. aponina* had been reported (Ubierna & Sánchez Castillo, 1991).

GENUS *CYCLOTELLA*

C. choctawhatcheeana Prasad *et al.* (1990)

This taxon is synonymous with *C. caspia* in the North American, Northern Great Plains training set and in fossil African sequences (Carvalho *et al.*, in press); the morphological identity of the Spanish taxon was confirmed at the CASPIA Workshop, Paris, 1993.

Cyclotella distinguenda Hustedt 1927

(Syn. *Cyclotella operculata* auct. *non* (CA Agardh) Brébisson; *Cyclotella tecta* Håkansson & Ross 1984)

Spanish specimens (diameter 7-25µm, striae 12-14/10µm) matched well the type description. The undulating, hyaline central area had a single puncta in some of the smallest specimens which is characteristic of the variety *unipunctata,* but the feature was not constant and small specimens were only found as part of populations dominated by larger valves. Since KLB (1991) note the variability of the central area in this species, all specimens were classed as *C. distinguenda.*

GENUS *DIPLONEIS*

Diploneis didyma (Ehrenberg) Ehrenberg 1854

(*Navicula* [*Pinnularia*] *didyma* Ehrenberg 1841)

The taxonomic identification of *D. didyma* was made on the basis of the less pronounced constriction at the valve centre compared to the similar taxon *D. bombus* Ehrenberg (Van der Werff & Huls, 1957-1974), and matched well the description in KLB (1986). KLB's specimen is intermediate between the two taxa depicted in the former reference, however, and the taxon is morphologically identical to the diatom designated *D. bombus* from the latter reference in the Tunisian material (L. Ben Khelifa, pers. comm.).

GENUS *FRAGILARIA*

Fragilaria fasciculata (C. Agardh) Lange-Bertalot 1980 sensu lato

(Syn. *Diatoma fasciculatum* C. Agardh 1812; *Diatoma tabulatum* C. Agardh 1832; *Synedra fasciculata* (Agardh) Kützing excl. descr. et excl *Synedra fasciculata* Ehrenberg 1832; *Synedra affinis* Kützing 1844; *Synedra hamata* W. Smith 1853)

Two forms in the Spanish data-set fall within the type description, but are distinct. *Fragilaria fasciculata* var. 1 refers to the typical, robust species depicted in KLB (1991) Tab. 135 Figure 14. *Fragilaria fasciculata* var. 2 refers to valves of similar dimensions but with finer striae thickness and which resembled specimens in KLB (1991) Tab. 135, Figures 6-7.

Fragilaria ulna var. *acus* (Kützing) Lange-Bertalot 1980

(Syn. *Synedra acus* Kützing 1844; ?*Synedra delicatissima* W. Smith 1853)

Fragilaria ulna var. *acus* has been merged into the complex of *Fragilaria ulna* by KLB (1991). The morphology of the finer *F. ulna* var. *acus* was clearly distinct from the robust *F. ulna* in the Spanish data-set and they were maintained as separate varieties.

GENUS *MASTOGLOIA*

Mastogloia smithii var. *lacustris* Grunow 1878

Mastogloia smithii var. *lacustris* is separated from *M. smithii* var. *smithii* in KLB (1986) on the basis of striae density (striae ≤18/10µm in the former and ≥18/10µm in the latter, and by the shape of the valve ends (blunt versus +/- capitate). Valves of striae ≥18/10µm occurred with +/- capitate ends in the Spanish data-set and therefore overlapped traits of both varieties. They resembled closely those depicted in Gasse (1986) as *Mastogloia smithii* var. *lacustris*; the two varieties are not separated in the by CASPIA and the variety *lacustris* is the only species name adopted here.

GENUS *NAVICULA*

Navicula cryptotenella Lange-Bertalot 1985

(Syn. *Navicula tenella* (Brébisson ex Kützing 1849 sensu Grunow 1880; *Navicula radios* var. *tenella* (Brébisson ex Kützing) Van Heurck 1885)

The type species is described as lanceolate with acute ends and variable dimensions (length 14-40µm, width 5-7µm, striae (12) 14-16 (18)/10µm) and has a small, irregular central area and striae radial at the centre to parallel at the ends.

Two distinct varieties were recognised in the Spanish data-set, the smaller *N. cryptotenella* var. 1 [classic] (length 18-33µm, width 5-6µm, striae 14-16/10µm, cf. KLB, 1991, Tab. 60, Figures 1-4) and a coarse variety, *N. cryptonella* var. 2 [large] (length 32-48µm, width 7.5-8.5µm, striae 11-13µm) which exceeds the published valve dimensions but which matches the description closely in other respects.

Navicula cuspidata (Kützing) Kützing 1844

(Syn. *Frustulia cuspidata* Kützing 1833; *Navicula cuspidata* var. *ambigua* (Ehrenberg 1843) Cleve 1894; *Navicula cuspidata* var. *heribaudii* M. Peragallo; *Navicula accurata* Hust. 1950)

Two distinct varieties were recognised in the Spanish data-set, a 'classic' variety with +/- parallel striae, *Navicula cuspidata* var. 1 [classic] (cf. KLB 1986, Tab. 43, Figures 1-4) and another with extreme radial, irregular and widely-spaced striae, *N. cuspidata* var. 2 [splayed] (cf. KLB 1986, Tab. 43, Figures 5-7).

They were separated from *N. halophila* by the presence of a chambered craticula, and by their parallel striae at the poles compared to the slightly radial striae in *N. halophila.*

Navicula duerrenbergiana Hustedt in Schmidt *et al.* 1934

Specimens occurred at low frequency in the data-set which matched closely the description of *Navicula duerrenbergiana.* More commonly a central stria was shortened on one side of the valve at the centre. Since this is a characteristic regarded as species-specific in similar taxa such as *Navicula perminuta,* they were maintained as a separate entity, *N.* cf. *duerrenbergiana.*

Navicula halophila (Grunow) Cleve 1894

(Syn. *Navicula cuspidata* var. *halophila* Grunow in Van Heurck 1885; *Navicula halophila* var. *subcapitata* Ostrup 1910; *Navicula buderii* Hustedt 1954; *Navicula halophila* f. *robusta* Hustedt 1959;

Navicula pseudohalophila Cholnoky 1960; *Navicula adsidua* Archibald 1971)

Three varieties were recognised in the Spanish data-set, none of which matched closely taxa with which this taxon has been confused such as *N. ammophila*, *N. elkab*, or *N. halophila* f. *tenuirostris*. The most common form, *N. halophila* var. 1 [small] (length 20-26µm, width 6.5-8µm, striae 20-24/10µm) was elliptical to linear-lanceolate with fine, parallel striae becoming slightly radial at the poles. Specimens of similar morphology, but length c. 30-45µm were designated *N. halophila* var. 3 [large]. Infrequent linear-lanceolate valves with more radial, irregular striae, a relatively broad central area and rostrate poles (cf. KLB 1986, Tab. 44, Figure 18) were designated *N. halophila* var. 2.

Navicula phyllepta Kützing 1844

(Syn. *Navicula minuscula* var. *istriana* Grunow in Van heurck 1880; *Navicula lanceolata* var. *phyllepta* (Kützing) Van Heurck 1885)

Specimens described as *Navicula phyllepta* (length 17.5-30.5µm, width 6-8µm, striae 15-18/10µm) matched closely the dimensions of the type description, and had a characteristically small central area and striae slightly radial at the centre to parallel at the poles. Valves were lanceolate and the frustule margins did not have any distinct angles, as in the type species, but they lacked the characteristically drawn out ends (cf. KLB, 1986, Tab. 32, Figures 5-11). The striae at the centre were typically all of the same length, but in some specimens 1-2 striae were shortened on one side of the valve; some of the specimens in KLB (1986) show the same trait.

This species resembled closely the 'blunted' *N. phyllepta* depicted in Gasse (1986, Plate XVIII, Figure 1), so the species designation has been maintained here.

Navicula cf. *salinicola* Hustedt 1939

Specimens described here as *Navicula* cf. *salinicola* (length 12-27µm, width 4-5 (6)µm, striae 12-15/10µm) are typically lanceolate with acute ends, as in the type species, but in single populations include valves with +/- parallel sides and blunt ends. They are larger and coarser than the type species (length 7-17 (20)µm, width 2-3 (4.5)µm, striae 17-20/10µm).

The taxon resembled closely *Navicula* sp. 2 (af. *salinicola* Hüst.) from Afar in Gasse (1986, Plate XVIII, Figures 7-13), where it is suggested that the variability in valve dimensions for this species probably exceeds that given in the type description.

Navicula sp. 2 [af. *cryptocephala/salinarum*]

Specimens designated *N. salinarum* Grunow in the data-set matched the type description closely and were distinct from this species.

Navicula sp. 2 (length 19.5-28µm, width 7-7.5µm, striae 15-17/10µm) did not match any described taxa closely enough to be assigned a specific name. Valves were elliptical-lanceolate and the dimensions fitted closely those of *N. cryptocephala* (length 20-40µm, width 5-7µm, striae 14-17/10µm) but the poles varied from acute to slightly capitate in contrast to the thin, drawn out rostrate ends characteristic of the type species depicted in KLB (1991, Tab. 64, Figures 1-8). The central area of some specimens was small, +/- circular and asymmetrical, as in *N. cryptocephala*, and matched well the extreme specimen in KLB (1991, Tab. 64, Figure 5), but in others was more irregular. The strongly lineate striae were strongly radial at the centre to converged at the ends, as in *N. cryptocephala* and *N. salinarum*, and the valve morphology overall bore more resemblance to a small variety of the latter.

GENUS *NITZSCHIA*

Nitzschia compressa var. *vexans* (Grunow) Lange-Bertalot 1987
(Syn. *Nitzschia obscura* Grunow; *Nitzschia vexans* Grunow in Van Heurck 1881)

Populations exhibited a continuum of variability from characteristic elliptic valves to linear-elliptic forms which resembled *Nitzschia punctata* fo. *minor* in Gasse (1986) but which were not separated here. The species was separated from *Nitzschia compressa* var. *compressa* by the latter's increased valve size (valve width > 9µm), and by the increased size and lower density of punctae.

Nitzschia cf. *fonticola* Grunow in Cleve & Moller 1879
(Syn. *Nitzschia* (*palea* var.?) *fonticola* Grunow; *Nitzschia fonticola* (Grunow) Grunow in Van Heurck 1881; *Nitzschia kuetzingiana* var. *romana* Grunow; *Nitzschia romana* Grunow; *Nitzschia minima* Meister 1935; *Nitzschia macedonica* Hust. 1945; *Nitzschia subromana* Hust. 1954; *Nitzschia manca* Hust. 1957)

As in the East African data-set (Gasse, 1986: *Nitzschia* sp. af. *fonticola* types), specimens lacked the characteristic drawn-out capitate ends of the type species.

Nitzschia frustulum/liebetruthii:-
- *Nitzschia frustulum* (Kützing) Grunow in Cleve & Grunow 1880 var. *frustulum*
- *Nitzschia liebetruthii* Rabenhorst 1864

(See KLB (1988) for full list of synonyms)

Following taxonomic imperatives adopted in CASPIA Workshops, these two species were separated by the lack of a central node in the keel puncta in *Nitzschia liebetruthii*, although attached valves can sometimes show both characteristics in the same frustule.

Nitzschia latens group:-

This group is poorly-defined (Gasse, 1986). In the Spanish data-set two species were distinct, *Nitzschia pusilla* and *Nitzschia aurariae*. Other members of the *latens* group comprised larger elliptical valves which were uncommon and were not identified to species level.

- *Nitzschia pusilla* Grunow 1862 emend. Lange-Bertalot 1976

Valve morphology (length 15-24μm, width 3.5-4.5μm, fibulae 13-18/10μm, hyaline) matched well the description and photograph in KLB (1988, Tab. 79, Figure 13). Unlike the rest of the group, valves are linear-lanceolate rather than linear-elliptical, with characteristic drawn out ends. The density of fibulae was consistently high and exceeds that of similar species.

- *Nitzschia aurariae* Cholnoky 1966

Valve morphology (length 8-14μm, width 2.5μm, fibulae 15-17/10μm, hyaline) matched well the type description. The species is distinguished from other members of the *latens* group generally by its small size, and in particular by the narrowness of the linear-elliptic valves.

3.5 LABORATORY METHODS - PRESERVATION STUDY I (REGIONAL SURVEY)

3.5.1 Diatom analysis

3.5.1.1 Subsampling and slide preparation

For Part A of the Regional Survey, long cores from the Ebro Basin and La Mancha were subsampled at (2) 10-50cm intervals depending on the core length (50cm for cores >5m long). For the analysis of preservation in short cores (Part B), the surface sediment (0.5cm depth) and basal samples (1cm) were used.

The aim was rapid assessment of diatom preservation. Experimental screening at a magnification of x40 of uncleaned sediment known to contain diatoms showed that clays obscured the presence of diatoms. Full slide preparation was made for all samples as described in 3.4.2.1 above.

3.5.1.2 Assessment of diatom preservation

For rapid assessment of diatom preservation a 5-point abundance scale was used. 'Very abundant' referred to full preservation with little sign of dissolution. Dissolved but countable assemblages with 1-3 species dominant were classed 'abundant'. Those with 1-2 dissolved species dominant at low frequency and difficult to count were classed 'occasional'. 'Rare' referred to sparse, dissolved fragments, often exclusively of *Campylodiscus clypeus*, and 'nil' to samples without diatoms preserved. The categories 'abundant' and 'occasional' were also used to describe the few sparse, fragmented assemblages encountered which would be difficult to count to >250 or to 100 valves respectively, but which were not dissolved. Abundance classes were checked again towards the end of the project to ensure consistency.

3.6 LABORATORY METHODS - PRESERVATION STUDY II (LONG-CORE SURVEY)

3.6.1 Diatom analysis

Following cleaning of core sections, described in the following section, long cores taken in Summer, 1992 were subsampled at 20-50cm intervals depending on the core length. Slides were prepared and diatom preservation assessed as in Preservation Study I.

3.6.2 Stratigraphic description and analysis of organic remains

Cores were stored in the laboratory at 4°C. The upper surface of Livingstone cores was cleaned by scraping horizontally with a clean scalpel to avoid smearing. The sediment was sufficiently consolidated to clean off any surface contamination on the underside of each core slice. Sediment texture and composition were described for all core sections (Cobra and Livingstone) using the Troels-Smith system (Aaby & Berglund, 1986) modified and simplified to incorporate gypsum as an element. Sediment scrapes were mixed with water and their content described under a low power binocular microscope; 10% HCl was added to a second scrape to assess carbonate effervescence. The matrix was described as clay, silty clay or marly clay within which gypsum bands (>c. 40% gypsum) were distinguished as a separate unit. Sand, gypsum and tufa/detrital carbonates were described in detail from sieved subsamples using ordinal abundance scales, as explained below. Colour was described using Munsell Soil Colour Charts.

10-20g wet weight of sediment was taken for sieving from 1cm or 2cm core slices according to core type (Livingstone or Cobra respectively). Sampling intervals varied from 16-50cm according to core length (50cm for cores >5m long) or at closer intervals where marked stratigraphic change occurred.

Most samples contained heavily flocculated clays requiring disaggregation. The chosen technique reflected the need to preserve both calcareous and vegetative remains. The use of HCl, pyrophosphates (Kontrovitz *et al.*, 1991) or an ultrasonic bath may destroy ostracods. Subsamples were therefore weighed and placed in plastic beakers with 100ml 3% H_2O_2 for 1½ hours to disaggregate the clays without damaging organic remains by oxidation. They were wet sieved over a nest of sieves (300µm, 180µm and 125µm); the fraction less than 125µm was discarded and other fractions stored in alcohol prior to sorting.

The aim was a rapid but comprehensive assessment of the potential of these sites for a palaeoclimatic study rather than a definitive palaeoecological analysis. The proportion of gypsum in the sediment was estimated roughly on a 5-point abundance scale in the initial stratigraphic description and the relative proportions of different gypsum crystals (prismatic, lenticular and aggregate) were described from sieved subsamples. Molluscs and seeds were separated and counted for calculation of abundance per g wet weight. Most shells were intact; broken shells were counted if the upper whorls only were missing, and other fragments were not included. The abundance of charophyte oospores and ostracods was estimated per fraction and expressed on a five-point scale related to the approximate abundance per g wet weight. Ostracod valves were counted when more than half the shell was present. Ostracod abundance in particular was underestimated since clay pelletisation obscured small valves, but sufficed for a coarse estimate. Vegetative remains and charcoal abundance were estimated on a 4-point scale without quantification.

The stratigraphy was plotted using TILIA 1.11 and TILIAGRAPH 1.18 (Grimm, 1991).

3.6.3 Preliminary pollen analysis

Preliminary pollen analyses were made of cores from three sites (AAMA, DMDN and EFTL). 1cm^3 subsamples were taken at 20-50cm intervals and oven-dried. Pollen analysis was carried out by Prof. Tony Stevenson at Newcastle University using standard techniques (Stevenson & Harrison, 1992).

3.7 LABORATORY METHODS - HOLOCENE PALAEOCLIMATE STUDY (THE LAGUNA DE MEDINA)

3.7.1 Core correlation and stratigraphic description

Livingstone core sections were cleaned and the lithology of the three, closely-spaced parallel cores from different boreholes (Cobra and Livingstone sections) was described as in Section 3.6.2 above. A master sequence was constructed by correlation across the three cores to provide a single, continuous sediment record which alternated between core sections from different boreholes. The use of tops and bases of core sections was avoided since they were more likely to be contaminated or compressed.

Correlation was based upon the matching between core sections of major stratigraphic boundaries. Correlation in upper levels was confirmed by gross changes in ostracod species assemblage composition for the part of the sequence from 612-410cm depth, where alternation between boreholes was necessary but where there were no major lithostratigraphic boundaries.

After subsampling for diatom and pollen analysis, the master Livingstone sequence was sectioned at 1cm intervals. Other core sections were stored intact to allow absolute correlation of sediment from levels across the three boreholes for radiocarbon dating.

Subsamples for the remainder of stratigraphic analyses were taken every 4cm, including an overlap between DMDN2 and DMDN4/DMDN3 from 612-410cm for the test of correlation. Samples were disaggregated as in Section 3.6.2, but sieved over a single 250µm sieve to simplify counts and abundance estimates. A subsample size of 15-25g was chosen primarily to accommodate macrofossil, ostracod shell chemistry, mollusc and gypsum analyses. It was consequently larger than necessary for palaeoecological analysis of levels with abundant ostracods or foraminifera.

3.7.2 Diatom analysis

3.7.2.1 Counts

The master core was subsampled at 4cm intervals prior to sectioning Livingstone cores to enable organic laminae to be sampled preferentially. Diatom slides were prepared and counted as described in Section 3.4.2 above.

3.7.2.2 Dissolution index

A simple dissolution index (Flower, 1993) was used to describe the state of preservation of each assemblage by the proportion of the total number of valves which was relatively well-preserved compared to those which were in an advanced state of dissolution. The criteria used to describe different genera and taxa are described in Table 3.2 below. Long, pennate diatoms such as *Fragilaria* and *Nitzschia* spp. are often fragmented even in undissolved assemblages, so the degree of fragmentation was not included.

3.7.2.3 *Analysis of partially-dissolved diatom assemblages for derivation of a modified transfer function*

To refine interpretation of the Laguna de Medina fossil diatom record, a modified transfer function was derived which included additional diatom data from partially dissolved diatom assemblages of the recent sediments of other Spanish salt lakes.

Table 3.2 Diatom dissolution: criteria used for counting valves.

SPECIES	'WELL-PRESERVED'	'DISSOLVED'
Cyclotella spp.	valve margin intact	valve margin open
Chaetoceros spp.	resting spore intact	no intermediate state of dissolution identifiable
Fragilaria spp.	striae intact	striae enlarged
Raphid species and raphe valves of monoraphid species	distal raphe ends and valve centre intact	valve centre only intact; proximal raphe ends enlarged
Rapheless valves of *Cocconeis* spp.	valve intact	valve margin not intact; striae enlarged
Rapheless valves of small *Achnanthes* spp.	valve margin intact	no intermediate state of dissolution identifiable
Campylodiscus and *Surirella* spp.	marginal chambers intact	marginal chambers open
Nitzschia granulata, varieties of *N. compressa*	valve intact	valve margins open
Other *Nitzschia* spp.	fibulae and striae intact	fibulae missing

The uppermost sediments of cores with diatoms preserved towards the surface were subsampled at 2-10cm intervals to identify the first significant evidence of diatom dissolution and to assess whether a major change in species composition had occurred above, independent of the effects of dissolution. Where assemblages were countable, and not fully-preserved throughout the core, one sample was counted per lake using the counting methods described in Section 3.4.2 above.

3.7.3 Loss on ignition and carbonate content

Standard methods were used to measure sediment moisture, organic and carbonate content (Stevenson *et al.*, 1987, Digerfeldt *et al.*, 1992) by dry weight and loss on ignition ('LOI') at 550°C and 925°C, using 1.5g subsamples taken every 2cm over the master core sequence. The carbonate proportion was calculated from the LOI at 925°C (Dean, 1974).

3.7.4 Pollen analysis

Pollen subsamples were taken every 8cm and analysed as described in Section 3.6.3 above. Approximately 250-500 pollen grains were counted per sample, depending on pollen preservation, by Prof. Tony Stevenson, Newcastle University.

3.7.5 Ostracod and Foraminifera analysis

3.7.5.1 Counts

Adult ostracods for shell chemistry analysis (Section 3.7.6.2 below) were picked from wet sieved subsamples prior to counting. A limited number of samples were picked and counted from wet sediment to provide intact carapaces for taxonomic identification. The majority of calcareous microfossils were counted from dried subsamples, however, since the flocculated clays remaining in many wet subsamples obscured small valves. The process of drying split intact ostracod carapaces apart and damaged fragile valves, so preservation was described prior to drying according to the simple distinction between largely fragmented and intact assemblages. Subsamples were then oven-dried and weighed again.

For palaeoecological analysis, an attempt to count a random fraction of each subsample on a gridded picking tray using a modified version of the method of Danielopol & Casale (1988) was abandoned since ostracod abundance was too great. Where preserved, approximately 350-500 valves were counted per sample, either from the whole sample or, more often due to the large subsample size, from a well-mixed weighed fraction. Abundance per g dry weight (prior to sieving) was calculated.

3.7.5.2 Taxonomy

Ostracod identifications were made from the taxonomic literature and confirmed and improved with the kind assistance of Dr Huw Griffiths of Hull University. In addition to the general taxonomic works of Athersuch *et al.* (1989), Moore (1961) and Griffiths *et al.* (1993), key references used are mentioned below.

Cyprideis torosa (Jones, 1850) and *Darwinula stevensoni* (Brady & Norman, 1870) are easy to recognise (e.g. Kilenyi & Whittaker, 1974, Meisch, 1988). *Eucypris mareotica* (Fischer, 1855)

Gauthier, 1928 [synonym *Eucypris inflata*] was distinguished principally by its inflated dorsal view, approximately 3/5 of the valve length and equal to or greater than the width, and by its broad interior lamella (Gauthier, 1928a); its identification was confirmed by comparison with surface sediment assemblages of Málaga lakes where it has been reported as monospecific (Baltanás *et al.*, 1990). The genus, *Candona*, is distinctive; the identification of specimens as *Candona neglecta* (Sars, 1887) was based upon the less angular dorsal margin compared to *Candona angulata* (H. Griffiths, pers. comm.). Both the marginal tubercles on the inner right valve and the overall morphology of *Heterocypris salina* (Brady, 1868) matched well specimens photographed in Meisch & Broodbakker (1993). *Plesiocypridopsis newtoni* (Brady & Robertson, 1870) was distinguished from the genera *Potamocypris* and *Cypridopsis* by its right valve overlapping the left rather than vice-versa, and from *Sarscypridopsis* by its lack of a heavily punctate valve surface (Griffiths *et al.*, 1993, Meisch & Broodbakker, 1993). Valves varied in length from 0.73-0.82mm, which is slightly larger than figures quoted in Baltanás & García-Avilés (1993) for the Canary Islands, but within the dimensions given by Meisch & Broodbakker (1993) for the same islands. An inflation along the anterior ventral margin was likely to be species specific (H. Griffiths, pers. comm.) and variation in valve morphology otherwise was probably due to the distinction between males and females.

The identification of the *Ilyocypris* to species level was uncertain. A distinct anteroventral concavity on both valve surfaces was not present in the similar species, *I. gibba, I. bradyi, I. australiensis, I. lacustris* or *I. schwarzbachi* (Kempf, 1975, Van Harten, 1979, Meisch, 1988, H. Griffiths, pers. comm.). The feature was found in '*Ilyocypris* sp' from the Camargue, however (Zaninetti & Tetart, 1982) and they appear to be conspecific. No attempt was made to identify the *Limnocythere* to species level.

The foraminifera, *Ammonia beccarii* (Linné) was distinguished from its variety *A. beccarii* (Linné) var. *tepida* (Cushman) [syn. *A. tepida*] on the basis of the number of chambers in its outer whorl. Specimens from the Laguna de Medina commonly had 8-9 chambers, whereas the type species of the *A beccarii* var. *tepida* has 6-7 (Schnitker, 1974). Specimens matched well *A. beccarii* depicted by Schnitker and from the Camargue (Zaninetti, 1982). Taxonomic uncertainties are apparent from the literature; in accordance with the type description, *A. tepida* depicted in Blanc-Vernet (1982) and Gasse *et al.* (1987) had only 7 chambers, but specimens in Banner & Williams (1973) ranged from 6-8 chambers. Laboratory experiments have shown the two are conspecific and *A. beccarii* var. *tepida* and other varieties exhibit temperature-dependent morphological variation (Schnitker, 1974), but they were separated for this study. The identification of rare Milolidae and another species resembling '*Elphidium* sp' in Zaninetti (1982, Plate 1, Figures 6-7) was not pursued.

3.7.6 Ostracod shell chemistry analysis

3.7.6.1 Species selection

Cyprideis torosa was selected for analysis since it was abundant in most levels from the core base to 600cm (coinciding with the majority of levels with diatoms), has strong valves which are easy to clean and its shell chemistry has been worked on extensively (e.g. Chivas *et al.*, 1986a, De Deckker *et al.*, 1988, Teeter & Quick, 1990, Anadón & Julià, 1990).

The partitioning of trace elements in ostracod shells is genus-dependent. Although *Plesiocypridopsis newtoni* was abundant above 600cm its taxonomy was uncertain until late in the study and the presence of juvenile or adult valves of more than one genus was possible. Valves were small, fragile and difficult to clean due to their wide interior lamellae. The study was therefore restricted to *C. torosa.*

3.7.6.2 Analysis of modern ostracods

Modern populations of *C. torosa* were sought to assess the extent to which variation in the fossil sequence could be due to natural variability. The ostracod inhabits permanent waters (Kilenyi & Whittaker, 1974). To locate a modern population surface sediment from all permanent and semi-permanent sites in the data-set was screened.

The analysis was restricted to adult ostracod carapaces preserved with body parts intact, that is, which were living in the water at the time of sampling. One valve from each carapace was separated, cleaned and analysed as described below.

3.7.6.3 Analysis of fossil ostracods

Three adult valves per sample were analysed from 8cm-interval subsamples initially. Where ostracods were abundant but poorly-preserved five valves were analysed instead to produce a more reliable mean value; less than three were present in some levels. Following the first analytical run, the subsample resolution was increased to x4cm over levels with marked fluctuations in chemical ratios.

The length in graticule units, appearance (transparent, semi-transparent or white) and any signs of damage or surface concretions was recorded for each valve. Intact, clean carapaces were chosen by preference. Valves were cleaned with a fine paintbrush (size oooo) in distilled water (Holmes, 1992b) under a Wild 3MZ binocular microscope at x10 to x40 magnification. Patches of carbonate or organic matter were scraped off with a zoological dissecting pin where necessary. Cleaned valves were placed in a sterile Sterilin test tube and dissolved in 2ml 5% v/v Aristar HCl overnight. The Ca, Mg and Sr content of shells was measured using an inductively coupled plasma atomic emission spectrometer and Mg:Ca and Sr:Ca ratios calculated. Both valves of some carapaces were run to check for laboratory error; after verifying their overlap the results for one valve from each was removed from the data.

The machine was calibrated and drift-corrected as for water chemistry analysis (Section 3.4.1) using a standard of 50ppm Ca, 0.5ppm Mg, Sr and Fe. From previous work, there can be a significant drift in the precision of results of runs carried out on different days. This is likely to be due to slight differences in the composition of the calibration standard consequent upon dilution of standards of known composition. The associated error becomes significant on analysis of trace element concentrations. Using a technique developed at Kingston University to correct for this (Bridgwater, 1995), an additional aragonite blank was run at the beginning, middle and end of each run to adjust the results of different runs.

Table 3.3 Aragonite standard results used for correction of ostracod shell chemistry results.

	MOLAR RATIOS			
	Mg/Ca	Mean Mg/Ca	Sr/Ca	Mean Sr/Ca
RUN 1 *24/2/94*	0.00083		0.00226	
	0.00083		0.00226	
	0.00082		0.00226	
	0.00082	0.00083	0.00225	0.00226
RUN 2 *10/6/94*	0.00062		0.00148	
	0.00060		0.00148	
	0.00060	0.00061	0.00145	0.00147

The aragonite standard was prepared from crushed shells of the American hard-shelled clam, *Mercenaria mercenaria*. 0.05 g of aragonite powder was dissolved in 100 ml 5% v/v Aristar HCl. Six separate standards of identical composition were prepared (coefficients of variation of 4.82% for Mg/Ca and 0.76% for Sr/Ca for the results of ten analyses each of each standard during a single machine-run). The shift in machine readings between runs is illustrated by the discrepancy in mean values for 60 samples run on different days: 0.00086 and 0.00077 for Mg/Ca molar ratios, and 0.00170 and 0.00284 for Sr/Ca.

The results of the second ostracod shell chemistry analysis were corrected to be consistent with the first run by multiplying by correction factors of 1.54 for Sr/Ca and 1.36 for Mg/Ca (mean aragonite value Run1/mean aragonite value Run2), which were derived from aragonite readings given in Table 3.3 above. Results were displayed using Microsoft Excel and Deltagraph.

3.7.7 Mollusc analysis

3.7.7.1 Counts

Total molluscs were counted and abundances calculated as numbers of shells per g dry weight. Broken molluscs were included if the entire basal whorl was preserved; other fragments were ignored.

3.7.7.2 Taxonomy

The Hydrobids were the dominant mollusc, with a maximum shell length of 5mm and never more than six flattened whorls. This agrees with general descriptions (Plaziat, 1991, Beedham, 1972). The shell surface was smooth and the overall morphology matched well those depicted in Gasse *et al.* (1987) and Rosso & Gaillard, (1982). Since the generic taxonomy is uncertain (Plaziat, 1991) identification to species level was not attempted. The possible inclusion of smooth-shelled juvenile Potamids was investigated; Potamids tend to be larger (*P. conicus* ranges from 1-2.5cm; Plaziat, 1993) and have more than six whorls, with a more conical shell and less rounded aperture (Lozouet, 1986). Furthermore, their recorded distribution does not extend as far northwest as Spain (Plaziat, 1993).

Cerastoderma glaucum (Brugière), a 'Cardium', was distinguished from the Atlantic species *C. edule* (L.) on the basis of its deep, narrow shell costulae which were smooth over the posterior region (Rosso & Gaillard, 1982).

Small *Bulinus* sp and planorbs were identified by reference to Petit-Maire *et al.* (1980) and Beedham (1972). Their identification to species level is difficult (Gasse *et al.*, 1987).

3.7.8 Plant macrofossil analysis

3.7.8.1 Counts

Fossil seeds were counted and abundances calculated as numbers of seeds per 5g dry weight. Broken seeds were counted as a half if cleanly broken in two, or as whole if most of both sides was preserved; other fragments were ignored.

3.7.8.2 Taxonomy

Three species of aquatic plant macrofossil dominate the fossil flora. In the *Ruppia* group, three species are known from Spain (Amat, 1984, Cirujano Bracamonte, 1990). *Ruppia* cf. *maritima* was identified on the basis of its bulbous, slightly asymmetrical shape and lack of a pronounced 'beak' (Katz *et al.*, 1965) compared to a second species, *R. drepanensis* which has a narrower, asymmetrical seed constricted at the centre, and a pronounced beak (Cirujano Bracamonte, 1990, and depicted with *R. maritima* in Davis, 1994). The seed morphology of aquatics of saline lakes is poorly-described (Davis, 1994), and no description was found for a third species, *R. cirrhosa*; while Cirujano Bracamonte (1990) suggests the plant is restricted to coastal waters, both *R. maritima* and *R. cirrhosa* have been reported from inland salt lakes of southern Spain (Amat, 1984). Pending a comparison with reference material, the identification of *R.* cf. *maritima* is therefore tentative.

The morphology of the common taxon, *Potomageton pectinatus,* is well-described, and identification was made by comparison with descriptions in Katz *et al.* (1965) and Cirujano Bracamonte (1990).

Seeds of *Zannichellia* sp. were distinguished from those of another genus common in salt lakes of southern Spain, *Althenia* (Amat, 1984), using descriptions in Katz *et al.* (1965) and Cirujano Bracamonte (1990). Seeds of *Althenia orientalis* are symmetrical and ± rectangular with rounded ends, whereas fossil seeds of *Zannichellia* sp. were asymmetrical, and the seed-base curved outwards more on one side than the other from the point of attachment of the stalk. From descriptions in Katz *et al.* (1965), immature *Zannichellia* seeds would be difficult to distinguish from *Althenia*; in effect, the identification was confirmed more by the reported occurrence of *Zannichellia obtusifolia* rather than *Althenia* in the modern lake (Fernandez-Palacios, 1990), since seeds were abundant in the recent lake sediments.

Chenopod seeds were abundant in few samples. These derive from genera of emergent plants such as *Salicornia*; they are difficult to distinguish to species level but are distinct as a family and were identified using Katz *et al.* (1965).

3.7.9 Charcoal analysis

Charcoal abundance was estimated as in Preservation Study II (Section 3.6.2).

3.7.10 Gypsum analysis

The relative proportions of different crystal morphologies were described as in Preservation Study II.

A more accurate estimate of total gypsum abundance for the Laguna de Medina core was made by estimating the percentage of gypsum in sieved samples at x8cm resolution, from which the abundance in dry sediment (pre-sieving) was calculated. Since dry weight measurements before and after sieving are based on sediment weight in g, and gypsum content on the percentage of crystals by volume in sieved subsamples, gypsum abundance is a qualitative estimate of relative abundance rather than the absolute proportion of gypsum by weight or volume in the sediment.

3.7.11 Radiometric AMS ^{14}C Dates

Alkaline, saline lakes fed by groundwater present particular problems for radiocarbon dating (Fontes & Gasse, 1991a, 1991b). Dates based on autochthonous carbonates or aquatic plant macrofossils are likely to suffer from a 'hardwater error' due to contamination by older carbon in the groundwater supply. Dates based on bulk sediment carbonate can be further affected by input of detrital carbonates from the catchment or can produce dates too young if recrystallisation occurs during the rise of aquifers. Terrestrial charcoal or plant remains use atmostpheric carbon and are potentially the most reliable sources of radiocarbon dates, but are often not preserved in high concentrations. This can be overcome to some extent by AMS ^{14}C dating, which can be performed on very small (1 mg) amounts of pure carbon.

Material was sought initially for three AMS ^{14}C dates to provide a chronology pending the results of nine further dates which have been approved but which lie outside the remit of the study because of time constraints. Charcoal and terrestrial seeds were used to give the most reliable results from a small number of dates, on the assumption that the charcoal was of terrestrial rather than aquatic origin.

The lower part of the core was selected for dating to provide a chronology for the base of the sequence. Levels with the highest concentrations of dateable material were identified during stratigraphic description. For each level a 2cm slice was taken from parallel levels across the three cores (up to 130g sediment) and sorted as described previously. Subamples were oven-dried immediately to prevent incorporation of modern carbon present in alcohol used in other analyses for preservation of organic remains. Material from the initial 1cm subsample of the master sequence was excluded for this reason.

Samples were cleaned in 10% HCl to remove surface carbonates, and particulate matter was removed by cleaning with a nylon paintbrush in distilled water. 2-5mg dry charcoal or 5-10mg seeds per sample were submitted for processing to the AMS ^{14}C Facility at Tucson, University of Arizona, USA.

CHAPTER FOUR

MODERN DATA-SETS AND DIATOM-SALINITY TRANSFER FUNCTION

4.1 INTRODUCTION

In this chapter predictive models are developed for palaeoenvironmental interpretation of fossil diatom assemblages. It is concerned primarily with the derivation of a diatom-salinity transfer function to quantify the relationship between modern diatom species assemblage composition and salinity. For a successful transfer function, salinity should make a significant contribution to the total variance in the diatom data. A variety of exploratory statistical analyses are performed to establish the significance of salinity and other variables, prior to derivation of the transfer function.

A second model is developed for direct but qualitative inferences of lake-level change to complement palaeosalinity reconstruction. This is derived from a separate investigation into the relationship between diatom species assemblage composition and differences in lake permanence and/or water depth.

4.2 ENVIRONMENTAL DATA-SET

4.2.1 Quality and range of environmental variables

The geographic distribution of sampling sites is given in Figure 4.1. Full details are given in Appendices 1, 2 and 3 (site data) and Appendix 4 (modern sample data). The total data-set comprises 118 surface sediment or epiphyton diatom samples from 87 lakes, with full water chemistry data collected where possible. Duplicate samples from individual lakes were taken in different seasons.

4.2.1.1 Lake area

In many cases, surface area was reported in the literature; in other cases it was estimated approximately from dimensions given in Pardo (1948) for lakes which were not known to have been altered dramatically by human impact, or was estimated from 1:50 maps.

Surface area of the 87 lakes ranged from 0.01-13.3 km^2 and is summarised for the three main salt lake regions in Figure 4.2a. Most lakes are very small (<0.5 $km^{2)}$ in all regions; sites of <0.05 km^2 include small artificial salt pans, but also a relatively large number of Andalucían salt lakes. Most lakes

Figure 4.1 Map showing the distribution of sampling sites for collection of the modern training set

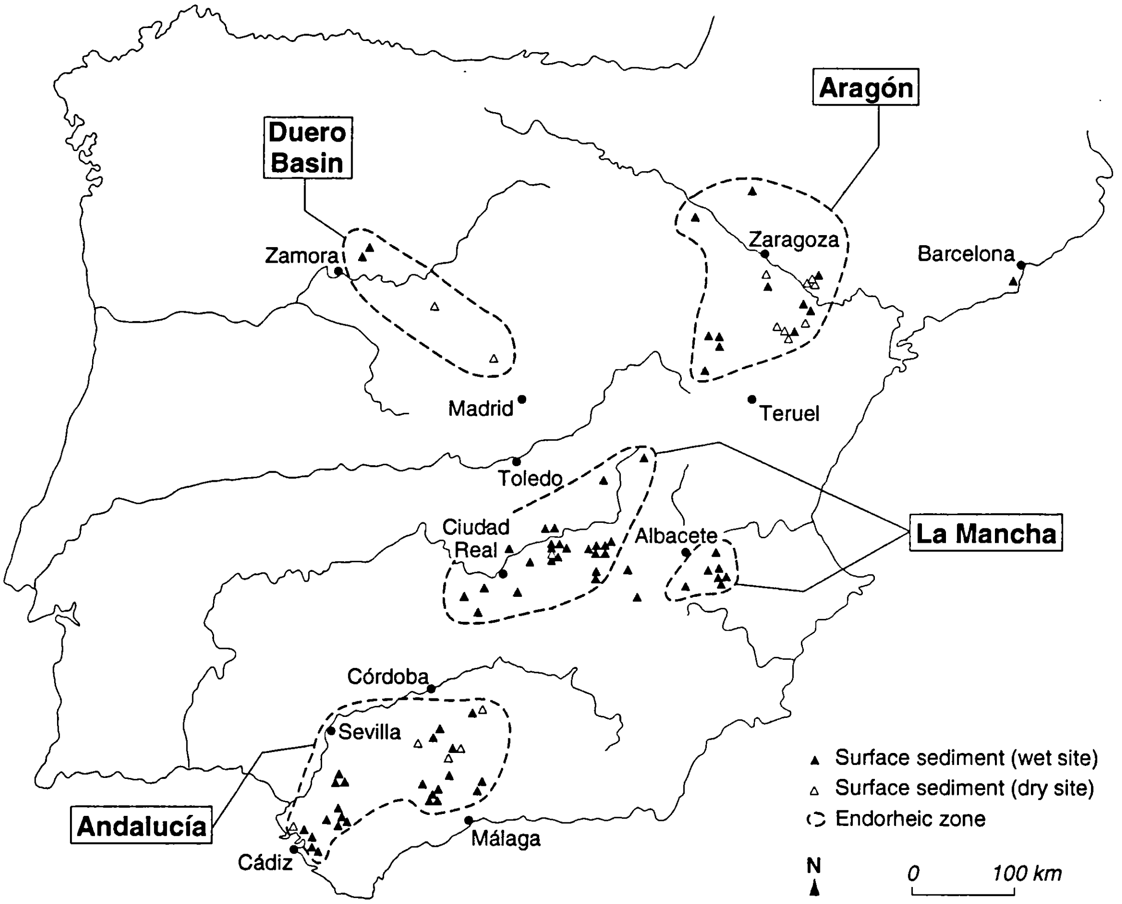


Figure 4.2 **Histograms showing the distribution of different limnological characteristics across the 87-lake data-set.**

Figure 4.2a Lake area

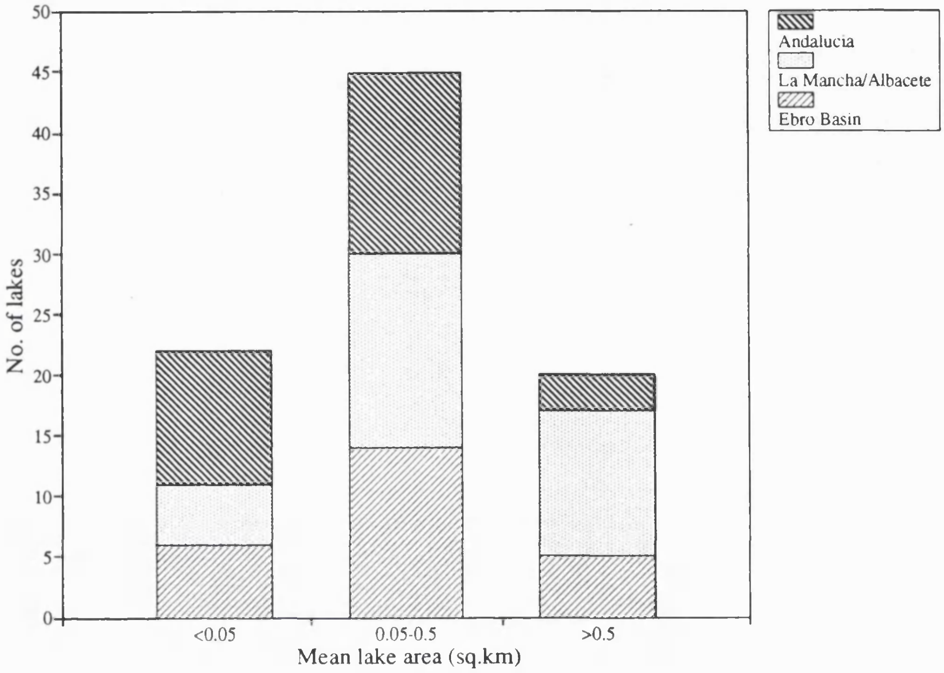


Figure 4.2b Lake Permanence

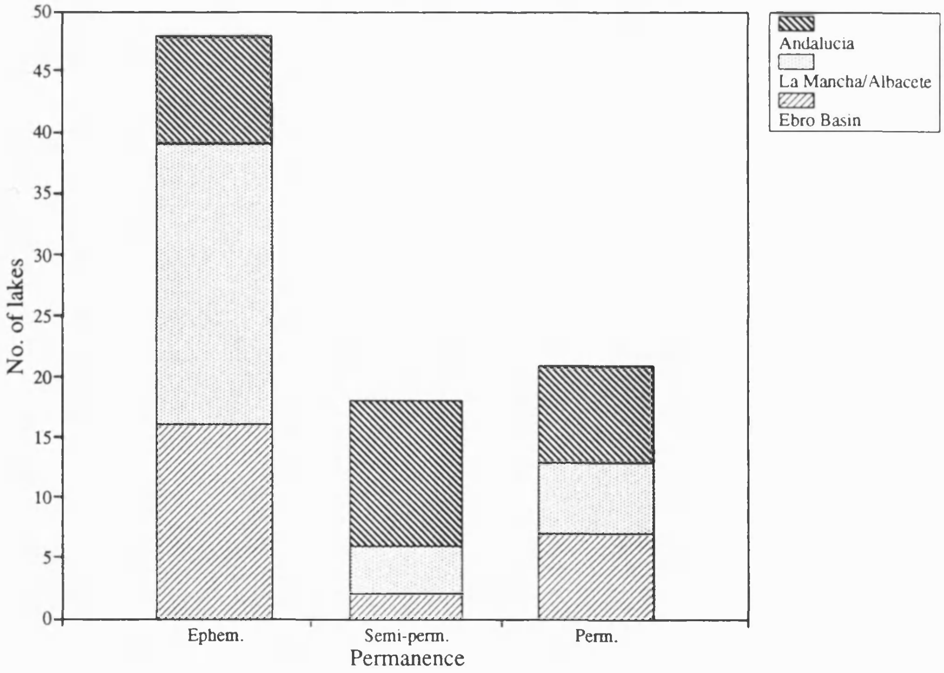


Figure 4.2c Water depth

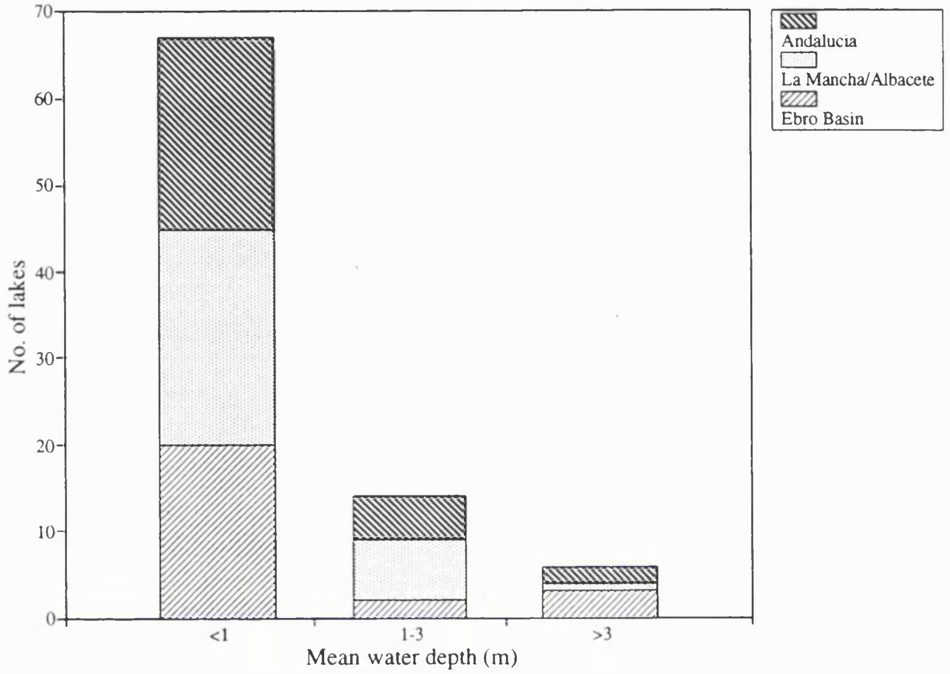
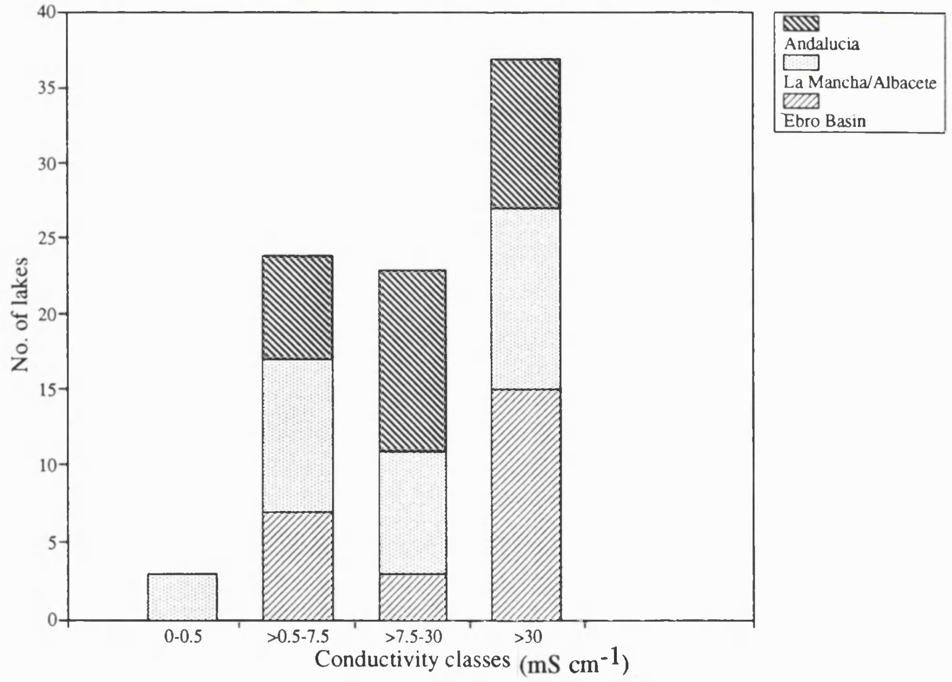


Figure 4.2d Water conductivity



>0.5 km^2 are in the La Mancha/Albacete region of central Spain. Within this category only three are larger than 2 km^2. The Lagunas de Fuente de Piedra, Málaga and de Gallocanta, Teruel are exceptionally large (12.19 km^2 and 13.30 km^2 respectively).

4.2.1.2 Lake permanence

Many lakes are ephemeral, summer-dry lakes. They occur mainly in central Spain and the Ebro Basin, and are less common in Andalucía (Figure 4.2b). Semi-permanent lakes include both those which retain water through the summer in many years and those which are hypersaline and in which groundwater levels are maintained at the sediment surface in summer due to the formation of a salt crust, such that they do not dry out completely. Most sites in Andalucía which are semi-permanent or permanent are endorheic systems. Semi-permanent endorheic lakes are rare in central Spain and the Ebro Basin, and most of the permanent lakes in these regions are either artificial or karstic systems.

4.2.1.3 Water depth

The distribution of approximate maximum water depth is given in Figure 4.2c and is derived from spring measurements where possible; lakes which were dry when sampled are assumed shallow (<1m deep). The majority of lakes are shallow. Apart from in Andalucía, most lakes of water depth 1-3m or >3m deep are artificial or open karstic systems.

4.2.1.4 Conductivity

To establish mean conductivity classes for description of the 87-lake data-set, missing values for sites from which only one sample had been collected were taken from the literature. The majority of sites with missing values were dry when sampled.

Conductivity data were complete for most sites wet when sampled. The Laguna de Salada, Chiprana [HSAL] is a deep lake with relatively stable chemistry (Vidondo *et al.*, 1993) and the conductivity for HSAL2 (7/91) was taken as the duplicate of the HSAL1 (7/90) value. The conductivity of HPD1 (the coastal lagoon, Estany de la Podrida I, 8/92) was taken as the August value in 1993 monitoring data which was kindly provided by the Llobregat environmental agency, Barcelona.

Samples span a salinity gradient from fresh to hypersaline (0.15 to 338 mS cm^{-1}). Figure 4.2d shows the distribution of sites within different conductivity classes which approximately represent different water salinity classes, as described in Section 1.2.5.1. Only three sites fall within the strict definition of fresh waters (<0.5 mS cm^{-1}, <0.5 g l^{-1}), but 24 sites are oligosaline (>0.5-7.5 mS cm^{-1}, >0.5-5 g l^{-1}), without any geographic bias. Oligosaline sites with conductivity <1 mS cm^{-1} are mostly artificial or open systems. Mesosaline sites (>7.5-30 mS cm^{-1}, >5-20 g l^{-1}) are well-represented, but uncommon in the Ebro Basin. Many sites in the data-set are polysaline to hypersaline (>30 mS cm^{-1}, >20 g l^{-1}). Most of the metasaline or hypersaline sites (>50 mS cm^{-1}, >40 g l^{-1}) occur in central Spain or the Ebro Basin rather than in Andalucía.

4.2.1.5 pH

The pH values of 34 samples from wet lakes were missing due to the failure of pH meters in the field and to missing Newcastle/Durham values. Crude estimates were made either from the literature or from laboratory measurements made later, on the basis that pH appeared to have risen in other samples by c. 0.5 pH units since measurement in the field. Since water samples had been filtered, changes in pH consequent upon continued aerobic activity were minimised.

It can be argued that absolute accuracy in pH measurements is not necessary for a salt lake environmental data-set, since the pH of salt lakes can fluctuate by up to one pH unit within a single day (Hammer, 1986). Thus single pH measurements taken at different times of the day for different lakes are at best only a general indication of pH, with a relatively large margin of error compared to the mean. Single measurement have been used successfully in salt lake studies to show the significance of pH variation between acid and alkaline waters, however (cf. Gasse *et al.*, in press). Although the accuracy of the estimated measurements was probably reduced still further, the data were therefore retained as a general indicator of alkalinity. Most sites were alkaline, and pH ranged from 6.3 to 9.8.

4.2.1.6 Turbidity

As noted in Chapter 3, the use of a secchi disc to estimate water transparency was not feasible. Field observations relied instead on an assessment of the relative concentration of suspended sediment in the waters. This is the main variable influencing turbidity in shallow salt lakes; in deep, permanent lakes with negligible suspended sediment, planktonic blooms are the major cause of loss of water clarity, but their effects are minimal compared to the turbidity of shallow lakes (Alonso, 1985).

As with pH, a single measurement may not represent the mean. From field observations, most lakes are exposed and wind stress is probably an important factor affecting water turbidity. Its influence varies with the season and lakes were more turbid during spring.

Turbidity was estimated from field observations and compared to qualitative data in Alonso (1985) which had been based on the same criteria. Turbidity was expressed on a 3-point qualitative scale (transparent, semi-turbid and turbid) and a spring value was used where possible if estimates were at odds with each other. Semi-turbid waters maintained some water clarity, whilst turbid waters were virtually opaque. Since the turbidity scale relates to a simple increase in the amount of suspended sediments, the use of a scale from 1 to 3 in statistical analyses below is justified on the basis that it then approximates a meaningful logarithmic scale.

4.2.1.7 Nutrient status

The nutrient status of Spanish salt lakes varies significantly between sites, and some lakes, especially in urban locations, are highly eutrophic (Alonso, 1985).

Data on nutrient status were of insufficient quality to be included in statistical analyses. As noted in Chapter 3, nitrates were below detection in many samples and were omitted from the environmental data-set due to the number of missing values; facilities were not available to analyse trace phosphate concentrations. Crude estimates of eutrophication (described on a 3-point scale) were taken from the literature (especially Alonso, 1985 and Furest & Toja, 1984) but they were not included in analyses since nutrient status is complex and cannot be summarised meaningfully without further data.

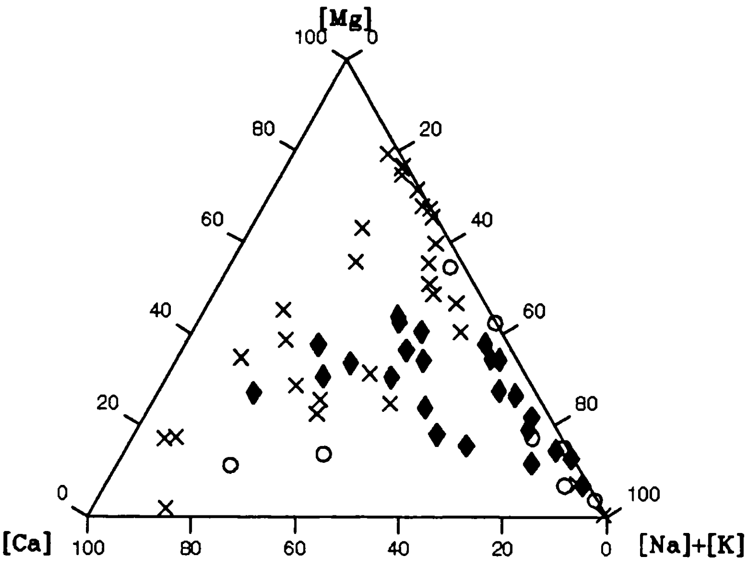
The response of diatoms to phosphorus has been demonstrated previously by the successful development of transfer functions for nutrient reconstruction (Hall & Smol, 1992, Bennion, 1994, Fritz *et al.*, 1993b). If nutrient status were a major unexplained gradient in the training set, which correlated with salinity, it could affect the accuracy of the salinity transfer function. Evidence for the influence of nutrients on diatom assemblage composition is assessed in unconstrained ordinations performed on diatom species data below.

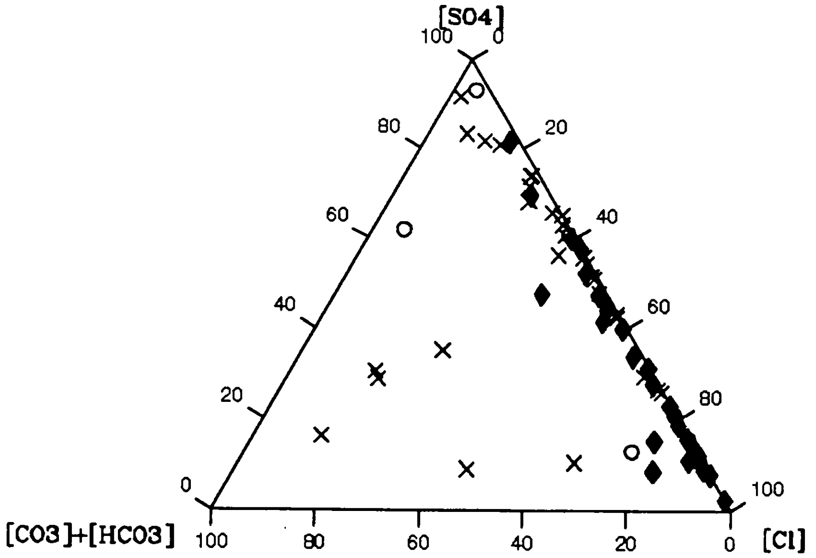
4.2.1.8 Other major ions

Data for major ions [Cl], [SO_4], [CO_3], [Na], [Mg] and [Ca] were missing for 8 dry sites and for 8 wet sites sampled during the project (unfiltrable samples, ELLL1 and CGSQ3, hypersaline samples, ETRZ1, EPNH1 and EQU11, two destroyed samples, CARJ1 and DHND1, and for the lagoon HPD1) and were either missing or unreliable (ionic balances unmatched) for all Newcastle and Durham University samples (12 samples from wet sites).

For samples from wet sites, water chemistry data were taken from the literature or from duplicate project samples, if conductivities matched closely (ELLL1, CGSQ3, CARJ1, DHND1, BGDE1, ECHC1, HCHI1, HEST1, HLDP2, HPD1, HSAL1, HSAL2). This left 8 wet sites for which full chemistry data were missing (BCCA1, EGRA2, GSAR3, HBDP1, HGAL1, HLCA1, HLOR1, HLZO1).

Figure 4.3 Ternary diagrams of major cations and anions. [○ = Ebro Basin, × = La Mancha, ♦ = Andalucía.]





Ternary diagrams of major anions and cations are given in Figure 4.3 for 74 sites with full water chemistry data. Carbonates are only the dominant anions in a small group of fresh or oligosaline lakes in the La Mancha/Albacete region whose salinity does not exceed the calcite branchpoint (c. 3 g l^{-1} TDS), above which other ions may dominate (Hardie *et al.*, 1978). There is a geographic bias in other sites towards a tendency for sulphate dominance in La Mancha/Albacete, central Spain and chloride dominance in Andalucía which reflects the contrast between their location within continental and marine evaporites respectively. The few sites included from the Ebro Basin are of mixed sulphate- or chloride-dominance, reflecting the local geological variability (Comín, 1988).

Cation proportions are more variable, although there is a tendency towards [Mg] and [Na+K] dominance rather than [Ca]. The contrast between [Mg] dominance in central Spain and [Na+K] dominance in Andalucía again reflects the origin of underlying evaporites (minerals such as gypsum, dolomite or epsomite versus NaCl-rich strata).

4.2.1.9 Relationship of conductivity with total salinity

The relationships between conductivity and total dissolved solids ('TDS' in gl^{-1}) are complex. A linear relationship often obtains at lower salinity but conductivity tends to increase exponentially with TDS in hypersaline waters (F. Gasse, pers. comm.). An approximate relationship for chloride waters (Heurteaux, 1988) was used above (Section 4.2.1.4) to describe lake salinity classes, but it can vary significantly according to brine composition (De Deckker & Forester, 1988).

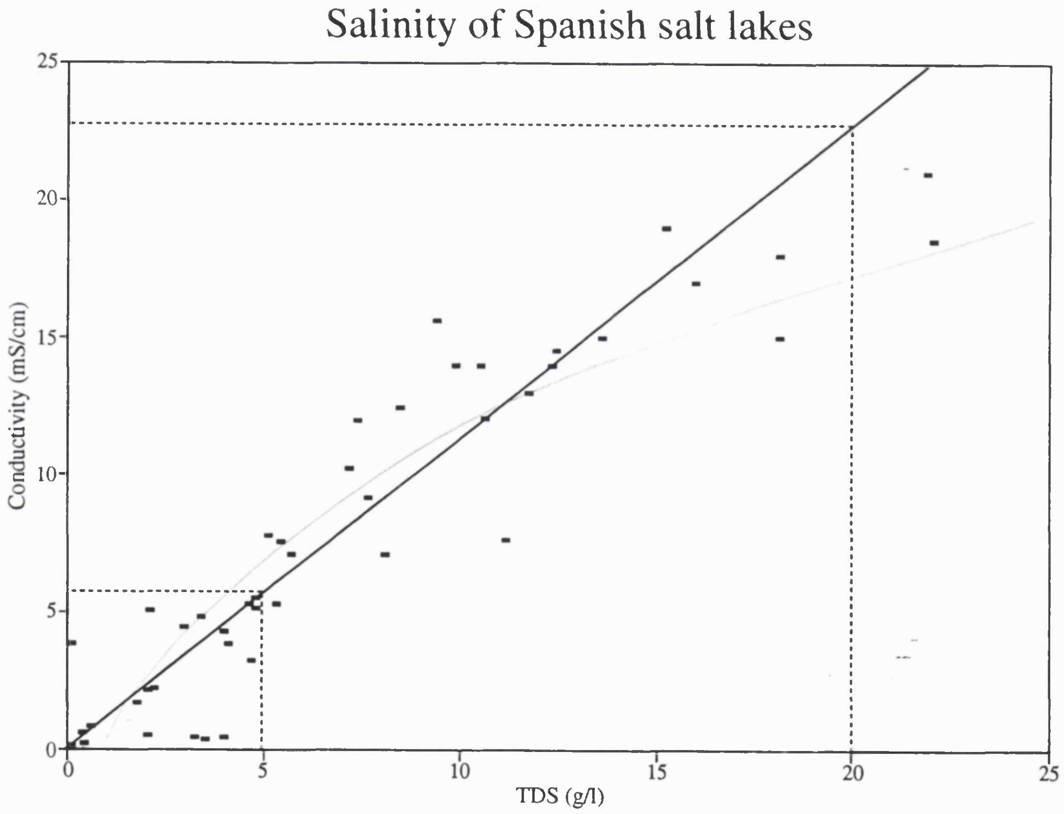
To enable more accurate definition of water salinity classes in terms of their equivalent conductivity for qualitative interpretation of palaeoecological sequences, the relationship between conductivity and TDS for the Spanish samples is given in Figure 4.4 for the ecologically important salinity range of fresh-oligosaline-mesosaline.

The fresh-oligosaline boundary (0.5 gl^{-1}) is at c. 0.5 mS cm^{-1}, the oligosaline-mesosaline boundary (5 gl^{-1}) is at c. 6 mS cm^{-1}, and the mesosaline-polysaline boundary (20 gl^{-1}) is at c. 23 mS cm^{-1}. These are close to the values determined by Heurteaux (1988), of 0.5, 7.5 and 30 mS cm^{-1} respectively.

4.2.2 Summary of training set environmental variables (74 samples)

The training set used for calibration of the salinity transfer function comprises only those samples with relatively well-preserved (countable) diatom assemblages and full water chemistry data. A breakdown of the total data-set is given in Table 4.1. 44 of the 118 samples do not obey these criteria and are not included in the training set. 16 of these samples contained diatoms but lacked full water chemistry data

Figure 4.4 Scatter plot showing the relationship of conductivity with total dissolved solids ('TDS') over the salinity range fresh to mesosaline, with fresh-oligosaline and oligosaline mesosaline salinity boundaries marked by dotted line.



either because the lakes were dry when sampled, or because data for major ions were missing, for reasons discussed above in Section 4.2.1.8. Diatoms were absent in a further 28 samples.

Of the 118-sample data-set, a total of 74 samples from 57 sites obey these criteria and are included in the training set.

Table 4.1 **Summary of the total modern sample data-set. (Samples in bold are included in the training set.)**

Sample type	No. samples
Total number of samples	*118*
Diatoms absent - dry sites	17
Diatoms absent - wet sites	11
Diatoms present - dry sites, no chemistry	8
Diatoms present - wet sites, partial chemistry	8
Diatoms present - wet sites, full chemistry	**74**

A summary of lake codes and relevant environmental data for the 74 training set samples is given in Table 4.2 for ease of reference, with major ions expressed as proportions of total cations and anions. Data for molar concentrations (in meq l^{-1}) are given in Appendix 3. These samples form the basis for the following analyses.

4.2.3 Principal Components Analysis ('PCA') of the training set environmental variables

4.2.3.1 Introduction

Principal components analysis ('PCA') is an ordination technique for indirect gradient analysis which assumes a linear response appropriate for environmental data (Davis, 1986). PCA was performed on the environmental data-set to determine its underlying structure and establish the major environmental gradients and any extreme 'outlier' samples. The program CANOCO version 3.10 (ter Braak, 1988, 1990) was used for this and all other ordinations, and the program CALIBRATE (Juggins & ter Braak, 1992) for graphical representation of the results.

Salinity was expressed both as conductivity and as total dissolved solids (TDS in gl^{-1}). The choice of other environmental variables is based mainly on those used in the recent development of other diatom-

Table 4.2 Summary of relevant limnological data for the training set (74 samples). [Initial letter of site codes refer to regions: A=Córdoba, B=Málaga, C=Sevilla, D=Cádiz, E=La Mancha, G=Albacete, H=Ebro Basin, I=Duero Basin.]

SITECODE	ALTIT (m asl)	MEAN AREA (km^2)	PERM	TURB	EUTR	WATER DEPTH (m)	COND (mS/cm)	Ph	TDS (g/l)	ANION SUM (meq/l)	CATION SUM (meq/l)	CATIONRATIO	ANION RATIO	Na+K%	Mg%	Ca%	Cl%	SO4%	CO$_3$+ HCO$_3$%
AAMA1000	380	0.04	3	1	1	3.0	13	9.0	11.76	177.88	237.21	0.762	0.020	43.23	36.46	20.31	54.08	44.01	1.92
AAMA2000						2.5	14	8.7	12.35	192.49	226.21	4.147	0.005	80.57	12.73	6.70	54.85	44.68	0.48
ASBL1	420	0.48	1	3	1	0.1	33	8.4	62.12	998.33	1038.19	1.368	0.003	57.77	37.69	4.54	68.57	31.09	0.34
ASBL2						0.5	0.38	9.2	3.50	54.86	64.16	1.143	0.018	53.34	26.98	19.68	59.72	38.47	1.81
ATSC1	180	0.11	1	2	1	1.0	37	7.6	42.32	659.92	682.20	3.943	0.002	79.77	11.56	8.67	87.69	12.13	0.18
AZNR1	300	0.38	3	1	2	9.5	4.4	6.3	2.98	49.78	45.68	11.510	0.119	92.01	6.78	1.21	80.83	8.53	10.64
BCCA2	800	0.04	3	1	2	1.5	21	9.7	21.92	290.06	340.05	0.789	0.003	44.09	40.39	15.51	42.05	57.66	0.30
BDCE1	460	0.10	2	3	1	0.2	15	8.3	13.63	223.46	230.67	1.134	0.009	53.13	23.78	23.09	59.25	39.83	0.92
BFNT1	410	12.19	2	3	1	0.1	43.5	8.3	93.35	1508.70	1553.19	2.958	0.001	74.74	21.67	3.59	92.13	7.73	0.13
BGDE1000	800	0.12	3	1	2	7.0	4.3	8.3	3.97	58.85	67.62	0.227	0.021	18.48	27.00	54.52	16.67	81.31	2.01
BGDE2000						8.2	0.5	8.3	3.97	58.85	67.62	0.227	0.021	18.48	27.00	54.52	16.67	81.31	2.01
BRTS1	450	0.17	1	3	2	0.5	46.5	8.6	63.55	1022.38	955.36	1.902	0.004	65.55	27.54	6.92	85.43	14.16	0.41
BSDA2	460	0.13	1	3	2	0.3	90.5	8.4	103.57	1789.90	1755.15	1.529	0.004	60.46	36.42	3.12	83.50	16.13	0.37
CALC1000	20	0.05	2	1	1	0.8	7.1	7.7	5.71	88.25	104.24	1.881	0.077	65.29	15.49	19.22	77.75	15.10	7.15
CALC2000						0.6	12	7.7	7.40	112.70	132.84	1.851	0.050	64.92	16.64	18.44	79.38	15.85	4.78
CARJ1000	40	0.02	2	2	2	0.9	15	8.3	18.15	293.22	312.82	1.404	0.007	58.40	17.92	23.69	80.56	18.74	0.70
CARJ2						0.6	18	8.3	18.15	293.22	312.82	1.404	0.007	58.40	17.92	23.69	80.56	18.74	0.70
CGSQ1	440	0.25	2	3	1	0.8	19	8.0	15.22	263.74	263.74	6.572	0.027	86.79	12.80	0.41	86.51	10.81	2.67
CGSQ2						0.6	25.5	9.7	25.83	380.34	389.40	5.709	0.017	85.10	13.97	0.93	88.03	10.31	1.66
CGSQ3						0.02	350	8.3	217.56	5139.20	5139.20	4.037	0.001	80.15	19.64	0.22	80.01	19.86	0.13
CTRJ1	130	0.03	2	2	1	2.0	5.3	8.2	4.66	70.06	86.79	0.683	0.060	40.57	41.08	18.35	51.62	42.70	5.68
CTRJ2						1.6	7.6	8.5	5.47	84.48	101.81	0.613	0.042	38.00	43.66	18.34	54.65	41.36	3.99
CTRJ3						0.5	25.6	8.5	27.44	432.48	367.07	0.766	0.011	43.36	49.00	7.64	53.80	45.14	1.07
CZRR1	50	0.55	1	2	1	0.03	338	6.6	333.02	6357.32	4673.35	4.880	0.000	82.99	14.41	2.60	97.83	2.13	0.05
DCMS1	60	0.21	2	2	2	1.5	7.8	8.9	5.15	91.74	79.70	0.513	0.021	33.89	33.65	32.46	64.43	33.56	2.01
DDUL1000	110	0.09	2	1	1	2.0	5.3	7.7	5.32	86.29	78.84	0.345	0.041	25.64	37.64	36.72	26.68	69.39	3.92
DDUL2000						1.3	9.2	7.3	7.68	117.09	132.01	0.371	0.024	27.04	39.39	33.58	28.76	68.92	2.32
DHND1000	100	0.04	2	2	1	0.6	5.1	7.6	2.13	34.48	33.74	0.430	0.146	30.06	30.58	39.36	39.70	47.59	12.71
DMDN0000	35	1.4	2	1	1	0.8	12.1	7.0	10.61	165.95	192.98	0.912	0.020	47.70	34.16	18.15	50.90	47.17	1.93
DMDN1000						0.7	15.66	8.2	9.40	165.53	165.92	0.394	0.020	28.26	50.20	21.55	66.74	31.31	1.95
DPRA1	2	0.01	3	1	1	1.0	77.7	8.3	59.67	603.82	601.87	2.259	0.007	69.32	26.33	4.35	90.52	8.76	0.72
DPRB1	2	0.01	3	1	1	1.0	71.8	8.3	53.06	563.13	582.21	2.238	0.007	69.12	26.61	4.27	83.82	15.53	0.65
DSLD1	100	0.19	1	2	1	1.0	17	7.4	16.00	201.43	235.07	0.632	0.021	38.73	42.57	18.69	45.99	51.99	2.01
DSLD2						0.3	27	8.1	28.57	418.79	441.33	0.731	0.011	42.23	49.06	8.71	50.64	48.28	1.08
DTJE1	40	0.19	3	2	1	0.3	10.25	8.4	7.18	107.31	117.54	0.764	0.010	43.32	30.42	26.26	39.45	59.55	1.00
DTLL1	70	0.71	1	3	1	0.04	36	8.0	43.41	698.39	650.25	3.065	0.004	75.40	19.00	5.61	78.76	20.85	0.39
EACH1	669	0.71	1	1	3	0.1	40	8.9	107.12	1867.11	1868.77	0.291	0.007	22.52	76.30	1.18	43.75	55.51	0.73
EALB1	645	0.8	1	1	1	0.25	5.15	7.7	4.80	76.39	72.89	0.235	0.032	19.01	38.55	42.44	25.39	71.47	3.14

EALM1	675	0.26	1	1	2	0.3	12.5	9.9	8.46	130.74	124.49	127.222	0.330	99.22	0.35	0.43	64.81	10.37	24.82
ECHC1	645	0.25	3	1	2	1.09	3.8	8.3	0.13	62.28	67.43	0.179	0.044	15.16	45.10	39.75	15.08	80.67	4.25
ECHC2000	645	0.25	3	1	2	0.9	3.8	8.3	4.11	62.28	67.43	0.179	0.044	15.16	45.10	39.75	15.08	80.67	4.25
ECLD1	690	0.06	3	1	3	1.0	2.1	8.4	2.06	31.83	27.41	0.067	0.104	6.26	17.09	76.66	7.48	83.08	9.44
ECPL1	900	0.08	1	1	3	1.5	2.2	7.7	2.24	34.63	30.58	0.091	0.070	8.34	17.34	74.32	2.01	91.46	6.52
ECRR1	680	0.1	1	1	3	0.02	0.15	7.5	0.14	1.65	2.98	0.494	1.137	33.05	22.37	44.58	16.30	30.50	53.20
EGRA1	645	0.1	3	1	2	1.5	7.7	8.2	11.18	178.23	193.21	0.272	0.017	21.37	63.12	15.50	24.54	73.74	1.72
EHIT1	830	1.5	1	2	1	0.04	7.1	8.3	8.09	128.39	137.05	0.316	0.016	24.00	55.61	20.39	24.62	73.82	1.56
ELLL1	690	0.96	1	1	3	0.1	38	9.3	13.16	356.54	356.54	0.914	0.010	47.74	46.64	5.61	48.20	50.84	0.95
EMNJ1	670	1.06	1	2	3	0.15	22	7.8	28.87	428.40	475.67	0.615	0.007	38.08	55.43	6.49	56.87	42.39	0.74
ENVG1	620	0.5	1	1	1	0.05	14	8.0	9.84	150.24	186.65	0.851	0.009	45.97	24.75	29.29	72.65	26.51	0.84
EPBL1	654	0.38	2	2	3	2.0	5.5	7.7	4.83	77.34	71.22	0.635	0.055	38.84	31.36	29.79	38.66	56.12	5.23
EPZL1	620	0.46	1	1	3	0.1	14.5	8.8	12.42	170.67	214.21	1.073	0.016	51.76	40.33	7.91	37.81	60.58	1.61
EQUE1	650	0.001	1	1	2	0.1	38	8.5	81.03	1307.79	1518.59	0.442	0.001	30.64	67.89	1.47	34.78	65.13	0.09
ESLC1	668	0.44	1	3	2	0.03	49	8.3	184.29	3260.42	3037.72	0.387	0.008	27.89	71.44	0.67	45.03	54.14	0.83
ETRY1	670	0.03	3	1	2	0.2	1.7	8.0	1.77	24.50	28.56	0.140	0.072	12.29	34.78	52.93	11.72	81.59	6.69
GCNJ1	860	4.64	3	1	1	4.0	0.67	7.8	0.40	6.64	3.71	0.167	1.156	14.29	1.78	83.93	17.58	28.82	53.61
GCRL1	855	1.22	1	3	3	0.05	34	8.6	45.59	809.04	806.74	0.732	0.004	42.25	48.70	9.05	73.79	25.84	0.37
GLNG1	820	1.84	3	1	1	2.7	0.55	8.1	2.03	5.28	6.10	0.347	0.612	25.76	28.78	45.46	26.95	35.07	37.97
GMJN1	880	0.06	1	1	1	0.09	49	7.8	173.34	2849.26	3045.02	0.510	0.012	33.78	65.50	0.72	47.27	51.51	1.22
GNVL1	1080	0.01	1	2	1	0.03	0.21	9.3	0.43	2.78	4.11	0.474	2.405	32.15	25.52	42.33	13.25	16.12	70.63
GONT1	840	3.84	2	3	1	0.8	4.85	8.0	3.40	49.85	67.37	0.677	0.021	40.38	50.95	8.67	68.67	29.3	2.03
GONT2						1.5	0.5	9.7	3.26	53.04	58.04	0.711	0.082	41.57	53.16	5.27	63.33	29.11	7.56
GPTR1	860	1.74	1	1	3	0.7	3	9.0	27.39	431.90	557.24	0.594	0.015	37.28	59.64	3.08	50.83	47.72	1.45
GRSA1	873	0.12	1	1	2	0.1	61.5	8.3	95.31	1491.73	1605.01	0.302	0.017	23.17	74.77	2.06	32.67	65.7	1.63
GSAR1	873	0.25	2	2	1	0.7	23	8.2	61.05	1018.45	1158.37	0.225	0.010	18.36	79.25	2.39	36.08	62.94	0.98
GSAR2						0.2	50	8.9	70.27	1068.16	1143.31	0.226	0.009	18.44	78.89	2.66	31.97	67.12	0.91
GSLB1	940	0.36	2	2	3	0.8	18.5	8.7	22.06	337.66	421.55	0.290	0.053	22.45	76.69	0.85	26.9	68.09	5.01
GSLB2						0.5	25	8.9	29.46	439.49	514.90	0.271	0.044	21.32	77.72	0.96	26.6	69.17	4.24
HCHI1000	150	0.5	3	1	1	1.2	3.2	7.2	4.72	68.12	68.15	0.632	0.028	38.71	13.62	47.67	4.331	92.97	2.70
HEST1	325	1.0	3	1	1	8.0	0.8	7.4	0.60	8.77	8.97	0.282	0.476	22.00	11.14	66.85	6.043	61.69	32.27
HLDP2	324	1.92	1	2	1	0.05	40	7.3	212.74	3639.82	3916.99	5.343	0.003	84.24	15.13	0.64	84.11	15.6	0.29
HPD11	0.5	0.01	3	1	2	0.2	30.9	9.0	21.38	350.06	398.09	3.369	0.007	77.11	17.17	5.72	88.54	10.77	0.69
HSAL1000	150	0.23	3	1	1	5.0	54	8.5	67.63	1141.47	1071.77	0.742	0.010	42.59	54.52	2.89	38.54	60.5	0.96
HSAL2						5.0	54	8.5	67.63	1141.47	1071.77	0.742	0.010	42.59	54.52	2.89	38.54	60.5	0.96
IVRN1	690	0.02	1	1	3	0.15	14	9.4	10.49	156.81	178.16	24.354	0.143	96.06	3.53	0.41	74.65	12.85	12.50

KEY: PERM = lake permanence (1=ephemeral, 2=semi-permanent, 3=permanent. TURB = turbidity (1=transparent, 2=moderate turbidity, 3=high turbidity). EUTR = eutrophication (1=low, 2=moderate, 3=high; not used in analyses). TDS = total dissolved solids. CATION RATIO = [Na]+[K]:[Mg]+[Ca]; ANION RATIO = $[CO_3]+(HCO_3]:Cl+SO_4]$;
ION PERCENTAGES = proportions of total cations or anions

salinity transfer functions (Cumming & Smol, 1993, Fritz *et al.*, 1993a, Gasse *et al.*, in press), in which it has been demonstrated that the expression of major ions as molar concentrations is representative of total salinity, but is less representative of variation due to differences in brine composition than molar proportions and ratios. Major ions were expressed as molar ionic concentrations in meq l^{-1}, as molar percentages of total cations or anions, and as the molar cation and anion ratios, [Na]+[K]:[Ca]+[Mg] and $[CO_3]+[HCO_3]:[Cl]+[SO_4]$. Conductivity, TDS and lake area were $\log_{10}$-transformed, and maximium water depth was square-root transformed to reduce the skewness in their distributions.

Spanish salt lakes also differ in their permanence and turbidity and the inclusion of these variables is a departure; other biota such as ostracods are ecologically-sensitive to these qualities (Hammer, 1986), and some relationship between lake permanence, turbidity and diatom assemblage composition has been noted by Gasse *et al.* (1983). Three lake-permanence categories, ephemeral, semi-permanent and permanent, were expressed as ordinal variables, and turbidity on a scale of 1 to 3.

PCA was performed on a correlation matrix of the resultant data-set of 74 samples and 24 environmental variables.

4.2.3.2 Results

The eigenvalues and cumulative percentage variance of the data accounted for by the first four principal components (eigenvectors of the correlation matrix) are given in Table 4.3.

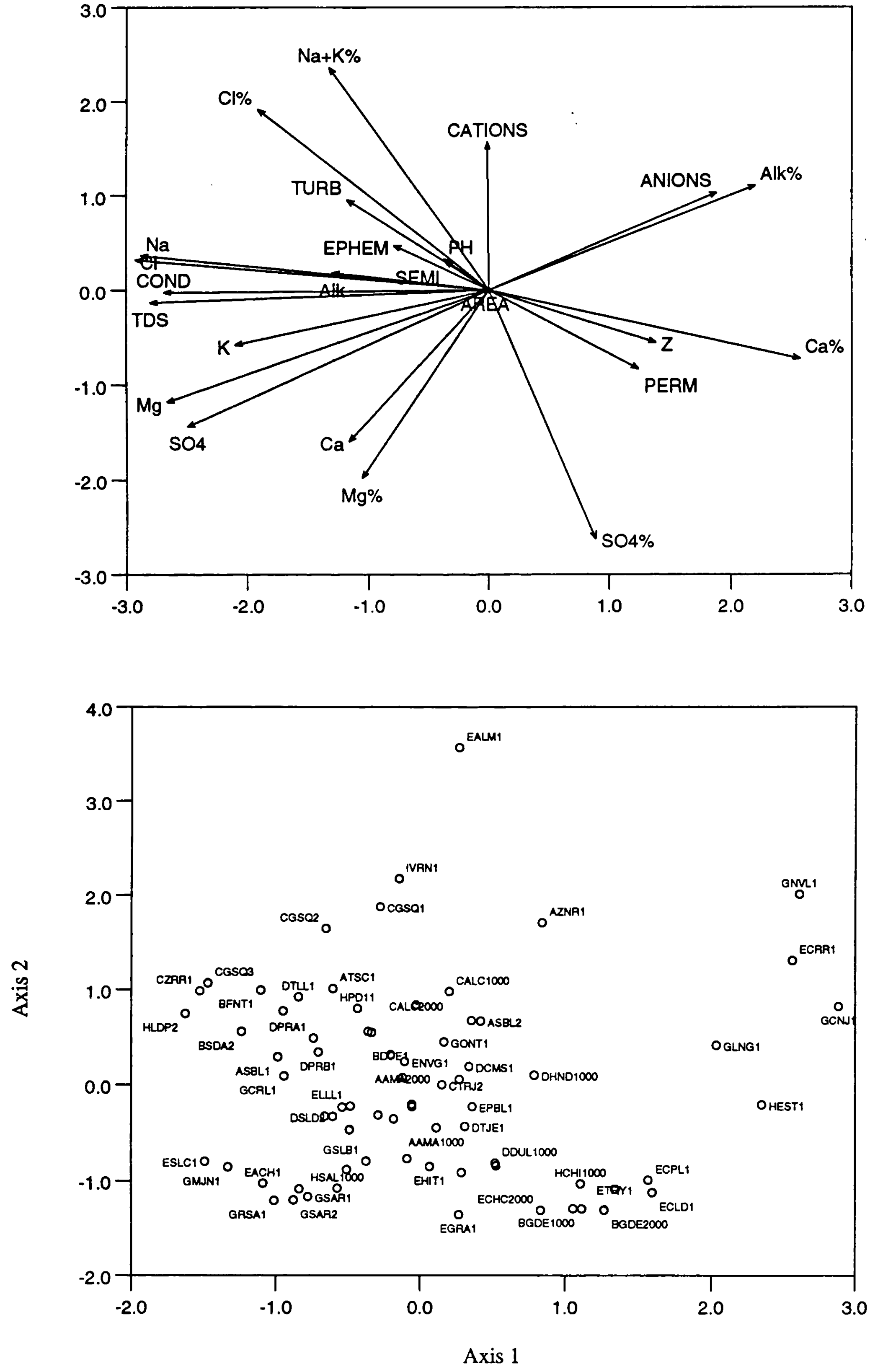
Table 4.3 **Summary of eigenvalues and cumulative percentage variance of the species (ie. environmental data) for PCA of 74 samples and 24 environmental variables.**

	Axis 1	**Axis 2**	**Axis 3**	**Axis 4**
Eigenvalues	0.375	0.159	0.095	0.077
Cumulative % variance of species data	37.5	53.4	62.9	70.6

Over 50% of the variance is accounted for by the first two axes. The first two principal components therefore account for a large proportion of the total variance in the environmental data.

A sample biplot of Axis 2 against Axis 1 is given in Figure 4.5. The vector length of environmental variables is approximately proportional to their variance, and the smaller the angle between vectors, the greater is their positive correlation. Water salinity and ionic composition variables are the most

Figure 4.5 **Sample biplot of Axis 2 against Axis 1 for PCA of 74 samples and 24 environmental variables.**



COND=conductivity, TDS=total dissolved solids, ANIONS=anion ratio, CATIONS=cation ratio, TURB=turbidity, EPHEM, SEMI, PERM = permanence classes, Z=water depth. 'Na' = molar concentration, 'Na%' = molar proportion.

important, and the variables expressing total salinity, that is, conductivity and TDS (total dissolved solids), are highly correlated. Lake area and pH are the least important.

The variables Cl and Na (scores of -0.98 and -0.96) and TDS and conductivity (scores of -0.93 and -0.90) and, to a lesser extent, Mg (score of -0.89) are very highly negatively correlated with Axis 1. The variables Ca% (score of 0.86) and, to a lesser extent, Alk% and Anion Ratio (scores of 0.73 and0.63) are highly positively correlated with Axis 1. Axis 2 is highly correlated with SO_4% and to a lesser extent with Mg% (scores of -0.88 and -0.66 respectively). The results confirm that molar concentrations are highly correlated with total salinity variables, but that samples are dispersed according both to salinity and ionic composition.

A group of low salinity, alkaline sites is separated to the right of the diagram (GNVL, ECRR, GCNJ, HEST and GLNG), which reflects the lack of carbonate-rich lakes of higher salinity in the data-set. Lake permanence is not important in separating the group; the latter four are relatively deep and permanent, and are correlated most closely with these variables, but GNVL and ECRR are ephemeral.

An outlier with very high scores on Axis 2, EALM, is unusual in terms of both cation and anion composition. It has extreme high Na+K% values and low Mg% values (99.2% and 0.35% respectively) and high carbonate concentration compared to its salinity (10.64% cf. <5% for other salt lakes).

The remainder of samples forms a group in which sites are dispersed along Axis 1 according to salinity; NaCl-rich, hypersaline sites plot to the left of the diagram, and Ca-rich, alkaline, low salinity sites to the right. In the direction of Axis 2, sites are separated further according to ionic composition; this gradient separates NaCl-rich sites towards the top of the diagram from $MgSO_4$-rich sites towards the bottom, without any clear relationship to salinity other than a dominance of sulphate-rich or alkaline sites at lower salinity, towards the bottom right of the diagram.

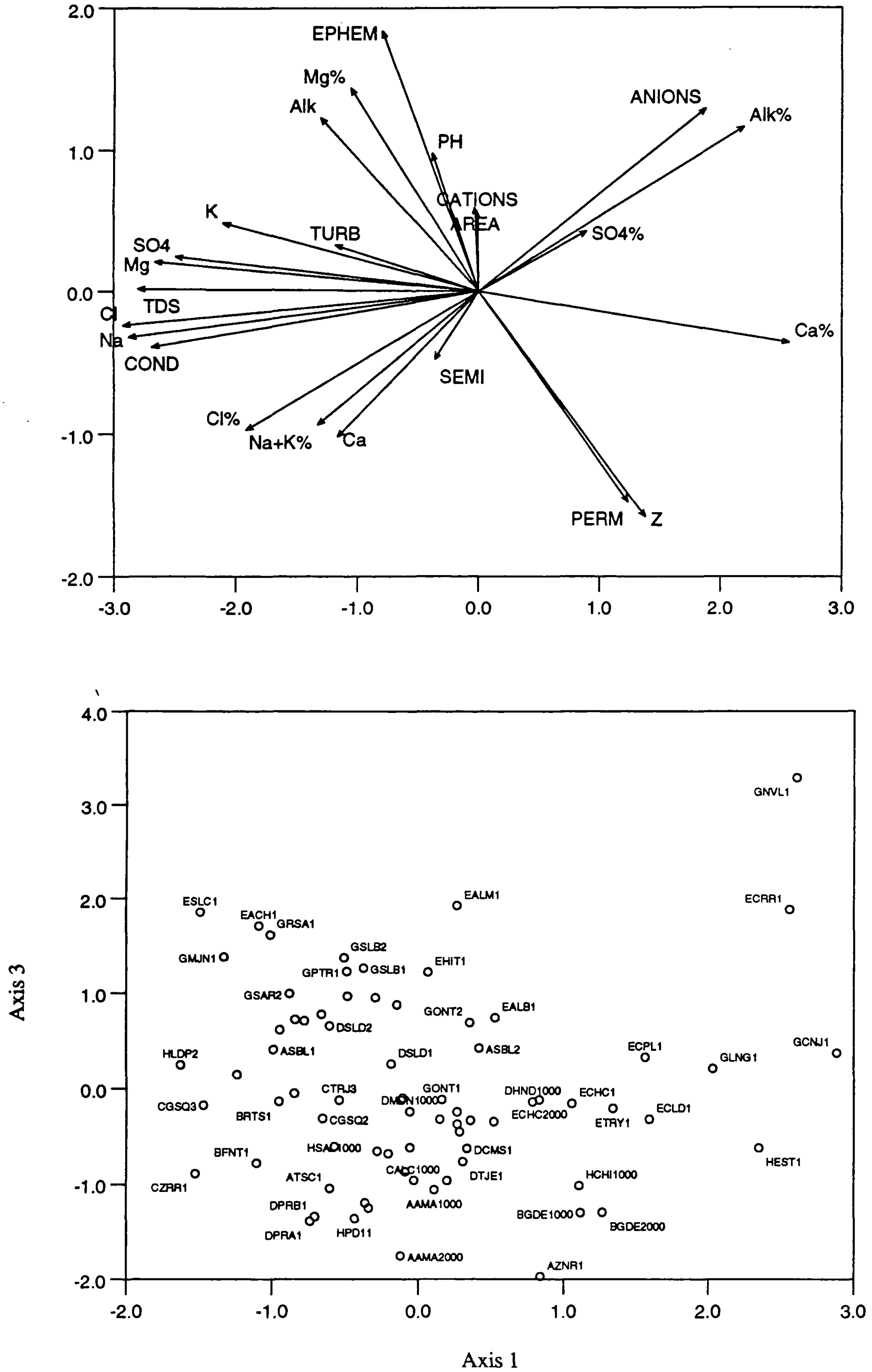
Variation according to water depth or permanence is better represented in a sample biplot of Axis 3 against Axis 1 (Figure 4.6), in which ephemeral sites are separated clearly from deep, permanent sites along a gradient from the top left to bottom right of the diagram.

4.3 MODERN DIATOM TRAINING SET

4.3.1 Summary of modern diatom samples (74 samples)

Preservation was sufficient in 71 samples for a count of c. 500 or c. 300 valves depending on sample diversity. The abundance of fragile *Nitzschia* species in many samples, which are particularly prone

Figure 4.6 Sample biplot of Axis 3 against Axis 1 for PCA of 74 samples and 24 environmental variables.



COND=conductivity, TDS=total dissolved solids, ANIONS=anion ratio, CATIONS=cation ratio, TURB=turbidity, EPHEM, SEMI, PERM = permanence classes, Z=water depth. 'Na' = molar concentration, 'Na%' = molar proportion.

to dissolution (Ryves, 1994) indicates that a bias caused by total dissolution of the valves of particular species is unlikely to have occurred. Valves were highly fragmented but countable to >250 valves in three other samples, ESLC1, GSLB1 and GSLB2.

Diatom counts for the 74 samples in the training set were transformed to percentages using the program TRAN (Juggins, unpublished program). The modern diatom data-set comprised a total of 255 species, 183 of which were present at >1% in one or more samples.

4.3.2 Detrended Correspondence Analysis (DCA) of the modern diatom training set

4.3.2.1 Introduction

Detrended correspondence analysis (DCA) is a technique for indirect gradient analysis, whereby the main patterns of variation in ecological species data are extracted by ordination, and species distribution along the most important ordination axes (1-3) is then interpreted in the light of external knowledge of environmental data. It assumes a unimodal response applicable to ecological data-sets, wherein species distribution along a given ecological gradient tends to approach a normal distribution. In contrast to correspondence analysis (CA), detrended correspondence analysis performs well on data-sets with long (>2 standard deviation units along the first ordination axis) ecological gradients of variation; the additional process of 'detrending' preserves the ecological distances between samples by removing the arch effect which would be produced in correspondence analysis (Hill & Gauch, 1980).

DCA was performed with detrending by segments and non-linear rescaling on the 74-sample diatom training set to determine the major floristic gradients in the species data. Rare species were downweighted in all analyses.

4.3.2.2 Results

Preliminary analyses (not reported) were performed on a data-set of 74 samples, with 183 diatom species present at >1%. Outlier samples had a major influence on the analysis; their progressive removal in further analyses (outliers ASBL2, then ASBL2/HSAL1/HSAL2, and finally, ASBL2/HSAL1/HSAL2/HEST1) produced new outliers each time and the distribution of samples and species was compressed in the direction of Axis 2. The Spanish data-set is heterogeneous and 28 species >1% have only one occurrence. Since DCA is designed to maximise the difference between samples it is sensitive to rare species (Jongman *et al.*, 1987). To reduce the influence of rare species further, but to maintain the ecological information provided by samples with unusual species composition, the data-set was reduced to species present at >1%, with ≥2 occurrences, or with 1 occurrence at ≥10%. Rare, unidentifiable species grouped in a generic 'sp.' category have no ecological meaning and were also deleted. The resultant data-set of 146 species was used in the following ordinations.

The eigenvalues and cumulative percentage variance accounted for by the first four axes in DCA1 of the full training set are given in Table 4.4. Both Axis 1 and Axis 2 are long gradients (6.4 and 4.0 s.d. units respectively) and together account for 9.5% of the variance in the data ($\lambda_1 = 0.894$, $\lambda_2 = 0.789$). This is low but comparable with the results of similar analyses performed on species-rich data-sets with many zero values (Hall & Smol, 1992, Fritz *et al.*, 1993a).

From the sample plot of Axis 2 against Axis 1 for DCA1 (Figure 4.7), the sample ASBL2 is a major outlier with a low score on Axis 2. To explore the variation in the rest of the diatom data more fully this sample was made passive in a second analysis of 73 samples, DCA2. The eigenvalues and cumulative percentage variance accounted for by the first four axes in DCA2 are given in Table 4.5 above and are similar to those of DCA1. From the sample plot of Axis 2 against Axis 1 for DCA2 (Figure 4.8), there are no major outliers, although samples with high scores on Axis 1 or 2 are scattered.

The plot of species scores for Axis 2 against Axis 1 in DCA2 of 73 samples (Figure 4.9) indicates the main floristic gradients in the data-set. Salinity or its correlates have a clear influence in the direction of Axis 1, which is by definition the axis which indicates maximum species dispersal. Species characteristic of fresh or oligosaline waters such as *Cyclotella ocellata* (CY009A), *Cyclotella radiosa* (CY019A), *Aulacoseira granulata* (ME003A) *Fragilaria ulna* var. *acus* (SY003A), *Cymbella laevis* (CM012A), *C. amphicephala* (CM016A), *Navicula capitoradiata* (NA745A) and *Brachysira vitrea* (BR001A) have high scores on Axis 1 and plot towards the right of the diagram, whereas those of saline waters such as *Amphora* sp. 1 [cf. *acutiuscula*] (AM9985), *Navicula crucicula* var. *cruciculoides* (NA304A), *Gyrosigma peisonis* (GY021A), *Navicula* cf. *salinicola* (NA9838), *Mastogloia pumila* (MA005A), *Pleurosigma salinarum* (PL050A) and *Navicula phyllepta* (NA9839) have low scores and plot to the left.

Salinity may not be the only variable influencing the distribution along Axis 1. Species regarded as alkaliphilous (Gasse, 1986) tend to plot to the right of the diagram (e.g. *Aulacoseira granulata* [ME003A], *Cyclotella distinguenda* [CY028A], *C. pseudostelligera* [CY002A], *Cymbella amphicephala* [CM016A]), whereas those of NaCl-rich waters (Gasse, 1986) plot to the left (e.g. *Amphora coffeaeformis* [AM006A], *Gyrosigma peisonis* [GY021A], *M. elliptica* [MA002C], *Navicula crucicula* var. *cruciculoides* [NA304A] , *Navicula* cf. *salinicola* [NA9838] and *Nitzschia compressa* var. *vexans* [NI200C]).

Table 4.4 **DCA1: summary of eigenvalues and cumulative percentage variance of the species data for DCA of 74 samples and 146 species present at ≥1% and with >1 occurrence, or 1 occurrence at ≥10%.**

DCA1	Axis 1	Axis 2	Axis 3	Axis 4	Total inertia
Eigenvalues	0.894	0.789	0.617	0.493	17.625
Cumulative % variance of the species data	5.1	9.5	13.1	15.8	

Table 4.5 **DCA2: summary of eigenvalues and cumulative percentage variance of the species data for DCA of 74 samples and 146 species present at ≥1% and with >1 occurrence, or 1 occurrence at ≥10%.**

DCA2	Axis 1	Axis 2	Axis 3	Axis 4	Total inertia
Eigenvalues	0.894	0.730	0.596	0.536	16.847
Cumulative % variance of the species data	5.3	9.6	13.2	16.4	

Figure 4.7 Sample plot of Axis 2 against Axis 1 for DCA1 of 74 samples

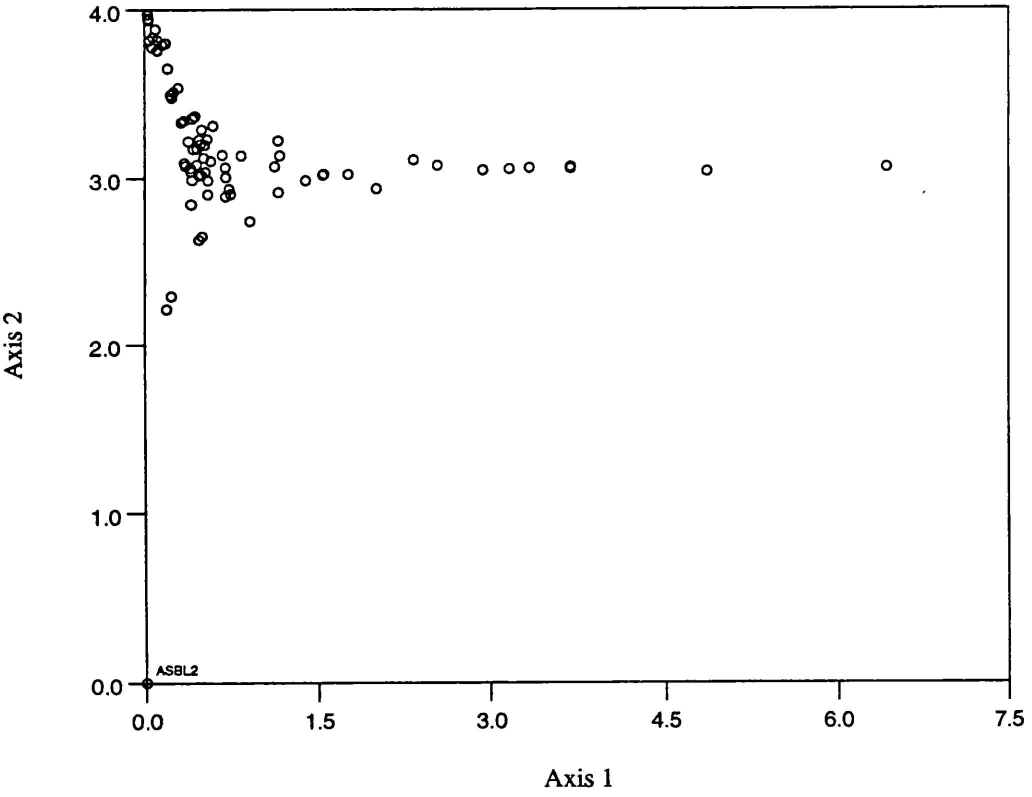


Figure 4.8 Sample plot of Axis 2 against Axis 1 for DCA2 of 73 samples

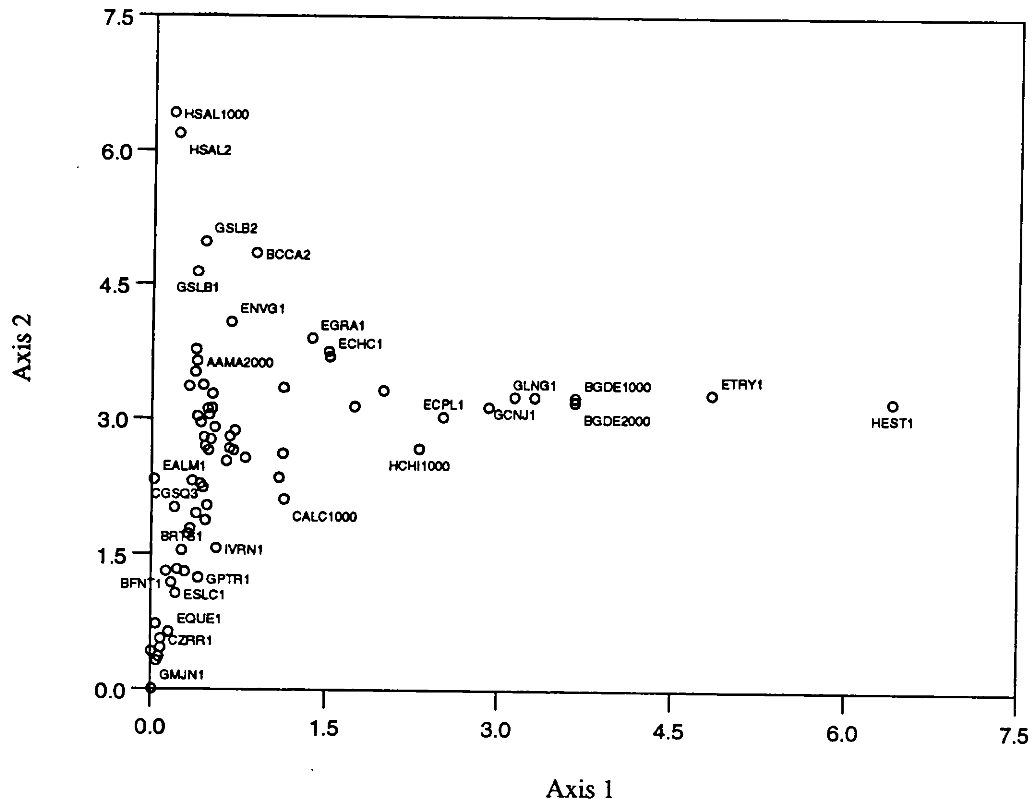
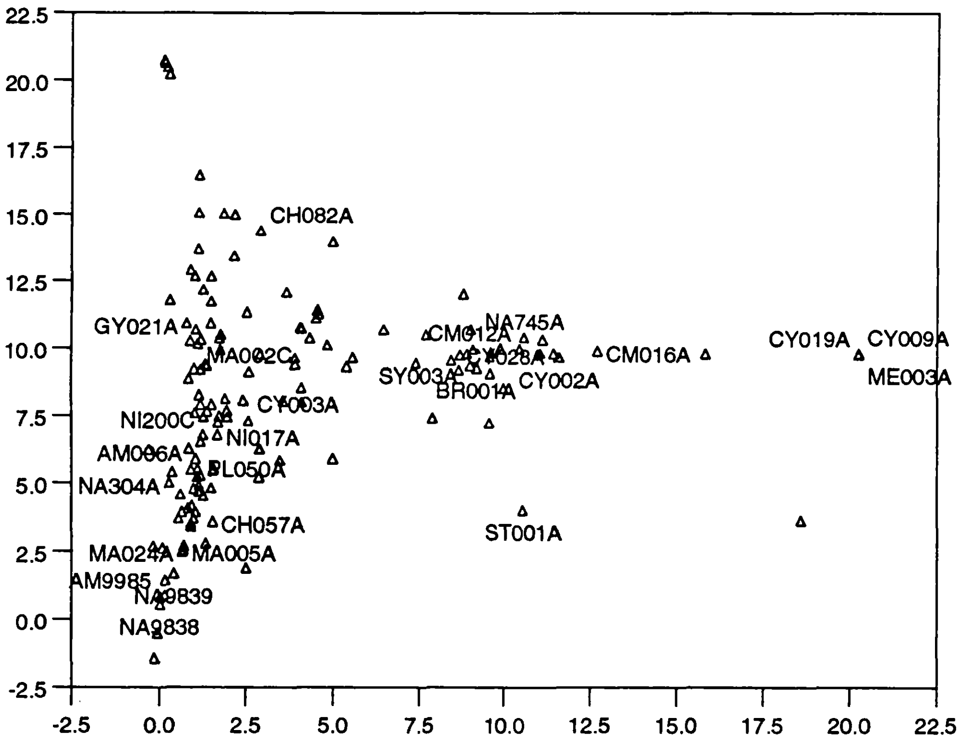


Figure 4.9 **Plot of species scores for Axis 2 against Axis 1 in DCA2 of 73 samples and 146 species**



Planktonic species comprise taxa from the genera *Cyclotella*, *Stephanodiscus*, *Aulacoseira* and*Chaetoceros*, and the species, *Nitzschia gracilis* [NI017A]. This excludes *Fragilaria*, *Synedra* and *Nitzschia* species whose life habit may be either planktonic or benthic (Round *et al.*, 1990). They tend to have high scores on Axis 1 but their scores are spread along 75% of the range. This suggests variables such as water depth also influence species distribution, either directly or indirectly, but to a lesser extent than salinity.

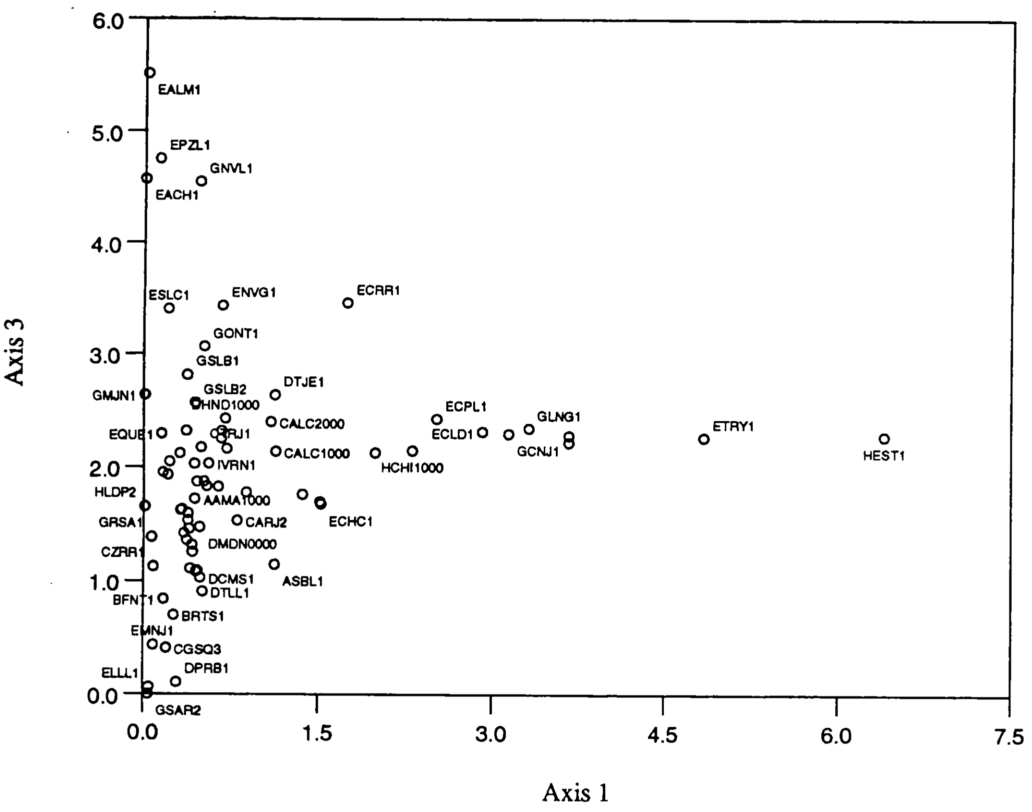
The distribution of species along Axis 2 is compressed to the right of the diagram (low-salinity, high alkalinity sites) and widely-scattered to the left of the diagram. The potential underlying environmental influence is unclear.

In the sample plot of Axis 3 against Axis 1 (Figure 4.10), sites of Andalucía (site codes with initial letters A-D) are separated from sites of La Mancha (E and G) along Axis 3. This could reflect biogeographical factors, or the regional distinctions noted in section 4.2.1 between chloride- and sulphate-dominated waters or differences in lake permanence, for example. The influence of environmental gradients other than salinity is explored in constrained ordinations below.

Nutrient status is not a major floristic gradient in the data-set since there is no consistent trend in nutrient preference in the diagram. From published data based on freshwater lakes of Michigan, North America (Fritz *et al.*, 1993b), the distribution of freshwater diatoms in Figure 4.8 bears no relation to their phosphorus optima; *Cyclotella ocellata* [CY009A] (1.18μgl^{-1}) and *Aulacoseira granulata* [ME003A] (18.51μgl^{-1}) plot in the same ordination space on the diagram and are separated along Axis 1 from *C. distinguenda* [CY028A] (9.68μgl^{-1}), and along Axis 2 from *Stephanodiscus hantzschii* [ST001A] (21.58$\mu g.^{-1}$). Euryhaline diatoms characteristic of polluted or nutrient-enriched waters (Germain, 1981) such as *Navicula phyllepta* [NA9839], *Cocconeis placentula* var. *euglypta* [CO001B], or *Nitzschia pusilla* [NI152A] are similarly scattered. This suggests other water chemistry variables are a more important influence.

In summary, salinity is a major determinand of diatom species assemblage composition. It may not be independent of other variables such as ionic composition or water permanence, but nutrient status is unlikely to represent a major unexplained gradient of variation which could affect the validity of a salinity transfer function.

Figure 4.10 Sample plot of Axis 3 against Axis 1 for DCA2 of 73 samples



4.4 CANONICAL CORRESPONDENCE ANALYSIS (CCA) OF THE TRAINING SET DATA

4.4.1 Introduction

Canonical correspondence analysis (CCA) was used to establish the statistical significance of measured environmental variables ('explanatory variables') in explaining the floristic gradients in the diatom species data ('response variables'). CCA is a constrained ordination technique for direct gradient analysis. It assumes a unimodal response applicable to ecological data-sets, whereby species distribution along a given ecological gradient tends to approach a normal distribution. In contrast to indirect gradient analysis, where ordination axes are interpreted in the light of external knowledge of environmental gradients, species occurrences are related directly to environmental variables in CCA, such that the influence of the particular environmental variables of interest can be established more unequivocally. This is achieved by constraining the ordination axes to be linear combinations of environmental variables, so variance in the diatom data can be directly related to environmental variance (ter Braak, 1986).

PCA indicated that molar concentrations are highly correlated with total salinity variables. In CCA, major ions are expressed only as ionic ratios and proportions (17 explanatory variables). Species scores are scaled to be weighted averages of the site scores and rare species are downweighted in all analyses. Sites are plotted as linear combinations of environmental variables.

4.4.2 CCA1 of the training set samples (74 samples, 17 explanatory variables)

CCA1 was performed on the 74-sample, 146-species training set, with 17 explanatory variables. Summary statistics are given in Table 4.6. A total of 7.5% of the variance in the diatom data is contained in the first two axes of CCA1 (λ_1 = 0.760, λ_2 = 0.554). The species-environment correlations for Axis 1 (0.963) and Axis 2 (0.923) are high, and the 17 variables together explain 26.1% of the variance in the diatom data. These eigenvalues and those of DCA1 of the full training set (0.894, 0.789) are similar. Since the DCA Axis 1 eigenvalue reflects the maximum separation of the species data this indicates that the measured environmental variables have a significant influence on diatom species assemblage composition, and that the environmental data express the main ecological gradients.

The sample biplot for Axis 2 against Axis 1 in CCA1 is given in Figure 4.11. The sample HSAL2 has extreme, high scores on Axis 2. Other unusual samples, with extreme influence in the CCA (>5, cf. Hall & Smol, 1992), are listed in Table 4.7. The removal of sample HSAL2, and separately of samples ECRR1, GCNJ1 and GNVL1 with the highest influence produced new outliers and increased the scatter to the right of the resultant CCA sample biplots (not reported). This suggests the data-set may be unstable for samples which have high scores on Axis 1. These are the most diverse and heterogeneous samples of the diatom training set. Since the analysis is not improved by the removal of outliers, all 74 samples are retained in the following to avoid loss of ecological information.

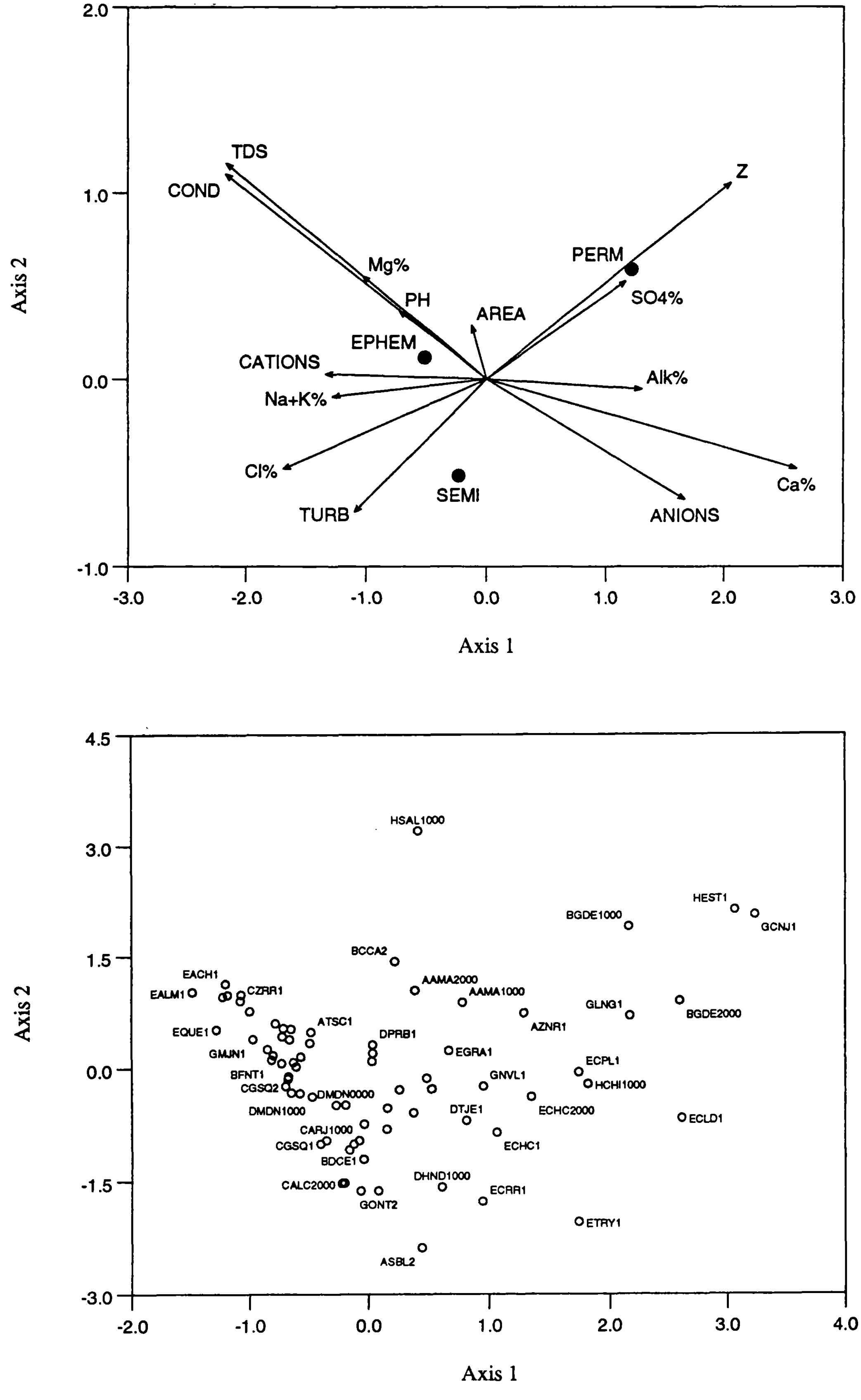
Table 4.6 **CCA1: summary statistics for CCA of 74 samples, 146 species and 17 explanatory variables**

CCA1	Axis 1	Axis 2	Axis 3	Axis 4	Total Inertia
Eigenvalues	0.760	0.554	0.482	0.467	17.625
Cumul. % variance of species data	4.3	7.5	10.2	12.8	
Cumul. % variance of the species-environment relation	16.5	28.6	39.1	49.3	
Sum of canonical eigenvalues					4.594

From vector lengths on the sample biplot, the variables most important in explaining the variance in the diatom data are salinity (conductivity and TDS), Ca%, the anion ratio ($[CO_3]+[HCO_3]:[SO_4]+[Cl]$) and water depth. Inter-set correlations of environmental variables with the first 3 axes are given in Table 4.8. Many variables are highly correlated with Axis 1 (correlations of >0.500 or <-0.500). Ca% (correlation +0.839) and the salinity variables (-0.698, -0.696) are most highly correlated with Axis 1. The structure of Axis 2 is unclear since it is not highly correlated with any variables. Axis 3 is highly correlated with the ephemeral lake category and with Alk%.

Many environmental variables are highly correlated with each other. The weighted correlation matrix (Table 4.9) shows salinity variables (conductivity and TDS) are highly correlated both with each other and with variables expressing ionic composition. They are highly positively correlated with Cl% and negatively with the anion ratio, Alk% and Ca%. The correlation with Cl% is a function of increased NaCl concentration at higher salinities. The very high negative correlation with the anion ratio, Alk% and Ca% is due both to the higher relative proportion of carbonate and bicarbonate in fresh waters, below the calcite branchpoint (Hardie *et al.*, 1978) and to the lack of carbonate-rich salt lakes in the data-set. Ephemeral and permanent lake categories are highly correlated with water depth but less so with salinity. Turbidity, pH and lake area (the less important variables) are not highly correlated with other variables.

Figure 4.11 Sample biplot of Axis 2 against Axis 1 for CCA1 of 74 samples, 146 species and 17 explanatory variables.



COND=conductivity, TDS=total dissolved solids, ANIONS=anion ratio, CATIONS=cation ratio, TURB=turbidity, EPHEM, SEMI, PERM = permanence classes, Z=water depth.

Table 4.7 **Summary of samples with extreme influence (>5) in CCA1 of 74 samples, 146 species and 17 explanatory variables.**

SAMPLE	ENVIRONMENTAL VARIABLE	INFLUENCE
AZNR1	Water depth	6.1
BGDE2	Water depth	5.8
CZRR1	pH	5.3
EALM1	Cations	9.1
ECHC1	TDS	5.0
ECLD1	Ca%	5.2
ECRR1	Conductivity	6.0
	TDS	5.2
	Alk%	14.2
EQUE1	Area	6.6
GCNJ1	Ca%	6.4
	Alk%	11.9
GNVL1	Alk%	11.6

Table 4.8 **Inter-set correlation of environmental variables with Axes 1-3 of CCA1. [High inter-set correlations (>0.50 or <-0.500) are emboldened.]**

ENVIRONMENTAL VARIABLE	AXIS 1	AXIS 2	AXIS 3
Conductivity	-0.698	0.340	-0.230
pH	-0.233	0.111	-0.106
Water depth	0.661	0.325	-0.339
Area	-0.041	0.088	0.086
Turbidity	-0.354	-0.218	-0.146
Cation ratio	-0.431	0.008	-0.007
TDS	-0.696	0.358	-0.044
Anion ratio	0.537	-0.197	0.280
Ephemeral	-0.408	0.086	0.576
Semi-permanent	-0.174	-0.358	-0.307
Permanent	0.662	0.305	-0.313
Ca%	0.839	-0.145	0.224
Mg%	-0.331	0.170	-0.153
Na+K%	-0.412	-0.029	-0.053
Cl%	-0.543	-0.147	-0.156
SO_4%	0.378	0.161	-0.093
Alk%	0.421	-0.016	0.561

Table 4.9 Weighted correlation matrix of 17 environmental variables in CCA1. [High correlations (>0.5 or <-0.5) are emboldened.]

	Cond	pH	WD	Area	Turb	Cat	TDS	Anio	Eph	Semi	Perm	Ca%	Mg%	Na+K%	Cl%	SO_4
Conductivity	1.00															
pH	.02	1.00														
Water depth	-.40	-.13	1.00													
Area	-.08	-.12	-.06	1.00												
Turbidity	.27	.12	-.33	.30	1.00											
Cation ratio	.38	.08	-.17	-.06	.24	1.00										
TDS	**.86**	.12	-.40	-.03	.30	.39	1.00									
Anion ratio	**-.79**	.01	.33	.00	-.34	-.22	**-.74**	1.00								
Ephemeral	.20	-.02	**-.55**	.14	.07	.14	.34	-.21	1.00							
Semi-perm	.01	.00	.03	.02	.35	.01	-.07	.08	**-.61**	1.00						
Permanent	-.24	.02	**.60**	-.18	-.47	-.16	-.31	.15	-.46	-.42	1.00					
Ca%	**-.70**	-.26	.39	-.04	-.37	**-.55**	**-.75**	**.55**	-.24	-.09	.37	1.00				
Mg%	.18	.22	-.17	.12	.02	**-.57**	.24	-.16	.11	.06	-.19	-.33	1.00			
Na+K%	.43	.02	-.18	-.07	.30	**.97**	.42	-.33	.10	.03	-.15	**-.54**	**-.61**	1.00		
Cl%	**.55**	.03	-.28	.01	.47	**.78**	**.52**	**-.50**	.09	.19	-.32	**-.62**	-.37	**.85**	1.00	
SO_4%	-.29	-.01	.24	-.02	-.40	**-.78**	-.29	.18	-.11	-.14	.28	.44	**.51**	**-.82**	**-.90**	1.00
Alk%	**-.62**	-.04	.11	.02	-.20	-.07	**-.57**	**.76**	.02	-.12	.11	.46	-.28	-.14	-.32	-.12

4.4.3 Variance partitioning and CCA of the significant explanatory variables

4.4.3.1 Introduction

For the successful application of the transfer function, salinity must explain a significant proportion of the variance in the diatom data independent of other variables. Interaction with other variables is indicated by the foregoing. Partial CCA with variance partitioning can be used to quantify the relative strength of salinity and the other environmental gradients, each represented by different sets of variables, and their independent contribution to the variance of the species-sample data matrix (Borcard *et al.*, 1992, Gasse *et al.*, in press).

The explanatory variables were split into sets representing the major environmental gradients in the data and CCA with forward selection was performed to establish the significance of variables within each set, using Monte Carlo permutation tests as a test of significance. The Bonferroni test (Manly, 1992) was used to establish the value of *P* for which successive variables were retained as significant in each set. Variables significant at the $P = 0.05$ level (first variable in each set), 0.025 level (second variable, $P/2$) and 0.016 level (third variable, $P/3$) were retained. 99 Monte Carlo permutation tests were used to establish significance to two decimal places and 999 permutations for sets in which accuracy to the third decimal place was necessary.

Variance partitioning by partial CCA was perfomed on the sets of significant variables to establish the significance and relative strength of their contribution to the variance in the diatom data. To establish the unique contribution of each set of significant variables, the effects of other variables ('covariables') were removed by multiple linear regression and a partial CCA was performed on the set of significant variables alone. Partial CCA was then performed on all combinations of paired sets, with other sets as covariables, to establish the interaction, or 'overlap' between sets. The amounts of variation explained in each case were transformed to percentages by dividing the sum of canonical eigenvalues by the total inertia according to the procedure described in Borcard *et al.* (1992) and applied in palaeolimnological studies by Gasse *et al.* (in press) and Jones & Juggins (in press). Their overall influence on diatom assemblage composition was then assessed further in a CCA of the significant variables.

4.4.3.2 Selection of sets of variables

Five sets of variables which represent major environmental gradients were identified as follows. From previous work (Gasse *et al.*, in press), variables representing salinity and ionic composition were split into three sets: 'Salinity', 'Cations' (ratios and proportions) and 'Anions'. From PCA and CCA results, water depth and lake permanence represent another major gradient and were included as a 'Water

Table 4.10 **Summary of potential variance explained in CCA1 with 17 explanatory variables.**

Environmental variable	**Potential % variance explained**
Area	0.21
pH	0.30
Na+K%	0.30
Mg%	0.30
Cation ratio	0.31
SO_4%	0.32
Semi-perm	0.36
Turbidity	0.40
Cl%	0.42
Ephemeral	0.42
Alk%	0.46
Anion ratio	0.47
TDS	0.58
Permanent	0.58
Water depth	0.58
Conductivity	0.59
Ca%	0.66

Table 4.11: Summary of potential variance explained in CCA with 15 explanatory variables and results of forward selection with 5 sets of explanatory variables. [Highlighted variables are retained as significant at progressively increasing levels within each set of $P = 0.05$, 0.025 and 0.016.]

Explanatory variable	Potential % variance explained	Explanatory variable sets	*P*-value	% total variance explained
Na+K%	0.27	*CATIONS:*		
pH	0.29	Ca%	**0.01**	
Mg%	0.29	Mg%	0.04	
Cation ratio	0.29	Cation ratio	0.55	7.2
SO_4%	0.30			
Semi-perm	0.34	*SALINITY:*		
Turbidity	0.37	Conductvity	**0.01**	
Cl%	0.39	TDS	0.09	5.3
Ephemeral	0.40			
Alk%	0.40	*WATER QUALITY:*		
Anion ratio	0.46	Permanent lakes	**0.001**	
Water depth	0.49	Water depth	**0.001**	
Permanent	0.55	Ephemeral lakes	**0.011**	7.5
TDS	0.57			
Conductivity	0.57	*ANIONS:*		
Ca%	0.64	Anion ratio	**0.01**	
		Cl%	**0.01**	
		Alk%	0.06	6.5
		TURBIDITY:		
		Turbidity	**0.01**	2.2

Stability' set.

A summary of the potential variance explained prior to forward selection in CCA1 of 17 variables is given in Table 4.10 above. Turbidity was included as a separate set since it potentially explains a relatively high percentage of variance compared to the other 16 variables and is not highly correlated with other variables. Lake area and pH are of minimum significance in Table 4.10. To reduce the number of groups lake area and pH were excluded, leaving five groups of environmental variables: Salinity (2 variables), Cations (4 variables), Anions (4 variables), Water Stability (1 continuous and 3 nominal variables) and Turbidity (1 ordinal variable).

4.4.3.3 Results

The potential variance explained by each of the 15 variables in CCA and the results of forward selection of the 5 sets of explanatory variables are given in Table 4.11 above. All 5 sets are significant, and comprise a total of 9 significant variables. Three sets are represented by single significant variables (Salinity, Cations and Turbidity); Anions are represented by two variables (Anion ratio and Cl%) and Water Stability by water depth and the 3 lake permanence categories, which in each case explain significantly independent directions of variation within each set. Non-significant variables have been identified (e.g. TDS) which do not explain directions of variance in the data additional to stronger, significant variables in their set due to autocorrelation, and which are therefore redundant.

Table 4.12 **CCA2: Summary statistics for CCA of 74 samples and 9 significant explanatory variables.**

CCA2	Axis 1	Axis 2	Axis 3	Axis 4	Total Inertia
Eigenvalues	0.752	0.511	0.447	0.337	17.625
Cumul. % variance of species data	4.3	7.2	9.7	11.6	
Cumul. % variance of the species-environment relation	24.7	41.4	56.1	67.2	
Sum of canonical eigenvalues					3.047

Summary statistics are given in Table 4.12 above for CCA2 performed on the full training set of 74 samples, with 9 significant explanatory variables representing the major environmental gradients in the data. The total percentage variance in the diatom data explained is 17.3%. From Table 4.11, the sum of the percentage variance explained by individual sets after forward selection was 28.7%. The relatively low discrepancy between the two figures indicates there is overlap between the influence of different environmental variables.

The results of variance partitioning of the sets of significant environmental variables are given in Figure 4.12 and show both the unique amount of variance in the diatom data explained by each set, and the amount of interaction between sets.

The independent contributions to the variance of the sets, Salinity (1.92%), Cations (2.05%), Anions (3.01%), Turbidity (1.56%) and Water Stability (6.48%) account for 87% of the total variance explained in the CCA. The Water Stability set (water depth and lake permanence) accounts for more than twice the variance of any other set; salinity makes a smaller contribution but is significant nonetheless. No interaction is shown between two pairs of sets (Salinity and Water Stability, and Turbidity and Cations), and the level of interaction between others is less than <0.4%. These figures are very low, and indicate that the sets represent largely independent directions of variation in the data. The main interactions are between salinity and the cation and anion groups (0.33% and 0.18%) which again indicates a degree of autocorrelation. From the earlier CCA results, the lack of interaction between Salinity and Water Stability sets in particular is surprising; it is possible that some interaction is contained within additional, unexplained gradients in the data.

The sample biplot for the forward selected CCA2 with 9 significant variables is given in Figure 4.13. The percentage variance of the species data explained by the first two axes in CCA2 (7.2%) is relatively close to that of DCA2 (9.6%), and the dispersal of samples along Axis 1 is similar to that of DCA. This confirms the influence of the measured variables on species composition. Cations (inter-set correlation 0.831), salinity (-0.699), water depth (0.676), permanent lakes (0.675), Anion ratio (0.539) and Cl% (-0.551) are all highly correlated with Axis 1. Samples are dispersed along a major salinity gradient from top right (low salinity) to bottom left of the diagram which also correlates closely with their distribution according to ionic composition. Another major gradient according to water depth and lake permanence is apparent from top left (shallow, ephemeral lakes) to bottom right (deeper, permanent lakes). Samples with high scores on the salinity gradient are clustered and those with low scores are highly scattered.

The structure of Axis 2 is unclear, as in DCA2, and is most highly correlated with salinity (inter-set correlation -0.483). Sample dispersal is compressed by three samples with extreme high scores on Axis 2, ECRR1, GNVL1 and ASBL2, and by one sample with a low score, HSAL1. Although none of the samples has extreme reported influence (maximum ECCR1: conductivity 6x), the samples with high scores are from ephemeral lakes whose low salinity at the time of sampling was partly due to refilling

Figure 4.12 Diagram showing the partitioning of the total variance explained in CCA of 9 significant variables within sets, into unique percentage variance explained by sets (within boxes) and the interaction between sets, and unexplained variance.

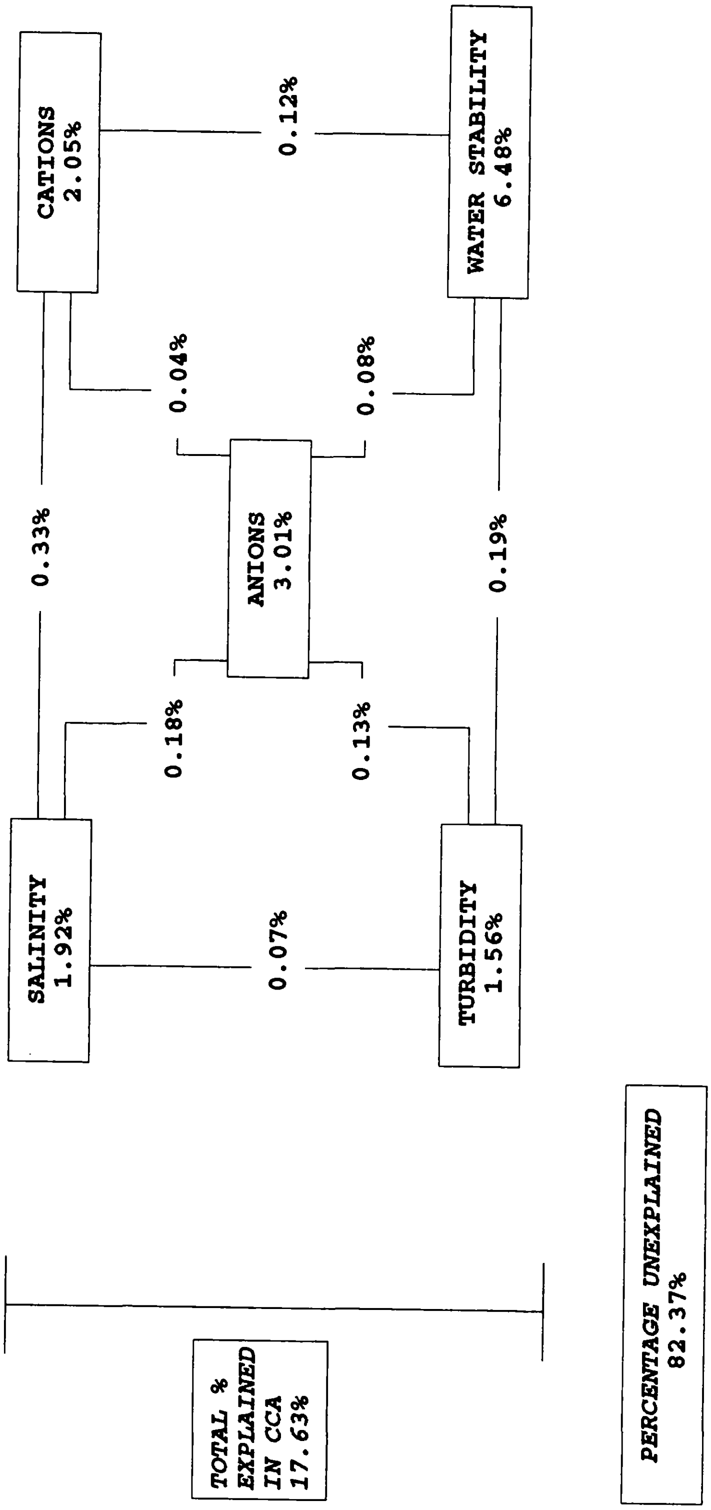
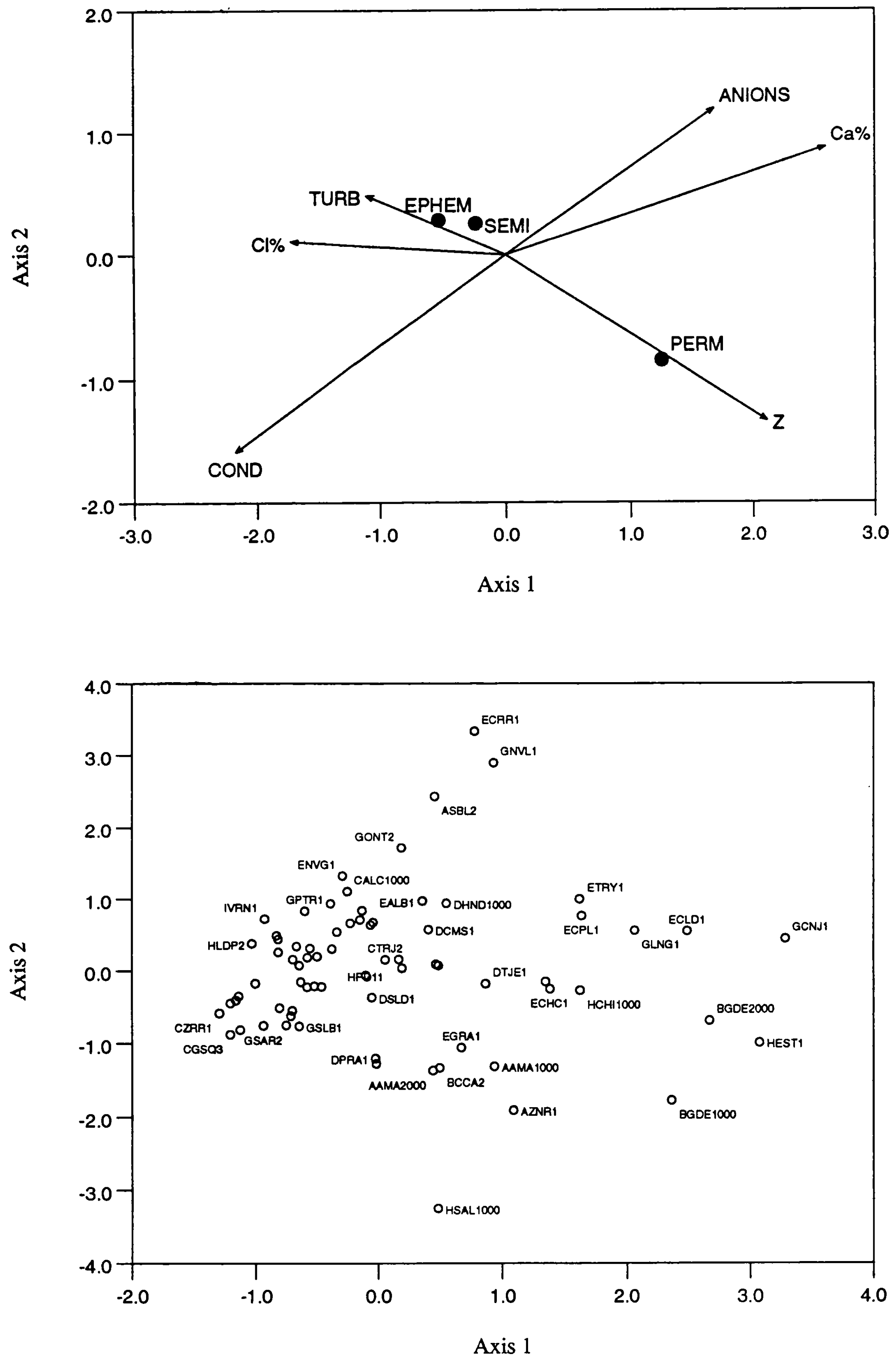


Figure 4.13 **Sample biplot of Axis 2 against Axis 1 for CCA2 of 74 samples and 9 significant explanatory variables.**



COND=conductivity, ANIONS=Anion ratio, TURB=turbidity, EPHEM, SEMI, PERM = permanence classes.

after recent rain storms; two are artificially-desiccated and rarely hold water, whilst the third, ASBL2, is usually mesosaline. HSAL1, Laguna Salada, Chiprana, is also unusual in being the only permanent, hypersaline lake in the data-set.

A species plot of Axis 2 against Axis 1 is given in Figure 4.14; these four samples are dominated by taxa rare, or only common at low frequency, in the rest of the data-set. ASBL2 is dominated to 90% by *Navicula erifuga* [NA173A], whilst ECRR1 and GNVL1 are dominated by aerophilous diatoms, *Hantzschia petitiana* [HA003A], *Navicula mutica* [NA025A] and *N. paramutica* [NA555A], all of which are absent or rare in other samples. Similarly, HSAL1 the rare taxa, *Nitzschia stompsii* [NI205A], *Brachysira aponina* [BR009A] are common in HSAL1. Axis 2 is therefore more likely a reflection of the influence of extreme samples than an indication of a major gradient of unexplained variation in the data.

Samples are more evenly dispersed in the sample biplot of Axis 3 against Axis 1 (Figure 4.15). The salinity/cation vectors now lie along Axis 1, and Axis 3 is highly correlated with semi-permanent lakes (-0.508) and turbidity (-0.501). As in the DCA, there is a separation of sites of La Mancha (site code initials E and G) towards the top of the diagram and those of Andalucía (A to D) towards the bottom. From the environmental vectors, the distinction may be a function of increased chloride dominance in sites of Andalucía, or the restricted distribution of the deeper, more permanent saline lakes which are largely confined to this region. The most saline lakes (semi-permanent 'damp' lakes) are of the highest turbidity.

The species plot for Axis 3 against Axis 1 is given in Figure 4.16. The same taxa are coded as for DCA (Section 4.3.2), and, as in DCA, freshwater and saline species are separated along Axis 1, the direction of variation of salinity. In CCA, their position along the salinity gradient also indicates their weighted-average conductivity optima, which are discussed in the appropriate section below which relates to the derivation of a salinity transfer function (Section 4.5).

In summary, the results of PCA, DCA and CCA ordinations of the calibration data-set indicate that the measured environmental variables have a significant influence on diatom species assemblage composition. Conductivity is the strongest of the two salinity variables, and salinity has the independent and significant contribution to the variance in the diatom data necessary for the derivation of a salinity transfer function.

Figure 4.14 Species plot of Axis 2 against Axis 1 for CCA2 of 74 samples and 9 significant explanatory variables.

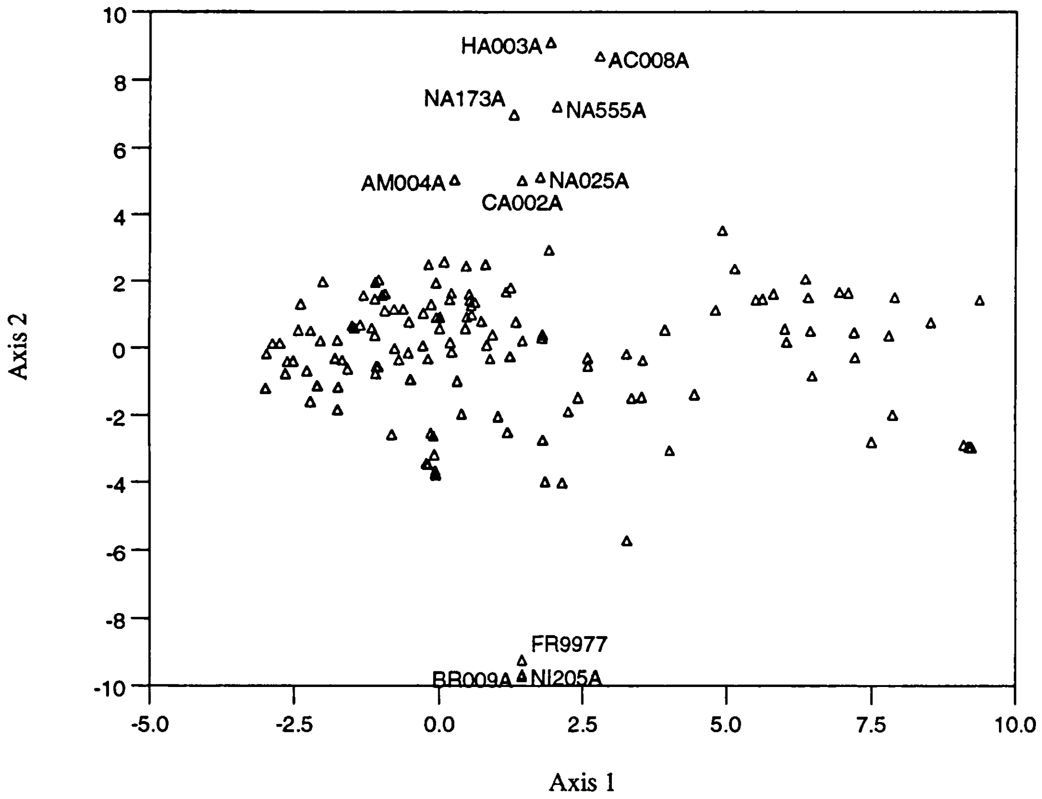
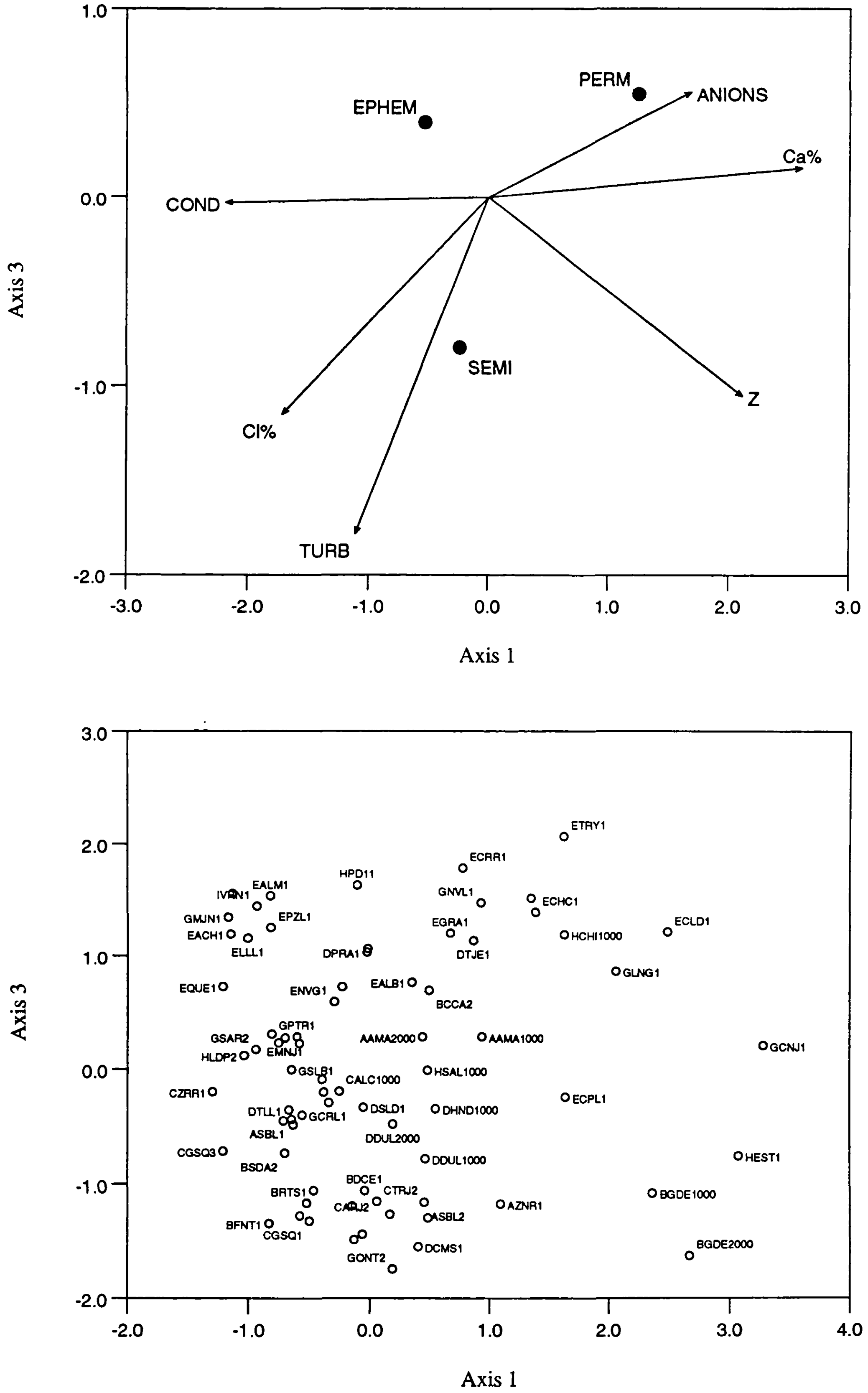
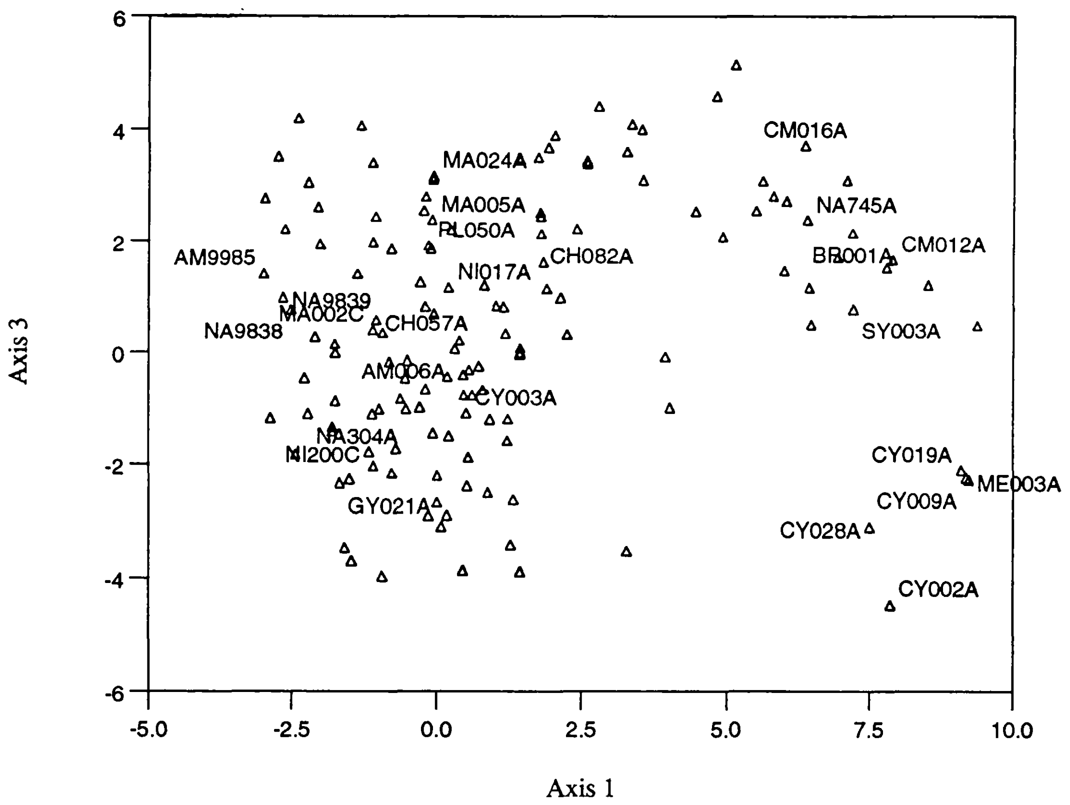


Figure 4.15 **Sample biplot of Axis 3 against Axis 1 for CCA2 of 74 samples and 9 significant explanatory variables.**



COND=conductivity, ANIONS=Anion ratio, TURB=turbidity, EPHEM, SEMI, PERM = permanence classes.

Figure 4.16 Species plot of Axis 3 against Axis 1 for CCA2 of 74 samples and 9 significant explanatory variables.



4.5 DEVELOPMENT OF A SALINITY TRANSFER FUNCTION

4.5.1 Introduction

The transfer function approach employs multivariate statistical techniques based upon principles of weighted averaging ('WA'). The techniques used are now well-established (cf. Birks *et al.*, 1990). Modern diatom-salinity relationships are derived by weighted averaging regression. Species optima and tolerance ranges are calculated for each taxon on the assumption that diatoms are most abundant in waters close to their salinity optimum. The optimum, or 'indicator value' (ter Braak, 1987) is the average of lake salinities where it occurs weighted proportionally by its abundance, with absent species carrying zero weight. The underlying assumption is one of a unimodal response, approximating a species-packing model when the optima are evenly-distributed with salinity and have equal tolerances and maxima (ter Braak, 1987). The weighted averaging optimum for a taxon is therefore estimated by:-

$$\hat{u}_k = \sum_{i=1}^{n} y_{ik} x_i \ / \sum_{i=1}^{n} y_{ik}$$

where $\hat{u}_k$ is the optimum of takon k, y_{ik} is the abundance of takon k in sample i of n samples, and x_i is the value of the environmental variable (salinity).

The estimated tolerance range is the weighted average standard deviation:-

$$\hat{t}_k = \sqrt{\sum_{i=1}^{n} y_{ik} (x_i - \hat{u}_k)^2 \ / \ \sum_{i=1}^{n} y_{ik}}$$

where $\hat{t}$ is the tolerance of species k.

Quantitative palaeosalinity estimates can then be inferred from sediment core fossil diatom assemblages using weighted averaging calibration procedures. Assuming again that diatoms abundant in a fossil assemblage were living in lake waters close to their optima, the inferred salinity is estimated as the weighted average of the salinity optima of all taxa in the fossil assemblage. This is given by:-

$$\hat{x}_i = \sum_{k=1}^{m} y_{ik} \hat{u}_k \;/\; \sum_{k=1}^{m} y_{ik}$$

where $\hat{x}_i$ is the estimated optima for sample *i* of a data-set of m taxa.

Species often do not equal tolerance ranges. The optimum can be modified to downweight the influence of species according to the breadth of their tolerance range, such that taxa with narrow tolerances are given more weight, as follows:-

$$\hat{x}_i = \frac{\sum_{k=1}^{m} y_{ik} \hat{u}_k / \hat{t}_k^2}{\sum_{k=1}^{m} y_{ik} / \hat{t}_k^2}$$

Tolerance-downweighting both improves the efficiency of the calibration and is ecologically satisfying since taxa with narrow tolerance ranges are usually better environmental 'indicator species' (Juggins, 1992).

The program CALIBRATE (Juggins & ter Braak, 1992) was used for WA regression of the calibration data-set (74 samples) to derive and compare salinity transfer functions for conductivity and TDS, using both simple and tolerance-downweighted WA. For WA, 169 taxa present at >1% were included, apart from indeterminate generic categories.

Salinity data were $\log_{10}$ transformed to reduce the skewness in their distributions such that they approximated a normal distribution (ter Braak & Prentice, 1988). Techniques for deshrinking were applied to compensate for shrinking of the estimated salinity range which is inherent in weighted averaging and results from taking averages twice during regression and calibration (Gasse *et al.*, in press); inverse deshrinking regression was used in preference to classical deshrinking since it is appropriate where accuracy across the environmental gradient as a whole is more important than at high or low values in particular (ter Braak & van Dam, 1989).

The predictive ability of the transfer functions was assessed by the correlation coefficient (r^2) between measured and inferred salinity, the apparent root mean squared error (RMSE) of prediction, and the equivalent jackknifed values. Jackknifing involves salinity prediction for each sample based on the remainder of samples in the data-set other than the one to be tested. Jackknifed RMSE therefore gives a more reliable indication of predictive ability than the apparent error since less bias is caused by sample resubstitution.

The reliability of transfer functions is reduced by the inclusion of outlier samples with an unusual diatom flora or a poor relationship between diatoms and the environmental variable of interest. Gasse *et al.* (1993) recommend the removal of all samples whose jackknife-inferred residuals (observed-inferred salinity values) exceed 25% of the total range of the variable. An initial identification of outliers was made in this way; criteria adopted for their removal thereafter are discussed below.

4.5.2 WA regression of the training set and removal of outliers

Log_{10}-transformed sample estimates for conductivity and TDS WA regression of the full training set (74 samples) are given in Appendix 5a. Potential outliers were defined by jackknife residuals exceeding 0.84 and 0.68 for conductivity and TDS respectively. This produced seven samples for conductivity (ASBL2, BGDE1, CGSQ3, ECRR1, GNVL1, GONT2 and HEST1), and seven for TDS (CGSQ3, ECHC1, ECRR1, EGRA1, ELLL1, GNVL1 and HEST1).

Summary statistics are given in Table 4.13. There is a large discrepancy between jackknife RMSE and apparent RMSE (c. 0.5 compared to c. 0.3). The poor performance under jackknifing is a result of the heterogeneous nature of the data, and the relatively small size of the data-set, such that there are many samples dominated by rare taxa which are poorly predicted when left out of the training set.

Hill's N_2 diversity index (Hill, 1973) for samples is included in Appendix 5a and reflects the effective number of occurrences across the data-set of the taxa within. From low sample N_2 values, the rare taxa are most frequent in samples at the extremes of the salinity spectrum, where coverage of the salinity gradient is also less complete, and the large jackknife residuals (ie outliers) stem mainly from samples in this range, for which salinity estimates are most inaccurate upon their removal in jackknifing. Although in some cases this may reflect a poor relationship between diatoms and water chemistry, the removal of all potential outliers would result in a loss of ecological information in parts of the gradient where the data-set is already truncated.

The selection of outliers for deletion is therefore based also upon their performance in simple WA. The positions of potential outliers are indicated on scatter plots of observed against inferred salinity for conductivity and TDS using simple WA in Figure 4.17. For conductivity, four samples are outliers (BGDE1, CGSQ3, ECRR1 and GONT2) but three others have relatively low residuals (ASBL2, GNVL1 and HEST1) and are retained. For TDS, three samples are outliers (ECRR1, ECHC1 and EGRA1) and four are retained (CGSQ3, ELLL1, GNVL1 and HEST1).

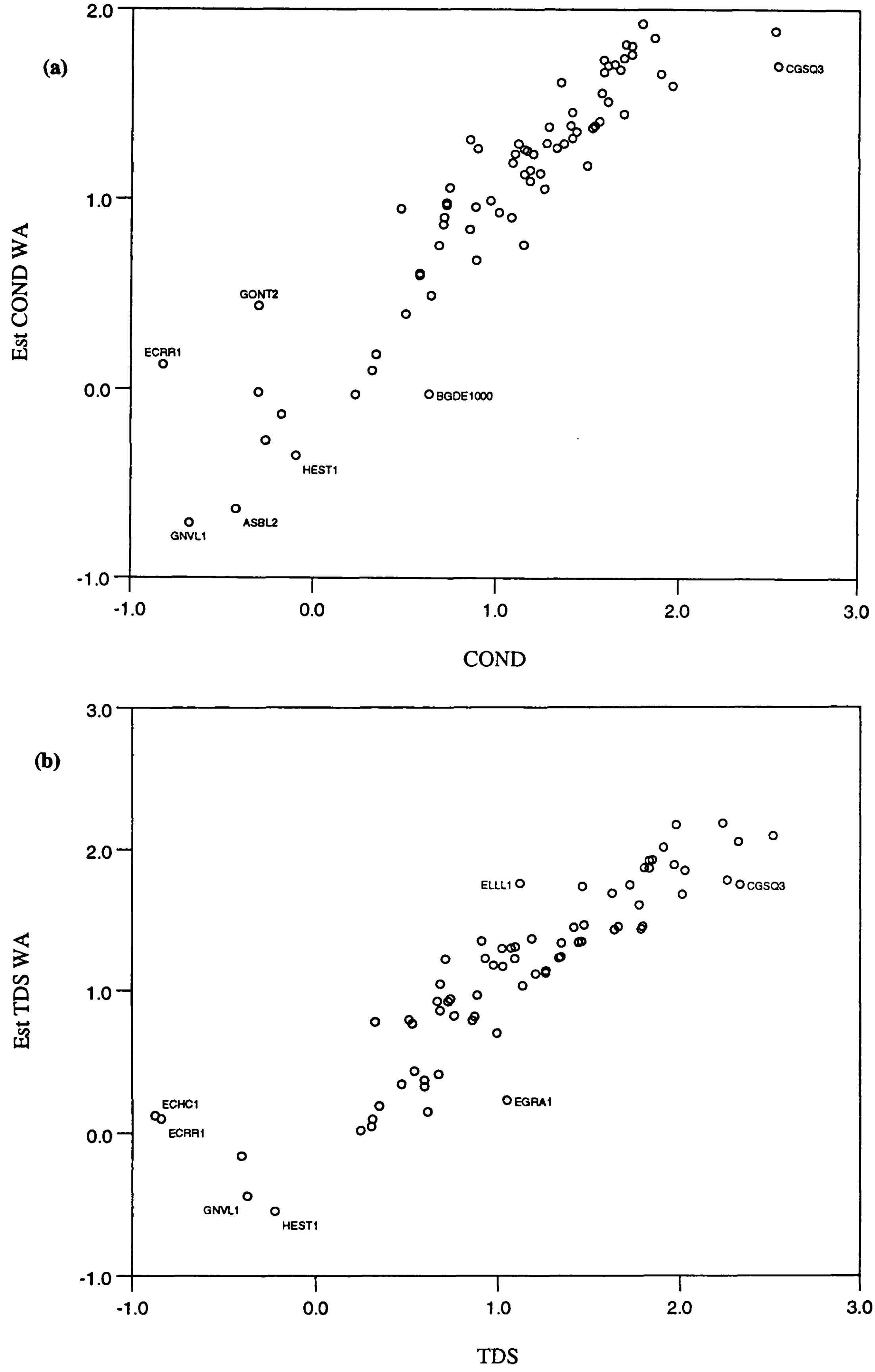
Table 4.13 **Summary statistics for conductivity and total dissolved solids ('TDS') WA and tolerance-downweighted ('Tol d/w') WA regression of the full training set (74 samples, 169 species present at >1%) with cross-validation by jackknifing.**

	CONDUCTIVITY		TDS	
	r^2	RMSE	r^2	RMSE
Simple WA	0.85	0.27	0.82	0.31
Tol d/w WA	0.85	0.26	0.85	0.28
Jack. WA	0.49	0.49	0.53	0.49
Jack. Tol d/w WA	0.45	0.50	0.54	0.49

Table 4.14 **Summary statistics for conductivity (70 samples) and total dissolved solids ('TDS', 71 samples) WA and tolerance-downweighted ('Tol d/w') WA regression after removal of outliers, with cross-validation by jackknifing.**

	CONDUCTIVITY		TDS	
	r^2	RMSE	r^2	RMSE
Simple WA	0.91	0.18	0.86	0.25
Tol d/w WA	0.92	0.18	0.89	0.23
Jack. WA	0.57	0.41	0.59	0.43
Jack. Tol d/w WA	0.48	0.45	0.50	0.47

Figure 4.17 Scatter plots of observed versus inferred salinity for (a) conductivity and (b) TDS, based on simple WA regression of 74 samples



4.5.3 Derivation of a salinity transfer function

These outliers were deleted in further WA regressions of the data. The results are given in Appendices 5b for conductivity and 5c for TDS. Summary statistics for simple and tolerance-downweighted WA regression of the reduced training sets are given in Table 4.14 above for conductivity (70 samples) and TDS (71 samples). Performance is poor under jackknifing. This is a result of the heterogeneous nature of the data and the relatively small size of the training set; there are many samples with 'unique' assemblages and taxa which are poorly predicted when left out of the training set. For both conductivity and TDS, the jackknifed r^2 values are higher and RMSE is lower for simple WA than for tolerance-downweighted WA. This indicates that simple WA performs better in spite of its slightly lower predictive ability in terms of apparent errors, and it is used for calibration of the transfer function.

Conductivity is the more reliable of the two salinity variables in terms of apparent errors (simple WA $r^2 = 0.91$ [conductivity] and 0.86 [TDS]), and their performance in terms of r^2 and RMSE is similar under jackknifing.

The salinity transfer function is therefore derived from conductivity using simple WA on a reduced training set of 70 samples. Figure 4.18 shows the strong, linear relationship between observed and inferred salinity, with low scatter along the length of the salinity gradient apart from the extreme, hypersaline sample, CZRR1 for which salinity is underestimated.

4.5.4 Conductivity optima and tolerance ranges

A list of back-transformed optima and tolerance ranges for 96 common taxa with >5% maximum relative abundance and >1 occurrence is given in Table 4.15, together with the number of samples in which they occur, their maximum relative abundance and Hill's N_2 diversity index (Hill, 1973). For individual taxa, the effective number of occurrences, Hill's N_2, reflects the number of samples which influence the weighted-average estimates, and salinity estimates are more reliable for taxa with high N_2 values.

Conductivity optima for common taxa range from 0.3 to 76 mS cm^{-1}. Based on the approximate relationship between conductivity and salinity established in Section 3.2.1.9, only 3 taxa have optima which fall within the strict definition of fresh waters (<0.5 mS cm^{-1}); others are distributed between oligosaline (20 taxa; 0.5-<6 mS cm^{-1}), mesosaline (49 taxa; 6-<25 mS cm^{-1}) and polysaline or hypersaline (20 taxa; ≥25 mS cm^{-1}). N_2 values are generally highest for taxa with optima in the conductivity range c. 4-30 mS cm^{-1}, which indicates predictive error is likely to be lower for salinity reconstruction in the middle of the salinity range. Estimated optima and tolerance ranges may be

4.18 Scatter plot of observed versus inferred salinity (conductivity) for transfer function based on simple WA regression of 70 samples.

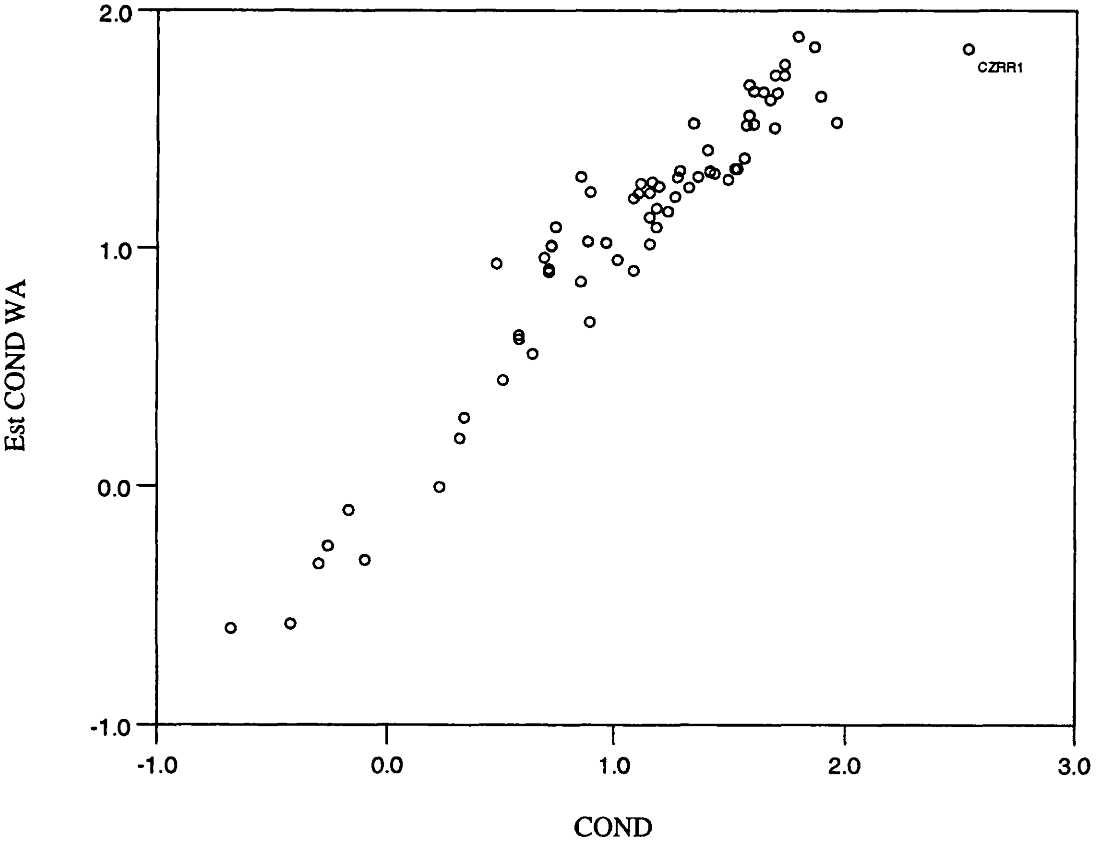


Table 4.15 **List of back-transformed salinity optima and tolerance ranges, and diversity statistics, for 96 common diatom taxa (present at >5% and in >1 sample).**

CODE	SPECIES	N	Max %	N_2	OPT	OPT - TOL	OPT + TOL	TOL RANGE
NA021E	*Navicula cincta* fo. *minuta*	2	7.52	1.56	76.39	72.74	80.21	7.47
RH008A	*Rhopalodia acuminata*	2	7.52	1.87	75.69	72.07	79.48	7.40
AM123A	*Amphora cymbamphora*	2	9.22	1.68	73.88	70.35	77.58	7.23
AM9985	*Amphora* sp. 1 [cf. *acutiuscula*]	26	82.66	5.59	65.47	18.84	227.52	208.68
AM065A	*Amphora holsatica*	3	12.53	1.31	65.19	25.40	167.31	141.90
MA005A	*Mastogloia pumila*	4	59.95	1.28	61.46	22.45	168.27	145.82
ZZZ996	*Navicula* cf. *recens*	3	7.74	1.41	57.66	17.19	193.43	176.23
NA265B	*Navicula bulnheimii*	2	7.71	1.22	53.70	22.84	126.67	103.43
BR009A	*Brachysira aponina*	2	15.42	1.61	53.70	22.84	126.27	103.43
NI205A	*Nitzschia stompsii*	3	14.5	2.02	52.77	40.79	68.28	27.50
PL050A	*Pleurosigma salinarum*	6	5.69	1.77	49.52	14.30	171.48	157.18
FR9977	*Fragilaria fasciculata* var. 2	5	52.1	2.36	47.48	27.70	81.40	53.70
NA304A	*Navicula crucicula* var. *cruciculoides*	19	36.27	5.02	42.94	21.78	84.67	62.88
NA9839	*Navicula phyllepta*	19	45.45	5.29	40.38	19.13	85.27	66.15
HA001A	*Hantzschia amphioxys*	15	51.71	4.2	39.21	15.17	101.35	86.18
NA675A	*Navicula tenelloides*	4	46.84	1.96	38.26	11.94	122.55	110.61
NA9840	*Navicula* cf. *duerrenbergiana*	4	25.62	1.17	38.10	20.50	70.80	50.29
NA9838	*Navicula* cf. *salinicola*	33	89.87	7.79	32.76	14.47	74.13	59.66
AM002A	*Amphora acutiuscula*	24	30.91	4.88	32.01	17.05	60.12	43.07
NA565A	*Navicula perminuta*	12	27.5	3.1	30.03	18.76	48.09	29.33
NA092A	*Navicula spicula*	3	5.49	1.4	26.53	19.39	36.31	16.92
CM023A	*Cymbella pusilla*	27	61.31	9.13	26.30	12.23	56.59	44.36
NA067A	*Navicula crucicula* var. *crucicula*	6	5.47	1.75	26.22	14.09	48.79	34.70
NI027A	*Nitzschia microcephala*	6	46.21	1.16	24.00	11.64	49.50	37.86
EN003A	*Entomoneis alata*	13	7.75	3.08	23.07	8.42	63.21	54.80
NI200C	*Nitzschia compressa* var. *vexans*	20	62.88	8.48	22.98	10.84	48.70	37.86
NI036A	*Nitzschia obtusa*	15	9.85	2.84	21.55	13.88	33.46	19.58
NI152A	*Nitzschia pusilla*	13	45.68	4.06	21.09	10.46	42.52	32.06
GY021A	*Gyrosigma peisonis*	24	33.08	5.92	20.68	12.06	35.45	23.39
CO001B	*Cocconeis placentula* var. *euglypta*	37	22.35	16.2	20.66	8.35	51.11	42.76

SY008A	*Fragilaria pulchella*	18	20.52	2.13	19.93	12.17	32.63	20.46
AP002A	*Amphipleura rutilans*	3	15.77	1.2	18.53	12.64	27.15	14.50
AC159A	*Achnanthes fogedii*	6	50.29	1.8	17.70	11.42	27.43	16.01
NA010A	*Navicula pygmaea*	13	11.48	4.64	17.61	7.39	41.98	34.59
PG004A	*Plagioptris lepidoptera*	3	5.32	1.69	16.55	5.04	54.43	49.39
AM006A	*Amphora coffeaeformis*	25	33.14	6.56	16.54	5.50	49.74	44.24
NI016A	*Nitzschia apiculata*	35	22	13.7	16.23	8.67	30.40	21.73
NA9845	*Navicula cryptotenella* var. 2	5	48.2	1.76	16.11	7.61	34.11	26.50
SY001A	*Fragilaria ulna*	16	13.23	2.81	15.91	8.17	30.97	22.80
NI007A	*Nitzschia hungarica*	37	11.78	13.5	15.49	7.51	31.95	24.44
ZZZ998	*Navicula* sp. 8	3	19.56	1.27	15.20	13.19	17.51	4.31
NI9957	*Nitzschia* cf. *fonticola*	29	91.7	11.2	14.55	6.67	31.74	25.07
AM9991	*Amphora* sp. 2 [*tenerrima/ten.* type]	15	5.48	7.06	14.42	4.24	49.00	44.76
NI203A	*Nitzschia liebetruthii*	32	15.79	8.32	14.33	5.28	38.88	33.60
NI149A	*Nitzschia pseudofonticola*	3	27.09	2.2	14.15	12.77	15.67	2.90
NA9849	*Navicula halophila* var. 3	14	47.07	2.42	13.87	7.22	26.63	19.41
NI008A	*Nitzschia frustulum*	33	11.36	13.1	13.84	6.59	29.05	22.47
NA9851	*Navicula halophila* var. 1	19	29.64	3.89	13.76	3.66	51.70	48.04
AN009A	*Anomoeoneis sphaerophora*	20	12.41	5.17	13.72	7.36	25.59	18.24
NA9841	*Navicula cuspidata* var. 2	3	15.16	1.13	12.89	6.38	26.05	19.67
NA023A	*Navicula gregaria*	23	58.87	3.79	12.82	6.30	26.12	19.83
NA003B	*Navicula cryptotenella* var. 1	24	26.29	5.8	12.27	2.44	61.79	59.35
NA9846	*Navicula* sp. 2 [*cryptocephala/salinarum* type]	19	37.57	4.5	11.93	5.79	24.60	18.81
SY005A	*Fragilaria fasciculata* var. 1	27	25.59	6.97	11.38	5.11	25.35	20.24
MA002C	*Mastogloia elliptica*	6	6.06	3.13	11.11	6.58	18.76	12.18
FR007A	*Fragilaria vaucheriae*	2	15.79	1	10.23	4.35	24.06	19.71
ST001A	*Stephanodiscus hantzschii*	5	8.52	1.55	10.21	2.89	36.04	33.15
AN009D	*Anomoeoneis sphaerophora* fo. *costata*	7	5.08	3.67	9.76	5.47	17.39	11.92
CM031A	*Cymbella minuta*	6	5.91	3.14	9.70	4.92	19.15	14.23
NA054A	*Navicula veneta*	44	35.46	14	9.35	4.40	19.87	15.46
AC016A	*Achnanthes delicatula*	14	13.74	5.71	9.01	4.80	16.88	12.08
NA035A	*Navicula salinarum*	14	37.41	3.57	8.90	3.48	22.74	19.25
CY003A	*Cyclotella meneghiniana*	25	19.65	8.79	8.64	5.05	14.79	9.75
NI009A	*Nitzschia palea*	29	19.17	8.45	8.54	3.01	24.22	21.21

NA066B	*Navicula capitata* var. *hungarica*	8	15.18	4.16	8.34	4.40	15.83	11.43
NI014A	*Nitzschia amphibia*	10	5.47	5.31	8.34	4.64	15.02	10.38
NI207A	*Nitzschia desertorum*	8	12.2	2.3	8.15	5.35	12.42	7.06
AM9990	*Amphora veneta* var. 1	27	44.28	4.63	7.69	4.06	14.54	10.48
NI204A	*Nitzschia elegantula*	14	11.52	5.6	7.40	3.20	17.13	13.93
NI206A	*Nitzschia solita*	12	15.03	4.1	7.35	4.32	12.51	8.19
AM004A	*Amphora veneta* var. 2	27	48.16	3.37	7.15	1.39	36.75	35.36
MA001B	*Mastogloia smithii* var. *lacustris*	9	47.22	2.89	6.17	3.37	11.33	7.96
CH057A	*Chaetoceros* cf. *muelleri*	19	44.38	2.94	5.27	2.07	13.46	11.39
AM021B	*Amphora arcus* var. *sulcata*	3	77.32	2.99	4.90	3.22	7.44	4.22
NA9842	*Navicula cuspidata* var. 1	23	11.18	8.09	4.15	0.81	21.25	20.44
CM022A	*Cymbella affinis*	7	13.48	2.2	3.66	1.71	7.85	6.14
DE002A	*Denticula elegans*	6	10.75	2.56	2.65	1.63	4.30	2.66
GO003A	*Gomphonema angustatum*	5	14.51	1.23	2.17	1.09	4.31	3.22
NA9843	*Navicula* cf. *wildii*	5	6.27	3.38	1.94	0.90	4.16	3.26
AC013A	*Achnanthes minutissima*	19	36.35	5.06	1.88	0.87	4.09	3.22
FR006A	*Fragilaria brevistriata*	10	85.85	1.24	1.55	0.69	3.49	2.80
CM050A	*Cymbella subaequalis*	4	8.96	2.66	1.52	0.51	4.49	3.98
SY003A	*Fragilaria ulna* var. *acus*	10	12.54	2.7	1.47	0.47	4.60	4.13
BR001B	*Brachysira vitrea* fo. *lanceolata*	9	11.11	2.63	1.38	0.42	4.60	4.18
CM015A	*Cymbella cesatii*	6	9.73	4.3	1.36	0.67	2.76	2.09
GO014A	*Gomphonema angustum*	4	7.71	1.73	1.04	0.37	2.94	2.57
CY019A	*Cyclotella radiosa*	2	6.19	1.06	0.83	0.31	2.23	1.92
FR002C	*Fragilaria construens* var. *venter*	4	9.45	2.34	0.83	0.28	2.45	2.17
CY009A	*Cyclotella ocellata*	2	65.03	1.01	0.81	0.13	4.92	4.79
AM012A	*Amphora pediculus*	6	17.01	1.32	0.72	0.14	3.64	3.50
CY028A	*Cyclotella distinguenda*	6	86.27	2.05	0.62	0.33	1.16	0.83
NA745A	*Navicula capitoradiata*	3	5.35	1.26	0.61	0.18	2.13	1.95
NA173A	*Navicula erifuga*	10	90.11	1.1	0.44	0.05	4.23	4.19
NA555A	*Navicula paramutica*	2	6.32	1.3	0.44	0.01	21.01	21.00
CM004A	*Cymbella microcephala*	10	17.03	5.27	0.34	0.80	3.86	3.06

KEY: N (no. of occurrences), MAX% (maximum abundance), N_2 (Hill's N_2 diversity index) and conductivity optima ('OPT') and tolerance ranges ('TOL'). Optima and tolerance ranges are given in mS cm^{-1}. Taxa with optima in different salinity classes (boundaries set at 23.0, 6.0 and 0.5 mS cm^{-1}) are separated by a double line.

unreliable for taxa with few occurrences.

Taxa with narrow tolerance ranges are potential indicator species, and are found at all salinities but are most common in oligosaline or fresh waters. Some taxa have narrow tolerance ranges but are also rare and have low N_2 values, however; their apparent stenohalinity may instead be artefact of the restricted range of samples in the data-set, and they are not reliable indicator species. As noted above, such taxa are most frequent at either end of the salinity spectrum in the Spanish data-set. Only one of the freshwater species whose optima are estimated at <0.5 mS cm^{-1}, *Cymbella microcephala*, is well-represented in the data-set, and in hypersaline waters *Navicula bulnheimii* occurs only in 2 samples from one lake (HSAL), for example.

Most taxa with optima in the oligosaline class, apart from those whose optima approaches the oligosaline-mesosaline boundary, have narrow tolerance ranges (<10 mS cm^{-1}). Of the well-represented taxa, those whose upper tolerance does not extend into the mesosaline class, and which are potentially the most useful indicators, comprise *Cymbella affinis*, *Navicula* cf. *wildii* and *Achnanthes minutissima.*

Many taxa with optima in the mesosaline class and N_2 values >3 have relatively broad tolerance ranges, but some taxa such as *Amphora coffeaeformis* and *Nitzschia frustulum* this does not extend to oligosaline waters and they are potentially useful indicators of salinity change across this threshold. Potential indicator species, based on their relatively narrow tolerance range (c. 10-12 mS cm^{-1}) comprise *Amphora veneta* var. 1, *Nitzschia amphibia*, *Navicula capitata* var. *hungarica*, *Cyclotella meneghiniana*, *Achnanthes delicatula*, *Anomoeoneis sphaerophora* fo. *costata*, *Mastogloia elliptica*, *M. smithii* var. *lacustris* and *Nitzschia solita.* Many of these, such as *Nitzschia amphibia,* are known from fresh/oligosaline waters elsewhere. Their tolerance limits extend to the upper range of the oligosaline class and, rather than being indicators of mesosaline waters, they are indicative of waters close to the oligosaline/mesosaline boundary.

Taxa with the broadest tolerance ranges (>50 mS cm^{-1}) occur in the polysaline-hypersaline class. This is in agreement with the increased euryhalinity of saline lake diatoms, which are able to withstand major fluctuations in salinity (cf. Gasse *et al.*, 1987). This applies to all the most abundant taxa of the class, such as *Amphora acutiuscula*, *Navicula* cf. *salinicola*, *Navicula phyllepta*, *Navicula crucicula* var. *cruciculoides*, and *Amphora* sp. 1 [cf. *acutiuscula*], whose tolerance ranges extend into the mesosaline class.

In summary, a successful salinity transfer function has been derived for conductivity. Salinity reconstruction is likely to be most reliable in the middle of the salinity spectrum, where diatoms are well-represented. Summary statistics are given in Table 4.16, including inverse deshrinking regression coefficients which are used to deshrink the initial values and improve the final conductivity estimates (Gasse *et al.*, in press).

Table 4.16 **Summary statistics for salinity (conductivity) transfer function, showing deshrinking regression coefficients**

No. of samples	No. of taxa	Inverse deshrinking regression coefficients	
70	169	b0 = -0.24	b1 = 1.23

4.6 CCA WITH *TWINSPAN*: THE INFLUENCE OF OTHER ENVIRONMENTAL VARIABLES

4.6.1 Introduction

The results of CCA with variance partitioning indicated that there was significant variation in the data-set related both to ionic composition and to water depth and/or lake permanence; the latter accounted for more than twice the variance in the diatom data than any other environmental gradient. The relationship between salinity and water depth is complex, and the ability to make qualitative inferences as to these parameters would provide valuable support for quantitative palaeosalinity reconstruction.

In this section the relationships are explored between diatom species assemblage composition and variation in the above variables. TWINSPAN (Hill, 1979) is a technique for cluster analysis which separates samples into groups on the basis of differences in species assemblage composition. TWINSPAN was performed on the 74-sample training set; the separation of the sample groups identified from the output diagram were explored using the results of CCA2.

4.6.2 Results and comparison with other regions

The full output diagram of the TWINSPAN analysis is given in Appendix 6, from which seven groups of characteristic taxa are identified. A summary of the taxa characteristic of the more saline sites (Groups 1-5) is given in Table 4.17. In addition to total salinity, the groups are separated to some extent by both ionic composition and ephemerality, as follows.

Group 1 (filled circles):- 12 samples from ephemeral, sulphate-rich lakes of La Mancha, and one from the chloride-rich L. de Zarracatín (CZRR1) in Andalucía.

Group 2 (filled diamonds):- 8 samples from ephemeral and shallow, semi-permanent 'damp', chloride-rich lakes of Andalucía, and 2 samples from permanent, shallow coastal lagoons.

Group 3 (open circles):- the majority of semi-permanent lakes in the data-set other than saline 'damp' lakes (14 samples), together with two samples from the permanent lake, L. Amarga (AAMA).

Group 4 (open triangles):- variable; mainly ephemeral lakes of varying ionic composition and includes semi-permanent lakes of La Mancha (13 samples).

Group 5 (open diamonds):- all saline, permanent lakes except AAMA, of varying ionic composition (9 samples), two samples from the semi-permanent CALC, and 2 ephemeral, low salinity samples (ASBL2, ECRR).

Group 6 (filled triangles):- 8 samples from fresh or oligosaline lakes, all but one of which are permanent and relatively deep

Group 7:- An 'outlier' at TWINSPAN level 3, Group 7 comprises GNVL1 only (ephemeral, low salinity).

Samples are classed according to these groups on the CCA2 sample biplot of Axis 3 against Axis 1 for 9 significant explanatory variables in Figure 4.19, in which the outlier, Group 7, plots within Group 5.

Group 6 (filled triangles) derives from low-salinity, permanent alkaline lakes and forms a completely separate group, as would be predicted from the foregoing, which includes the majority of planktonic diatoms in the data-set together with benthic diatoms of fresh or slightly oligosaline water (e.g. *Cymbella affinis, C. microcephala, C. cesatii, Achnanthes minutissima* and *Brachysira vitrea*). The overlap of groups along the rest of the salinity gradient (Axis 1) reflects the euryhalinity of many saline lake diatoms (Williams, 1990).

The separation of groups otherwise is likely to be by the influence of other environmental gradients. Groups 1-3 and Group 5 are separated to some extent from each other but Group 4 overlaps all, which indicates that differences in assemblage composition are not definitive in separating out different lake types.

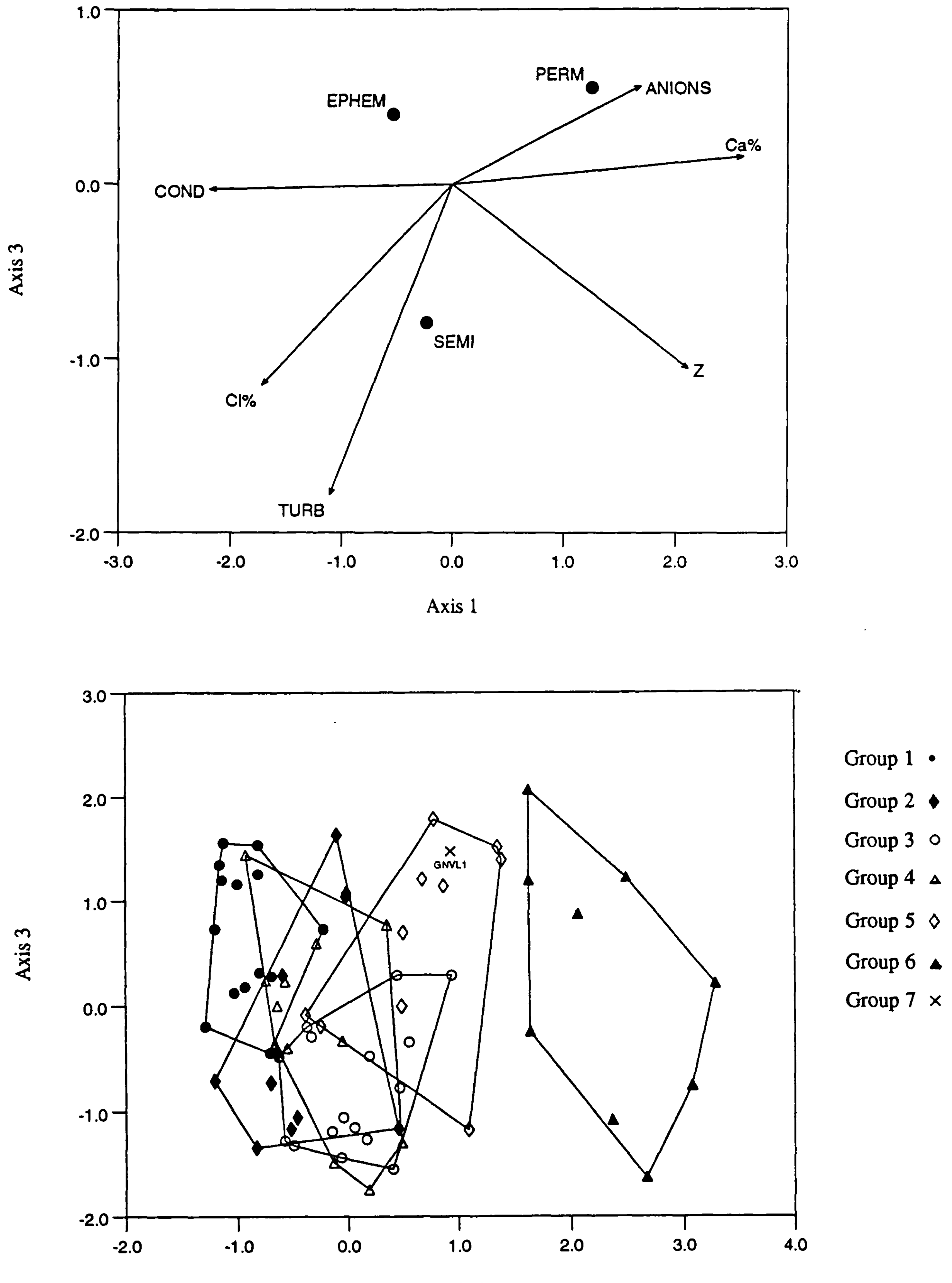
Separation by brine composition

Groups 1 (mainly sulphate) and 2-3 (chloride) are separated quite well by brine composition, as in the CCA, but there are no indicator species of sulphate waters. Only two taxa, *Nitzschia pusilla* and *Hantzschia amphioxys*, are restricted to Group 1. The former species is common in African carbonate

Table 4.17 List of common diatom taxa which characterise TWINSPAN Groups 1-5 and a summary of their relative abundance in each group. (X compared to x denotes abundance relative to other groups.)

SPECIES	CODE	1	2	3	4	5
Nitzschia pusilla	NI152A	X				
Amphora sp. 1 [cf. *acutiuscula*]	AM9985	X	X	x	x	
Navicula phyllepta	NA9838	X	X		x	
Navicula cf. *salinicola*	NA9839	X	X		x	
Hantzschia amphioxys	HA001A	X				
Amphora coffeaeformis	AM006A	x	X	X		
Amphora veneta var. 1 [small]	AM004A	x			x	
Navicula sp. 2 [af. *cryptocephala/salinarum*]	NA9846			X	X	
Navicula veneta	NA304A	x	X	x	x	
Cymbella pusilla	CM023A		x	X	x	X
Nitzschia elegantula	NI204A			x		X
Chaetoceros cf. *muelleri*	CH057A		x	X	x	x
Amphora arcus var. *sulcata*	AM021B					X
Amphora veneta var. 1 [large]	AM9990			X		
Campylodiscus clypeus	CP001A			X	X	
Gyrosigma peisonis	GY021A		x	X	x	
Navicula gregaria	NA023A		x	X	x	
Nitzschia apiculata	NI016A		x	X	x	
Nitzschia cf. *fonticola*	NI9957		x	X	X	
Fragilaria fasciculata var. 1 [classic]	SY005A		x	X	X	x
Nitzschia compressa var. *vexans*	NI200C		X	X		
Achnanthes delicatula	AC016A			X	x	
Cocconeis placentula var. *euglypta*	CO001B		X	X		x
Navicula veneta	NA054A			X	x	x
Nitzschia hungarica	NI007A		x	X	X	
Nitzschia frustulum	NI008A			X	X	
Cyclotella meneghiniana	CY003A			X	X	X
Gomphonema parvulum	GO013A				x	X
Mastogloia smithii var. *lacutris*	MA001B				X	x
Nitzschia amphibia	NI014A			x		x
Fragilaria ulna	SY001A			x		X
Freshwater benthic taxa	-					X

Figure 4.19 Sample biplot of Axis 3 against Axis 1 for CCA2 with 9 significant explanatory variables, classed by TWINSPAN groups.



COND=conductivity, ANIONS=Anion ratio, TURB=turbidity, EPHEM, SEMI, PERM = permanence classes.

lakes (Gasse *et al.*, 1987) and the latter occurs in both chloride and carbonate lakes in North America (Busch & Kubly, 1980); their distribution may relate more to the ephemerality of lake waters, as discussed below. *Nitzschia amphibia* occurs only in sulphate waters of Tunisia (Ben Khelifa, 1989), but is restricted to chloride waters both here and in East Africa (Gasse, 1986).

There are some possible indicators in Groups 2-3 for chloride waters, which are not abundant in either Group 1 or Group 4. Some species with a reported preference for chloride waters (Gasse, 1986) are clearly restricted to Groups 2-3; the most common taxa are *Nitzschia compressa* var. *vexans* and *Gyrosigma peisonis*. *Amphora veneta* var. 1 is another possible indicator. *Amphora coffeaeformis* and *Cymbella pusilla* occur only at low frequency in sulphate lakes; the former has an observed preference for chloride waters in African waters (Gasse, 1986), whilst the latter occurs in both sulphate and chloride waters of the Sahara (Gasse *et al.*, 1987). The *Mastogloia*'s are restricted to chloride waters in the Spanish data-set, but are known from both carbonate and sulphate systems elsewhere. *Nitzschia elegantula* and *Amphora arcus* var. *sulcata* favour chloride waters in Africa (Gasse, 1986, Ben Khelifa, 1989) but were dominant here in sulphate waters of a Group 4 lake, ECHC.

Some diatoms which are common but only at low frequencies in the Spanish data-set (not included in Table 4.17) such as *Anomoeoneis sphaerophora* and *Anomoeoneis sphaerophora* fo. *costata* are common at greater abundances in carbonate lakes of Africa (Gasse *et al.*, in press).

Separation by lake permanence/water depth

Groups are also separated by lake permanence. The clearest distinction is by the presence of plankton. The planktonic diatoms, *Cyclotella meneghiniana* and *Chaetoceros* cf. *muelleri* and (at lower frequency) *C. wighami*, are restricted largely to Groups 3 and 5 (semi-permanent lakes which retain water levels in summer, and permanent lakes). They occur even in the shallowest of these (e.g. DHND, 0.6m deep). The distinction is not absolute for *Chaetoceros*; *C.* cf. *muelleri* resting spores were found most consistently here, but were at their greatest abundance in GPTR, an ephemeral lake classified in Group 2. This genus forms drought-resistant cysts and its abundance could reflect stress conditions rather than those optimal for its growth (Johansen & Rushforth, 1985).

The majority of taxa are benthic, which reflects the shallowness of the lakes. A distinction based on the abundance of diatoms of aerial habitats is ambiguous, but there is a tendency towards their dominance in Groups 1 and 2, more restricted occurrence in groups 3 and 4, and rarity in Group 5. These diatoms are also common on estuarine intertidal mud flats, and mainly comprise *Nitzschia pusilla*, *Hantzschia amphioxys*, *Amphora coffeaeformis*, *A. acutiuscula*, *Nitzschia compressa* var. *vexans* and *Gyrosigma peisonis*, and small raphid taxa such as *Navicula phyllepta* and *N.* cf. *salinicola* (Patrick &

Reimer, 1966, Busch & Kubly, 1980, Germain, 1981).

There is a general trend in the opposite direction towards the dominance of benthic, aquatic taxa in more permanent waters. A more distinct separation is not apparent according to the abundance of epiphytic taxa, whose dominance would be predicted in more permanent lakes where communities of aquatic macrophytes are more extensive. Few of the benthic taxa of Groups 3 and 5 have been described as epiphytic; *Fragilaria ulna* is restricted to these groups and is thought to have a preference for an ephiphytic habitat (Ben Khelifa, 1989). Others are also abundant in ephemeral lakes. *Cocconeis placentula* var. *euglypta*, for example, is most abundant in groups 3 and 5 but is found across Groups 2-5 including in ephemeral lakes which lacked aquatic macrophytes. Some species such as *Amphora arcus* var. *sulcata* are restricted to permanent lakes with extensive aquatic macrophytes, but these plot to the left of the diagram and the influence of lower salinity on their distribution is possible.

4.7 DISCUSSION

4.7.1 The transfer function

The results of exploratory PCA, DCA and CCA ordinations indicated that variables reflecting total salinity, brine composition, water depth/permanence and turbidity make a significant and independent contribution to the total variance in the diatom data.

The DCA was used to explore additional variance according to nutrient status, which is the most obvious source of unexplained variation in the data other than random 'noise' common in these data-sets (Birks *et al.*, 1990). Nutrients are probably significant at the fresh water end of the spectrum at least (cf. Bennion, 1994, Fritz *et al.*, 1993b), but there was no evidence for species dispersal by reported nutrient preferences to suggest that the accuracy of a salinity transfer function may be compromised. Some of this variance may be accounted for indirectly by correlation with water depth and lake permanence, since productivity is related to factors such as lake stability (Wetzel, 1983). In Spain, the nutrient levels of many shallow, unstable salt lakes are also high due to the input of urban waste or irrigation water (Montes & Martino, 1987), but the lack of evidence for the influence of nutrients within samples from these systems suggests salinity has an overriding influence.

A transfer function was generated for conductivity, the strongest of the two salinity variables. Its predictive ability (apparent r^2 = 0.91) is high compared to transfer functions from other saline lake regions (apparent r^2 = 0.83-0.89 for three North American and African data-sets; Fritz *et al.*, 1991, Cumming & Smol, 1993, Gasse *et al.*, in press), although performance was poor under jackknifing due to the heterogeneity and small size of the data-set.

In general, there is a marked difference between taxa characteristic of fresh or slightly oligosaline waters to those of mesosaline or more saline waters, and salinity reconstructions are more likely to be reliable in the oligosaline-mesosaline salinity range. Species were less well-represented at the extremes of the salinity spectrum, in hypersaline waters in particular. These phenomena are partly due to the limited number of samples from these waters; in addition, the polysaline-hypersaline class covers a wide range of salinity, and taxa have broad tolerance ranges, so the estimated optima are inherently less well-defined.

4.7.2 Taphonomic factors

The training set includes samples taken at different seasons of the year. Cumming & Smol (1993) and Fritz *et al.* (1993a) discuss the problem in fluctuating, saline lakes of North America of the lack of a close relationship between the chemistry of single water samples and the composition of surface sediment diatom assemblages, which integrate diatoms from different seasons. Cumming & Smol (1993) recommend the use of samples taken from a single season where multiple sampling is not feasible. Diatom samples appear to show a relatively good relationship with water chemistry in the Spanish data-set, however. Spring and Summer, 1992 samples from individual lakes plotted close together on the PCA and CCA diagrams (apart from ASBL), which indicates a lack of seasonal fluctuations in this year; in Summer 1993, a drought year, water samples from CGSQ and CTRJ were unusually saline and show corresponding differences in diatom assemblages. Most lakes in the North American data-sets are dominated by planktonic diatoms which bloom at different seasons of the year. In contrast, many Spanish salt lakes are shallow and often dominated by benthic taxa, and it is possible surface sediment assemblages in lakes where the photic zone extends to the lake-bed are more likely to be dominated by taxa living in the lake at the time of sampling. When added to the unpredictability of interannual fluctuations in water chemistry of Spanish salt lakes, this supports the use of samples from different seasons for derivation of a transfer function.

The accuracy of a transfer function may also be affected by dissolution of diatom frustules, but there was little evidence here for significant dissolution in surface sediments.

4.7.3 Comparison of salinity optima with other saline lake data-sets

A comparison of the salinity optima of a range of taxa common in the Spanish data-set with those of African and North American ('NGP') saline lake data-sets is given in Table 4.18. African values are back-transformed from quoted conductivity estimates, and NGP values are in TDS. Only 12 of the 27 taxa are common in the NGP data-set, compared to 26 in the African data-set, which underlines the greater floral affinities between Spain and Africa.

Table 4.18 **Comparison of esimated Spanish salinity optima with those of other saline lake data-sets. [For comparison across the entire salinity range, relatively rare taxa (N_2>2) are included from fresh/hypersaline waters, and common taxa (N_2>5) from other parts. African data from Gasse et al. (in press); northern Great Plains, North America ('NGP') data from Fritz et al. (1993a)].**

SPECIES	SPAIN (Cond. mS cm^{-1})	AFRICA (Cond. mS cm^{-1})	NGP (TDS gl^{-1})
Mastogloia pumila	61.5	18.6	-
Nitzschia stompsii	52.8	10.2	-
Pleurosigma salinarum	49.5	37.2	-
Navicula crucicula & vars	43.0, 26.2	-	22.0
Navicula phyllepta	40.4	35.4	-
Navicula cf. *salinicola*	32.8	29.5	-
Amphora acutiuscula	32.0	7.9	13.2
Cymbella pusilla	26.3	9.1	8.5
Entonomoneis alata	23.1	15.8	-
Nitzschia compressa undiff. (=*N. punctata*)	23.0	7.2	11.1
Cocconeis placentula var. *euglypta*	20.7	0.5	-
Amphora coffeaeformis	16.5	11.5	8.5
Nitzschia hungarica	15.5	10.2	9.6
Nitzschia frustulum	13.8	4.2	-
Anom. sphaeorophora	13.7	7.6	-
Navicula cryptotenella	12.3	3.8	-
Fragilaria fasciculata & vars	11.4, 47.5	45.7	-
Cyclotella meneghiniana	8.6	6.0	3.4
Nitzschia palea	8.5	0.9	2.9
Nitzschia amphibia	8.3	0.5	1.9
Nitzschia elegantula	7.4	5.0	-
Amphora arcus var. *sulcata*	4.9	7.1	-
Denticula elegans	2.7	4.7	8.9
Achnanthes minutissima	1.9	0.3	-
Fragilaria ulna var. *acus*	1.5	0.2	1.8
Cymbella cesatii	1.4	0.1	-
Cymbella microcephala	0.3	1.6	2.2

As remarked upon in a comparison of the flora of saline lakes of the NGP with those of Mexico, Africa and Australia (Fritz *et al.*, 1993a), overall salinity preferences between fresh and more saline waters are similar between regions for many taxa such as, in mesosaline/hypersaline waters, *Mastogloia pumila, Pleurosigma salinarum, Navicula crucicula, N. phyllepta, N.* cf. *salinicola* (*sensu* Gasse, 1986) *Entomoneis alata, Amphora coffeaeformis* or *Nitzschia hungarica* and, in fresh/oligosaline waters, *Cymbella microcephala, C. cesatii, Fragilaria ulna* var. *acus, Achnanthes minutissima, Amphora arcus* var. *sulcata* or *Cyclotella meneghiniana.*

At the freshwater end of the spectrum, an artificial truncation has been suggested in the NGP data, whereby the salinity optima of common freshwater taxa are overestimated due to a lack of samples from fresh waters (Fritz *et al.*, 1993a). This also applies to the Spanish data-set, in which the cosmopolitan freshwater species, *Achnanthes minutissima,* for example, has an estimated optimum within the oligosaline class.

Taking into account that NGP values are quoted as TDS rather than conductivity, all the NGP optima apart from *Denticula elegans* (Spain 2.7 mS cm^{-1}, Africa 4.7 mS cm^{-1}, NGP 8.9 gl^{-1}) are either closer than the African optima to the Spanish values, or are similar to the African optima. African optima tend to be low for taxa with a Spanish optimum in the mesosaline range; the optima of *Nitzschia compressa, Cocconeis placentula* var. *euglypta, Navicula cryptotenella* and *Nitzschia palea* all fall in the oligosaline or fresh water class, for example. This may be partly due to the better coverage of fresh waters in this data-set.

It could also derive from taxonomic differences; some groups of taxa such as the *Nitzschia palea* group are poorly-defined (CASPIA Workshop, 1992, unpublished). Other taxa may have been split in one data-set, but not in the other. *Cocconeis placentula* var. *euglypta* is a common taxon in brackish waters (Patrick & Reimer, 1966) but has a fresh water optimum in the African data-set; it is possible saline water forms have been separated as a different species. In the Spanish data-set, the affinity of *Fragilaria* fasciculata var. 2 with *F. fasciculata* in the African data-set is clear, but *F. fasciculata* var. 1 is probably a different species.

In general, NGP optima are close to the Spanish optima, but the flora of this region is different to that of Spain. African optima show greater similarities at the saline end of the spectrum, and the flora is very similar to that of Spain. The lower optima in less saline waters may be largely a function of the better representativity of fresh waters in the larger, African data-set. It can be concluded that the African data-set is more likely to be a source of reliable analogues for Spanish taxa than is the NGP data-set, but an assumption of global salinity optima may equally apply.

4.7.4 Reconstruction of brine composition

Gasse *et al.* (in press) have recently developed additional transfer functions for brine composition on a large data-set (282 samples) from African salt lakes. Although ionic composition makes a unique contribution to variance in the diatom data in the Spanish data-set a transfer function would not be applicable due to the limited range in water chemistry of Spanish salt lakes. A high correlation was demonstrated between ionic composition and salinity since its main variation is due to the restriction of high proportions of calcium and carbonate/bicarbonate to fresh waters, and to the relationship between chloride concentration and salinity which stems from characteristic patterns of brine evolution (Hardie *et al.*, 1978).

Instead, TWINSPAN was used to investigate potential indicator species of different brine types. The lack of indicator species for sulphate waters is in accord with the reduced importance of sulphate in the CCA. Although chloride is highly correlated with salinity, indicator species identified for chloride waters, such as *Nitzschia compressa* var. *vexans* and *Gyrosigma peisonis*, were not restricted to high-salinity sites, and provide potential additional information on water quality.

4.7.5 Qualitative interpretation of lake-level change

Many workers have used the ratio of planktonic:benthic species as a relative lake-level indicator, even though the relationships are not necessarily simple (Battarbee, 1991). In this study, the technique was supported in general terms by a distinction between the presence of plankton in permanent and non-hypersaline semi-permanent lakes, and the higher abundance of aerophilous taxa in ephemeral and hypersaline semi-permanent lakes in which the formation of a salt crust prevents summer desiccation. The latter become extremely shallow in the summer months and in this respect may offer extensive aerial habitats similar to typical playa lakes. Most ephemeral and hypersaline semi-permanent lakes plot to the right of CCA diagrams and are also the most turbid in the data-set. The lack of plankton and abundance of aerophilous taxa is in accord with the results of other research, which suggests that high turbidity (related to sediment resuspension in the shallow, wind-stressed lacustrine environment of ephemeral lakes) can restrict the growth of both the plankton and benthos, through reduction in the depth of the photic zone to a few millimetres (Hecky & Kilham, 1973, Busch & Kubly, 1980). The presence at lower frequency of reported aerophilous taxa in more permanent lakes may derive from shallow habitats in the littoral zone; *Gyrosigma peisonis*, for example, reaches peak abundances in samples taken from the edge rather than the centre of semi-permanent lakes (CGSQ, DCMS, GSAR).

Although semi-permanent and permanent lakes have the most extensive aquatic macrophyte communities, a separation on the basis of epiphytic diatoms was not definitive. This is confirmed by the assemblage composition of modern epiphytic diatom samples screened during the project, which were dominated by genera such as *Mastogloia, Rhopalodia* and small *Nitzschia*'s which are known also to inhabit the bottom mud, and *Cocconeis placentula* var. *euglypta*. The epiphytic diatom, *C. placentula* var. *euglypta*, is also known from other surfaces (Patrick & Reimer, 1966); it is reported as abundant on the surface of ostracod valves (Margalef, 1953), for example, and dominated the diatom assemblage of a floating algal mat from an ephemeral lake in the data-set, El Salobral, Córdoba (ASBL1).

4.8 SUMMARY

In summary, a Spanish diatom-salinity transfer function has been developed successfully for conductivity ($r^2 = 0.91$), based on a data-set of 70 samples from 55 lakes. The transfer function can be applied to fossil diatom assemblages to provide a continuous, quantitative palaeosalinity curve.

A comparison of the estimated Spanish optima of common diatom taxa with those of other regions indicated that the Spanish flora has most in common with the African data-set, but for cosmopolitan taxa an assumption of the global applicability of salinity optima may be valid.

In TWINSPAN analysis, indicator species for chloride-rich waters were identified (e.g. *Nitzschia compressa* var. *vexans* and *Gyrosigma peisonia*), but no strong indicator species for sulphate or carbonate waters were found. This may relate in part to the poor representativity of carbonate-rich waters in the Spanish data-set.

A technique for qualitative interpretation of lake-level change was validated through TWINSPAN analysis, wherein diatoms of different habitat preferences (planktonic versus benthic or aerophilous) were shown to vary according to the permanence (or depth) of lakes. This provides a model for qualitative interpretation of lake-level change, independent of diatom-based palaeosalinity reconstruction.

CHAPTER FIVE

STUDIES OF DIATOM PRESERVATION AND SELECTION OF THE STUDY SITE

5.1 INTRODUCTION

Diatom dissolution in salt lake sediments can seriously affect the reliability of palaeosalinity reconstruction, or result in the complete loss of the fossil diatom record. The results are presented in this chapter for a comprehensive three-part survey which focusses on the quality of diatom preservation in Spanish salt lake sediments; this was carried out for selection of a study site of high potential, and as the basis for a separate study of factors affecting diatom preservation.

The design and sampling strategy were discussed in Chapter 3, and are summarised here for purposes of clarification. Preservation Study I (Regional Survey) was designed to incorporate a large number of sites from which to select sites of potential for further assessment in Study II. Following a preliminary survey in Preservation Study IA, Study IB comprises a survey of diatom preservation in short cores from the recent sedimentary environment of lakes throughout Spain, from which a sub-set of sites is selected for Preservation Study II. In Preservation Study II (Long-Core Survey) the quality of diatom preservation in longer sediment sequences is assessed. For selection of the study site, this is combined with an assessment of the lithology and broader palaeoecological potential of the sediment sequences, from which the Laguna de Medina is selected for detailed analysis of Holocene palaeoclimate change.

The ability to predict the quality of diatom preservation in salt lake sediments would be an asset in palaeoecological research. Preservation Study III is an analysis of the combined data-set of diatom and environmental data collected for Studies I and II, which is aimed at establishing the predictability of preservation in the recent and Holocene sediments of different types of lake.

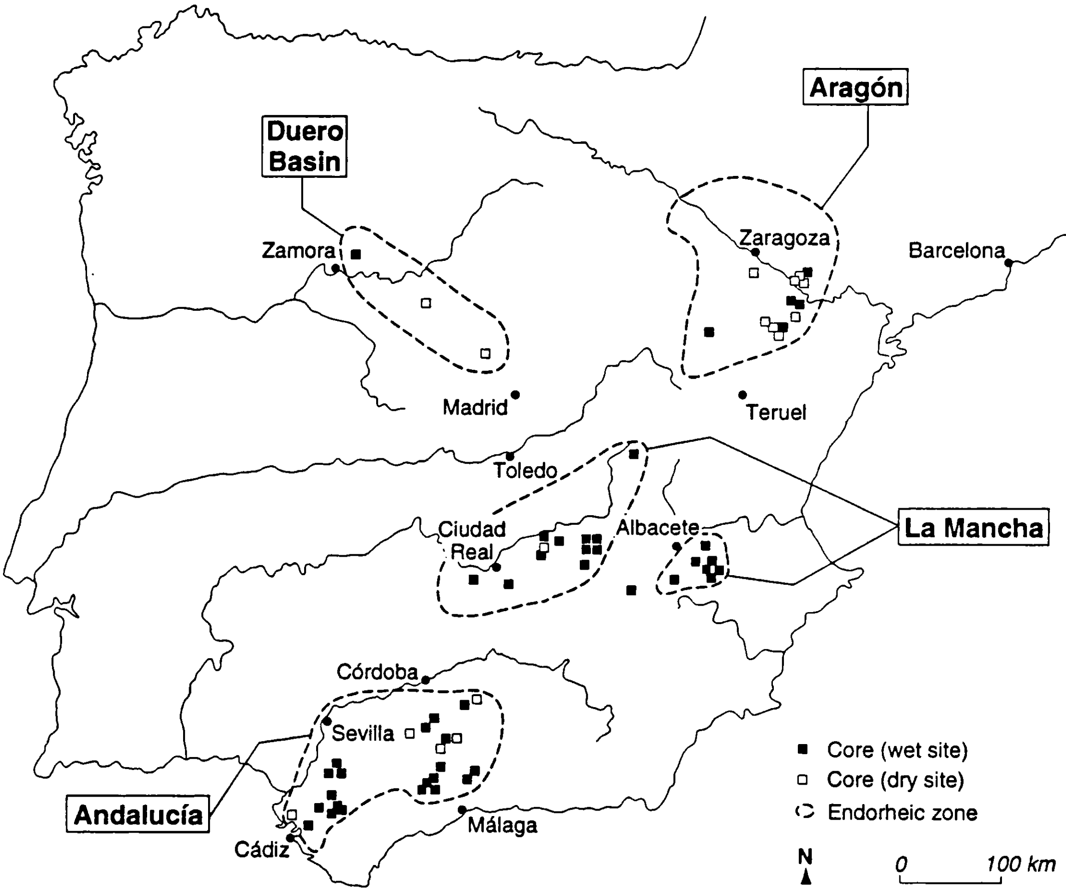
5.2 PRESERVATION STUDY I: REGIONAL SURVEY

5.2.1 Part A: Diatom preservation in long cores from the Ebro Basin and La Mancha

5.2.1.1 Results

The distribution of coring sites is given in Figure 5.1. The 10 sites involved (9 from the Ebro Basin

Figure 5.1 Preservation Study I: map showing the distribution of coring sites.



and 1 from La Mancha) are indicated in Appendix 4, which gives core and diatom preservation data. Full site details are given in Appendices 1, 2 and 3.

The 10 lakes comprise 4 ephemeral (summer-dry), 1 semi-permanent, (dries every few years), 1 hypersaline, semi-permanent lake in which a salt crust in summer prevents evaporation to dryness, and 4 permanent sites. The ephemeral lakes were dry when sampled and water depth otherwise varied between 0.05-8m. Three of the permanent sites were oligosaline and the other 7 were all hypersaline.

Sediment-core diatom preservation is summarised in Figure 5.2. Diatoms were absent throughout in the ephemeral lakes, Laguna Guallar [HGUA], Laguna Salada Pequeña [HPEQ], Laguna del Pito [HPIT], Laguna de Zaida [HZAI] and the semi-permanent Laguna de la Salineta [HLDS]. Those of the Laguna de Gallocanta [HGAL], a shallow but large (13.3 km^2), semi-permanent lake were poorly preserved (fragmented rather than dissolved) in the top 4cm only.

Diatom preservation was highest in the four permanent, deep lakes. Diatoms were affected by dissolution below 4cm depth in the 40cm diatom sequence of the 5m-deep, hypersaline Laguna Salada, Chiprana [HSAL], whereas the 3 oligosaline lakes, HCHI, HEST and ECHC, had full preservation to varying depths >20cm below the surface sediment.

5.2.1.2 Discussion

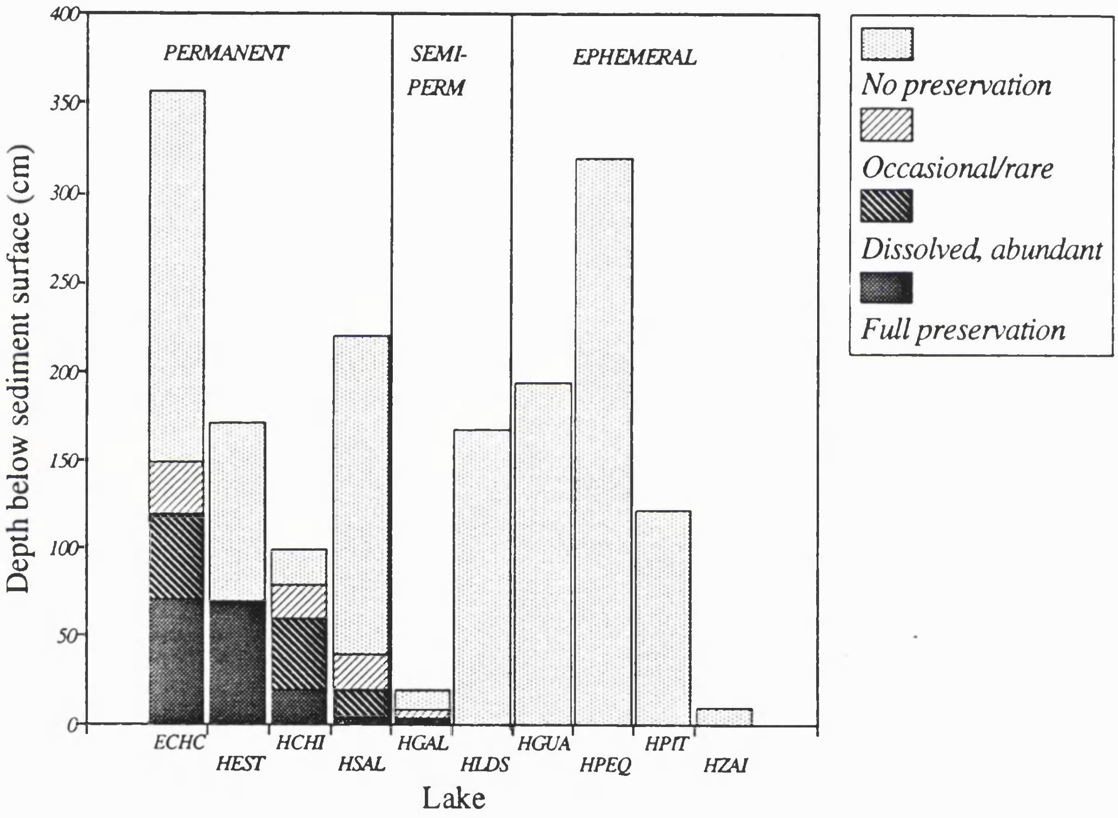
None of the lakes was retained as a site of high potential. Of those with diatoms, the Laguna de Gallocanta [HGAL] is of tectonic origin (Comín *et al.*, 1983) and was the only basin in its natural state, but preservation was poor. The Laguna Salada, Chiprana is regarded as semi-natural (Balsa *et al.*, 1991), but it is fed by irrigation water and preservation in the top 40cm probably relates to human impact (Davis, 1994). Similarly, the Laguna Chica is an artificially-controlled fish farm, and diatom preservation is again restricted to the upper sediments. The two reservoirs, HCHI and HEST (formerly an ephemeral lake) are artificial. The preliminary results show a distinction between shallow, ephemeral and deeper, permanent lakes which suggests the significance of these parameters for diatom preservation. On this basis semi-permanent and permanent lakes were given priority in Part B.

5.2.2 Part B: Regional short-core survey

5.2.2.1 Results

The distribution of coring sites is given in Figure 5.1 above. Site and sample details are given in Appendices 1-4.

Figure 5.2 Preservation Study I, Part A: summary of core diatom preservation.



Diatoms were preserved at the base of 13 short cores out of a total of 45. The 32 sites without basal diatoms include 24 of 25 shallow, ephemeral lakes sampled, whose conductivity varied from 0.2-338 mS cm^{-1}, and 5 hypersaline semi-permanent lakes.

A summary of the 13 sites in which diatoms are preserved to some extent in the recent sediments is given in Table 5.1. The preservation categories 'abundant' and 'very abundant' refer to assemblages for which a full diatom count would be possible. All lakes falling into these categories are either permanent or semi-permanent lakes, whose origins relate in some way to processes of substrate dissolution.

5.2.2.2 Discussion

The relationship between measured environmental variables and diatom preservation is considered separately, in Preservation Study III. The influence of lake permanence on diatom preservation is clear, however, and is taken into account in assessing site potential for Preservation Study II. In the following discussion, a sub-set of 14 sites is selected for Preservation Study II, the Long-Core Survey, from the combined assessment of near-surface diatom preservation, lake hydrology and morphometry, and evidence for human impact, the criteria for which were discussed in Chapter 3.

In spite of their good diatom preservation, none of the sites with 'full' preservation was retained. The artificial influence on the re-sampled Laguna Chica [ECHC] was noted in section 5.2.2.2. The Lagunas del Taray [ETRY] and de la Celadilla [ECLD] are both artificially-maintained (Prof. C. Montes, pers. comm.). Both these lakes and the Laguna Lengua [GLNG], part of the Ruidera system, are karstic with major aquifer flow (Florín *et al.*, 1993, González Martín *et al.*, 1987) and therefore of low potential. Similarly, groundwater is the main source of input to the Laguna de Zoñar [AZNR] and it is relatively insensitive to interannual variations in precipitation; lake level only fluctuates by around 1m compared to its water depth of >9m, and the lake has an outflow in very wet years (Recio Espejo & Tirado Coello, 1982b).

All lakes where diatoms were preserved and which were not known to be either artificial or 'open' karstic systems with major groundwater outflow were included. These were all in Andalucía and comprised the Laguna Amarga, Córdoba [AAMA], Lagunas de la Alcaparrosa [CALC] and de Arjona [CARJ], Sevilla, and Lagunas Dulce, Espera [DDUL] and de Medina, Cádiz [DMDN]. The Laguna Grande, Málaga [BGDE] had not been cored but was selected for its reported permanence and low salinity (Ubierna León & Sánchez Castillo, 1992).

Although the lakes of Andalucía showed the best diatom preservation, they are all solution lakes whose

Table 5.1 **Preservation Study I: selected limnological characteristics for sites with diatoms preserved in the recent sedimentary environment.**

SITE CODE	NAME	REGION	LAKE ORIGIN	PERM'CE	WATER DEPTH (m)	COND. (mS/cm)	CORE DEPTH PS I (cm)	PRES'N AT CORE-BASE
AAMA	L Amarga	Andalucía	Dissolution	Perm	3.0	13.0	15	occas
ADLC	L Dulce, Lucena	"	"	Ephem	damp	e:5.0	10	occas
AZNR	L de Zoñar	"	"	Perm	9.5	9.5	15	very abund
BDCE	L Dulce, Campillos	"	"	Semi	0.2	15.0	15	rare
CALC	L de la Alcaparrosa	"	"	Semi	0.8	7.1	15	rare
CARJ	L de Arjona	"	"	Semi	0.9	15.0	21	abund
DDUL	L Dulce, Espera	"	"	Semi	2.0	5.3	7	abund
DMDN	L de Medina	"	"	Semi	0.8	12.1	6	abund
EACH	L de Alcahozo	La Mancha	Weath'd sinkhole	Ephem	0.1	40.0	30	rare
ECHC	L Chica, Villafranca	"	Weath'd contact	Perm	0.9	3.8	23	very abund
ECLD	L de la Celadilla	"	Karstic	Perm	1.0	2.1	10	very abund
ETRY	L del Taray	"	Karstic	Perm	0.2	1.7	34	very abund
GLNG	L Lengua	Albacete	Karstic	Perm	2.7	0.6	16	very abund

* Data on lake origins from Montes & Martino (1987) Torres Esquivias et al (1989) (general 'dissolution' lakes), Florín & Montes (1993) (La Mancha lakes), Gonzalez *et al.* (1987) (L Lengua).

stability is uncertain. Whilst they were described by Furest & Toja (1984) as 'truly endorheic', subsidence or subterranean flow is more likely to complicate the salinity:climate relationship than in simpler basins. Several lakes in close proximity were selected to assess the potential for a regional study, wherein correlation of palaeosalinity records would support a regional climatic influence rather than the dominance of local hydrological effects. Other lakes of southern Spain [DTLL, CTRJ, CZRR, ASBL above, and AHDA not cored previously] were therefore included primarily on the basis of their location and, in the case of the Laguna de los Tollos [DTLL] and El Salobral [ASBL], on the possible adverse effects on the recent sediment record compared to deeper sediments of accelerated sediment infilling consequent upon documented drainage and erosion from ploughing (Furest & Toja, 1984, Nature Reserve guard, pers. comm.). These form two clusters in the provinces of Córdoba and Sevilla/Cádiz, central and southwest Andalucía.

Other selected sites were in La Mancha. La Ontalafía [GONT] is a semi-permanent, low salinity lake surrounded by steep hills whose topography might induce a more focussed, deep sediment record. The core for Study I was collected from the lake edge, and its lack of basal diatoms could be due to the high-energy littoral environment (Flower, 1993). The Laguna de Fuentillejo [EFTL] is a volcanic basin (Hernández-Pacheco, 1932) and was selected on the grounds of the exceptional stability of crater lakes (Reeves, 1965), and of its steep topography. The Laguna de El Hito [EHIT], La Mancha, was formerly of greater extent prior to water diversion (Florín, pers comm). It is of ancient fluvial origin and, from data on La Mancha lakes (Florín *et al.*, 1993), is one of the few to be fed to a significant degree by surface water. Its sensitivity to precipitation has been attested (de Juana, 1990) and it is of low salinity (c. 5 gl^{-1}).

In summary, the 14 sites selected for Preservation Study II comprise 11 from Andalucía, southern Spain, and 3 from La Mancha, central Spain.

5.3 PRESERVATION STUDY II: LONG-CORE SURVEY

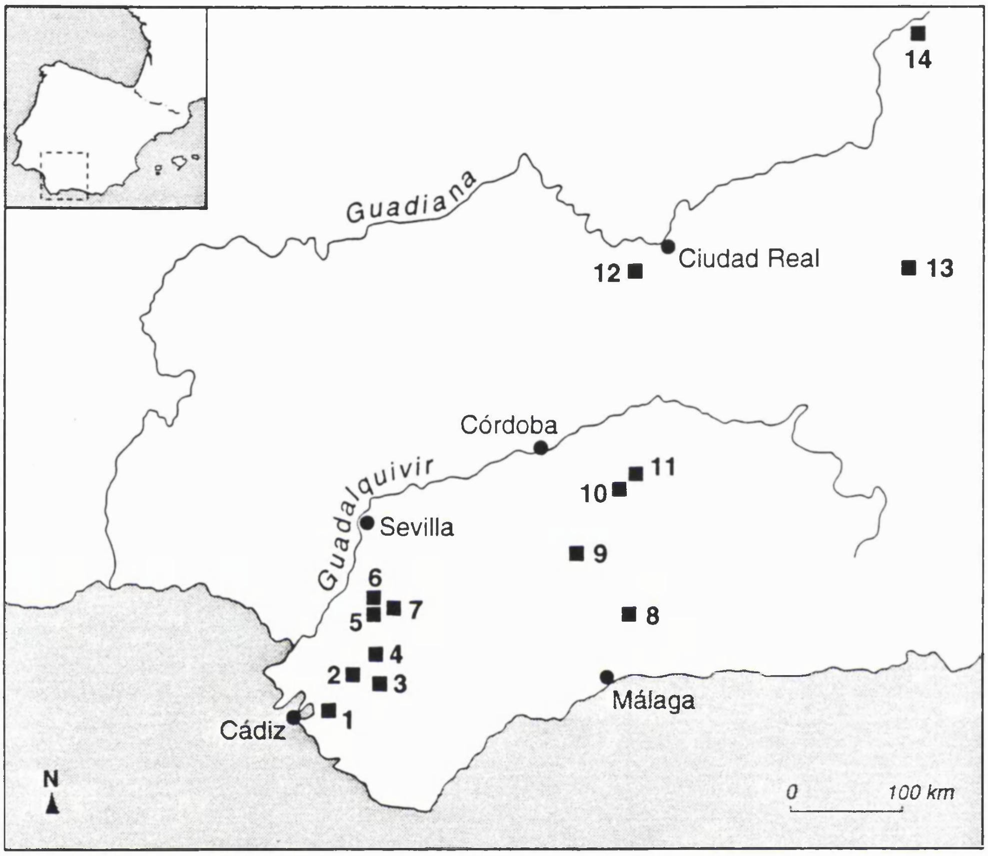
5.3.1 Results

The distribution of the 14 sampling sites is given in Figure 5.3. Keys to the modified Troels-Smith lithostratigrapy and palaeoecolgical abundance scales used to describe the sediment sequences are given in Figure 5.4. Detailed lithostratigraphic descriptions are given in Appendix 7.

5.3.1.1 La Ontalafía, Albacete [GONT] and El Hito, Cuenca [EHIT]

The sites were impossible to core. The sediments of La Ontalafía were very coarse and the water level

Figure 5.3 Preservation Study II: map showing the distribution of coring sites.



1. L. de Medina, Cádiz
2. L. de Los Tollos, Cádiz
3. L. Dulce, Espera, Cádiz
4. L. del Taraje, Sevilla
5. L. de Arjona, Sevilla
6. L. de la Alcaparrosa, Sevilla
7. L. de Zarracatín, Sevilla
8. L. Grande, Málaga
9. L. Amarga, Córdoba
10. El Salobral, Córdoba
11. L. Honda, Jaén
12. L. de Fuentillejo, Ciudad Real
13. La Ontalafía, Albacete
14. El Hito, Cuenca

Figure 5.4 **Preservation Study II: keys to (a) lithostratigraphic descriptions, and (b) palaeoecological abundance scales.**

(a) Key to lithostratigraphic description

Matrix		*Gypsum crystals < 50%* *	
☐	Silty clay	• •	Lenticular
▧	Clay-marl	⫽	Prismatic
▨	Gypsum band	✿ ✿	Twinned/aggregate
▥	Abundant reduced organics	● ●	Rounded translucent

* *Gypsum 5-point scale:* *Very abundant = gypsum band,*
Abundant-Occasional-Rare-(nil) indicated as 3-2-1-(0) crystal symbols

Lithostratigraphic transitions		*Other*	
-------	Sharp	▭	Tufa
———	Very sharp	NO REC	No recovery

(b) Key to palaeoecological abundance scales (related to wet sediment weight)

TILIA Scale	Diatoms	Ostracods	Molluscs	*Chara*	Seeds*
80	VA undiss	VA >500/g	VA >20/10g	VA >100/g	VA >15/10g
60	Abund. diss	Abund. 150-500/g	Abund. 11-20/10g	Abund. 10-100/g	Abund. 6-15/10g
40	- -	Frequ. 50-150/g	Frequ. 5-10/g	- -	Frequ. 3-5/10g
20	Occas. diss	Occas. 5-50/g	Occas. 1-4/10g	Occas. <10/g	Occas. 1-2/10g
+	Rare diss	Rare <5/g	Rare <1/10g	Rare 1-2 total	Rare <1/10g

* *Relative abundance of vegetative remains and charcoal*
assessed on a four-point scale (Very Abundant, Abundant, Occasional, Nil) without quantification.

was found to be artificially-maintained (Landowner, pers. comm.). Those of El Hito were hard and impossible to core past 102cm depth with either the Hiller or screw auger; the Cobra corer was not available.

5.3.1.2 Laguna de Fuentillejo, Ciudad Real [EFTL]

A 7.5m core was obtained using the Cobra corer on the dry lake-bed. The sediments were homogeneous sandy silty clay throughout. The only major stratigraphic changes were in colour and hardness. Some variability was noted in the content of rounded translucent crystals in the <180µm size fraction and of volcanic pebbles.

The sediments were exceptionally sterile. No diatoms, pollen or other palaeoecological remains were preserved.

5.3.1.3 Laguna Grande, Archidona, Málaga [BGDE]

A 247cm core was obtained from 7m of water using the Livingstone corer. The sediments were difficult to core owing to alternations between very soft silty clay or marly clay and hard salt bands; a longer core could not be extracted.

Diatoms were fully-preserved to 80cm depth and abundant but dissolved to 150cm depth. They were occasional or rare below this level to the core base. The analysis was not pursued (see discussion).

5.3.1.4 Lagunas de la Alcaparrosa [CALC] and de Arjona [CARJ], Utrera, Sevilla

Cores of 1.8m and 2m depth were collected in 0.63m and 0.60m of water in the Lagunas de la Alcaparrosa and de Arjona respectively, using the Livingstone and Cobra corers. The base of both reached limestone bedrock.

The lower levels and surface of the Laguna de Alcaparrosa only were screened for diatoms. Diatoms were rare at 10cm below the surface and absent from lower levels. The sediment at the core-base consisted of a friable 'soily' matrix with large limestone inclusions (180-172cm depth), compact dark grey clay with limestone and occasional molluscs (172-80cm depth) and soft grey-brown silty clays with abundant remains of reeds to the surface.

5.3.1.5 Laguna de Zarracatín, Utrera, Sevilla [CZRR]

A 500cm core collected from below the salt crust of this hypersaline lake with the Cobra corer did not reach the natural substrate. The stratigraphy is presented in Figure 5.5. Rare diatom fragments were found at 170cm depth in organic clays.

The sediments were homogeneous clay or silty clay in which the main stratigraphic transitions were in colour and compaction. Vegetative remains and seeds were rare. Well defined changes were recorded by the coincidence of high abundances of ostracods, aquatic molluscs, vegetative remains and charophytes around 350cm and 175cm depth. A shift in ostracod species composition occurred at c. 200cm depth from dominance by *Candona* and *Ilyocypris* spp. to *Eucypris mareotica.*

5.3.1.6 Laguna del Taraje, Las Cabezas, Sevilla [CTRJ]

A 137cm core was collected with the Livingstone corer from 1.6m of water. The sediments were too hard to core further with the Livingstone and the raft was not stable enough for the Cobra corer. The stratigraphy is presented in Figure 5.6. Diatoms were preserved in the surface sediment, but not at 5cm depth and below.

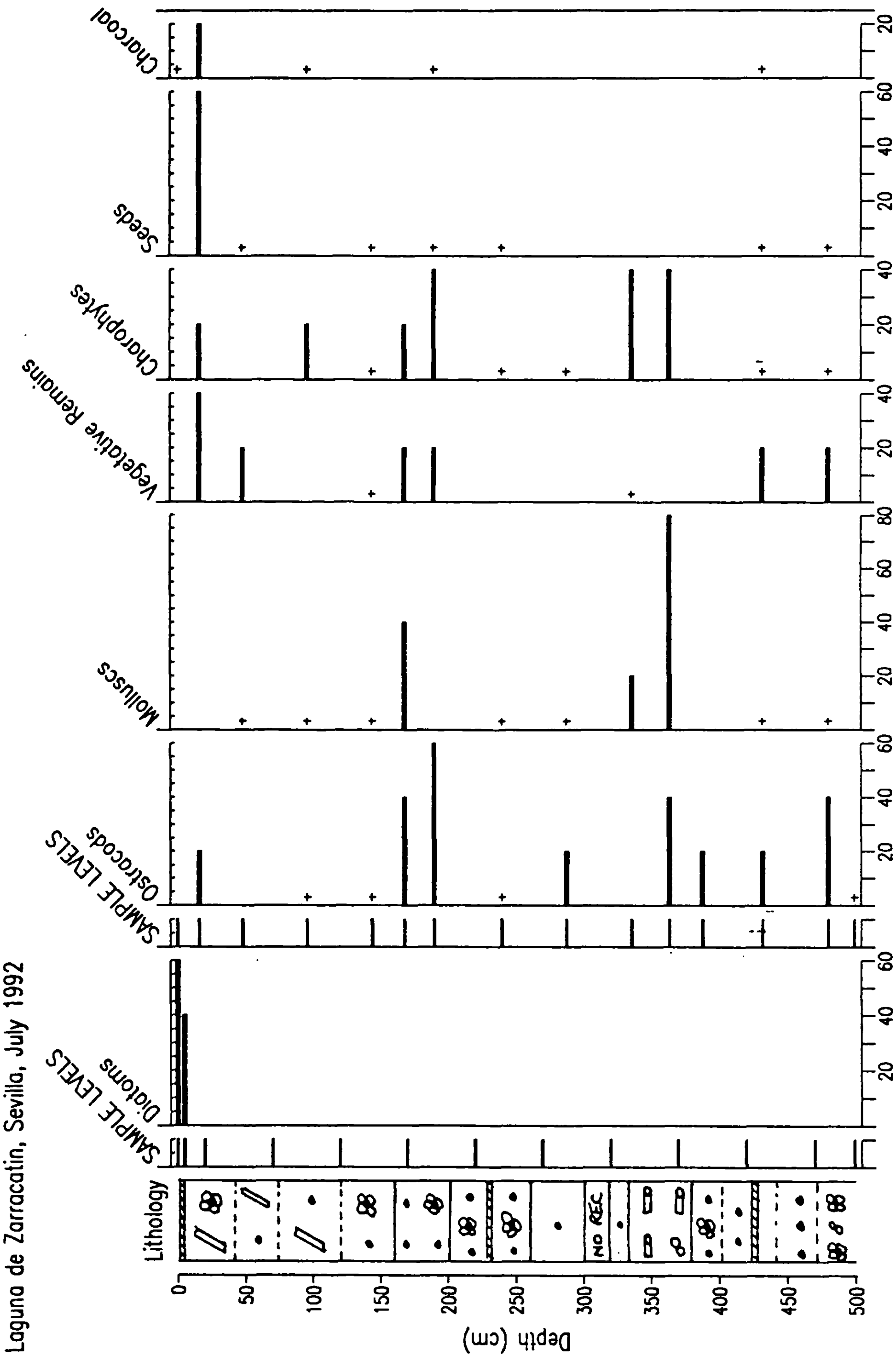
Charcoal was present throughout and was most abundant above 60cm depth. Organic content was high. Preservation in the hard basal clays was poor compared to the more variable and organic-rich levels above 112cm depth. Above 112cm depth macrofossils and aquatic molluscs were abundant, especially in the organic-rich levels between 97-79cm depth. Seeds were dominated by aquatics throughout. Ostracods were abundant in the unconsolidated silty clay towards the core top but poorly preserved (fragmented and sparse) below 16cm depth.

5.3.1.7 Laguna Dulce, Espera, Cádiz [DDUL]

A 380cm core was collected from 1.3m of water using the Livingstone and Cobra corers. The stratigraphy is presented in Figure 5.7. Diatoms were dissolved but abundant at 256-140cm and 70-60cm depth and were present in all levels analysed.

The lithology was highly variable with numerous very sharp transitions. Charcoal was present throughout and aquatic seeds were abundant. A rise in abundance of ostracods, vegetative remains and seeds above c.260cm depth coincided with increased diatom abundance and a change to marl-rich clay. Ostracods, aquatic molluscs and charophytes were very abundant above 156cm depth. No major changes in ostracod species composition were observed.

Figure 5.5 Long-core stratigraphy of the Laguna de Zarracatín, Sevilla.



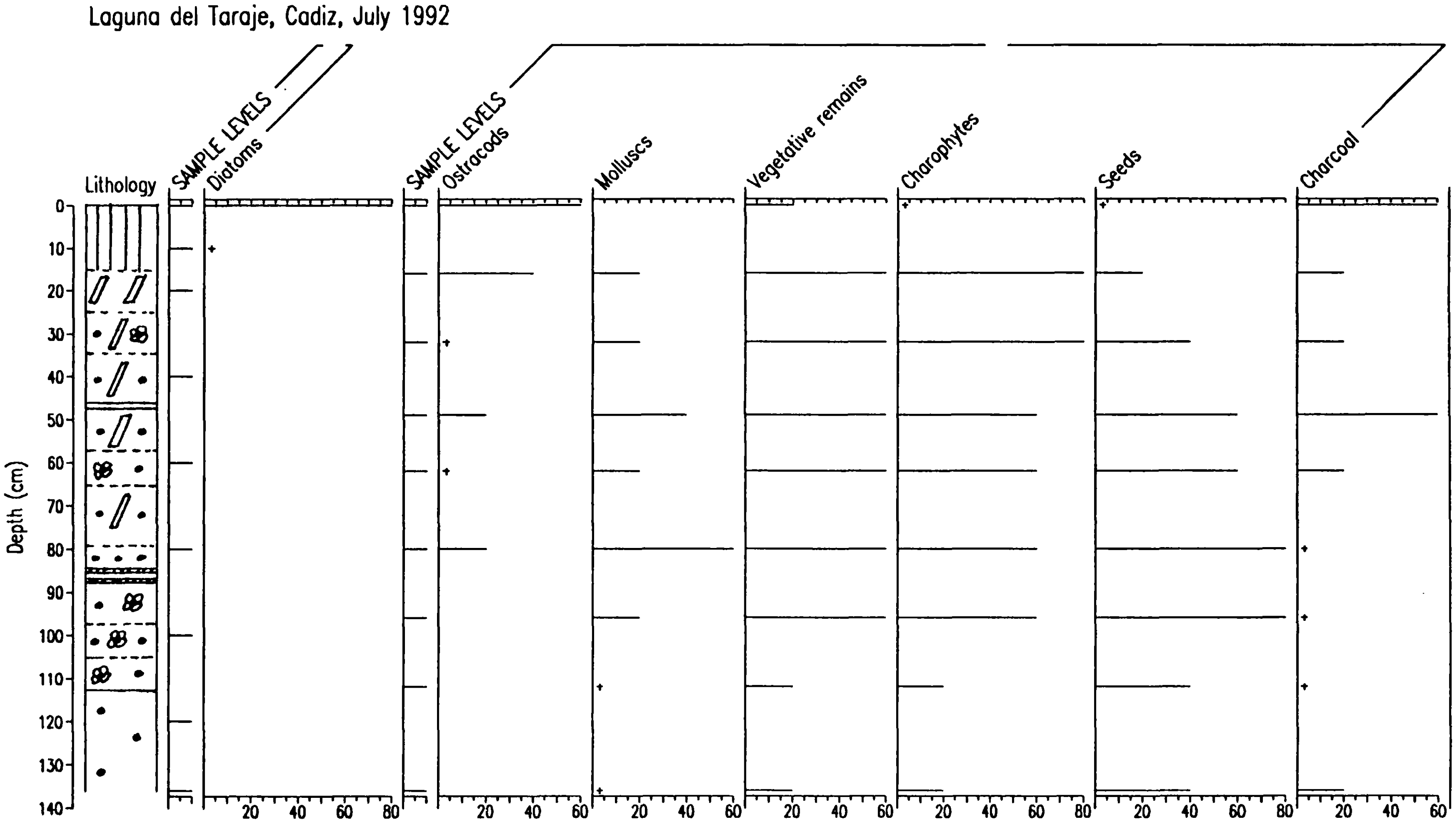


Figure 5.6 **Long-core stratigraphy of the Laguna del Taraje, Sevilla.**

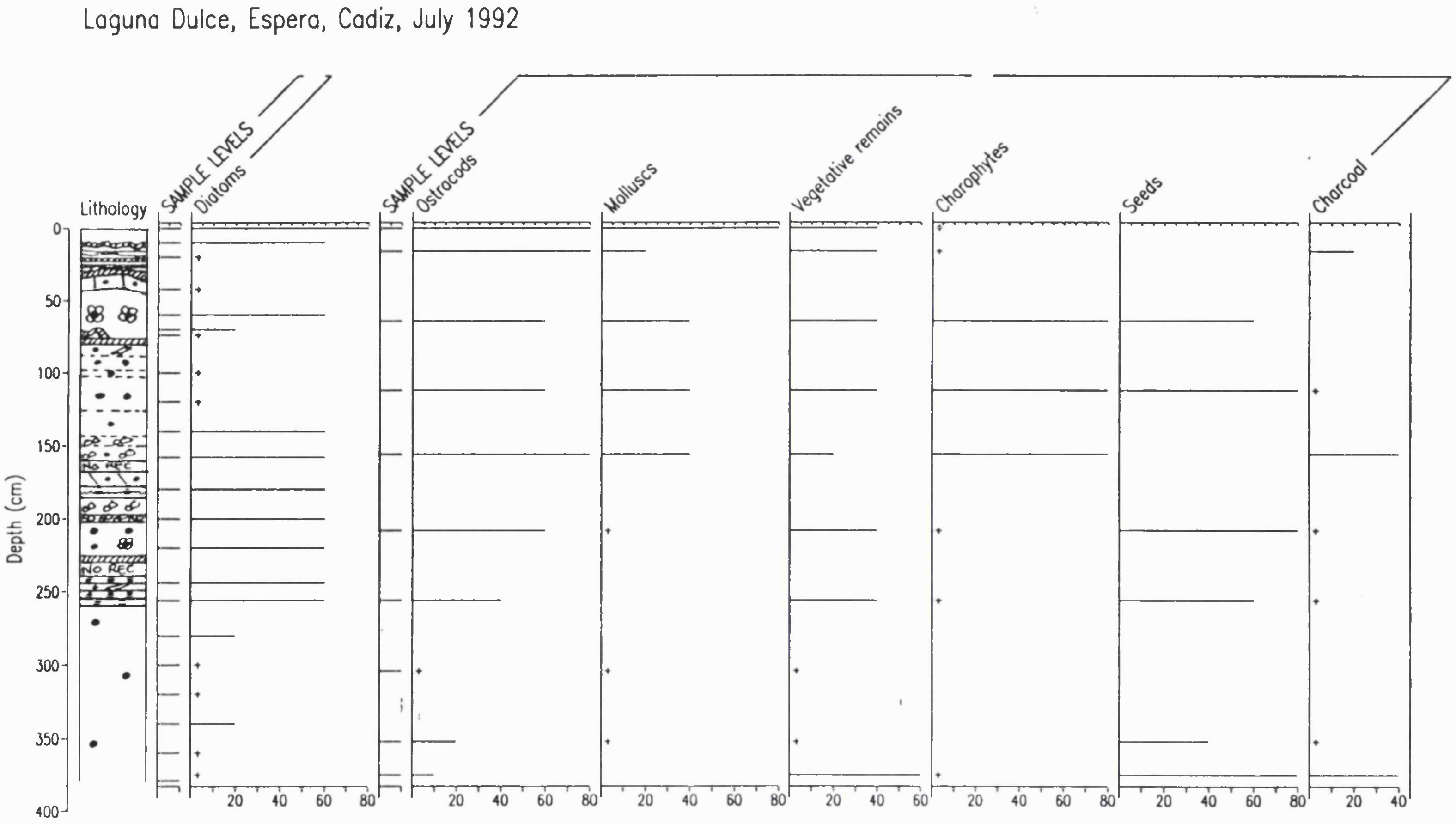


Figure 5.7 Long-core stratigraphy of the Laguna Dulce, Espera, Cádiz.

5.3.1.8 Laguna de los Tollos, Jerez, Cádiz [DTLL]

A 400cm core was collected from the dry lake-bed using the Hiller corer. The stratigraphy is presented in Figure 5.8. Abundant, dissolved diatoms including plankton were preserved from 340-180cm depth; they were absent in the top 1.5m and very rare at the base.

The sediment matrix was homogeneous, calcareous silty clay which varied mainly in hardness. Charcoal was abundant only at the surface. Sediments were low in organic content and no seeds were found; pollen preservation was poor. Ostracod preservation overall coincided with that of diatoms (c.350-140cm depth) and they were most abundant where molluscs and charophytes were also preserved. Sediments were virtually sterile above 140cm depth, at which depth a shift in ostracod species composition occurred from dominance by *Cyprideis torosa* and *Eucypris mareotica*, to *Plesiocypridopsis newtoni*.

5.3.1.9 Laguna de Medina, Jerez, Cádiz [DMDN]

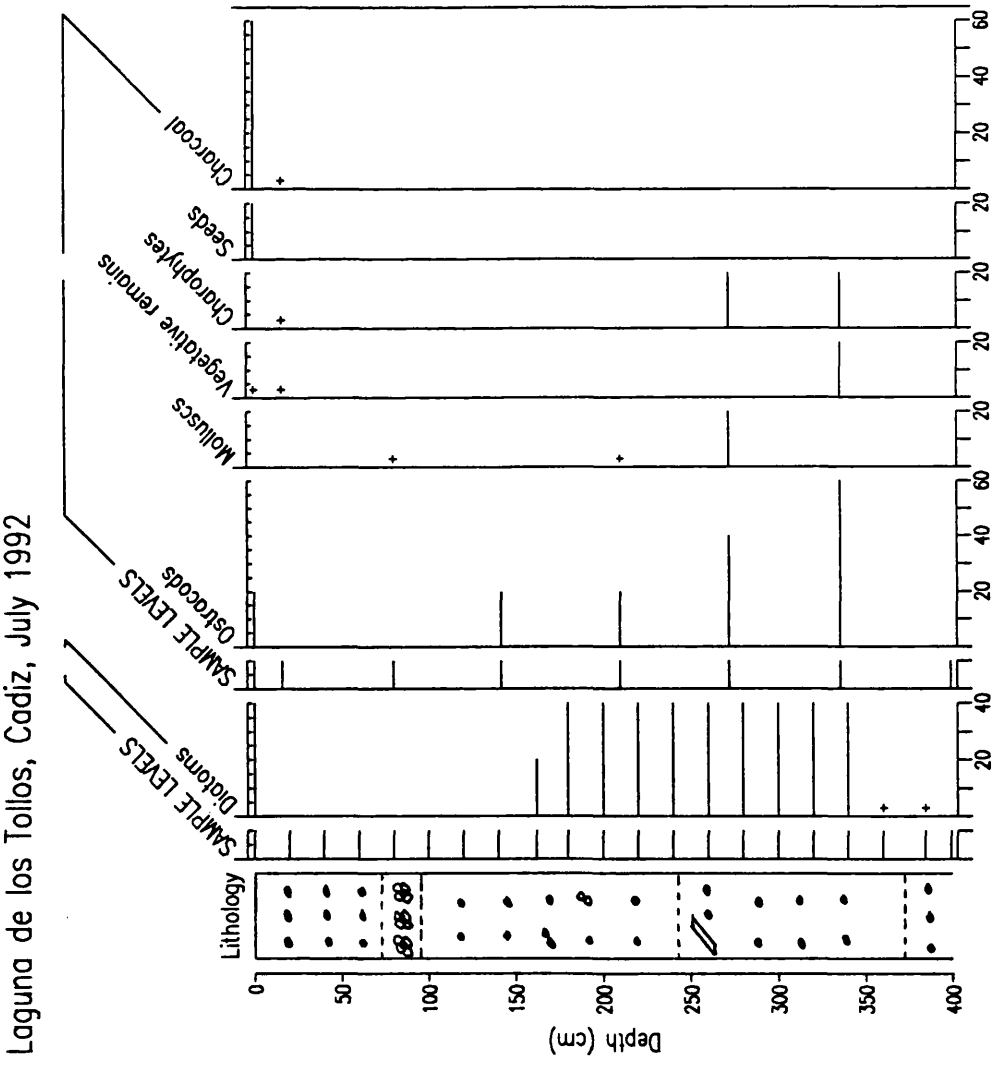
A 760cm core was collected from 0.7m of water using the Cobra and Livingstone corers. Sediments were still soft at the base. The stratigraphy is presented in Figure 5.9. Diatoms were preserved to varying degrees from the core-base to 460cm depth, and at the surface.

The lithology was highly variable both in organic content and gypsum abundance below c. 400cm sediment depth and was more homogeneous above. Charcoal was present below 300cm depth. Seeds were of aquatic species and not abundant. The core was rich in other organic remains. Levels with very abundant molluscs and vegetative remains below 450cm depth coincided with those where charophytes were least abundant, and molluscs were present throughout. Ostracods were abundant and relatively diverse (6 species) except in a hard band at 444cm depth; a major change in species composition occurred at c. 600cm depth. Pollen was well-preserved. The most salient feature of the preliminary pollen diagram (Prof. Stevenson, unpubl. data) for site selection was the lack of a well-defined olive rise, which has implications for the degree of human impact on the system (see Discussion).

5.3.1.10 Laguna Amarga, Lucena, Córdoba [AAMA]

A core of 338cm depth was collected in 2.5m of water using the Livingstone and Hiller corers operated from a raft. Basal sediments were hard silty clay rich in precipitated salt crystals, past which it would be difficult to core. The stratigraphy is presented in Figure 5.10.

Figure 5.8 Long-core stratigraphy of the Laguna de los Tollos, Cádiz.



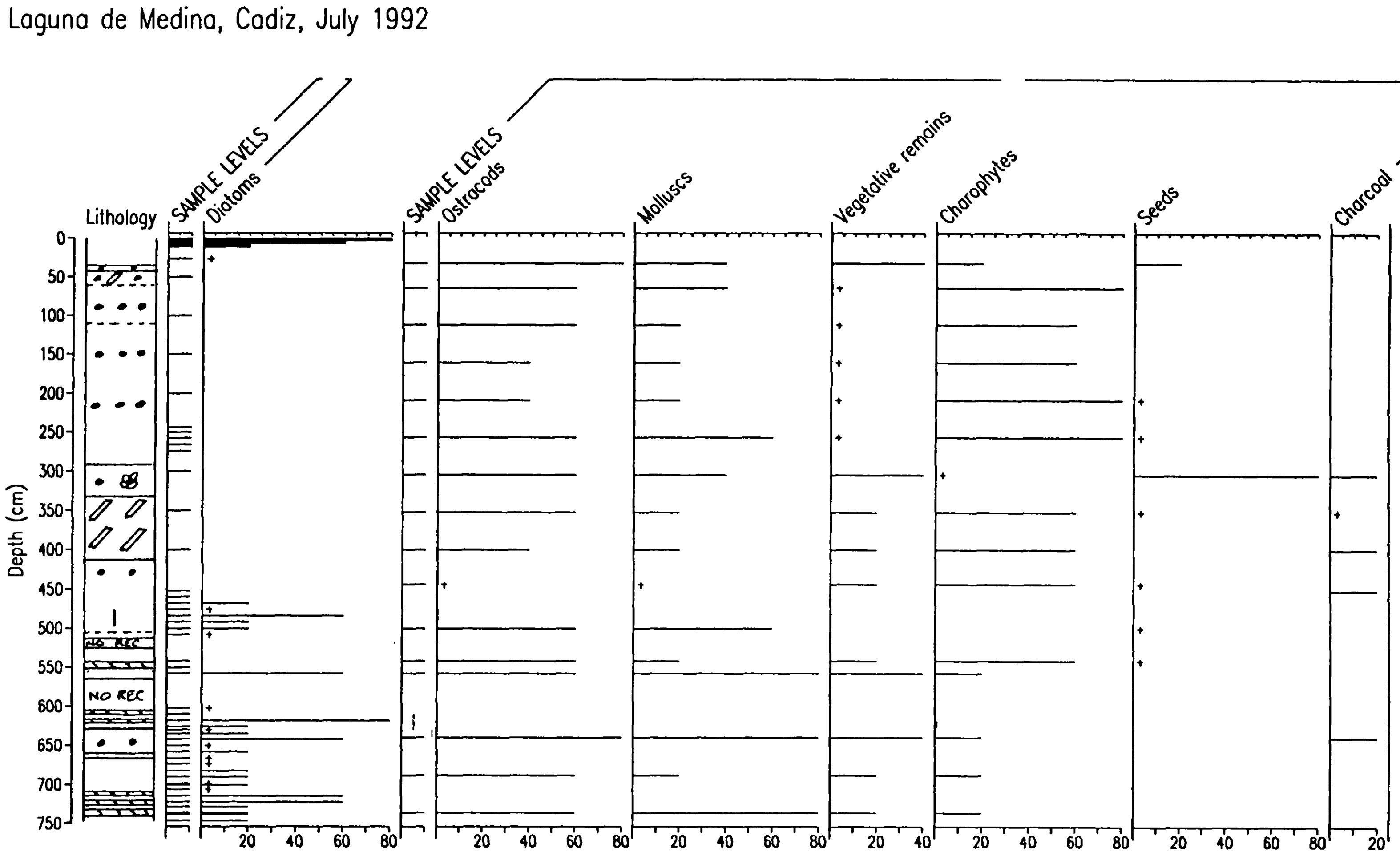


Figure 5.9 Long-core stratigraphy of the Laguna de Medina, Cádiz.

Figure 5.10 Long-core stratigraphy of the Laguna Amarga, Córdoba.

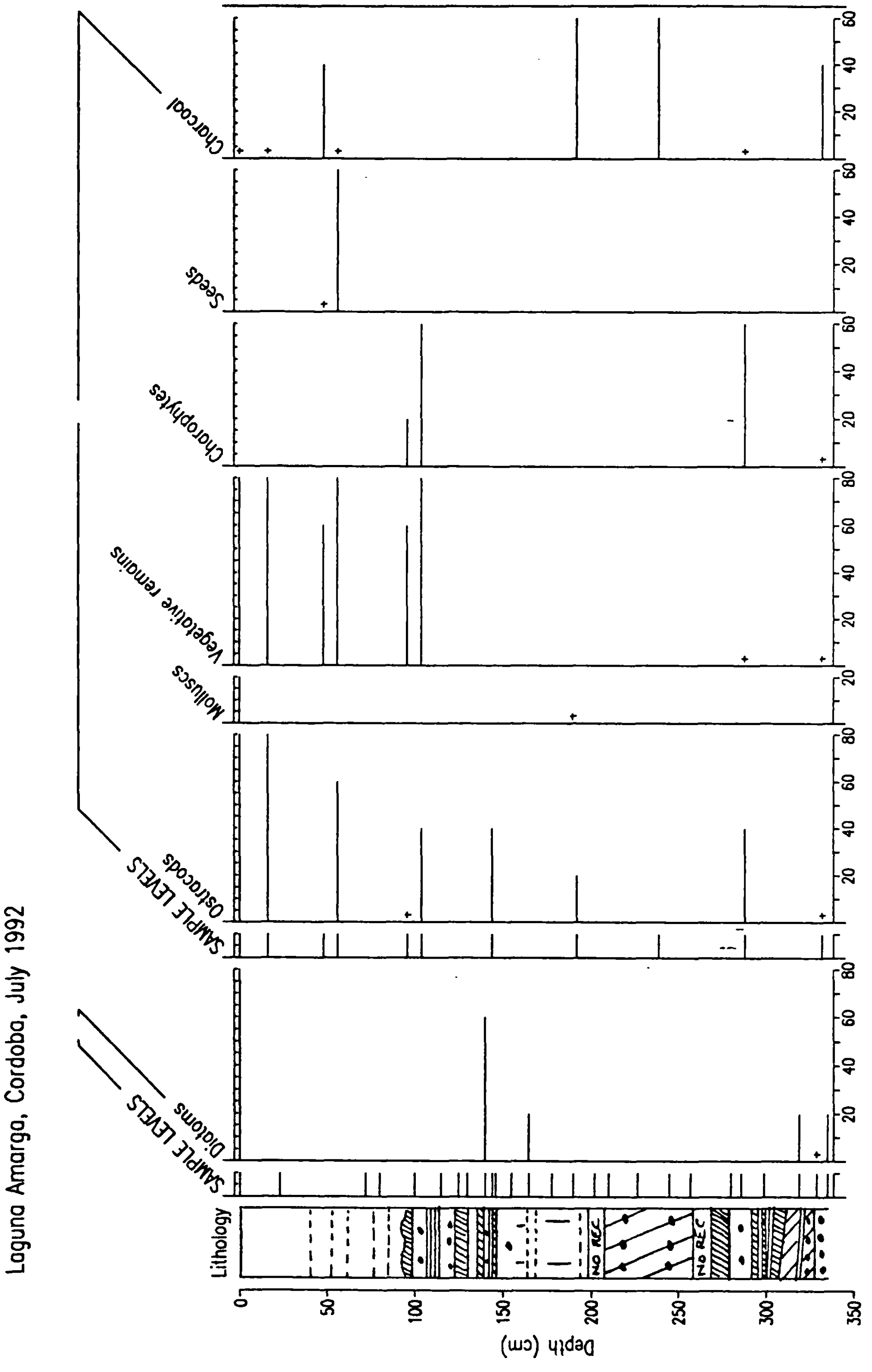
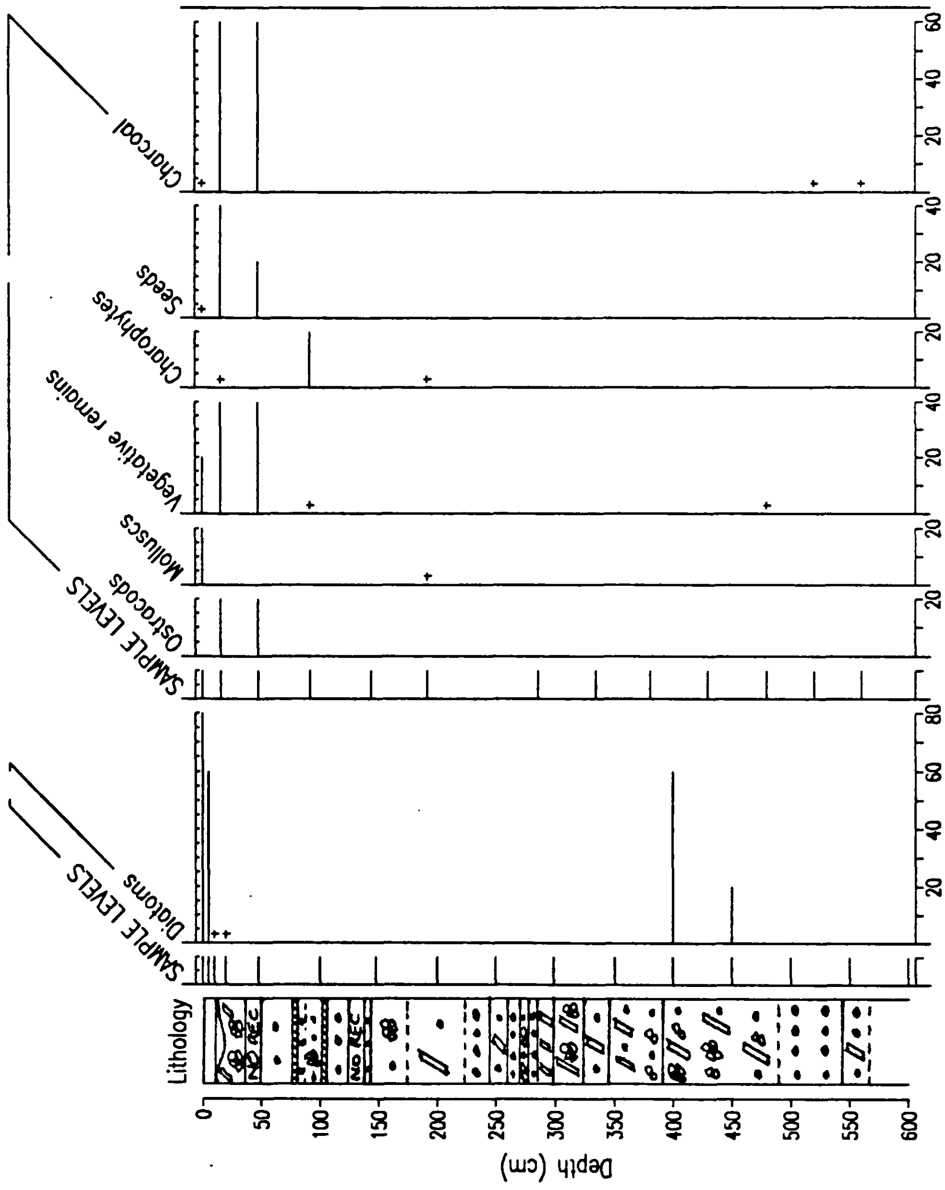


Figure 5.11 Long-core stratigraphy of El Salobral, Córdoba.



Diatom preservation was poor; occasional dissolved fragments were found in marly clays at the core base (335-319cm depth) and in two narrow organic-rich bands at 165cm depth and 140cm depth. The lithology was highly variable and alternated between clay, marly clay and gypsum bands of variable thickness. Charcoal was relatively abundant throughout. Samples below 150cm depth were relatively sterile in respect all organic remains. Ostracod abundance increased above 150cm depth to the core top, with no major changes in species composition. Vegetative remains were very abundant from 104cm depth, at which level a further charophyte peak occurred. Molluscs were absent throughout apart from a single fragment. Pollen was well-preserved. The profile of percentage of olive pollen in a preliminary pollen diagram (Prof. Stevenson, unpubl. data) showed a dramatic rise at 150 cm depth which was sustained to the surface and which coincided with a zone of laminated sediments.

5.3.1.11 El Salobral, Luque, Córdoba [ASBL]

A 600cm core was collected from 0.5m of water using the Cobra corer. Basal sediments were still soft. The stratigraphy is presented in Figure 5.11 above. Below the surface, dissolved diatom assemblages were preserved in only two samples, at 400cm and 450cm depth only.

Charcoal was abundant towards the surface and present at the core base. Organic remains were poorly preserved apart from above 50cm depth, where ostracods, charophytes and aquatic seeds were relatively abundant.

5.3.1.12 Laguna Honda, Jaén [AHDA]

A 273cm depth core was collected from 0.1m of water using the Livingstone corer. The top 10cm of sediment was lost, and diatoms were not preserved in the rest of the sequence. The analysis was not pursued.

5.3.2 Discussion

The three sites in La Mancha are excluded from further consideration for site selection. El Hito and La Ontalafía were impossible to core with the available equipment, and the Laguna de Fuentillejo was exceptionally sterile.

In Andalucía, the Laguna Grande, Archidona is also rejected despite its high organic content and diatom preservation. In addition to coring difficulties the lake appeared to have an intermittent outflow and was unlikely to be very sensitive to climate change. Its depth and roundness probably reflect a karstic origin with major aquifer input (Florín *et al.*, 1993).

The choice of sites for a Holocene study is therefore between two clusters of lakes in Córdoba and Sevilla/Cádiz. None of the sites is outstanding in its content of charcoal or terrestrial seeds for ^{14}C radiometric dating, so this is not a major factor in site selection.

The 3 sites of Córdoba are rejected for several reasons in addition to their poorer diatom preservation. Firstly, the topography and geology of Córdoba is more variable than southwestern Spain; the Laguna Amarga is located at an altitude 400m below El Salobral and the Laguna Honda so it would be difficult to separate real differences in climatic response from local hydrological factors.

The sediments of El Salobral and the Laguna Honda are relatively sterile. In El Salobral, very high recent sediment accumulation rates are documented from storm erosion since catchment ploughing (Nature Reserve Guard, pers. comm), and the sediment record recovered is probably of relatively recent origin. In the Laguna Amarga sequence, stratigraphic changes are clearly correlated with an 'olive rise' in the preliminary pollen diagram which probably reflects agricultural activity and suggests human impact has had a major influence on the system. In addition, the greater influence of groundwater flow (850 mm yr^{-1}) over that of precipitation and runoff (582 mm yr^{-1}; Torres Esquivias *et al.*, 1989) indicates the lake is probably less sensitive to climate change than others under consideration.

Of the cluster of 7 lakes in the region of Sevilla/Cádiz, the Lagunas de la Alcaparrosa and de Arjona are unsuitable since they do not contain long sediment records. Their basins are small, shallow and surrounded by irrigated agriculture. The Lagunas Dulce, Espera and del Taraje are also excluded. The Laguna del Taraje does not contain diatoms; although the Laguna Dulce has a good diatom record, the numerous very sharp stratigraphic transitions indicate possible gaps in sediment accumulation. Both are similar to the Laguna Amarga in the distinction between variable, organic-rich sediments in the upper core levels and reduced preservation in compact, more homogeneous clays at depth. It would be difficult to obtain longer cores from the lakes and it can be inferred that fluctuations towards the surface are primarily responses to human influence on the catchment. These two lakes are also located at higher altitudes than the other lakes in the region (110-130m asl compared to 30-70m asl).

The remaining three lakes, the Lagunas de los Tollos, de Zarracatín and de Medina, are all in close proximity and each is of potential for a Holocene palaeoclimatic study. For reasons given below, the Laguna de Medina is chosen as the site for a detailed study in this thesis, but the other two would provide suitable material for a regional study at a later date to test how far palaeoenvironmental change may be due to local hydrological versus regional effects. The reported recent desiccation of the Laguna de los Tollos as a consequence of diversion of arroyos for irrigation (Furest & Toja, 1984) indicates the influence of surface rather than subterranean inflow on lake level and suggests the lake is likely to have been sensitive to climate change in the past. Relatively good diatom and ostracod records are preserved at depth, although poor pollen and macrofossil preservation indicates radiometric dating would be difficult. The Laguna de Zarracatín is selected for its proximity to the other two sites and for the possibility of obtaining a long record with clearly defined evidence for palaeoenvironmental change. No diatoms are preserved but the ostracod record shows significant change. There is no evidence for major catchment erosion; chemical rather than clastic sedimentation may dominate under hypersaline conditions, providing a record spanning a relatively long timescale.

The semi-permanent lake, the Laguna de Medina, Cádiz, Andalucía is selected as the study site. The preservation of diatoms and other organic remains is very good compared to other sites, and there is no obvious evidence for major human impact. In contrast to other lakes the stratigraphy is more variable and organic-rich at depth rather than towards the surface, which indicates the potential for a palaeoenvironmental study on a Holocene timescale. Its hydrology is discussed in Chapter 2, where it is noted that current evidence appears to suggest the lake is less influenced by groundwater flow than other semi-permanent or permanent lakes in Andalucía and, by inference, it is more sensitive to climate change.

5.4 PRESERVATION STUDY III: FACTORS AFFECTING DIATOM PRESERVATION

5.4.1 Introduction

In the first two Preservation Studies, a data-set was built up of recent and Holocene sediment cores from lakes throughout Spain, for which modern limnological data on water chemistry, water depth, permanence and other environmental variables were also collected. Preservation Study III is a study of factors affecting diatom preservation in the recent sedimentary environment of Spanish salt lakes, which was made in order to establish whether easily-measured environmental parameters can be used to predict the quality of diatom preservation in different types of salt lake.

The study involves an assessment of preservation in modern, surface samples and recent, sub-surface samples from short cores (<50cm depth) collected from a range of lakes. The predictability of preservation on a longer timescale based on modern lake characteristics is assessed by comparison with diatom preservation in longer, Holocene sequences.

5.4.2 Preservation of modern diatom assemblages in surface-sediment samples

The sediment core data-set comprises 65 surface cores from 60 lakes, which were either full, had a negligible water depth (groundwater levels at the surface) or were dry when sampled. A summary of diatom preservation in surface sediments according to lake permanence and salinity for 59 lakes (minus

AHDA1, missing surface data) is given in Table 5.2. Where two samples were collected at different times from a lake, and preservation differed between samples, the higher preservation class has been used to characterise the lakes.

Diatoms are fully-preserved or fragmented and countable, but not significantly dissolved, in at least one of the surface sediment samples collected at different times from 44 out of the 59 lakes. These comprise the majority of samples regardless of permanence or salinity, and include samples from the soft sediment of lakes close to desiccation but not completely dry [BDCE, CBLL, CZRR and EDEH].

12 of the 15 samples without surface diatoms are from saline, ephemeral lakes, eight of which were dry when sampled. Diatoms are also absent in 2 of the other 3 sites: a semi-permanent, hypersaline lake, the Laguna de la Salineta [HLDS] and a low-salinity ephemeral lake, the Laguna de Fuentillejo [EFTL]. Finally, they are sparse and highly fragmented (uncountable) rather than dissolved in the oligosaline and ephemeral, but formerly permanent, lake, the Laguna Dulce, Lucena [ADLC].

Preservation differs between samples in five lakes which were sampled more than once in different seasons. It was higher either when lakes had been sampled wet rather than dry [BSDA, BRTS, DMDN], or in shallow (0.5cm) surface sediment samples compared to deeper 'handful' (c. 4cm) samples from Durham University archive [BSDA, EDEH].

5.4.3 Preservation of recent fossil diatom assemblages in short cores

A summary of diatom preservation in the recent sediments of the 60-lake data-set is given in Table 5.3. Preservation is assessed at the base of short cores (<50cm depth), or within the upper 20cm for long-core samples.

In respect to ephemeral lakes, diatoms are absent in all but two samples, regardless of salinity. They are fragmented rather than dissolved in the artificially-desiccated Laguna Dulce, Lucena (ADLC) sample, and very rare and dissolved in the Laguna de Alcahozo (EACH) sample, an ephemeral eusaline lake with algal mats preserved below the surface.

In respect to semi-permanent lakes, diatoms are also absent in samples from 8 out of the 9 high-salinity lakes, five of which are those where summertime groundwater levels are maintained at the surface due only to the formation of a salt crust. In the ninth lake, the hypersaline Laguna de Gallocanta, diatoms are fragmented rather than dissolved, but preserved in the top 4cm only.

In semi-permanent lakes of lower salinity, diatom preservation is variable. They are absent in La

Table 5.2 **Preservation Study III: summary of diatom preservation in surface sediments of 59 lakes according to lake permanence and salinity.**

MODERN DIATOM PRES'N	PERMANENT		SEMI-PERMANENT		EPHEMERAL	
	<15 mS cm^{-1}	>15 mS cm^{-1}	<15 mS cm^{-1}	>15 mS cm^{-1}	<15 mS cm^{-1}	>15 mS cm^{-1}
VA / A_{frag}	9	1	8	8	5	13
A_{diss} / O / R					1	
Nil				1	1	12

KEY: VA = Very abundant (full preservation), A_{frag} = Abundant (fragmented but countable), A_{diss}= Abundant (dissolved, countable), O = occasional, R = Rare.

Table 5.3 **Preservation Study III: summary of diatom preservation in recent sediments of 60 lakes (at <50cm core depth) according to lake permanence and salinity.**

CORE DIATOM PRES'N	PERMANENT		SEMI-PERMANENT		EPHEMERAL	
	<15 mS cm^{-1}	>15 mS cm^{-1}	<15 mS cm^{-1}	>15 mS cm^{-1}	<15 mS cm^{-1}	>15 mS cm^{-1}
VA / A_{frag}	8					
A_{diss} / O / R	1	1	7	1	1	1
Nil			1	8	6	25

KEY: VA = Very abundant (full preservation), A_{frag} = Abundant (fragmented but countable), A_{diss}= Abundant (dissolved, countable), O = occasional, R = Rare.

Ontalafía [GONT] sample, rare in the Laguna Dulce, Málaga [BDCE] sample, and sparse and fragmented near the surface and rare or absent below in samples from two other lakes, the Lagunas de Alcaparrosa [CALC] and del Taraje [CTRJ]. In the Lagunas Hondilla [DHND] and de Medina [DMDN] samples they are preserved as dissolved assemblages to <20cm depth. In the Lagunas de Arjona [CARJ] and Dulce, Espera [DDUL] they are dissolved but countable at 20cm depth. In a core collected from the dry lake-bed of the Laguna de Medina in the drought of Summer, 1993, a 10cm diatom record preserved in the sediments of the 1992 core had disappeared.

In respect to permanent lakes, diatoms are fully-preserved within the upper 20cm sediment of 8 out of 9 low-salinity lakes. They are dissolved at 20cm depth in samples from two other permanent lakes of high and low salinity respectively [HSAL and AAMA].

5.4.4 Summary of the relationship between diatom preservation and lake type using PCA and box-and-whisker plots

5.4.4.1 Introduction

The aim of this study is to establish how far easily-measured environmental variables can be used to predict whether a diatom record will be preserved in the sediments of different types of salt lake. The range of variables measurable rapidly in the field comprise water depth, conductivity, turbidity and pH, together with lake permanence.

In Chapter 4, principal components analysis ('PCA') was used to explore the major environmental gradients in the larger training set of 74 sites used for the transfer function. The above variables represent, or are highly-correlated with, the most important gradients.

Of the 60 lakes from which sediment cores were collected, 47 include water chemistry data. Chemistry data are missing for three sites wet when sampled, the Laguna Honda, Jáen [AHDA], the Laguna de Gallocanta [HGAL] and the Laguna Guallar [HGUA]. All the others are ephemeral lakes which were dry when sampled. None of the 13 sites without water chemistry data contains a sedimentary diatom record other than the 4cm of fragmented diatoms in the semi-permanent, hypersaline HGAL.

PCA was performed on an environmental data-set of 47 sites (one set of measurements from each lake), using the variables water depth, conductivity, turbidity, pH and lake permanence (permanent, semi-permanent and ephemeral), which were transformed as in Chapter 4 (Section 4.2.3). Diatom preservation in the recent sediments of the 47 sites is summarised in 3 categories: 1 = nil preservation, 2 = all dissolved classes, 3 = full preservation, and the sites were classified accordingly. Preservation differed between repeat samples in the Laguna de Medina, for which the better-preserved record was included.

5.4.4.2 Results

The results of PCA are shown in Figure 5.12, with sites coded according to diatom preservation.

The three preservation groups are separated along an axis from the top left to bottom right of the diagram. This represents an environmental gradient from shallow, ephemeral, hypersaline lakes without diatoms to deep, permanent freshwater lakes with full preservation, and indicates the importance of lake permanence, water depth and conductivity on diatom preservation. The additional influence of turbidity is indicated by the lack of diatoms in the most turbid sites.

The three groups of sites are relatively well-separated. The group with full diatom preservation is completely separated from the large group of sites in which fossil diatoms are not preserved in the recent sediments. Virtually all ephemeral lakes and all hypersaline, semi-permanent lakes in which summer desiccation is prevented only by formation of a salt crust fall into the latter group. With the exception of the ephemeral Laguna de Alcahozo [EACH], sites with partial preservation do not overlap the distribution of sites without diatoms, but there is overlap between sites with partial and full preservation, which reflects the variable preservation in the more saline semi-permanent and permanent lakes which was detailed above.

Although the three groups are relatively well-separated, it is not possible from the limnological characteristics of the component lakes to define absolute thresholds of water depth or salinity as predictors of diatom preservation. Diatoms are relatively well preserved in lakes as shallow as 0.6m deep (CARJ) and in lakes as saline as the hypersaline lake, HSAL.

Since pH is not an important variable in the PCA, its influence on preservation is assessed separately by means of a box-and-whisker plot which summarises the distribution of water pH across the three sets of sites classed according to diatom preservation (Figure 5.13). The total range of the box and whiskers represents the inter-quartile range, while the box represents 50% of the inter-quartile range (25% on either side of the median, the line dissecting each box).

From the relative position overall of the box-and-whisker plots, preservation tends to be poorer in sites of high pH. The boxes show a high degree of overlap, however, and the positions of the medians are close (pH of 8.0 - 8.5), which indicates that pH is unlikely to be a very important influence on diatom preservation in this data-set.

Figure 5.12 Sample biplot of Axis 2 against Axis 1 for PCA of 47 samples and 7 environmental variables, classed according to quality of diatom preservation. [• = diatoms absent, ♦ = dissolved, ▲ = full preservation.]

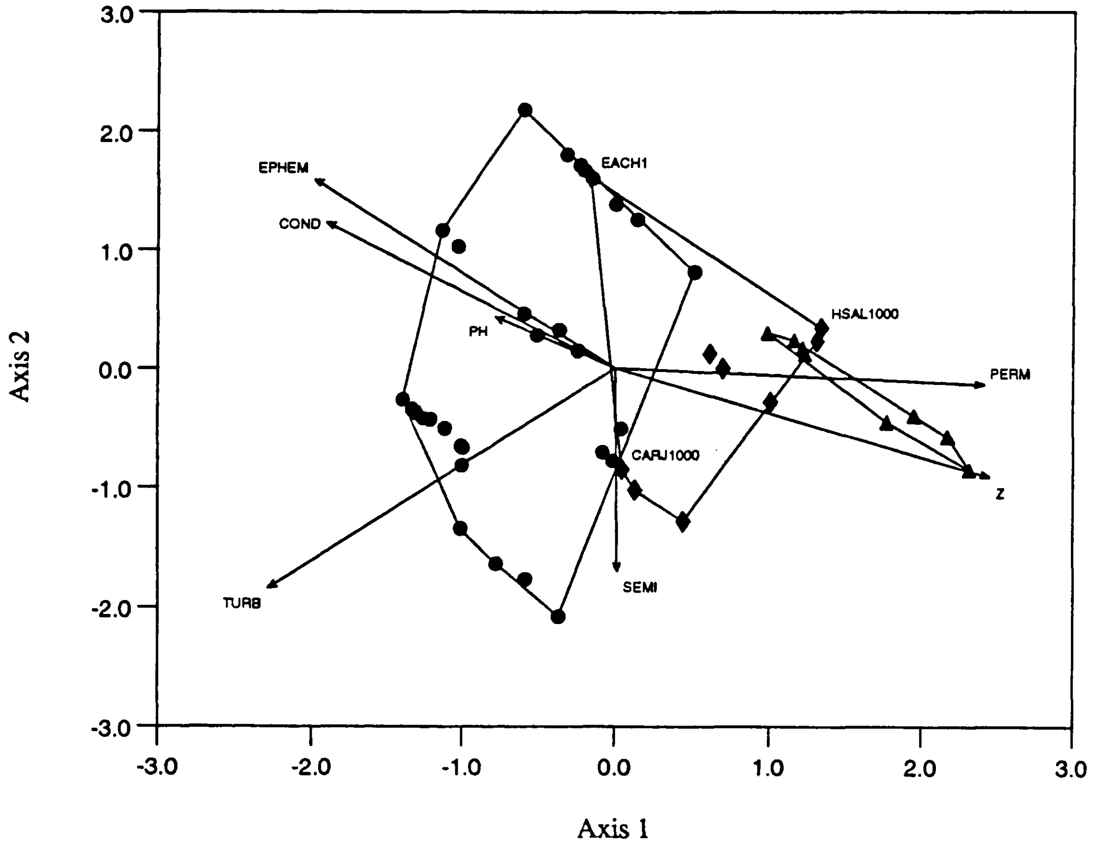
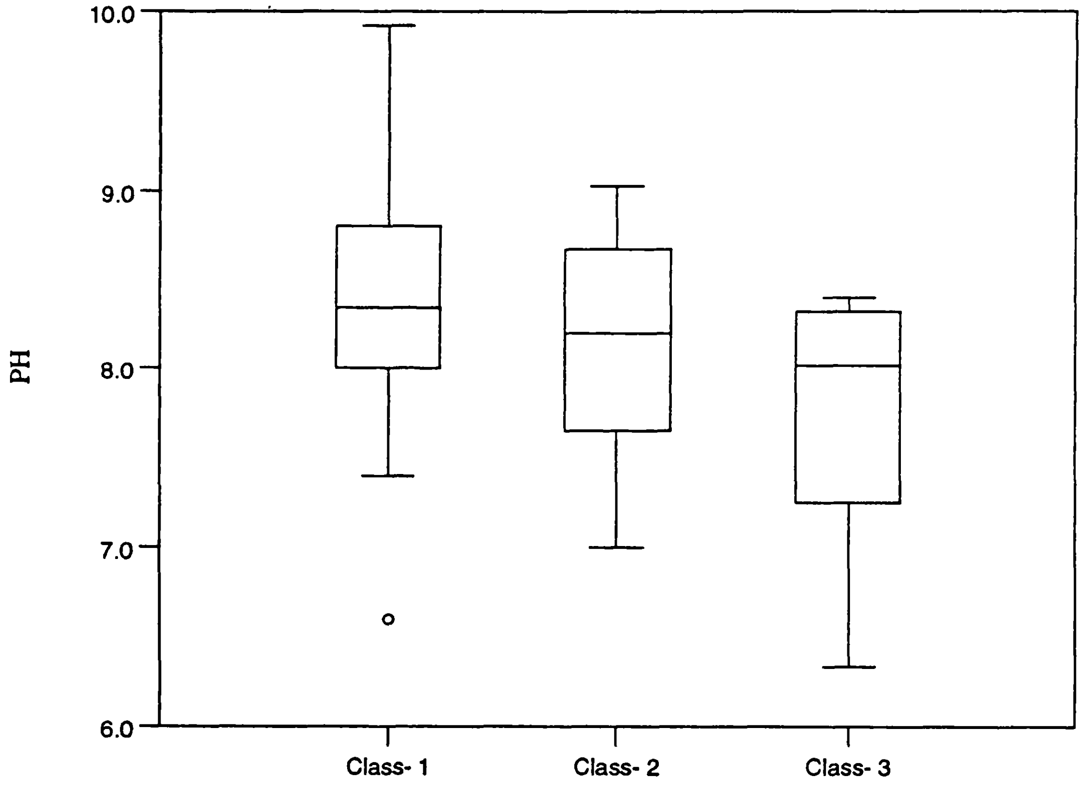


Figure 5.13 Box-and-whisker plot of sample pH for 47 samples classed according to quality of diatom preservation. [Class 1 = diatoms absent, Class 2 = dissolved, Class 3 = full preservation.]



5.4.5 Preservation of Holocene fossil diatom assemblages in long cores

A data-set of 20 long cores was collected during Preservation Studies IA and II. A comparison of diatom preservation in the recent and Holocene sediments of these lakes is given in Table 5.4.

Most of the currently permanent and semi-permanent lakes with recent diatom records preserved do not contain long, Holocene diatom records. Apart from the Laguna Grande, Archidona [BGDE], their current permanence can be related in all cases to artificial water input or other effects of human impact in the more recent past. Thus, the value of modern limnological conditions as indicators of past diatom preservation is limited since many lakes may have been completely different in the earlier Holocene; the Laguna Dulce, Lucena [ADLC] and Laguna de Medina [DMDN] are the only lakes for which preservation would be predicted successfully on the basis of lake permanence.

Most of the currently ephemeral lakes have never preserved a record. Although it is over simplistic to assume that this is a result of the consistently ephemeral status of these lakes, it confirms the low potential of ephemeral Spanish salt lakes for diatom preservation. Either changes in lake status have been insufficient to cross a threshold above which diatoms would be preserved, or other mechanisms have affected preservation.

Two lakes, DMDN and the Laguna de los Tollos [DTLL] preserve better records at depth. In both cases this can be related again to human impact, that is, to the adverse effects of drainage on lake levels (possibly coupled with processes of basin infilling) in the more recent past.

5.4.6 Discussion

The high quality of diatom preservation in surface sediments indicates diatom silica dissolution within the lake waters, prior to deposition, is not sufficiently important so as destroy the diatom record. Some countable assemblages were very fragmented, which would increase their tendency towards post-depositional dissolution, but none was significantly dissolved.

In contrast, the absence or poor preservation of surface sediment diatom assemblages in dry lake-beds indicates that post-depositional taphonomic processes operate very rapidly. From field observations (samples DTLL2 and DMDN2, Summer 1993), surface diatoms are preserved in dry lakes only when the remains of macrophytes or algal mats are still preserved as a thin, brittle surface layer. The significance of ephemerality may be related in part to wind deflation, which is common in ephemeral lakes and which can remove both organic matter and surface sediment (Pueyo Mur, 1978). The absence of diatoms in surface sediment samples from five very different, wet, ephemeral lakes which lacked

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Table 5.4 Comparison of diatom preservation in recent and Holocene sediments of 20 lakes. (Pres'n = diatom preservation; cores with diatoms preserved are highlighted by shading.)

SITE	PERMANENCE	RECENT PRES'N	HOLOCENE PRES'N	RECENT HUMAN IMPACT
AAMA	permanent	NO	NO	YES
BGDE	permanent	YES	NO	?
ECHC	permanent	YES	NO	YES
HCHI	permanent	YES	NO	YES
HEST	permanent	YES	NO	YES
HSAL	permanent	YES	NO	YES
CALC	semi-perm	±NO	NO	YES
CTRJ	semi-perm	NO	NO	YES
DDUL	semi-perm	YES	YES	?
DMDN	semi-perm	±NO	YES	YES
HGAL	semi-perm	±NO	NO	NO
HLDS	semi-perm	NO	NO	NO
ASBL	ephemeral	NO	±NO	YES
CZRR	ephemeral	NO	±NO	NO
DTLL	ephemeral	NO	YES	YES
EFTL	ephemeral	NO	NO	NO
HGUA	ephemeral	NO	NO	NO
HPEQ	ephemeral	NO	NO	NO
HPIT	ephemeral	NO	NO	NO
HZAI	ephemeral	NO	NO	NO

diatoms [EPNH, ETRZ, ECPC, EFTL, IFAF] indicates that a complexity of factors such as hypersalinity can prevent the development of diatom communities.

From the PCA, the correlated variables, lake permanence, water depth and salinity are important factors affecting preservation in the recent sedimentary environment. With the exception of 3 unusual lakes [ADLC, BDCE, EACH], sedimentary diatoms are not preserved in shallow (<1m deep), ephemeral lakes regardless of salinity, which indicates clearly that physical or chemical processes accompanying lake desiccation (such as groundwater movement, salt crystallisation or wind erosion) are particularly important in leading to diatom dissolution. The additional influence of salinity is suggested by the lack of diatoms in the sediments of hypersaline, semi-permanent lakes which do not dry out completely.

Diatoms are more likely to be preserved in the sediments of semi-permanent or permanent lakes, and showed a tendency towards better preservation in deeper, less saline lakes. The 'semi-permanent' lake category incorporates a continuum of sites with a varying tendency towards desiccation, and the influence of water depth probably relates to the greater frequency of desiccation (and poorer preservation) in shallower lakes.

Whilst this is a useful guideline for studies of recent environmental change, the unpredictability of diatom preservation within the semi-permanent group of lakes is indicated by the lack of well-defined preservation thresholds and by the overlap in the PCA between sites with partial and full preservation. There is further unpredictability incorporated into the variability of preservation within the 'partial' preservation category, which encompasses a continuum from rare fragments preserved, to countable assemblages. Better preservation would be predicted in the deep, semi-permanent, low-salinity lakes La Ontalafia [GONT] and the Laguna del Taraje [CTRJ], for example, and in the deep permanent mesosaline lake, Laguna Amarga [AAMA], and worse preservation in the shallow, semi-permanent Laguna de Arjona [CARJ].

Many factors have been postulated as contributing to the loss of the diatom record in saline lakes. In addition to water salinity and permanence, these include brine composition, temperature, pH, exposure, turbidity, sediment accumulation rate, texture and organic content, and diagenetic processes related to groundwater movement or the interstitial dissolution of silica (Flower, 1993), which tend to increase the tendency for diatom breakage and/or dissolution. Permanence, water depth and conductivity are probably indirectly related to many of these variables, and the results also confirm the complexity of the processes involved, such that the range of measured variables does not encompass the variation according to all the significant processes involved.

It is unlikely that an extended analysis of additional variables such as organic content and brine composition would produce definitive results. The data-set of semi-permanent and permanent lakes in Spain is very small and, compared to other salt lake regions, the range of lakes is restricted particularly in regard to the rarity of large, deep, saline lakes and carbonate-dominated saline lakes. Of the few permanent and semi-permanent lakes, most are subject to artificial water input and sedimentation processes may differ from those in natural lakes.

From the foregoing, the strongest predictor of diatom preservation is lake permanence. The comparison of preservation in recent and Holocene sediments confirmed the low potential of ephemeral Spanish salt lakes for diatom analysis over the longer term in spite of the possibility of wetter conditions having existed in the past. In respect to semi-permanent and permanent lakes in which some diatom record is currently preserved, recent human impact has been extensive in Spain and their preservation in recent sediments (or their absence in artificially-desiccated systems) cannot be used as a predictor for preservation over the longer term.

CHAPTER SIX

THE LAGUNA DE MEDINA I: LITHOSTRATIGRAPHY AND DIATOM ANALYSIS

6.1 INTRODUCTION

This chapter is concerned with the analyis of the fossil diatom sequence of the study site selected in Chapter 5, the Laguna de Medina, Cádiz, Andalucía. Descriptions of the lake and the geology and geography of its catchment are given in Chapter 2.

To assess fully the potential of diatoms for palaeosalinity and lake-level reconstruction, inferences from the diatom stratigraphic record are made independently of other complementary techniques in the first instance. The construction of a single 'master' sediment core sequence and the core lithostratigraphy are also described here to provide an analytical context, but palaeoenvironmental interpretation of the lithological record is reserved for Chapter 7 which deals with all other analytical techniques.

In respect to palaeosalinity change, the salinity transfer function derived in Chapter 4 is applied to the fossil diatom sequence, and the potential for reliable quantitative palaeosalinity reconstruction is explored. Qualitative palaeosalinity interpretation is also made from species preferences established in the Spanish training set and from those reported in the literature of other regions.

An independent reconstruction of lake-level change is made based on changes in the ratio of benthic (and aerophilous) to planktonic diatoms, the criteria for which were established in Chapter 4.

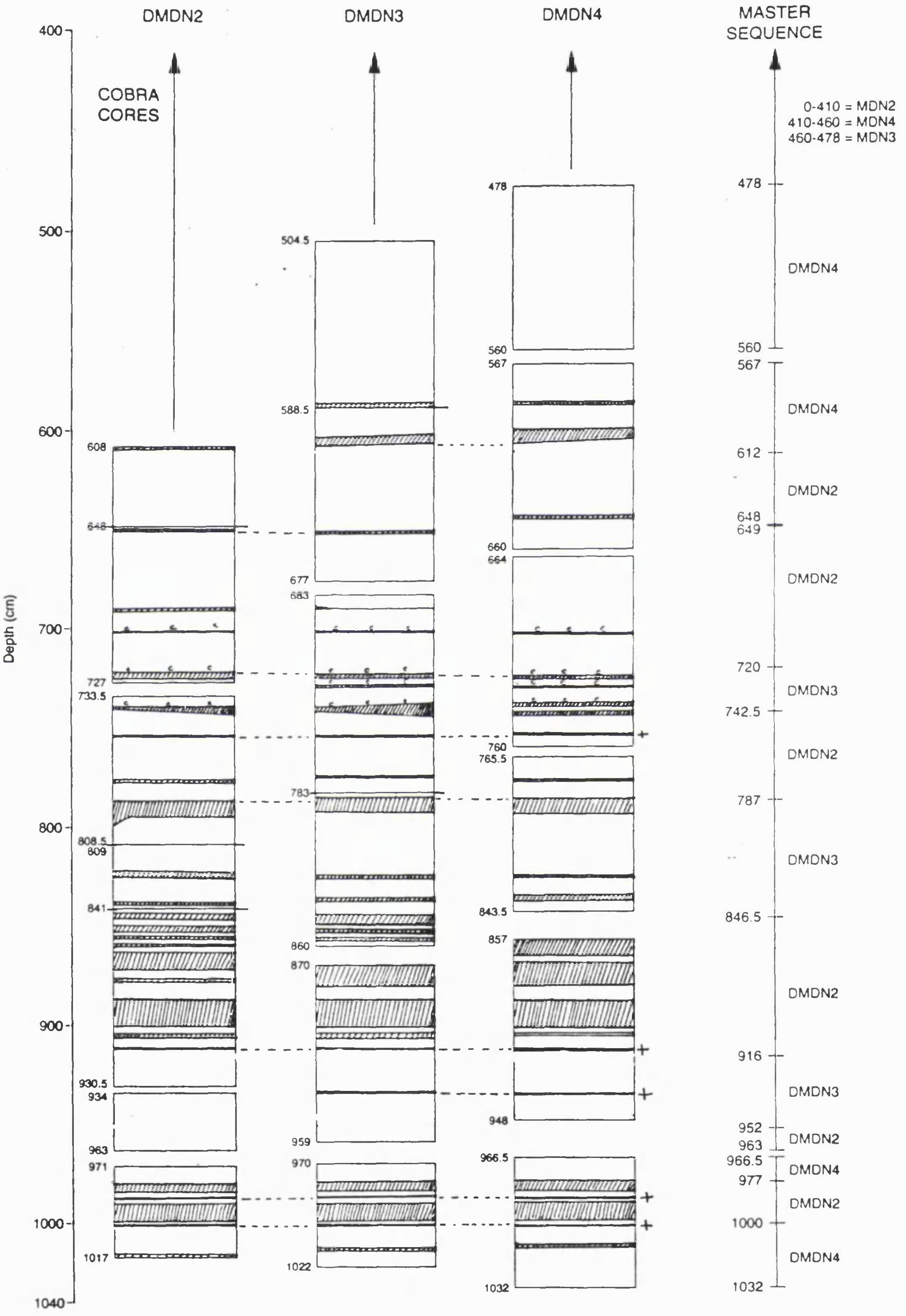
At all stages of the analysis there is an emphasis on the extent and implications of diatom dissolution on the reliability of the fossil diatom record for palaeoenvironmental reconstruction.

6.2 CORRELATION OF THE MASTER CORE

The three parallel cores from which a single master sequence is constructed comprise Cobra core sections for harder sediment from the surface to c. 480cm sediment depth, and Livingstone core sections for the remainder of the sequence to 1033cm depth, where softer sediments alternate with bands of gypsum.

The core sections used for the master sequence are indicated to the right of Figure 6.1, which shows

Figure 6.1 Diagram showing correlation of Livingstone core sections from three closely-spaced boreholes to form a single 'master sequence' for the Laguna de Medina.



KEY: core sections from 3 boreholes, DMDN2, DMDN3 & DMDN4 indicated by boxes; master sequence built from different core sections as indicated to right of the diagram (depth in cm)

——— + 'marker lamina'

C *Cerastoderma glaucum*

-------- main points of correlation

▨ gypsum band

the close correlation for the lower part of the sequence, 1033-478cm depth, between Livingstone core sections from the three adjacent boreholes, DMDN2, DMDN3 and DMDN4. The identification of major stratigraphic boundaries is based on the presence of gypsum bands, well-defined levels with abundant shells of the bivalve, *Cerastoderma glaucum* and distinct 'marker laminae'; the latter are <2cm thick and are distinguished by high abundance of charcoal (1001-999cm) or juvenile gastropods, *Hydrobia* (986-985cm), or by colour (pale yellow at 934-932cm, white with abundant *Hydrobia* at 913-911cm and olive green at 753-752cm).

The upper 478cm is homogeneous and lacks major lithostratigraphic boundaries. Sections from a single borehole, DMDN2 (which had the most complete recovery in this part of the sequence) are used for 410-0cm depth. In the DMDN2 sequence a short Livingstone core had then been collected, before reverting to the use of the Cobra corer. The DMDN4 Cobra core sequence is used instead for 478-410cm depth to provide a more continuous sequence, and to correlate definitely with the first master Livingstone core, which is from the same borehole. A small section from DMDN3 covers a gap from 478-460cm depth.

Correlation over depth range 612-410cm is supported by the location of ostracod species shifts in parallel subsamples screened from DMDN2 and DMDN4/DMDN3, although closer interval subsampling would be necessary to correlate to the nearest centimetre in this part of the sequence.

6.3 LITHOSTRATIGRAPHIC DESCRIPTION

The lithostratigraphy of the master sequence from 1033-478cm depth is depicted in Figure 6.1 above. The sediment sequence above 478cm depth is homogeneous and varies mainly in colour.

As an adjunct to the lithostratigraphic description, transitions surrounding gypsum bands are very sharp and many gypsum bands overlie thin layers of olive gray organic silty clay. Phases of massive lenticular gypsum are less well-defined; gypsum crystals are abundant, but are not bedded in definite bands. Lenticular gypsum dominates the sequence. Clear, prismatic crystals are restricted to samples from the core base to 504cm depth, where they occur at <25% abundance of the sieved fraction in many samples. Sand grains and tufa (formed on *Chara* stems) occur sporadically in most units, and consistently in samples above 408cm depth. Six major lithostratigraphic units are recognised.

Unit L1: 1033-946cm

1033-999cm

Matrix of compact, variable light gray 5Y 7/1, gray 5Y 5/1 and 6/1 bands of silty clay with abundant massive white lenticular gypsum. Thin gypsum band at 1011cm. Increase in marl content towards top of the sequence, which ends in a charcoal-rich black lamina. Very sharp transition to:

999-977cm

Two broad bands of gypsum, fining upwards in the lower band and downwards in the upper band, separated by bands of gray 5Y 5/1 or light gray 5Y 7/1 bands of silty clay. Lamina of abundant juvenile gastropods, *Hydrobia* sp., at 986-985cm. Very sharp transition to:

977-946cm

Matrix as 1033-999cm. Sharp transition to:

Unit L2: 946-916cm

Compact, marl-rich gray 5Y 6/1 silty clay with abundant charcoal and root/wood fragments up to 2 x 0.5cm dimensions. White carbonate flecks. Pale yellow 5Y 7/3 lamina at 934-932cm. Sharp transition to:

Unit L3: 916-786cm

916-830cm

Multiple gypsum bands with maximum crystal size of c. 1cm at 866cm with intervening matrix of compact, gray 5Y 5/1 and olive gray 5Y 5/2 silty clay. Fe at 840cm, vivianite at 848cm and white lamina at 913-911cm. Sharp transition to:

830-803cm

Bands of compact gray 5Y 5/1 and 6/1, and light gray 5Y 7/1 silty clay. Sharp transition to:

803-786cm

Matrix of compact, olive 5Y 5/3 silty clay with increasing content of massive lenticular gypsum and higher compaction to the top of the sequence, a gypsum band. Very sharp transition to:

Unit L4: 786-703cm

Major change in colour and texture. Band of dark gray 5Y 4/1 silty clay at base; bands of soft, olive gray 5Y 5/2 and 4/2 silty clay above with frequency of thin gypsum bands increasing towards top of sequence. Abundant shells of the bivalve, *Cerastoderma glaucum* above gypsum bands between 738-703cm. Sharp transition to:

Unit L5: 703-c.512cm

Compact olive gray 5Y 4/2 silty clay mottled with lighter olive-gray 5Y 5/2, dark gray 5Y 4/1 and very dark gray 5Y 3/1, with variable white carbonate flecks. Diagonal gypsum bands 608-600cm overlying olive 5Y 4/4 silty clay. Increase in lenticular gypsum above 600cm with thin gypsum bands at 642-641cm and 587-588cm. Gradual transition, which corresponds to change in sediment texture in sieved subsamples from buff cohesive silty clay pellets to low organic, gray silty clays to:

Unit L6: c. 512-0cm

Sediment compact at base, softer at c. 340-300cm, very compact in upper 300cm, and friable, dry in upper 10cm. Variable, gray 5Y 5/1 silty clay matrix mottled with, or with occasional bands of, olive gray 5Y 5/2 and 5Y 4/2 silty clay. Variable lenticular gypsum, flecks of white carbonate and yellow brown Fe, and patches of reduced organics. No sharp transitions.

6.4 DIATOM STRATIGRAPHY

The diatom stratigraphy is presented in Figure 6.2, expressed as percentage counts for taxa occurring at >2% abundance in more than one sample, or at >20% abundance in a single sample, for samples which were countable. The proportion of relatively well-preserved valves in each assemblage (the counting criteria for which were described in Chapter 3) is shown to the right of the diagram.

Diatom preservation is poor. Many assemblages, above 700 cm depth in particular, were countable only to 100 valves. The presence of valve fragments in very low concentrations, mainly of *Campylodiscus clypeus*, is indicated for uncountable levels without any well-preserved valves. Diatoms are not preserved in other levels of the 4cm-resolution sequence.

Of the countable assemblages, many are dominated by robust, heavily-silicified taxa which are least prone to dissolution (Fritz & Battarbee, 1986). Rather than the traditional methods of ordering taxa by salinity preferences, or simply by their order of appearance, the 7 dominant taxa are presented to the left of the diagram in their order of occurrence from the base of the core upwards, and less common taxa by their order of occurrence thereafter.

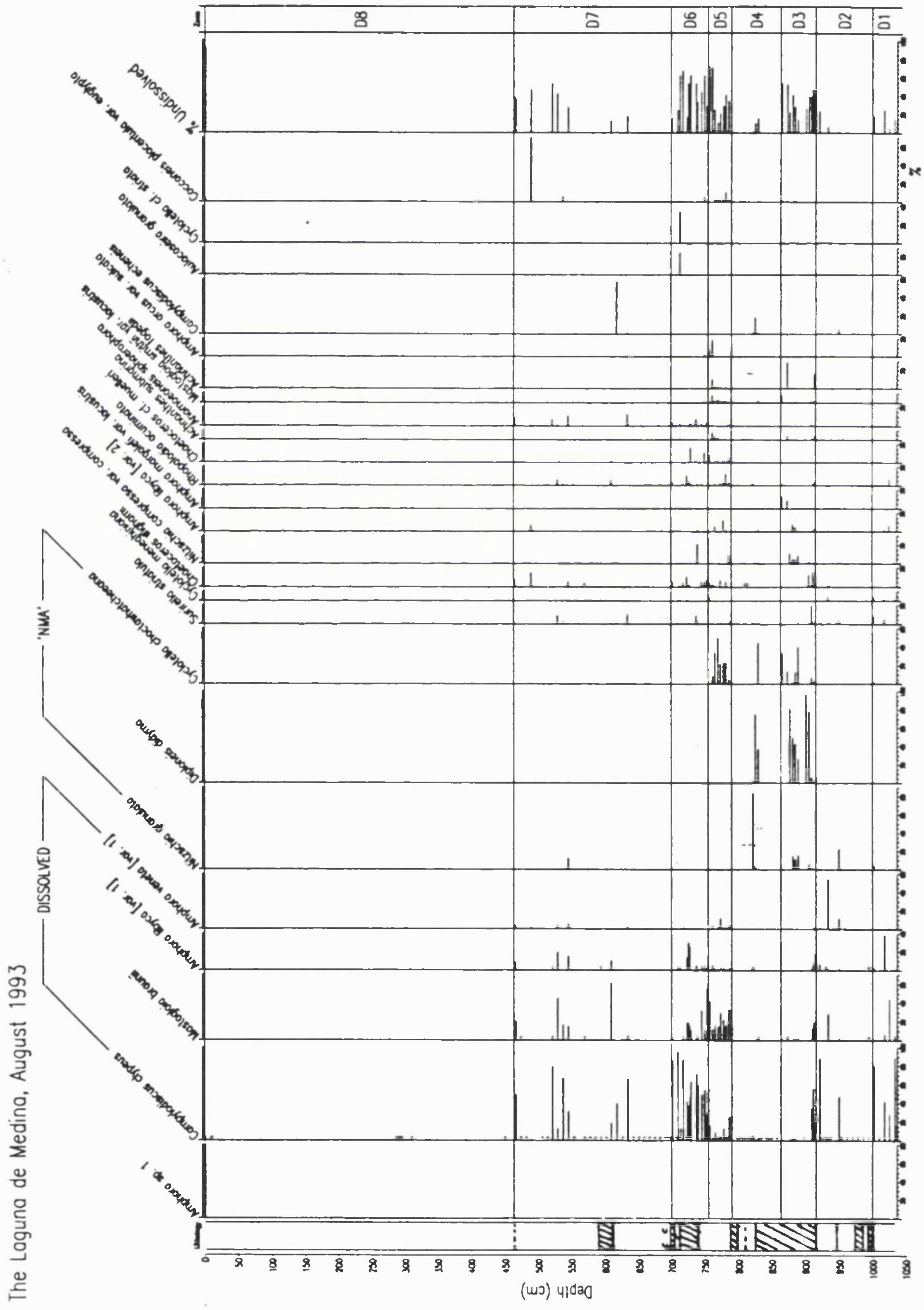
The clustering technique, constrained incremental sum of squares ('CONISS', Grimm, 1987), was applied to the data to distinguish stratigraphic units of similar diatom assemblage composition. The clusters produced were driven by gaps in the record, however, and did not clearly distinguish subtle changes in less abundant, more fragile diatom species. Since these may be ecologically significant, the diatom sequence was divided instead by observed changes in the total diatom flora. 8 biostratigraphic zones are recognised, which correspond also to changes in the state of diatom preservation and to lithostratigraphic units, as follows.

Zone D1: 1033-1000cm

(Lower part of lithostratigraphic Unit L1)

Poorly-preserved diatom assemblages of Zone D1 are of low diversity and dominated by the benthic diatoms, Campylodiscus

Figure 6.2 **The Laguna de Medina: diatom percentage diagram (for taxa occurring at >2% in >1 sample, or at >20% abundance in 1 sample), showing simple dissolution index for countable samples. ['NMA' = No Modern Analogue taxa; presence of diatoms in uncountable samples denoted by '+'.]**



Simplified lithology. **Shading = gypsum bands or phases of multiple banding.** C = *Cerastoderma glaucum* bands
----- = sharp transition, ——— = very sharp transition. Changes of colour and texture described in the text.

clypeus and Mastogloia braunii, with the occurrence in some levels of the planktonic taxon, Cyclotella meneghiniana, at <5%. This corresponds to light gray silty clays, with abundant massive lenticular gypsum, at the base of Unit L1.

Zone D2: 1000-916cm

(Upper part of lithostratigraphic Unit L1, and Unit L2)

Most of Zone D2 has only rare fragments of *C. clypeus*, with countable *C. clypeus/M. braunii* assemblages corresponding to better preservation at 946cm and above 920cm. The pale yellow lamina at 934-932cm contains a different, relatively well-preserved assemblage dominated by the robust *Amphora veneta* var. 1, other benthic diatoms, and the planktonic *Cyclotella meneghiniana* at <5%.

Diatoms are rare in the gypsum bands and upper, light gray silty clay of Unit L1, and in most of the charcoal-rich marly clay of Unit L2. Preservation is improved in the gradual transition to olive gray silty clays at the start of Unit L3.

Zone D3: 916-864cm

(Lower part of lithostratigraphic Unit L3))

Diatoms are relatively well-preserved in Zone D3 and species assemblage composition fluctuates through the sequence. Basal samples in the white lamina at 913-911cm are relatively diverse and, in addition to *Campylodiscus clypeus* and *M. braunii*, they include other benthic taxa such as *Surirella striatula*, *Achnanthes fogedii* and *A. submarina*, and the planktonic taxa *Chaetoceros wighami* and *Cyclotella choctawhatcheeana*, and low frequencies of the aerophilous *Navicula granulata* and *Diploneis didyma*. There is a shift at 900cm to 96% dominance by dissolved valves of *D. didyma*, followed by a minor gap in the record. Assemblages above this level alternate between *D. didyma* and *C. choctawhatcheeana*, with increased frequency of the aerophilous *Nitzschia compressa* var. *compressa*, and benthic *Amphora libyca* var. 2. *D. didyma* disappears towards the top of the sequence, in which *C. choctawhatcheeana* dominates to >40%, with relatively high abundances of benthic diatoms such as *Amphora margalefi* var. *lacustris*, *A. arcus* var. *sulcata* and *Achnanthes fogedii*.

Changes in diatom preservation and species assemblage composition correspond to alternations in the lithostratigraphy of unit L3, between bands of gypsum and intervening silty clays. Diatom preservation is poor within gypsum bands and assemblages are dominated by aerophilous taxa. Planktonic taxa reach peak abundances within the silty clay, especially in organic layers immediately underlying the thinnest of the gypsum bands.

Zone D4: 864-786cm

(Upper part of lithostratigraphic Unit L3)

Diatoms are rare in Zone D4 (*Campylodiscus clypeus* fragments) apart from a peak at 830-820cm depth of the aerophilous taxa, *Diploneis didyma* and *Nitzschia granulata*, with a mixed planktonic assemblage at 824cm of *D. didyma*, *Cyclotella choctawhatcheeana* and *Campylodiscus echeneis*.

This zone correponds to the upper part of Unit L3, with higher compaction, increased lenticular gypsum, less gypsum bands and a change from gray/olive gray to light gray silty clays.

Zone D5: 786-756cm

(Lower part of lithostratigraphic Unit L4)

The dissolution index for Zone D5 is misleading; although it indicates a low proportion of well-preserved taxa, these include many more fragile taxa which are not preserved in other zones, and dissolution is least advanced.

A consistent trend in species assemblage composition occurs through the sequence. The basal sample is dominated by *Campylodiscus clypeus*, *Mastogloia braunii* and the aerophilous *Nitzschia compressa* var. *compressa*. *C. clypeus* has a relatively low abundance in the rest of the sequence, which is dominated to 764cm by *M. braunii* and the planktonic *Cyclotella choctawhatcheeana*, together with a range of benthic diatoms such as *Amphora libyca* var. 1, *A. libyca* var. 2, *Rhopalodia acuminata*, *M. smithii* var. *lacustris* and *Cocconeis placentula* var. *euglypta*, and the planktonic taxa, *Chaetoceros wighami* and *C.* cf. *muelleri*. A decline in *C. choctawhatcheeana* and *Chaetoceros* spp. towards the very top of the sequence is paralleled by an increase in the benthic taxa, *M. braunii*, *Achnanthes submarina*, *M. smithii* var. *lacustris*, *A. fogedii* and *Amphora arcus* var. *sulcata*, which reach peak abundances at the top of the sequence.

This zone corresponds to the soft, olive gray silty clays of Unit L4.

Zone D6: 756-700cm

(Upper part of lithostratigraphic unit L4)

The main differences between the diatom flora of zone D6 and D5 are the absence of *C. choctawhatcheeana*, the consistent presence of *Anomoeoneis sphaerophora* and the poorer state of preservation. Most assemblages are dominated by the robust taxa, *Campylodiscus clypeus*, *M. braunii*, *Amphora libyca* var. 1, *Rhopalodia acuminata* and *Amonoeoneis sphaerophora*, together with the planktonic *Chaetoceros wighami* and *C. muelleri*. A single assemblage at 712cm is dominated by planktonic taxa comprising *Cyclotella striata*, *Aulacoseira granulata*, and *Stephanodiscus hantzschii*.

This zone corresponds to the upper part of Unit L4, where *Cerastoderma glaucum* shells overlie narrow gypsum bands within a similar sediment matrix to Zone D5.

Zone D7: 700-464cm

(Lithostratigraphic Unit L5 and part of Unit L6)

Zone D7 mainly comprises fragments or countable '*Campylodiscus* assemblages' with low abundance of *Chaetoceros wighami* towards the top of the sequence. *C. echeneis* and *Cocconeis placentula* var. *euglypta* dominate two levels (at 618cm and 488cm depth respectively).

This corresponds to the mottled olive gray and gray silty clays, with rare gypsum bands, of Unit L5.

Zone D8: 464-0cm

(Lithostratigraphic Unit L6)

Diatoms are not preserved in this part of the sequence, apart from rare *Campylodiscus clypeus* around 300cm depth and an assemblage dominated by *Amphora* sp. 1 [cf. *acutiuscula*] in the film of dry aquatic vegetation at the sediment surface.

This corresponds to the very compact, homogeneous silty clays of the upper sequence.

6.5 CALIBRATION OF FOSSIL DIATOM ASSEMBLAGES USING THE MODERN DIATOM TRANSFER FUNCTION

6.5.1 Introduction

To enable quantitative palaeosalinity reconstruction, simple weighted-average calibration with inverse deshrinking regression (Birks *et al.*, 1990) was used to infer past salinity from fossil diatom assemblages of samples from the Laguna de Medina core in which diatoms were countable. The conductivity transfer function derived in Chapter 4 was used for calibration, which was based upon 70 modern diatom and water chemistry samples.

Palaeosalinity reconstruction is based on the relative abundances of the range of fossil diatoms in the core which are also present in the training set, and the accuracy of the reconstruction is reduced if the fossil diatom assemblage does not have a good modern analogue. Following previous work (Jones & Juggins, in press), the results were assessed by analogue matching techniques, using the program MAT (Juggins, unpublished program) to establish the strength of the relationship between fossil and modern assemblages. An analogue measure for each fossil assemblage was calculated, based upon the minimum Chi-squared distance dissimilarity coefficient between the assemblage and its closest matches in the training set. To interpret the results, the results were related to the degree of dissimilarity between samples in the modern training set. The second percentile of the distribution of the modern training set samples in a dissimilarity matrix was used as a cut-off point for a good modern analogue, and the twentieth for a poor analogue.

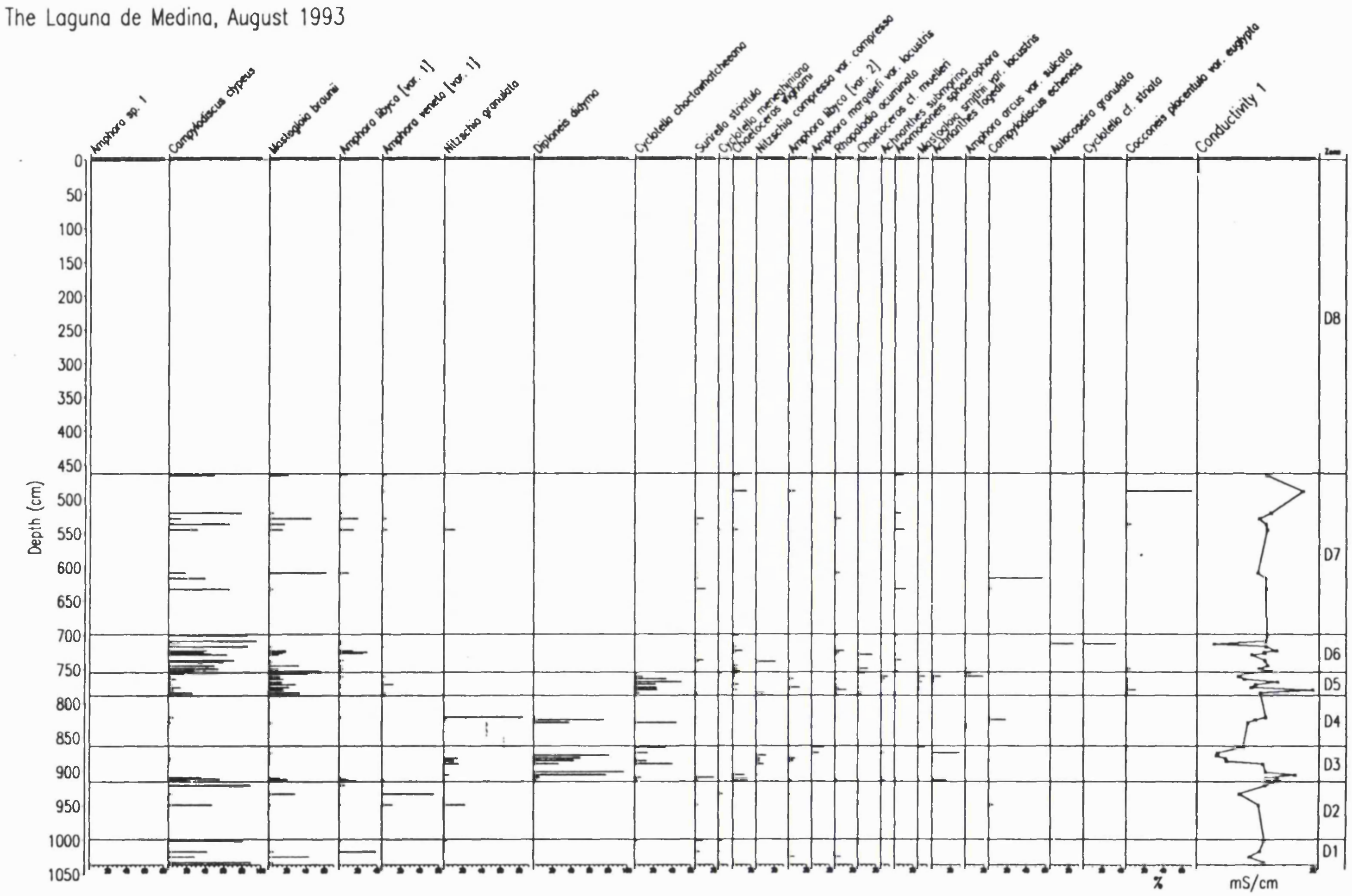
6.5.2 Results

6.5.2.1 Palaeosalinity reconstruction

Calibration results are given as $\log_{10}$ and back-transformed conductivity values in Appendix 8a. The diatom diagram is reproduced in Figure 6.3 with the reconstructed palaeosalinity curve displayed to the right, as 'Conductivity 1'. An extreme high reconstructed conductivity for the dry surface sediment sample, 78.7 mS cm^{-1}, is not plotted on the diagram. Symbols marked on the curve indicate levels for which salinity reconstruction was possible; diatoms were absent or uncountable in other samples taken every 4cm down the core.

The palaeosalinity curve for lower levels fluctuates within the range 2.9-18.1 mS cm^{-1}. Values are consistently low at the top of Zones D3 and D5, where diatoms are best-preserved and the planktonic component highest, and these zones also show the highest palaeosalinity fluctuations. Apart from

Figure 6.3 The Laguna de Medina: diatom percentage diagram showing estimated salinity for countable samples ('Conductivity 1').



individual high or low values, the curve shows little variation otherwise and values for the rest of the sequence tend to fall in the range 9-12 mS cm^{-1}, just above the oligosaline-mesosaline boundary.

6.5.2.2 Analogue matching

The fossil sequence has 70 diatom taxa, 46 of which are present in the training set. The percentiles of the matrix of dissimilarities for the modern training set are given below:

1st percentile	0.885
2nd percentile	**0.991**
5th percentile	1.112
10th percentile	1.187
20th percentile	**1.269**

The analogue measures for each of the fossil samples in different diatom zones are given in Table 6.1. Taking a cut-off point of 0.991, the second percentile, only one of the fossil diatom assemblages apart from the surface sediment sample has a good modern analogue. The assemblage from the pale yellow lamina at 934-932cm has a diverse assemblage dominated by *Amphora veneta* var. 1 and other diatoms which together are abundant and frequent in the modern training set (*Mastogloia braunii, Cyclotella meneghiniana, Chaetoceros wighami, Navicula pseudocrassirostris, Amphora libyca* vars. 1 and 2, and *Fragilaria pulchella*). None of the other assemblages has a good analogue even at the less rigorous cut-off level of the twentieth percentile, 1.269.

Abundance and diversity statistics for fossil and modern assemblages are given in Table 6.2, which lists the number of occurrences, Hill's N_2 diversity index and maximum abundance of the 8 most common fossil diatom taxa. From comparison of these statistics, the lack of modern analogues can be related to two distinct factors which are of varying importance in different parts of the core.

Firstly, the effects of dissolution are evident. Apart from their absence in diatom zone D8 and other parts of the core, the dominance in zones D1, D2, D6 and D7 of the robust species, *Campylodiscus clypeus* and *Mastogloia braunii* is the product of an artificial bias caused by dissolution. These species are common in the modern flora, but as a very minor component (<4%) of more diverse assemblages; other species with which they are commonly associated in fossil assemblages, *Amphora libyca* var. 1, *Surirella striatula* and *A. libyca* var. 2 also occur only at very low frequency in the modern flora.

As a corollary, this suggests a range of less robust taxa may have been lost completely. Some associated species, which are less robust and occur in assemblages with better preservation, are more

Table 6.1 **Analogue measures for reconstructed salinity of fossil samples, based on calibration using the modern diatom transfer function. (Samples given as mean sample depth in cm; minDC = minimum squared Chi-squared distance between fossil and modern samples.)**

SAMPLE	min DC	DIATOM ZONE
0-1	0.602	D7
465	1.279	
489	1.142	
521	1.327	
529	1.345	
537	1.288	
545	1.253	
609	1.371	
617	1.367	
633	1.288	
701	1.343	D6
709	1.365	
713	1.259	
717	1.352	
723	1.367	
725	1.367	
727	1.354	
729	1.239	
737	1.327	
739	1.349	
745	1.339	
749	1.285	
753	1.330	D5
757	1.213	
761	1.085	
765	1.304	
769	1.264	
773	1.262	
777	1.284	
781	1.225	
785	1.288	
787	1.081	
821	1.384	D4
825	1.401	
829	1.369	
865	1.255	
873	1.102	D3
877	1.400	
881	1.365	
885	1.362	
889	1.383	
901	1.410	
905	1.388	
909	1.331	
911	1.355	
912	1.187	
913	1.203	
921	1.349	D2
933	0.982	
949	1.280	
1001	1.361	D1
1017	1.360	
1025	1.334	
1033	1.365	

Table 6.2 **Comparison of abundance and diversity statistics between fossil and modern assemblages, for taxa abundant in the Laguna de Medina core, and summary of factors affecting interpretation.**

CODE	SPECIES	FOSSIL DATA			MODERN DATA			REASON FOR POOR ANALOGUE
		N	N2	MAX	N	N2	MAX	
CP001A	*Campylodiscus clypeus*	53	28.4	94.9	17	8.6	3.5	DISSOLUTION
MA004A	*Mastogloia braunii*	48	22.7	61.4	8	-	1.0	DISSOLUTION
AM9986	*Amphora libyca* var. 1	35	13.8	38.7	3	-	0.2	DISSOLUTION
NI022A	*Nitzschia granulata*	12	3.7	83.9	-	-	-	NMA
DP030A	*Diploneis didyma*	13	7.3	96.2	-	-	-	NMA
CY057A	*Cyclotella choctawhatcheeana*	21	11.2	50.1	-	-	-	NMA
SU008A	*Surirella striatula*	37	11.8	19.9	2	-	0.4	DISSOLUTION
CH082A	*Chaetoceros wighami*	25	15.6	15.9	5	2.4	1.9	DISSOLUTION

KEY N = no. of occurrences, N2 = Hill's diversity index (Hill, 1973), MAX = maximum % abundance, NMA = no 'ecological' modern analogue.

abundant in the modern data-set and may be under-represented in the core. *Navicula crucicula* var. *cruciculoides* [NA304A], for example, occurs in 11 fossil assemblages with a maximum abundance of 7.0% compared to 18 occurrences and a maximum of 36.3% in the modern data-set.

Secondly, the dominant species of zones D3, D4 and D5 in particular have no modern analogue at all in the modern data-set in spite, in some cases, of higher diatom preservation. This indicates their absence is due to ecological rather than taphonomic effects. The dominants comprise *Nitzschia granulata*, *Diploneis didyma*, *Cyclotella choctawhatcheeana*, *N. compressa* var. *compressa* and *Campylodiscus echeneis*. Other less abundant species in zones D3 and D5 such as *Achnanthes submarina* and *Diploneis smithii* var. *rhombica* also have no analogue. In addition, *D. didyma*, *N. granulata*, *N. compressa* var. *compressa* and *C. echeneis* are of a robustness similar to that of *Campylodiscus* and *Surirella* species, and are likely to be over-represented due to dissolution.

This indicates that quantitative palaeosalinity reconstruction using standard techniques is likely to be unreliable. Diatom dissolution has resulted in a poor match between fossil and modern assemblages in diatom zones D1, D2, D6 and D7, and a combination of a real 'ecological' lack of modern analogues and diatom dissolution for the poor match in zones D3, D4 and D5.

6.6 DERIVATION AND APPLICATION OF A MODIFIED 'MODERN + DISSOLVED MODERN ANALOGUE' TRANSFER FUNCTION

6.6.1 Introduction

In this section, a modified salinity transfer function is derived from a larger training set which incorporates additional, partially-dissolved diatom assemblages from the recent sediments of Spanish salt lakes. This is a departure from techniques applied in other studies. It is developed as an *ad hoc* means of improving the match between fossil and modern assemblages and increasing the accuracy of palaeosalinity reconstruction, for diatom studies where fossil assemblages are modified by dissolution.

In Chapter 5, Preservation Study III, sub-surface sediments of some salt lakes were shown to contain partially-dissolved diatom assemblages which were dominated by robust taxa. Assuming that the environmental conditions within which they were produced have not changed, that is, that there is no additional variation in the partially-dissolved diatom data due to a real difference in the original species composition of these samples relative to surface sediment samples or, by implication, to a change in water chemistry, it can be argued that the species assemblage composition of these samples represents that of the surface sediment assemblages subsequent to their partial dissolution. On the further assumption that the fossil assemblages of the Laguna de Medina have undergone similar taphonomic processes, the partially-dissolved assemblages are potential 'modern analogues' for fossil assemblages.

Similar assumptions underlie the derivation of a transfer function to quantify the relationship between dissolution of diatom silica and changes in diatom relative species abundance of samples from ocean sediments (Pichon *et al.*, 1992), although the research design in this case was based on laboratory experiments.

Partially-dissolved assemblages from recent Spanish salt lake sediments are referred to hereinafter as 'dissolved modern analogue', or '*DMA*' assemblages. In the following sections, the relationship between a data-set of *DMA* diatom assemblages and their corresponding surface sediment assemblages is explored in DCA and CCA ordinations. Their relationship to the fossil assemblages of the Laguna de Medina is explored in DCA ordination of a combined modern, *DMA* and fossil data-set, prior to derivation and application of a modified transfer function.

6.6.2 The 'dissolved modern analogue' ('*DMA*') data-set

To avoid the incorporation of samples from lakes where significant recent salinity change may have occurred, *DMA* assemblages are included only on the condition that observed changes in the flora down-core are related mainly to dissolution, that is, that no new dominant taxa are present other than the more robust taxa occurring at lower frequency in surface samples.

As described in Chapter 3 (Section 3.6.2.3) cores with diatoms preserved in the recent sedimentary environment were screened at a higher resolution following their initial identification in the Preservation Studies, in order to identify levels with suitable, partially-dissolved assemblages and to provide a reliable assessment of evidence for changes in species assemblage composition.

In long fossil diatom sequences with more gradual dissolution, such as BGDE1 and HSAL2, the selection was subjective and took into account the extreme nature of dissolution in the Laguna de Medina core. The sample was selected at the level where dissolution was sufficiently advanced for a major reduction in one or more species dominant at the surface to have occurred, rather than in levels above where the impact of dissolution was more subtle.

The total *DMA* data-set comprises assemblages from nine Spanish salt lakes, all of which are semi-permanent or permanent: AAMA, BGDE, CARJ, DDUL, DHND, DMDN, ECHC, HCHI and HSAL. Diatoms of other cores were either fully-preserved (e.g. ETRY, GLNG), showed a change in species composition (HEST) or, in short sequences, were more fragmented than dissolved prior to their total dissolution (e.g. BDCE, CALC, HGAL).

6.6.3 DCA and CCA of data-set of modern and *DMA* samples

Since some robust species are present at <1% in the modern training set, all species are included in the analyses apart from indeterminate categories. In other respects, DCA and CCA were performed as in Chapter 4, Section 4.3.2. Environmental data for *DMA* samples were taken as the duplicate of the corresponding modern sample.

An initial DCA (not reported) was performed on a data-set of 83 samples:- 74 modern and 9 *DMA*. As in the DCA of the original 74-sample training set in Chapter 4, the sample, ASBL2, was a major outlier which compressed the distribution of other samples and was omitted.

The sample plot of Axis 2 against Axis 1 is given in Figure 6.4 for DCA of 73 modern and 9 *DMA* samples. Samples are scattered along both axes. In the direction of Axis 1 (which contains 4.8% of the total variation) a negative relationship with salinity is maintained but is not as clear as in analysis of the original training set. Sites with hypersaline waters plot to the left of the diagram, and fresh waters to the right, but there is overlap at the centre of the distribution between some sites of widely-differing salinity such as HSAL and GONT2. This may be due either to the inclusion of rare taxa, or to the effects of additional variation arising from diatom dissolution.

Figure 6.5 shows the distribution of *DMA* samples in relation to the corresponding surface samples in the plot of Axis 2 against Axis 1. The distance between samples in ordination space, in S.D. units, is as follows:- BGDE 0.2, CARJ 0.6, DHND 0.9, DDUL 1.0, AAMA 1.6, HCHI 1.6, DMDN 2.0, ECHC 2.8 and HSAL 3.8. Dissolution has not had an overriding effect on relative species abundance for samples which plot closely together. Samples from the sites ECHC and HSAL are widely-separated; these lakes are dominated at the surface by relatively fragile taxa which are lost upon dissolution, *Fragilaria fasciculata* var. 2 (52%) and *Amphora arcus* var. *sulcata* (77%) respectively, and their *DMA* assemblages bear least resemblance to the modern assemblage.

6.6.4 DCA of modern, *DMA* and fossil data-set

DCA was performed on a combined species data-set of 137 samples comprising modern (74), *DMA* (9) and Laguna de Medina fossil (54) samples. Sample symbols are coded to show the distribution of the three different types of sample in the biplot of Axis 2 against Axis 1 in Figure 6.6.

The poor match between the fossil and modern, surface sediment assemblages (crosses and circles) is underlined by their separation in the diagram. *DMA* samples (diamonds) plot between the two and show some overlap with the distribution of fossil samples, which indicates they have a closer

Figure 6.4 Sample plot of Axis 2 against Axis 1 for DCA of 74 modern and 9 *DMA* diatom samples.

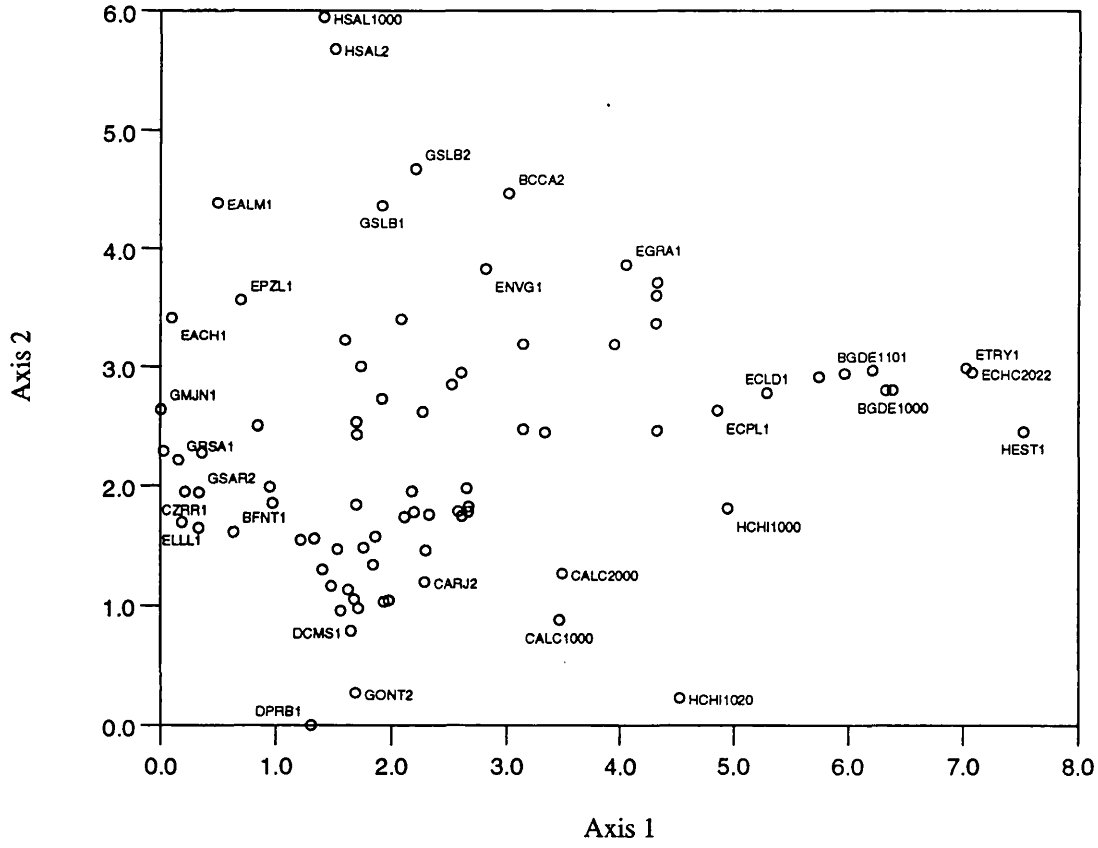


Figure 6.5 **Sample plot of Axis 2 against Axis 1 for DCA of 74 modern and 9 *DMA* diatom samples, showing the distance between *DMA* samples and their associated surface sediment sample. [Sample codes ending '000' refer to surface samples and others to sub-surface samples.]**

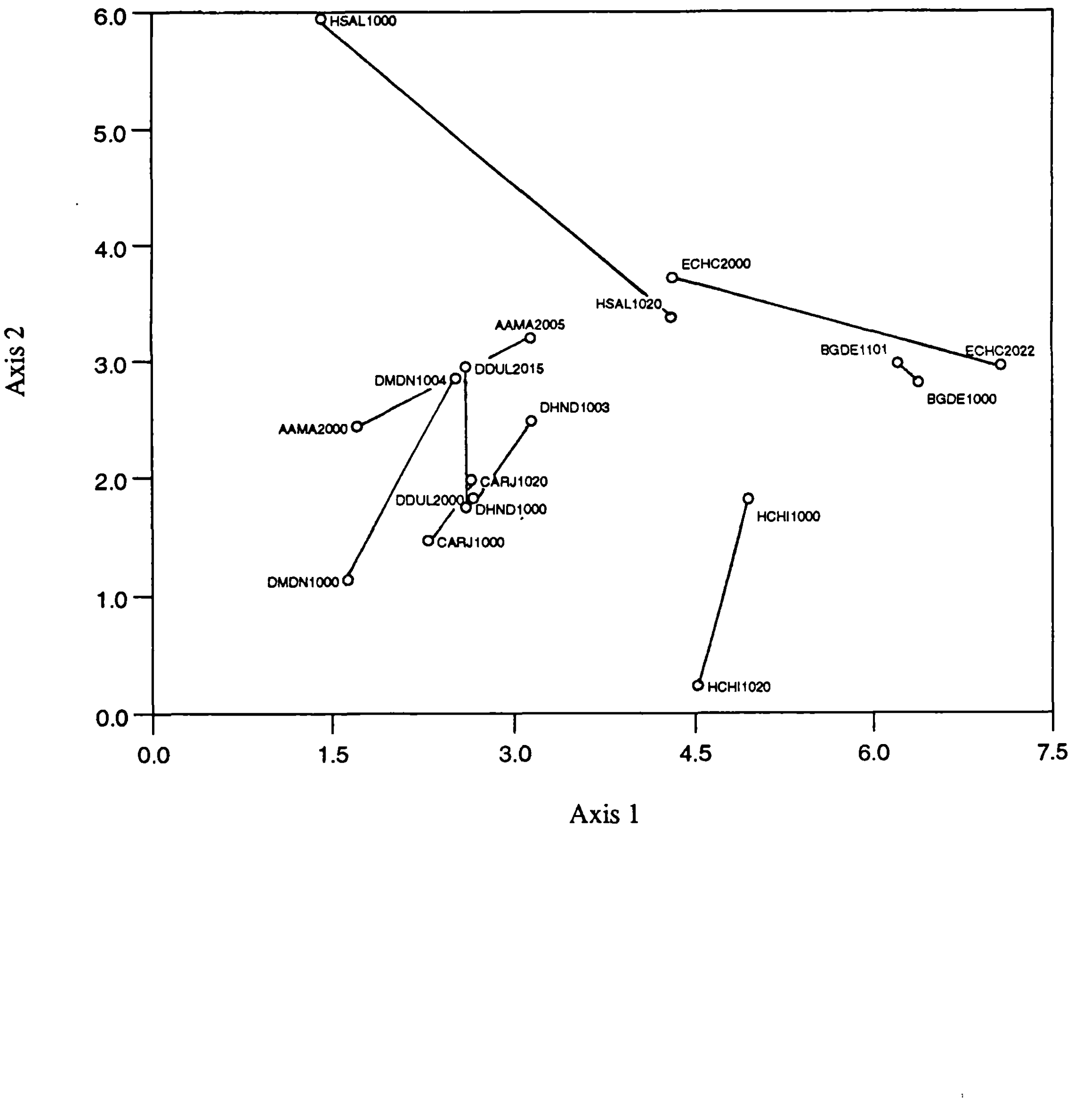
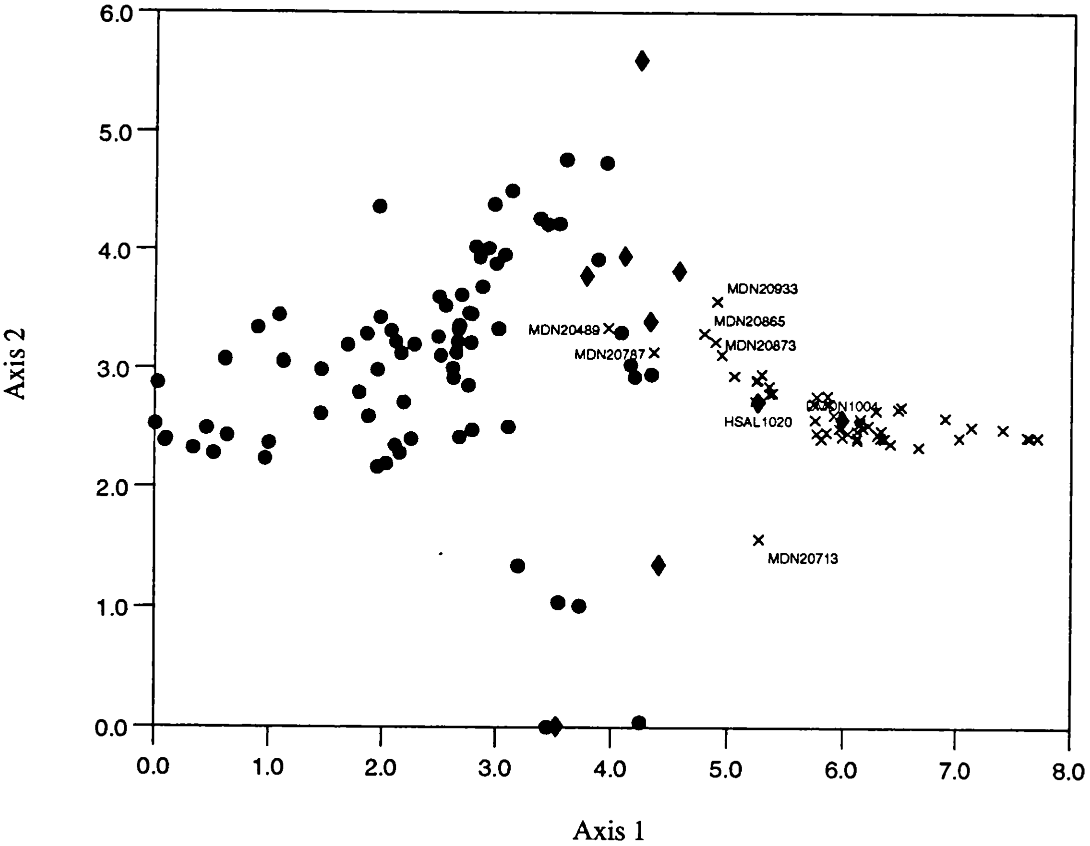


Figure 6.6 **Sample plot of Axis 2 against Axis 1 for DCA of 74 modern, 9 *DMA* and 54 Laguna de Medina fossil diatom samples, classed according to sample type. [● = modern sample, ♦ = *DMA* sample, × = Laguna de Medina fossil sample.]**



relationship. Only two *DMA* samples plot in the same ordination space as the main cluster of fossil samples, however. These comprise the Summer, 1992 sample from the Laguna de Medina itself (DMDN1004) and the sample from the Laguna Salada, Chiprana (HSAL1020), which are dominated by *Campylodiscus clypeus* and *Mastogloia braunii* respectively, the two species which dominate the fossil samples concerned.

Other fossil samples are scattered to the extreme left of their distribution, where they have a greater overlap with *DMA* samples. These fossil samples are 'unusual', relatively well-preserved assemblages with higher frequencies of additional taxa such as *Achnanthes fogedii* (MDN20865 and MDN20873) or *Cocconeis placentula* var. *euglypta* (MDN20489) and the fossil sample which had a good analogue in the original training set, MDN20933.

The fossil samples dominated by taxa with no 'ecological' modern analogue plot to the extreme right of the diagram and show no overlap with the modified training set samples, which reflects the continued absence of an analogue.

6.6.5 Derivation of a modified 'modern + *DMA*' transfer function

A modified transfer function for conductivity was derived by simple WA regression as in Chapter 4. The data-set comprised the 70 modern samples used in the original transfer function and 9 additional *DMA* samples.

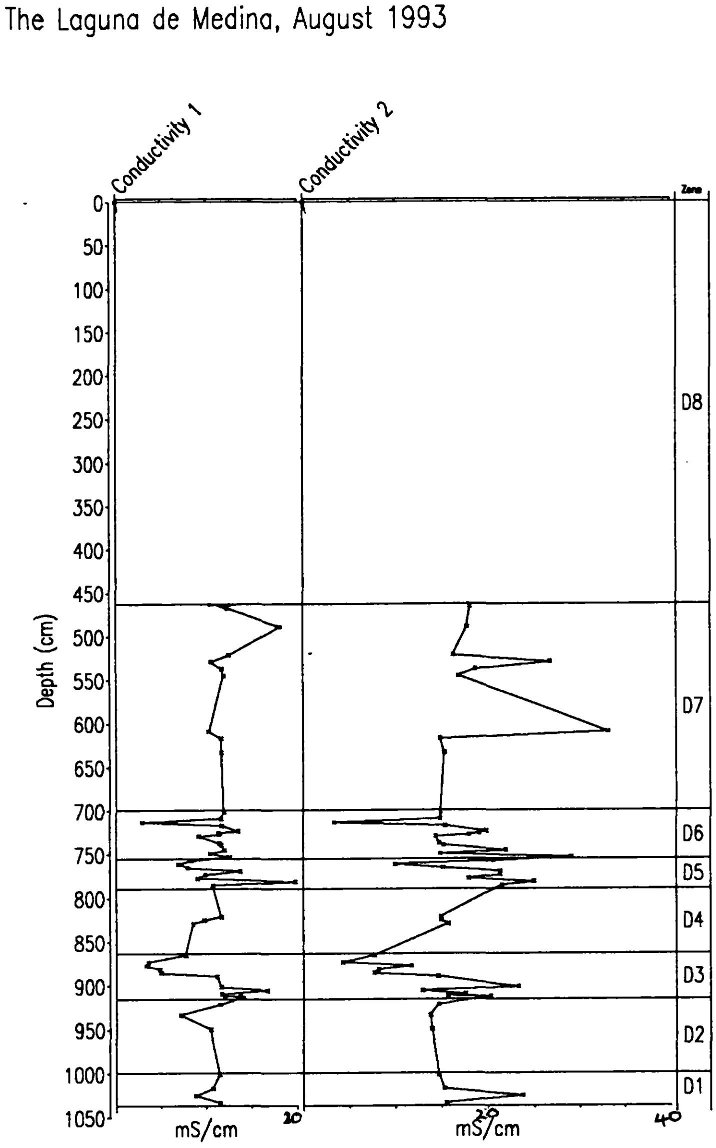
The results are not reported in full; the r^2 values for simple WA and jackknifing (0.91 and 0.56) are very similar to the summary statistics for the original analysis (0.91 and 0.57). This indicates that the inclusion of *DMA* assemblages has not affected the overall predictive ability of the transfer function.

6.6.6 Application of the modified transfer function

6.6.6.1 Palaeosalinity reconstruction

Simple WA calibration and analogue matching techniques were used as in Section 6.5.2 with the exception that all taxa other than indeterminate categories were included. Calibration results are given as $\log_{10}$ and back-transformed conductivity values in Appendix 8b. The reconstructed salinity curve ('Conductvity 2') is compared in Figure 6.7 with that derived by application of the original transfer function ('Conductivity 1'). An extreme, high value for the dry surface sample (75.4 mS cm^{-1} for Conductivity 2 compared to 78.7 mS cm^{-1} for Conductivity 1) is not displayed.

Figure 6.7 Diagram showing palaeosalinity curves derived from application of original ('Conductivity 1') and modified ('Conductivity 2') transfer functions, over different Diatom Zones.



The palaeosalinity curve fluctuates within the range 3.4-33.2 mS cm^{-1} compared to 2.9-18.1 mS cm^{-1} in the original analysis. The trends in the two curves are similar, with lowest reconstructed conductivity in Zones D3 and D5, but the results are consistently higher compared to the original analysis for assemblages dominated by *Campylodiscus clypeus* and *Mastogloia braunii* (D1, D2, D6 and D7); most of these reconstruct in the mesosaline range at 14-20 mS cm^{-1} compared to 9-12 mS cm^{-1} in the original analysis. *C. clypeus* has a modified optimum of 14.2 mS cm^{-1} which is close to the original estimate of 11.75 mS cm^{-1}. *M. braunii* has a modified optimum of 39.4 mS cm^{-1} and was not included in the original training set due to its low abundance. Thus the higher values are explained mainly by the influence of this single taxon.

6.6.6.2 Analogue matching

In the fossil sequence, 51 of the 70 fossil taxa are represented in the modified training set, compared to 46 in the original analysis. The percentiles of the matrix of dissimilarities for the modern + *DMA* data-set are given below:

1st percentile	0.912
2nd percentile	**1.009**
5th percentile	1.126
10th percentile	1.200
20th percentile	**1.283**

The analogue measures for each of the fossil samples in different diatom zones are given in Table 6.3. Taking a cut-off point of 1.009, the second percentile, most assemblages in Zones D1, D2, D6 and D7, together with the lowermost samples from Zone D3 now have a 'good analogue' in the modern flora. Most other samples in Zones D3, D4 and D5 have a less good fit; the match is relatively good for many samples in Zone D5, whereas those of D4 and the upper levels of Zone D3 do not have a good analogue even at the cut-off point of the twentieth percentile, 1.283.

Summary abundance and diversity statistics for common fossil species which occur in the modern training set are given in Table 6.4 below, ordered by the number of effective occurrences (N_2 values) in fossil assemblages.

Although *C. clypeus* and *M. braunii* are frequent in the modified training set and reach high maximum abundance, their N_2 values are low, and significantly lower than the equivalent statistics for the original training set. This indicates the small number of samples in which relative abundance approaches the new maximum, and palaeosalinity reconstructions for levels dominated by these two taxa may be

Table 6.3 **Analogue measures for reconstructed salinity of fossil samples, based on calibration using the modern + *DMA* transfer function. [Samples given as mean sample depth in cm; minDC = minimum squared Chi-squared distance between fossil and modern + *DMA* samples.]**

SAMPLE	min DC	DIATOM ZONE
0-1	0.606	D7
465	0.733	
489	1.142	
521	0.470	
529	0.928	
537	0.694	
545	0.899	
609	0.812	
617	0.964	
633	0.530	
701	0.509	D6
709	0.502	
713	1.220	
717	0.542	
723	0.949	
725	0.985	
727	0.867	
729	0.715	
737	0.534	
739	0.792	
745	0.837	
749	0.837	
753	0.811	D5
757	0.916	
761	1.070	
765	1.136	
769	1.199	
773	1.010	
777	1.096	
781	1.095	
785	1.002	
787	1.081	
821	1.323	D4
825	1.395	
829	1.321	
865	1.260	
873	1.102	D3
877	1.390	
881	1.324	
885	1.328	
889	1.368	
901	1.402	
905	1.357	
909	0.974	
911	0.818	
912	1.078	
913	1.041	
921	0.521	D2
933	0.887	
949	0.853	
1001	0.620	D1
1017	0.936	
1025	0.913	
1033	0.553	

Table 6.4 **Abundance and diversity statistics for common Laguna de Medina fossil diatom taxa which are affected by dissolution. [*DMA* = Dissolved Modern Analogue (partially-dissolved, recent assemblages), N = number of occurrences, Max% = maximum abundance, N2 = Hill's Diversity Index.]**

CODE	DIATOM SPECIES	FOSS	MODERN ONLY			MODERN+*DMA*		
		N2	N	N2	MAX	N	N2	MAX
CP001A	*Campylodiscus clypeus*	28.4	17	8.6	3.5	23	2.1	79.9
MA004A	*Mastogloia braunii*	22.7	8	-	1.0	13	1.6	67.0
AM9986	*Amphora libyca* v. 1	13.8	3	-	0.2	4	1.1	14.5
CH082A	*Chaetoceros wighami*	15.6	5	2.3	1.9	8	3.9	5.1
SU008A	*Surirella striatula*	11.8	2	-	0.4	4	3.7	0.4
AM007A	*Amphora commutata*	10.5	9	3.8	3.6	14	3.3	17.8
AN009A	*Anomoeoneis sphaerophora*	9.8	20	5.2	12.4	25	7.5	23.4
MA001B	*Mastogloia smithii* v. *lacustris*	9.7	8	2.9	47.2	10	3.1	98.6
AM9987	*Amphora libyca* v. 2	8.5	9	4.1	3.7	11	3.0	11.5
MA005A	*Mastogloia pumila*	6.7	4	1.3	60.0	5	1.4	63.0
CY003A	*Cyclotella meneghiniana*	5.7	25	8.8	19.7	28	10.5	22.3
NA304A	*Navicula crucicula* v. *cruciculoides*	5.6	18	5.0	36.3	21	6.3	36.3
CH057A	*Chaetoceros* cf. *muelleri*	5.0	19	2.9	44.4	22	4.0	44.6
AC159A	*Achnanthes fogedii*	4.4	6	1.8	50.3	7	2.0	50.4
AM9990	*Amphora veneta* v. 1	4.0	26	4.6	44.3	29	5.5	44.8
CO001B	*Cocconeis plac.* v. *euglypta*	2.7	35	16.2	22.4	38	17.4	22.5
NI204A	*Nitzschia elegantula*	2.1	14	5.6	11.5	15	5.7	11.6
AM021B	*Amphora arcus* v. *sulcata*	2.1	3	3.0	77.3	3	3.0	77.9
AM121B	*Amphora margalefi* v. *lacustris*	1.9	3	2.4	2.6	3	2.4	2.6
GY021A	*Gyrosigma peisonis*	1.3	23	5.9	33.1	27	6.6	77.9

inaccurate. The high estimated optimum for *M. braunii* in particular is a function of its abundance in the *DMA* assemblage of only one *DMA* sample, from the hypersaline lake, HSAL, in spite of its occurrence in 8 modern and 5 *DMA* assemblages ranging upwards in salinity from oligosaline.

Most other taxa show increased maximum abundance and N2 values in the modified training set, which indicates the reliability of palaeosalinity estimates has been improved, even if it is partly of a function of the 'duplication' of samples from single sites.

Fragile taxa such as *Navicula crucicula* var. *cruciculoides*, *Achnanthes fogedii*, *Nitzschia elegantula* and *Amphora arcus* var. *sulcata* are present only at lower frequency in *DMA* assemblages, which confirms they are probably under-represented in the core.

Some taxa do not follow this pattern. The relatively robust *Cocconeis placentula* v. *euglypta*, for example, was most abundant in a modern sample from another lake, DTLL. Similarly, *Cyclotella meneghiniana* showed a minor increase in abundance in the *DMA* data, but occurred at low frequencyin the fossil data (3.5% max.); dissolution in fossil samples could be more advanced than in *DMA* samples.

6.7 CRITERIA FOR QUALITATIVE PALAEOSALINITY INTERPRETATION OF FOSSIL DIATOM ASSEMBLAGES

6.7.1 Introduction

It has been established that quantitative palaeosalinity reconstruction is unlikely to be reliable due to the combined effects of diatom dissolution and of a lack of modern analogues for fossil diatoms in the Spanish training set.

In the absence of a reliable, continuous palaeosalinity record, characteristic fossil diatom assemblages are interpretated qualitatively at the end of this chapter, as a means of producing a record of relative palaeosalinity change by more 'traditional' palaeoecological techniques (Birks & Birks, 1980). Interpretation is based on the salinity preferences of diatom taxa in the Spanish training set, and on their reported preferences in other regions.

Although interpretation is more subjective than in quantitative reconstruction, the approach has the advantage that it provides a means of interpreting assemblages dominated by taxa with no modern Spanish analogue. Regional differences in apparent ecological preferences for common taxa in the modern Spanish data-set were discussed in Chapter 4, where it was concluded that the neighbouring region of North Africa is the most reliable potential source of complementary ecological data.

For taxa which are present in neither Spain nor North Africa, modern analogues can be sought in the diatom flora of geographically-removed regions (Juggins *et al.*, 1994). This is supported by the study in Chapter 4, where the saline-lake diatom flora of North America was found to differ from that of Spain, but within which individual salinity optima for taxa common to both regions were similar.

6.7.2 Diatom salinity preferences

Table 6.5 gives a comparison of estimated weighted-averaging salinity optima, and qualitative optima and tolerance ranges by water salinity classes, for the most common fossil diatom taxa. The data are derived from the modern Spanish training set, a combined African training-set of 282 sites (Gasse *et al.*, in press), a sub-set of this training set which comprises >100 samples from Tunisia (Ben Khelifa, 1989), North American training-sets of 66 sites from the northern Great Plains, USA (Fritz *et al.*, 1993a) and 65 sites in British Columbia, Canada (Cumming & Smol, 1993), and data compiled in Gasse *et al.* (1987) from coastal lagoons and inland salt lakes mainly in the Camargue, France, in eastern Spain (Noël, 1984, 1986), Africa (F. Gasse's data and e.g. Cholnoky, 1963), Sinai (Ehrlich, 1975, 1978) and Blue Lake, Utah, North America (Kaczmarska & Rushforth, 1983).

The palaeosalinity of fossil assemblages can be inferred from the salinity preferences of the dominant taxa, as follows. The salinity preferences of less frequent species are incorporated in the interpretation of the fossil sequence at the end of this chapter.

Assemblage 1: *Campylodiscus clypeus* + *Mastogloia braunii* + *Amphora libyca* + *Amphora veneta*

Campylodiscus clypeus is epipelic (Gasse, 1986) and euryhaline but it has a relatively narrow tolerance range restricted largely to mesosaline-polysaline waters; although the range in reported optima spans the full class (5.6 mS cm^{-1} Africa; 11.8 Spain; c. 20 Gt. Plains) it is not often found in oligosaline waters. As in Spain, it is rare in the modern African flora (6.5% max. abundance in the African data-set and 1% in the Tunisian data-set).

Mastogloia braunii is extremely euryhaline but has a preference for waters of a salinity close to the oligosaline-mesosaline boundary. Its occurrence in the Spanish training set is restricted to one site, the hypersaline Laguna Salada, Chiprana [HSAL], at a frequency too low for inclusion in the transfer function. It was also found at low frequency in hypersaline waters of Tunisia, but was more abundant (15%) in waters of salinity c. 5 gl^{-1} (Ben Khelifa, 1989). The estimated salinity optimum from the larger African data-set and the North American Great Plains ('NGP') data-set are similarly placed just below the oligosaline-mesosaline boundary (6 mS cm^{-1} and 4.8 gl^{-1}).

Table 6.5 **Regional comparison of salinity preferences of common Laguna de Medina fossil diatom taxa.**

DIATOM SPECIES	SPAIN Cond, mS cm^{-1}	AFRICA Cond, mS cm^{-1}	TUNISIA Salinity classes	GREAT PLAINS TDS gl^{-1}	BRITISH COL. TDS gl^{-1}	GASSE *et al.*, 1987 ~~& other~~ refs. Salinity classes
Achnanthes submarina	-					Euryhaline ?-OLIGO-MESO-?
Amphora arcus var. *sulcata*	4.9	7.1	OLIGO-MESO			Extreme euryhaline (OLIGO)-MESO-EU
Amphora commutata	5.7	4.8	OLIGO-(MESO)			Euryhaline OLIGO-MESO
Amphora libyca	var.1: 3.2 var.2: -	1.8	(FRESH)-OLIGO-MESO-(EU-HYPER)		0.3	Euryhaline FRESH-OLIGO
Amphora margalefi var. *lacustris*	14.1					
Amphora veneta	var.1: 7.7 var.2: 7.2	1.1	(FRESH)-OLIGO-MESO-(EU-HYPER)	7.3	1.4	Euryhaline (FRESH)-OLIGO
Anomoeoneis sphaerophora	13.7	7.6	(OLIGO)-MESO		vars 3.3-11.0	Extreme euryhaline (FRESH)-OLIGO---HYPER
Aulacoseira granulata	-	0.1		1.0		FRESH-(OLIGO)
Campylodiscus clypeus	11.7	5.6	(OLIGO)-MESO	18.9		Euryhaline (OLIGO)-MESO
Chaetoceros cf. *muelleri*	5.3	7.1		12.0		
Chaetoceros wighami	-					
Cocconeis placentula var. *euglypta*	20.7	0.5		8.9		Extreme euyhaline FRESH---HYPER
Cyclotella choctawhatcheeana	-			21.32		Euryhaline (OLIGO)-MESO-(EU)
Cyclotella meneghiniana	8.6	5.0	OLIGO-(MESO)	3.4	0.2	Euryhaline OLIGO-MESO
Diploneis didyma	-					Coastal marine (Van der Werff & Huls, 1957-1974)
Mastogloia braunii	-	6.0	OLIGO-MESO	4.8		Extreme euryhaline OLIGO--HYPER
Mastogloia elliptica	11.1	2.1		12.45		
Mastogloia pumila	61.5	18.6				
Mastogloia smithii var. *lacustris*	6.2	4.1		vars 3.2-17.4		Euryhaline (FRESH)-OLIGO-MESO
Navicula crucicula var. *cruciculoides*	42.9			22.03		
Navicula pseudocrassirostris	4.7		Rare: OLIGO-MESO			Stenohaline (>5 g l^{-1}) MESO-EU
Nitzschia compressa var. *compressa*	-	7.2	(OLIGO-MESO)-EU-(HYPER)	11.1		
Nitzschia elegantula	7.4	5.0	(FRESH-OLIGO)-MESO-(EU-HYPER)			
Nitzschia granulata	-					Coastal marine (KLB, 1988)
Surirella striatula	-		Rare: OLIGO			

REFERENCES: SPAIN: this study; AFRICA: Gasse *et al.* (in press); TUNISIA: Ben Khelifa (1989); GREAT PLAINS, N. America: Fritz *et al.* (in press), BRITISH COLUMBIA: Cumming & Smol (1993), AFRICA/other regions: Gasse *et al.*, 1987.

KEY: Conductivity ('Cond.') & TDS values relate to estimated weighted-averaging optima derived from regional data-sets. Water salinity classes: OLIGO = oligosaline, MESO = mesosaline-polysaline, EU = eusaline, HYPER = metasaline-hypersaline; observed tolerance range is indicated, with optimum range not in parentheses.

Amphora libyca (undifferentiated) is indicative of oligosaline waters; *A. libyca* var. 1 is rare in the Spanish training set, but *A. libyca* var. 2 has an optimum of 3.3 mS cm^{-1}. This compares well with the African optimum of 1.8 mS cm^{-1}. Its status as a species primarily of fresh waters (Gasse *et al.*, 1987) is supported by its occurrence in the British Columbian data-set (opt. 0.3 gl^{-1} TDS).

Amphora veneta (undifferentiated) is euryhaline but is a possible indicator of oligosaline or slightly mesosaline waters; the two varieties identified in the Spanish data-set were well-represented and showed similar preferences for a salinity approaching the oligosaline-mesosaline boundary (var. 1: 7.7 mS cm^{-1}, var. 2: 7.2 mS cm^{-1}). This exceeds the African optimum of 1.1 mS cm^{-1}, but is in accord with the general observation that, although it has been found in waters from fresh to hypersaline, it tends to be restricted to oligosaline waters (Gasse *et al.*, 1987).

A combination of the first two species is therefore taken as indicative of mesosaline waters. Their association with other *Mastogloia* species and with gypsum deposits in the Laguna de Medina fossil record is a feature common to African sequences (Gasse *et al.*, 1987) and supports the use of the African data as analogues. An increase in *A. libyca* var. 1 or *A. veneta* var. 1 at the expense of *C. clypeus* may indicate lowered salinity.

Assemblage 2: *Nitzschia granulata + Diploneis didyma + Cyclotella choctawhatcheeana*

Nitzschia granulata and *Diploneis didyma* are indicative of mesosaline or eusaline waters. As noted in the taxonomic discussion in Chapter 3, *Diploneis didyma* in the Spanish data-set is synonymous with the taxon designated *D. bombus* in the Tunisian data-set (Ben Khelifa, 1989). Both *Nitzschia granulata* and *D. didyma* have no modern analogue in the Spanish flora. In Tunisia, *D. bombus* and *Nitzschia granulata* occur together in assemblages dominated by stenohaline, eusaline 'marine' species (Ben Khelifa, 1989), and indicate upper mesosaline/polysaline, or eusaline conditions.

Cyclotella choctawhatcheeana has no modern analogue in the Spanish or African floras, but in the NGP data-set it has a relatively narrow tolerance range and an optimum in the mesosaline-polysaline range of 21.3 gl^{-1}. The global applicability of this optimum is supported both by work on fossil African sequences, where palaeosalinity inferences based on this taxon were not at odds with those made from accompanying species (Gasse *et al.*, 1987), and in this study by its association with the aforementioned taxa, and in other assemblages with *C. clypeus*.

Thus these taxa indicate waters of higher salinity, ranging from mesosaline to eusaline.

6.8 CRITERIA FOR QUALITATIVE LAKE-LEVEL RECONSTRUCTION

Lake-level change can be reconstructed from the palaeosalinity record if it is assumed that salinity is inversely proportional to lake level. In reality, the relationship between the two is complex (Gorham, 1961, Eugster & Jones, 1979, Watson, 1983) and, at its worst, salinity can be driven independently by changes in groundwater flow (Street-Perrott & Harrison, 1985, Wood & Sanford, 1990).

To strengthen interpretation the palaeosalinity record is assessed below against independent, diatom-based evidence for lake permanence, which is assumed to correlate with lake level. This is derived from principles established in Chapter 4, where the relative abundance of aerophilous, benthic and planktonic taxa were shown to relate to lake permanence (correlated with water depth), and in Chapter 5, where a significant relationship was established between lake permanence and diatom preservation potential in recent lake sediments.

In essence, assemblages dominated by planktonic taxa are interpreted as 'high' lake level, and those dominated by benthic or aerophilous taxa as 'low' lake level. As in palaeosalinity reconstruction, direct interpretation of lake-level change from fossil diatom species assemblage composition is affected by diatom dissolution. Since benthic and aerophilous taxa are more robust, it cannot be assumed that plankton were originally absent from assemblages dominated by 1-2 robust species.

6.9 DISCUSSION

6.9.1 The 'No Modern Analogue' problem

The lack of an ecological modern analogue for some dominant taxa in the Laguna de Medina core is unlikely to be a simple function of the relatively small size of the Spanish training set (57 sites). It applies also to the same taxa in similar fossil sequences from lakes in North Africa, where a transfer function has been derived from a larger data-set of 282 sites from North and East Africa and Niger (Gasse *et al.*, in press).

The most important species relevant to this study is *Cyclotella choctawhatcheeana* (formerly designated *C. caspia*) which is common in fossil assemblages of the northern Sahara (Fontes *et al.*, 1985, Gasse *et al.*, 1987) but absent from the African training set. Although the saline lakes of East Africa span a very wide range of ecological conditions (Gasse, 1983), the modern sampling sites from northern Africa are mainly shallow salt lakes, ponds and swamp environments; as in Spain permanent waterbodies in this region largely comprise artificial or riverine environments, and high altitude karstic lakes (Gasse *et al.*, in press). This indicates there may no longer be a good analogue either in Spain or North Africa for some limnological conditions which prevailed here in the earlier Holocene, although the problem is being addressed to some extent by the amalgamation of data-sets from different saline lake regions (Juggins *et al.*, 1994).

6.9.2 Diatom dissolution

The taphonomic problem of diatom dissolution is more serious. Dissolved '*Campylodiscus*' assemblages are probably the remnants of assemblages which would have had a good analogue in the modern data-set, but which cannot now be interpreted reliably using standard quantitative techniques. The reliability of qualitative palaeoecological interpretation of changes in relative species abundance is also affected. Changes in the relative abundance of two taxa with different salinity tolerances can only be interpreted confidently in terms of salinity change if their relative resistance to dissolution is similar.

The simple diatom dissolution index used in counting the fossil assemblage gave an indication of samples in which diatoms are relatively well-preserved (up to c. 60%), but is misleading in other respects due to the differing robustness of individual taxa. The highly resistant taxa, *Campylodiscus clypeus*, *Diploneis didyma* and *Chaetoceros* spp. were relatively well-preserved (valve margins and resting spores intact) in poorly-preserved assemblages, and the index for % 'undissolved' valves was higher than in better preserved assemblages dominated by more fragile taxa in a more advanced state of dissolution, such as *Cyclotella* spp. (valve margins dissolved). Thus, the index for Diatom Zone D5, where diatom diversity and preservation was highest, was lower than for low diversity '*Campylodiscus*' assemblages of Zone D6.

A more rigorous approach has been developed by Ryves (1994). A series of laboratory experiments was conducted in which patterns of diatom dissolution were quantified for diatoms common in the NGP saline lake data-set of North America. Changes in the relative species abundance and state of preservation of 11 different diatom assemblages were quantified over time, from an initial pristine condition to the total dissolution of a fixed concentration of a robust taxon used in each sample as a control. It was established that diatom dissolution follows a predictable sequence, and a 'dissolution ranking' was derived which orders 53 diatom species by their relative resistance to dissolution. The results for selected, relevant taxa are given in Table 6.6. The ordering separates groups of characteristic taxa which show significant differences in their response to dissolution. Within the confines of the experimental methodology, the ordering is approximate in some respects; amongst the most robust taxa, for example, *Campylodiscus clypeus* is known to be the most resistant, but is ordered fourth here (D. Ryves, pers. comm.).

Most taxa in the Laguna de Medina sequence are either included in this list, or show obvious

Table 6.6 **Approximate dissolution ranking of common Laguna de Medina fossil diatom taxa, based on a morphological comparison with Ryves (1994)'s experimental dissolution ranking of 53 taxa from the North American NGP Data-set.**

RANK	NORTH AMERICAN TAXON	EQUIVALENT TAXA, SPAIN (Laguna De Medina)
1	*Mastogloia elliptica*	*Mastogloia elliptica* *M. braunii*
4	*Campylodiscus clypeus*	*Campylodiscus clypeus* *C. echeneis* *?Diploneis didyma* *?Nitzschia granulata*
5	*Chaetoceros* cysts	*Chaetoceros* cf. *muelleri* *C. wighami*
6	*Anomoeoneis costata*	*Anomoeoneis sphaerophora*
9	*Amphora libyca*	*Amphora libyca* var. 1 *A. veneta* var. 1
10	*Fragilaria fasciculata*	*Fragilaria fasciculata*
11	*Surirella striatula*	*Surirella striatula*
14	*Rhopalodia gibba*	*Rhopalodia acuminata*
15	*Aulacoseira granulata*	*Aulacoseira granulata*
16	*Cocconeis placentula* var. *euglypta (-)*	*Cocconeis placentula* var. *euglypta (-)*
20	*Mastogloia smithii* var. *lacustris*	*Mastogloia smithii* var. *lacustris* *M. pumila*
23	*Cyclotella choctawhatcheeana*	*Cyclotella choctawhatcheeana*
27	*Brachysira vitrea*	*?Navicula pseudocrassirostris*
30	*Brachysira aponina*	*Cyclotella meneghiniana*
32	*Cyclotella meneghiniana*	*Achnanthes delicatula*
34	*Achnanthes delicatula*	*?A. submarina*
37	*Fragilaria brevistriata*	*Fragilaria brevistriata*
38	*Amphora pediculus*	*Amphora margalefi* var. *lacustris* *?Amphora libyca* var. 2
39	*Navicula halophila*	*?Navicula crucicula* var. *cruciculoides*

similarities in size, shape and robustness to North American diatoms; the dissolution ranking can be used to derive an approximate comparative dissolution ranking for most of the common Spanish fossil taxa, which is also presented in Table 6.6. Two taxa which are relatively frequent in the fossil record, *Amphora arcus* var. *sulcata* and *Achnanthes fogedii,* cannot be placed easily in this table but are obviously less robust than the dominant fossil taxa.

The Laguna de Medina fossil diatom record is dominated by taxa with high resistance to dissolution, that is, *Mastogloia braunii, Campylodiscus clypeus, Diploneis didyma* and *Nitzschia granulata.* Additional taxa which are present at low frequency, such as *Achnanthes submarina* and *Mastogloia smithii* var. *lacustris,* are less robust and their presence can be related in part to a less advanced state of dissolution. With the exception of *Chaetoceros* cysts, planktonic taxa are less resistant to dissolution than benthic or aerophilous taxa.

The dissolution ranking is used as an aid to qualitative palaeosalinity interpretation below; changes in relative species abundance of taxa with a similar resistance to dissolution are taken as more reliable than changes between species of differing robustness. The interpretation of assemblages dominated by one or two highly robust species is tentative since a range of other taxa is likely to have been lost completely.

6.9.3 The modified transfer function

Most workers suggest a bias in relative species abundance caused by differential diatom dissolution in modern training sets reduces the accuracy of palaeosalinity reconstruction (Fritz & Battarbee, 1986, Fritz*et al.*, 1991, Barker, 1992). This assumes that the fossil diatom assemblages are well-preserved, and their relative species abundance is comparable to the modern flora. In this study, however, the results of analogue matching between fossil and modern assemblages showed dissolution of fossil diatoms is sufficiently advanced for there to be virtually no relationship with species assemblage composition in the training set.

The development of a modified transfer function which incorporates partially-dissolved 'dissolved modern analogue', or '*DMA*' assemblages from recent salt-lake sediments into an extended training set was a departure from standard techniques, aimed at improving palaeosalinity reconstruction in studies where fossil assemblages have undergone significant dissolution. Although caution is necessary in adopting this technique, since real salinity change could have occurred subsequent to deposition of the *DMA* assemblages, a screening process was used to identify and remove samples from sequences where a real shift in species composition had occurred. Its potential value is indicated by the results of preliminary ordinations, which showed that *DMA* assemblages bore a greater resemblance to the fossil assemblages than did the modern samples. In addition, the predictive ability of the modified transfer function was equal to that of the original transfer function, and fossil diatom zones characterised by these taxa were found to have a good analogue subsequent to its application.

In this study, however, the two dominant taxa, *Campylodiscus clypeus* and *Mastogloia braunii*, were only present at a relative abundance equivalent to the fossil sequence in two samples of the modified training set, and palaeosalinity reconstruction was not reliable as a consequence. There are three possible explanations.

Firstly, the *DMA* data-set was relatively small, since only 9 out of 57 sites in the original training set contained suitable, partially-dissolved assemblages. For this region, the size of the *DMA* data-set cannot be increased greatly other than by data from elsewhere since, as shown in Chapter 5, diatoms are preserved near the surface only in the relatively few extant semi-permanent or permanent salt lakes, which are already included. Sampling of coastal lagoons is a possible solution.

Secondly, the technique relies on the inclusion of samples in a similarly advanced state of dissolution to the fossil samples. In this study, the relatively low abundance of the most robust species in most *DMA* assemblages suggests the assemblages were in a less advanced state of dissolution. A more rigorous approach would be to select *DMA* samples on the basis of similarities in the dissolution ranking of species between fossil and *DMA* assemblages. Higher resolution subsampling would be necessary to establish whether this were feasible; in many lakes diatoms are preserved to only a few cm below the surface and separate states of dissolution might not be identifiable.

Thirdly, their abundance in fossil sequences may be due not only to taphonomic factors, but also to ecological factors. The surface sediments of a carbonate-rich, Moroccan coastal wetland, Sidi Bou Rhaba (seasonal salinity range 3-12 g l^{-1}) were dominated by *C. clypeus* (27%), with *M. braunii* at 3%; assemblages were well-preserved and *C. clypeus* dominated the entire 116cm core (Flower *et al.*, 1992). Although the degree of dissolution is not reported, Gasse *et al.* (1987) note that assemblages dominated by these species are common in fossil sequences of the central Afar, Africa in association with gypsum deposits, whereas they are rare at the surface. Both environments are rare in the modern Spanish data-set. Carbonates are not a dominant anion in the inland salt lakes, and of the lakes sampled for *DMA* assemblages, near-surface gypsum bands occurred only in Laguna Dulce, Lucena, Cádiz (DDUL), below the depth sampled. Thus, these species' rarity in modern samples may also reflect differences in ecological conditions compared to fossil sequences.

In summary, the technique has the potential to provide a relatively rapid means of improving quantitative palaeosalinity reconstruction for cores with extreme dissolution. It is likely that its reliability would be improved by expanding the data-set to include Spanish coastal lagoons, and other salt lakes or lagoons of neighbouring North Africa.

6.10 INTERPRETATION OF PALAEOSALINITY AND LAKE-LEVEL CHANGE

6.10.1 Diatom preservation as an indicator of lake permanence

A positive relationship was established in Chapter 5 between sedimentary diatom preservation potential and lake permanence. On this basis it may be argued that the Laguna de Medina was either semi-permanent or permanent during deposition of all phases of the sediment sequence where diatoms are preserved. The best diatom preservation occurs in the laminated sediments of Diatom Zone D5, which are indicative of a permanent phase (Hardie *et al.*, 1978) and could represent relatively deep waters.

On its own the evidence is not particularly useful; the predictability of preservation in permanent lakes was not absolute, and it is also possible that diagenetic taphonomic processes could result in the dissolution of parts of the diatom sequence subsequent to its deposition. Thus, ephemerality cannot be inferred with confidence for parts of the sequence in which diatoms are rare or not preserved, or from relative changes in the state of diatom preservation in other sections.

6.10.2 Qualitative palaeosalinity and lake-level reconstruction from interpretation of fossil diatom assemblages

In respect to lake level, the dominance of benthic or aerophilous taxa throughout most of the sequence probably indicates that the lake was relatively shallow throughout, although the low frequency of planktonic taxa may be partly due to diatom dissolution.

None of the indicators of chloride waters identified in Chapter 4 are present, but 'No Modern Analogue' taxa, *Nitzschia compressa* var. *compressa* and *N. granulata* probably indicate chloride waters (Ben Khelifa, 1989). As noted previously, *Mastogloia* spp. are restricted to chloride waters in Spain, but not elsewhere; *Amphora arcus* var. *sulcata* characterises chloro-sulphate systems, but many others such as *Campylodiscus clypeus* and *Cyclotella choctawhatcheeana* have no marked preferences.

The fossil diatom sequence is interpreted as follows. Qualitative, palaeoecological interpretation is given in terms of different water salinity classes, and relative lake level, inferred from lake permanence indicators, is given in terms of 'high' and 'low'.

The diatom diagram was presented on pages 188 (with dissolution index) and 192.

***Diatom Zone D1* (1033-1000cm)**

Preservation: POOR
Salinity: OLIGOSALINE-MESOSALINE
Lake level: ?HIGH

Taking into account dissolution factors, an interpretation of these '*Campylodiscus* assemblages' as indicators of mesosaline waters close to the oligosaline-mesosaline boundary is supported by the occurrence at low frequency of the taxa which are relatively robust, but less so than the dominant taxa, *Cyclotella meneghiniana* (Spanish opt. 8.6 mS cm^{-1}, African opt. 5.0 mS cm^{-1}) and *Amphora libyca* var. 2. The dominance of *A. libyca* var. 1 at 1016 cm depth indicates oligosaline waters.

Most taxa are benthic but the presence of *C. meneghiniana* indicates permanent or semi-permanent waters. Very few valves of less robust species are preserved, and the taxon is probably under-represented. A very tentative interpretation of high lake-level can be made.

***Diatom Zone D2* (1000-916cm)**

Preservation: DISCONTINUOUS, POOR
Salinity: ?MESOSALINE (& OLIGOSALINE-MESOSALINE PHASE)
Lake level: ?

In samples where diatoms are preserved, the presence of *Campylodiscus clypeus* and *M. braunii* suggests full mesosaline salinity; this is supported at 948cm depth by the presence of *N. granulata* and *C. echeneis*, but the record is discontinuous. The assemblage at 933-932cm (the pale yellow lamina), dominated by *Amphora veneta* var. 1 with low frequency of *Cyclotella meneghiniana*, was reconstructed reliably at 7.2 mS cm^{-1} and indicates a brief phase of lower salinity (oligosaline-mesosaline).

Relative lake level cannot be inferred since preservation is too poor, and the diatoms are the most robust benthic and aerophilous species. A temporary high-stand is indicated at 933-932cm depth, by the presence of plankton.

***Diatom Zone D3* (916-864cm)**

Preservation: MODERATE
Salinity: FLUCTUATING MESOSALINE TO MESOSALINE-EUSALINE
Lake level: FLUCTUATING

Alternations between the dominant taxa, *Diploneis didyma* and *Nitzschia granulata*, and *Cyclotella choctawhatcheeana*, indicate fluctuating salinity from mesosaline/eusaline to mesosaline. Taxa with a greater tendency to dissolution than *C. choctawhatcheeana* are preserved, so this is unlikely to be due simply to dissolution. Mesosaline phases are supported by the presence of *Surirella striatula* (Spanish opt. 14.5 mS cm^{-1}, upper oligosaline in Tunisia), *Chaetoceros wighami* (Spanish opt. 15.3 mS cm^{-1}), *Amphora margalefi* var. *lacustris* (Spanish opt. 14.1 mS cm^{-1}). Eusaline phases are supported by the presence of *Nitzschia compressa* var. *compressa*; this taxon is synonymous with *N. punctata* and has an African optimum of 7.1 mS cm^{-1}, but is extremely euryhaline and regarded as a eusaline species in the Tunisian data-set, where a maximum abundance of 45% was attained in a sample of 40 gl^{-1} TDS).

The basal sample at 913-911cm (white lamina) is dominated by *Campylodiscus clypeus* and *M. braunii*, with relatively high abundance of other mesosaline indicators, *Achnanthes fogedii* (15%; Spanish opt. 17.7-17.6 mS cm^{-1}; occurs with '*Cyclotella caspia*' in estuarine fossil assemblages in Sweden [Liljegren, 1982]) and *Navicula crucicula* var. *cruciculoides* (7%; Spanish opt. 42.9 mS cm^{-1}), but also of 'oligosaline' taxa *A. libyca* var. 1 (9%; oligosaline) and *Amphora commutata* (3%; Spanish opt. 5.7 mS cm^{-1}, African opt. 4.8 mS cm^{-1}). A mixture of taxa characteristic of different waters is common to saline lake sequences and indicates fluctuating salinity, possibly on a seasonal basis.

This is matched by evidence for fluctuating water levels, indicated by the alternation between the aerophilous *N. granulata* and *D. didyma* and the planktonic *C. choctawhatcheeana* over most of the sequence. The complete disappearance of aerophilous taxa at the top of the sequence and dominance of *C. choctawhatcheeana* indicates a rise in lake level.

Diatom Zone D4 (864-786cm)

Preservation:	DISCONTINUOUS, POOR
Salinity:	MESOSALINE (& MESOSALINE-EUSALINE PHASE)
Lake level:	?FLUCTUATING

In samples where diatoms are preserved, the presence of *Campylodiscus clypeus* indicates mesosaline waters. Taxa which dominate the better-preserved assemblages at the centre of the sequence (*Nitzschia granulata, Diploneis didyma, Cyclotella choctawhatcheeana* and *Campylodiscus echeneis*) indicate a phase of higher salinity.

Preservation is too poor for interpretation of lake level, although short-term fluctuations can be inferred from the transition at the centre of the sequence from benthic *Campylodiscus* assemblages to mixed aerophilous/planktonic *N. granulata/D. didyma* and *C. choctawhatcheeana* assemblages.

***Diatom Zone D5* (786-756cm)**

Preservation: ± GOOD

Salinity: TREND FROM MESOSALINE TO OLIGOSALINE-MESOSALINE

Lake level: TREND FROM LOW-HIGH-LOW

The dominant species, *C. choctawhatcheeana*, indicates mesosaline waters over the lower and middle part of the sequence. This is supported by the presence of *Campylodiscus clypeus* and *Chaetoceros wighami*.

Reduced salinity is indicated at the top of the zone by the increase in *M. braunii* at the expense of *C. choctawhatcheeana*, parallelled by increases in fragile taxa with a preference for oligosaline waters. These comprise *C.* cf. *muelleri* (Spanish opt. 5.3 mS cm^{-1}, African opt. 7.1 mS cm^{-1}), *Achnanthes submarina* (syn. with *A. arenaria* and prefers oligosaline or mesosaline waters; Gasse *et al.*, 1987), *Mastogloia smithii* var. *lacustris* (Spanish opt. 6.5 mS cm^{-1}, African opt. 4.1 mS cm^{-1}, *A. fogedii* and *Amphora arcus* var. *sulcata* (Spanish opt. 4.9 mS cm^{-1}, African opt. 7.1 mS cm^{-1}, but shows extreme euryhalinity; Ben Khelifa, 1989).

The consistent abundance of *C. choctawhatcheeana* indicates high lake levels over much of the zone. Lower lake levels are inferred at the base and top of the zone by the dominance of benthic taxa; although resting spores of planktonic *Chaetoceros* species are relatively abundant here, they were were shown in Chapter 4 to have a tendency to occur also in ephemeral waters.

***Diatom Zone D6* (756-700cm)**

Preservation: MODERATE

Salinity: MESOSALINE (& OLIGOSALINE-FRESH PHASE)

Lake level: ?LOW WITH TEMPORARY HIGH STAND

The dominant taxa indicate mesosaline waters. A drop in salinity is indicated around 720cm by the peak of *Amphora libyca* var. 2 prior to a freshwater level at 712cm dominated by planktonic taxa such as *Aulacoseira granulata* and *Stephanodiscus hantzschii*.

Lake level is difficult to interpret. Although the diversity of these assemblages is relatively high, all taxa are more robust than planktonic taxa. It is tempting to infer that the complete absence of *Cyclotella choctawhatcheeana* indicates a drop in lake levels compared to Zone D5, but it could be an artefact of dissolution. The planktonic assemblage indicates a temporary high stand.

Diatom Zone D7 **(700-464cm)**

Preservation: DISCONTINUOUS, POOR
Salinity: OLIGOSALINE-MESOSALINE
Lake level: ?LOW

This zone is dominated by dissolved '*Campylodiscus*' assemblages; the relatively high abundance of *Amphora libyca* var. 1 probably indicates salinity close to the oligosaline/mesosaline boundary. A low stand is inferred tentatively but, again, preservation is poor.

Diatom Zone D8 **(464-0cm)**

Diatoms are not preserved apart from around 300cm depth, where the *Campylodiscus* assemblages indicate mesosaline waters.

6.10.3 Summary

In comparison with the quantitative salinity estimates, the qualitative palaeosalinity record also fluctuates above and below the mesosaline salinity range, without any evidence for major sustained salinity change. The main trends in the quantitative palaeosalinity curves were towards reduced salinity at the top of Zones D3 and D5. These are supported by qualitative inferences at the top of Zone D5 (a change to increased abundance of taxa with a preference for oligosaline waters), but not at the top of Zone D3, where the dominance of the 'No Modern Analogue' taxon of mesosaline waters, *Cyclotella choctawhatcheeana*, would not have been reflected in the quantitative reconstruction. This again indicates the probable unreliability of quantitative reconstruction.

Palaeosalinity interpretation relied on traditional palaeoecological techniques. This does not produce a continuous record, but has the important advantage that it overcomes the constraint on quantitative reconstruction of a lack of modern analogues for taxa abundant in fossil assemblages, by reference to ecological data from other regions. While diatom dissolution was such that interpretation relied heavily on the four taxa which dominated fossil assemblages, *Campylodiscus clypeus*, *Mastogloia braunii*, *Cyclotella choctawhatcheeana* and *Diploneis didyma*, it was consistent with inferences derived from the presence of other less robust taxa at low frequencies. The interpretation is strengthened compared to previous qualitative palaeoecological studies, since the large body of quantitative diatom and associated water chemistry data established through the development of transfer functions in Spain, Africa and North America can be exploited.

The effects of dissolution are such that detailed changes in salinity cannot be inferred with confidence within individual zones, especially in Zones D2 and D7 where diatom preservation is sporadic. Zones least affected by dissolution, for which the qualitative reconstruction should be most reliable, comprise Zones D3 and D5. Diatoms are also relatively well-preserved in temporary phases of fresh or oligosaline waters which correspond to distinct, thin sediment laminae (e.g. 933-932cm depth). This may indicate the influx of fresh waters consequent upon storm runoff (cf. Last & Schweyan, 1985).

It is possible that evidence for more saline phases is missing. Hypersaline waters of Spain are dominated by fragile taxa such as *Amphora* sp. 1 [cf. *acutiuscula*], *Navicula* and *Nitzschia* species which do not preserve well. Gasse *et al.* (1987) suggest assemblages dominated by extreme, euryhaline taxa such as *Mastogloia braunii* and *Anomoeoneis sphaerophora* can be indicative of more saline waters, but in this sequence they were accompanied always by the less euryhaline *Campylodiscus clypeus.*

The interpretation is summarised as follows. The start of the sequence is characterised by a phase of high lake levels and relatively low salinity (oligosaline-mesosaline) in Diatom Zone D1 (1033-1000cm depth). Diatoms are poorly preserved in Zone D2 (1000-916cm depth); the sequence is interpreted in terms of an increase in salinity compared to Zone D1, but lake levels are difficult to interpret. There is evidence for rapid fluctuation in salinity and lake level in Zones D3-D4 (916-786cm depth), in a phase of generally high salinity (mesosaline to mesosaline-eusaline) which indicates short-term, possibly seasonal, fluctuations in limnological conditions. Maximum lake levels and mesosaline salinity are attained in mid-Zone D5 (786-756cm depth), wherein a trend occurs from oligosaline-mesosaline salinity and lower lake levels at the top and bottom of the zone.

Diatom preservation is poor above this level, but the inferred increase in ephemerality above 500cm depth based on the absence of diatoms is supported to some extent by the lowering of lake levels inferred in Zone D7, and may indicate a long-term trend towards shallower waters.

The results are consolidated and discussed further in Chapter 8, where the relationship between palaeosalinity and lake level are considered in the light of similar palaeolimnological data derived from different analytical techniques.

CHAPTER SEVEN

THE LAGUNA DE MEDINA II: OTHER PALAEOENVIRONMENTAL ANALYSES

7.1 INTRODUCTION

In this chapter the results are presented for analyses of the Laguna de Medina core other than diatom analysis and the lithostratigraphic description, which were dealt with in Chapter 6. A core chronology is established, and results are given separately for three different types of evidence, which comprise basic sediment properties, ostracod trace-metal analysis, and the palaeoecology of calcareous microfossils, molluscs, plant macrofossils, pollen and macrofossil charcoal.

Inferences concerning palaeosalinity and lake-level change are made independently initially. The strength of the relationship with climate change is considered mainly in the light of pollen evidence for human impact. In Chapter 8 the conclusions reached from different lines of evidence are compared with the diatom-based palaeosalinity and lake-level reconstructions in order to assess the reliability of diatom-based inferences and to establish a unified interpretation of lake-level change.

7.2 CORE CHRONOLOGY

7.2.1 AMS radiocarbon dates

Results of three AMS radiocarbon measurements are given in Table 7.1. These provide a preliminary chronology pending results of nine further measurements which will be made in due course, but which are not included in the thesis due to time constraints. As noted below, suitable dating material is scarce in the sediments of the Laguna de Medina, and a large volume of sediment will need to be processed to produce reliable results.

The concentration of dateable material of terrestrial origin is very low throughout the core. No terrestrial seeds were found in core-screening at 8-cm intervals other than a chenopod-rich level at 1001-999cm depth, which forms the basal date. Charcoal was also rare and the other two dated samples were selected on the basis of the presence of major stratigraphic boundaries, and on their charcoal content.

The dates form a chronologically coherent series for the lower part of the sequence which spans part of the early-mid Holocene, c. 7,800-6,000 yr BP.

Table 7.1 **Results of AMS radiocarbon measurements for the Laguna de Medina master core. [Results are reported as radiocarbon age in years before present (1950 AD).]**

SAMPLE NUMBER	SAMPLE DEPTH	MATERIAL	^{14}C age (yr. BP)
AA-15035	788-786cm	charcoal	6,080±60
AA-15038	918-916cm	charcoal	7,310±65
AA-15037	1001-999cm	charcoal + chenopod seeds	7,860±75

The mean sediment accumulation rate calculated from these dates is 0.15cm yr^{-1} from 1000-917cm, 0.12cm yr^{-1} from 917-787cm and 0.16cm yr^{-1} from 787-0cm depth. The lithostratigraphic variability suggests sediment accumulation rate has fluctuated considerably, however, so interpolation and extrapolation of dates is not valid. The sequence from the core base to c. 700cm depth in particular includes very sharp contacts which could indicate gaps in sediment accumulation or fluctuations in chemical sediment accumulation rate, and the lithostratigraphic transition to the more homogeneous sediments of Unit L6 suggests a major change in the hydrological regime.

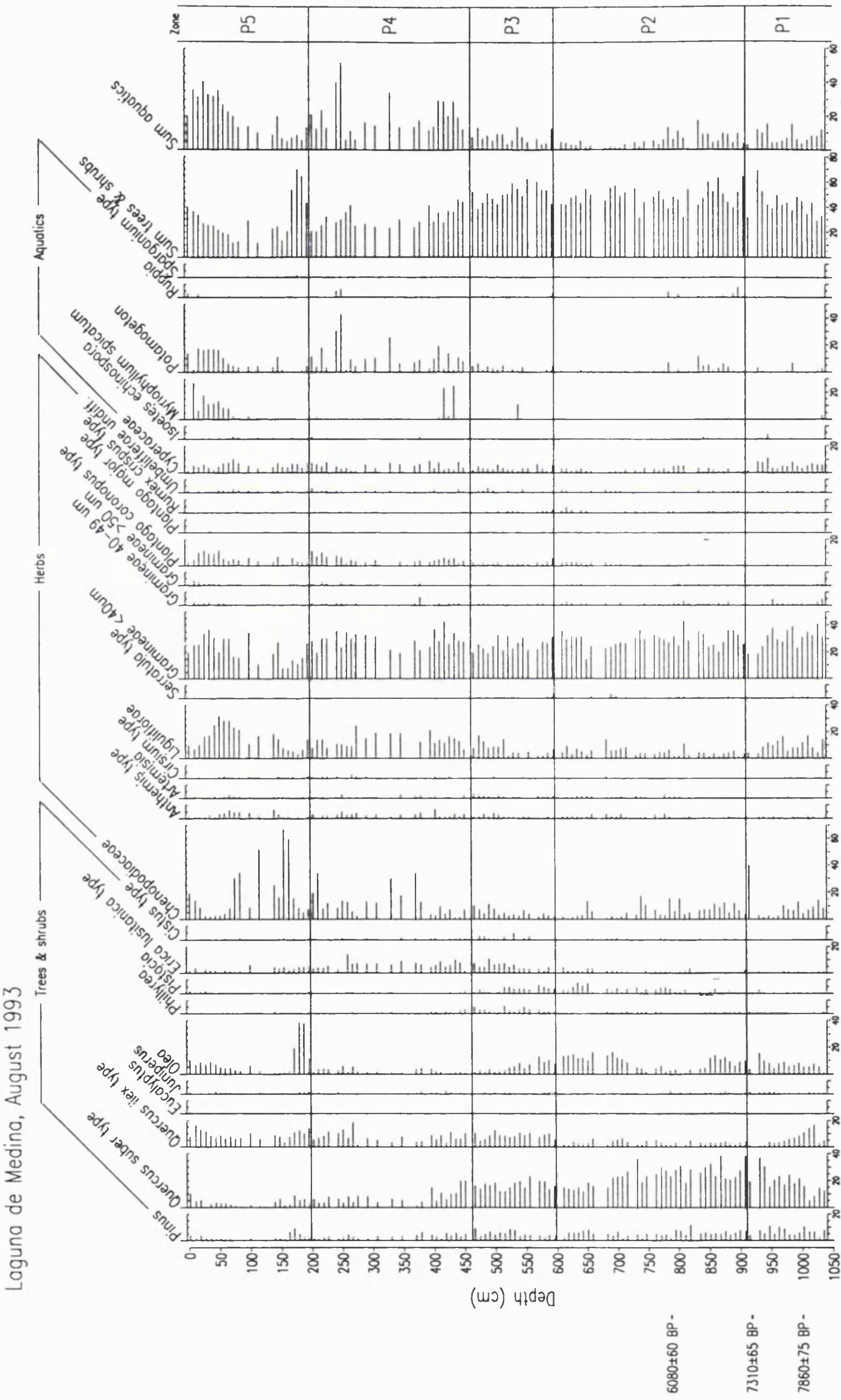
Pending the results of a series of dates to be obtained on samples from the top 700cm of the core, the lack of dating control prevents a straightforward chronology from being established. An indirect means of dating is therefore sought in the following section, in which the potential of the pollen record as a further source of chronostratigraphic data is explored.

7.2.2 Pollen-based chronostratigraphic correlation

Other than ^{14}C measurement, the pollen record provides the strongest potential source of other chronostratigraphic data for this sequence. Were it demonstrated that major synchronous changes in Holocene vegetation history were recorded in pollen profiles from the region, as a consequence either of widespread anthropogenic or climatic effects, a tentative chronology for other parts of the core could be inferred by stratigraphic correlation of the Laguna de Medina pollen data with other published material. Detailed interpretation of the pollen diagram is reserved for Section 7.5.3, but the diagram is presented here also for ease of reference, in Figure 7.1.

Palynological data from other well-dated Holocene sequences are sparse in the local study area itself. The only dated Holocene pollen diagrams from Mediterranean southwestern Spain are from two valley

Figure 7.1 The Laguna de Medina: summary pollen diagram.



mires in the province of Huelva, west of Cádiz, which together span the period c.5000 BP to the present (Menéndez Amor & Florschütz, 1964, Stevenson, 1985, Stevenson & Moore, 1988, Stevenson & Harrison, 1992). Pollen records from another site, a valley mire at Padul, Granada, close to the foothills of the Sierra Nevada in the Cordillera Bética (Menéndez Amor & Florshütz, 1962, 1964, Florschütz *et al.*, 1971, Pons & Reille, 1986a, 1986b), have been researched extensively, but the sequence ends at c.4450 BP and it is over 200km away and at a higher altitude (785m asl) than the study site (35m asl).

Because of the scarcity of local palynological evidence, chronostratigraphic correlation relies also upon the pollen record for vegetation change over a broader region, the Mediterranean zones of the Iberian Peninsula as a whole and North Africa.

The Mediterranean 'olive rise' in the Near East and southern Europe has formed a focus for research, and increases in *Olea* pollen have been taken as indicative of its early exploitation and later intensified cultivation (e.g. Huntley & Birks, 1983, Pons & Reille, 1986b, Pons *et al.*, 1990, Vernet, 1990, Stevenson & Harrison, 1992, Davis, 1994). Davis (1994) has compiled pollen evidence for the Iberian Peninsular, southern Portugal and Morocco and suggests there is consistent evidence for *Olea* at low frequency (<4% arboreal pollen) prior to c. 2500 BP. A slight increase and its continuous presence at <6% after this date in southern Spain and Portugal reflects the introduction of cultivars with the arrival of Phoenician traders, and a dramatic rise around 400 BP throughout Spain, but not Portugal, coincides with a phase of economic growth as Spain becomes an important overseas trading power. This interpretation is open to debate since the wild olive, *Olea europaea* var. *sylvestris*, is native to the region rather than introduced; the additional influence of climate on its distribution is possible since it is temperature-sensitive, and it can be uncertain whether the pollen represents the local or regional pollen rain since it is widely-dispersed (Bottema, 1991). These trends provide the strongest potential chronostratigraphic indicators, however.

The trends around 2500 BP cannot be identified clearly either in local pollen diagrams from southwestern Spain, or in the Laguna de Medina diagram. The *Olea* pollen curves for the coastal lagoon, the Laguna de las Madres 2, and the valley mire, El Acebrón 2, Huelva (Stevenson & Harrison, 1992) reach a maximum of less than 6% throughout and only one of them shows an increase at around 2500 BP. In addition, the *Olea* curve was continuous by 7840 BP rather than 2500 BP in the site of Padul (Pons & Reille, 1986b). In contrast, the *Olea* curve has two prominent peaks of over 16% in the lower portion of the Laguna de Medina diagram, one of which is dated prior to 7000 BP. The lake is surrounded by a natural terrace and uncultivated trees grow today in the mattoral; clearly, olive formed a significant component of the local natural vegetation around the lake and its presence in the earlier Holocene cannot be taken as a chronostratigraphic marker or as an indicator of human impact.

There is more convincing evidence for anthropogenic impact in the Laguna de Medina diagram at the start of Zone P5, where a major peak in *Olea* occurs, which falls off thereafter and shows a consistent increase above c. 100cm depth. In other parts of the Peninsula, a dramatic and consistent rise in olive pollen in the upper levels of sediment sequences has been interpreted in terms of a major change in agricultural practices around 400 BP (Davis, 1994). The twofold rise in *Olea* pollen in the Laguna de Medina diagram is more difficult to interpret, but it could be argued that the consistent rise above c. 100cm is most likely to equate to sustained agricultural change. In southwest Spain, there is a slight rise at this time in the El Acebrón diagram, but not in the Laguna de las Madres diagram, so chronostratigraphic correlation is based only on broader regional changes in land use. In its support, preliminary pollen analyses in other parts of southern Spain of the Laguna Amarga, Córdoba (Stevenson, unpubl. data) and Laguna Grande, Archidona, Málaga (Watts, unpubl. data), also show a major rise in olive pollen, at c. 150cm depth in the case of the Laguna Amarga. If this rise were dated to c. 400 BP a mean sedimentation rate over the last 400 years would be 0.25cm yr^{-1} for the Laguna de Medina. This is not unreasonable since erosion rates of many Spanish salt lakes have increased considerably with clearance of land for agriculture, especially during this century (Margalef, 1956, Montes & Martino, 1987). A highly tentative date of c. 400 yrs. BP is assigned to the 100cm depth level.

In regard to other possible indicators, pollen of the introduced genus *Eucalyptus*, is present at low frequency in the top 16cm of the Laguna de Medina diagram and it is a local chronostratigraphic marker at c. 40cm depth in El Acebrón, where its cultivation is documented from the 1890's onwards (Penfold & Willis, 1961 in Stevenson & Harrison, 1992). No plantations were observed in the Laguna de Medina catchment; the date of its local introduction is unknown but would postdate 1890.

In the Laguna de Medina diagram a major fall in arboreal pollen coincides with a rise in the pollen of ruderals such as *Plantago* species around 450-400cm depth, indicative of forest clearance. There is no equivalent in the pollen diagrams from Huelva, however. Stevenson & Harrison (1992) suggest inferred changes in land use in that region from 3550-250 BP reflect local phenomena and are unrelated to the documented and archaeological chronology of economic change in western Andalucía as a whole, other than the broad coincidence with urbanisation of a possible managed woodland system from 2450-750 BP (500 BC to 1200 AD). For the Laguna de Medina, it is tempting to infer a link between deforestation and the growth of the nearby city of Cádiz as an important Phoenician trading centre around 2750 BP (800 BC), but there is insufficient evidence in the regional pollen data itself.

In summary, a significant and consistent rise in the olive curve at 100cm depth is taken as a tentative chronostratigraphic marker for c. 400 BP. Pollen data for the region are scarce, and other vegetation changes are locally varible between sites and cannot be used as reliable marker horizons. Pending the measurement of a full series of ^{14}C dates, the chronology is uncertain for 786-100cm depth in particular.

7.3 BASIC SEDIMENT PROPERTIES AND LITHOSTRATIGRAPHIC INTERPRETATION

7.3.1 Results

The dry weight, organic content (LOI at 550°C), calcium carbonate content (calculated from LOI at 925°C) and gypsum abundance profiles are given in Figure 7.2 and are zoned according to the lithostratigraphic zonation scheme derived in Chapter 6, which is summarised to the left of the diagram. Gypsum abundance was estimated at 8cm intervals compared to a 2cm resolution for weight-loss measurements; these results are presented in histogram form rather than as an interpolated curve.

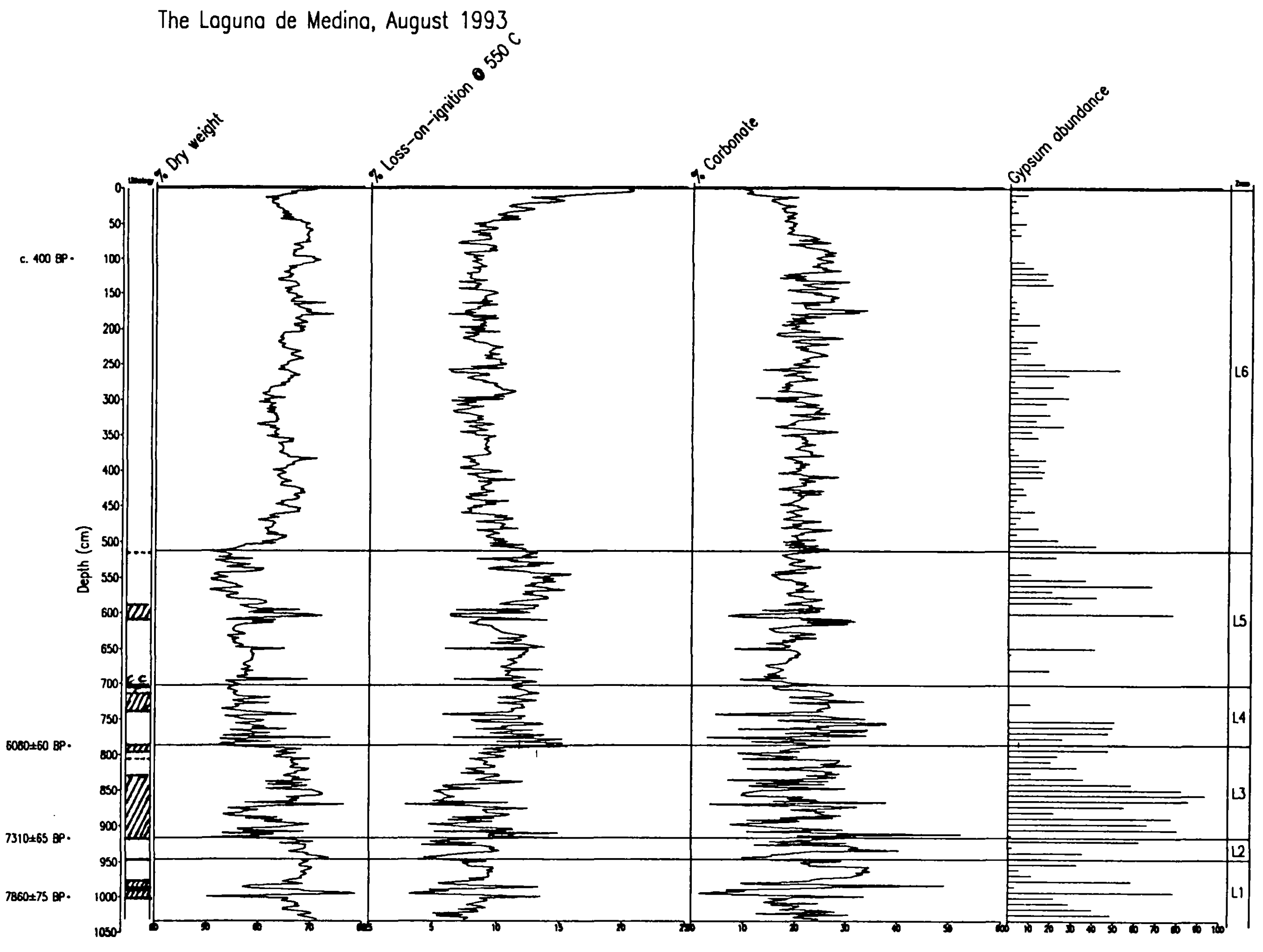
Dry weight is high (c. 50-70%) and organic content low (c. 5-15%) throughout the sequence. In the top 10cm, a peak in both corresponds to the more organic sediments of the dry lake-bed; organic content is at a maximum of >20%, which indicates rapid post-depositional degradation of organic matter thereafter.

Other than at the surface these properties show reverse trends, reflecting the reduced organic content of compact clay and gypsum-rich sediments. Peaks in % dry weight and minima in organic content (e.g. at 601cm depth) correspond to peaks in gypsum abundance and reflect the presence of gypsum bands. Some gypsum bands are not clearly represented in the weight-loss profiles (e.g. at 787cm depth) which reflects the difficulty of getting a sufficiently small, representative subsample from gypsiferous sediment.

The major trend in sediment composition is a transition at c. 500cm depth from fluctuating sediment composition to a phase of more uniform composition, in Unit L6 (c. 500cm depth to surface). Dry weight values are high in Unit L6 despite the low abundance of gypsum, which reflects the extreme compaction of these sediments. Below 500cm depth, low dry weight values and high LOI at 550°C values are exhibited consistently in Units L4 and L5 (786cm to c. 500cm depth, c. 6080 BP at base), and correspond to the least compact, organic-rich clays of the sequence.

Carbonate content may be slightly overestimated since some of the LOI at 925°C could derive from loss of water bound in clay particles (Digerfeldt *et al.*, 1992). In comparison with marl (carbonate content >50%) it tends to be relatively low (c. 15-35%) throughout. Major peaks are in single samples and correspond either to sedimentary carbonate content (e.g. the pale yellow lamina at 934-932cm) or biogenic carbonate content (the 'mollusc lamina' at 986-985cm and the white lamina rich in molluscs

Figure 7.2 The Laguna de Medina: basic sediment properties (wet density, loss on ignition at 550°C, carbonate and gypsum abundance).



Simplified lithology. Shading = gypsum bands or phases of multiple banding. C = *Cerastoderma glaucum* bands
----- = sharp transition, —— = very sharp transition. Changes of colour and texture described in the text.

at 913-911cm), and fluctuations in the profile may reflect in part changes in the abundance of calcareous macrofossils or microfossils.

The carbonate profile shows similarly decreased fluctuation in the upper levels but in this case the transition occurs at 600cm depth. This is the level above which gypsum bands are absent, and the carbonate profile is again linked closely to patterns of gypsum precipitation. Most carbonate minima (gypsum bands) are preceded immediately by carbonate maxima and are sometimes succeeded by them, which is in accord with the changing patterns of brine composition to be expected during concentration or dilution with lake-level change (Eugster & Hardie, 1978). There are no other clear underlying trends apart from in the top 75cm, where $CaCO_3$ content declines to c. 10% and suggests the possibility of diagenetic carbonate formation in levels below.

7.3.2 Interpretation

In other saline lake studies fluctuations in dry weight, organic content and carbonate content have been used to infer phases of catchment erosion where it can be assumed that the variation arises mainly from changes in the allochthonous input of clastics or carbonate minerals (e.g. Flower *et al.*, 1989, Davis, 1994). This has a bearing on palaeoclimatic interpretation since it is can indicate climate change or catchment disturbance related to human impact or tectonism. In this study variability in the measured sediment properties arises mainly from within-lake processes, however, and any signal for allogenic changes in sediment composition has been overriden by the strength of variability related to primary or authigenic salt precipitation. More detailed mineralogical analyses, such as calculation of total organic carbon content (cf. Kennedy, 1994), or SEM analysis of carbonate weathering, could be used to separate the relative influence of allogenic, endogenic and authigenic processes.

Gypsum crystal morphology and patterns of gypsum sediment accumulation can be an indicator of lake-level change. Based on a model of characteristic sedimentary facies proposed by Hardie *et al.* (1978), the dominance of massive lenticular gypsum above 504cm depth suggests an overall trend towards increased ephemerality, and possibly lower lake levels, in the upper core sequence, Unit L6. This represents displacive crystal formation in saline groundwaters beneath the sediment surface as a lake dries out, and it destroys the structure of any laminated sediments beneath (Hardie *et al.*, 1978). Periodic drying of the lake in the earlier Holocene is indicated by similar lenticular phases in Units L1 and upper L3. In general, however, higher lake levels in these units can be inferred from the preservation of laminated sediments indicative of permanent waters, and by the consistent presence of prismatic gypsum below 504cm depth, which is precipitated from open waters (Watson, 1983, Last & Schweyen, 1985, Magee, 1991).

In respect to more detailed inferences, the reverse graded bedding of Unit L3, where gypsum crystal size increases upwards to a maximum of c. 1cm long at 866cm depth, is a typical product of slower crystal growth at the sediment-water interface as equilibrium is reached (Magee, 1991) and could indicate a lake-level lowering. Last (1990) discusses the difficulty of inferring the relative direction of lake-level change in evaporite studies, however; the presence of gypsum bands indicates saturation of the lake and sediment pore waters with respect to gypsum, but is not always an indicator of lake-level lowering. In Ceylon Lake, Canada, the presence of gypsum bands was thought to result from an increase in groundwater level in an otherwise dry lake for which the preceding sediment record had been lost through processes such as wind deflation (Last, 1990, Teller & Last, 1990). The solubility of gypsum increases with chloride concentration, and in some cases gypsum precipitation can occur as a response to fresh water input rather than increasing salinity (Watson, 1983, 1985). In addition to complications caused by early diagenetic crystal formation, redissolution of gypsum can occur if it is not buried rapidly beneath impermeable sediment (West *et al.*, 1979), and the record is likely to be incomplete.

It is tempting to infer highest lake levels in Units L4 and L5 (786-c.500cm depth). Organic content of the sediment matrix is highest in these units, as indicated by the sediment description (soft olive-gray clays) and by the high LOI values at 550°C in spite of the presence of gypsum in places. This indicates either the less rapid degradation of organic matter (or increased productivity), to be expected in more stable, permanent waters. Whilst evidence for similar phases in other units could have been removed by the effects of diagenetic crystal formation, the preservation of the sediment characteristics in itself suggests the more prolonged 'permanent' state of the system (Eugster & Kelts, 1983).

7.3.3 Summary

In summary, increased ephemerality overall is inferred from the dominance of massive lenticular gypsum in the upper sediment record, in Unit L6.

The presence of gypsum bands in Units L1-L4 (1033-703cm depth), and to a lesser extent in L5, is reflected also in fluctuating dry weight and LOI profiles and is taken as an indicator of fluctuating salinity and water levels. In contrast to the upper sediment record, gypsum was often precipitated from open waters rather than through groundwater movement during desiccation. It is inferred that the lake dried out periodically in the earlier Holocene, but lake levels were higher than in the more recent past (or retained water for more prolonged periods).

The detailed evidence is ambiguous. The most prolonged period of permanent waters and relatively high lake levels may have obtained during the deposition of the most organic units, L4 and L5 (786 -

c.500cm depth, c. 6080 BP at base).

7.4 OSTRACOD TRACE-METAL ANALYSIS AND VALVE MORPHOLOGY

7.4.1 Introduction

In this section the results are presented for trace-metal analysis of *Cyprideis torosa* valves, which are preserved in an almost continuous sequence from the core base to 600cm depth, and are rare around 300cm depth.

The relationship between the shell-chemistry ratios and salinity can be complex. As a means of assessing the viability of the results, ostracod valves from the living population of a salt pan are analysed first. Data on the variation in ostracod valve characteristics provide additional information by which to assess the trace-metal record, and are an independent indicator of the extent of seasonal or short-term fluctuation in the chemistry of the host waters.

7.4.2 Trace-metal analysis of modern *Cyprideis torosa* populations

7.4.2.1 Results

The ostracod, *Cyprideis torosa*, currently inhabits only two sites of the modern data-set, the adjacent salt pans DPRA and DPRB of the Salinas de Belen Nuevo, Puerto Real, Cádiz which were sampled in August, 1993. These are of similar salinity and brine composition (60 gl^{-1} and 53 gl^{-1} TDS, Na-[Mg]-Cl); Na and Cl concentrations are high, with [Mg] 26% and [Ca] 4% in both cases, sulphates 8-15% and carbonates <1% of the total cation and anion concentrations measured in meq l^{-1}.

Ostracods were sparse in the sandy sediment of DPRA1; only one of the carapaces was preserved with soft-parts so the results are omitted. They were more abundant in DPRB1, in algal mats on a sandy-clay substrate. The results are given in Table 7.2 for trace-metal analysis of one valve per carapace, where carapaces were preserved in pristine condition with delicate surface spines and soft-parts intact.

The mean Mg/Ca molar ratio is 0.0154, and the range 0.0121-0.0205. The mean Sr/Ca molar ratio is 0.0035, and the range 0.0031-0.0044. There are not enough samples for full numerical analysis, but the results show considerable variation in both parameters.

Table 7.2 **Corrected results for shell chemistry analysis of modern *Cyprideis torosa* valves from the Salinas de Belen Nuevo, Puerto Real, Cádiz (site DPRB).**

#	VALVE LENGTH (mm)	DESCRIPTION	Mg/Ca (molar)	Sr/Ca (molar)
1	1.12	♀ LV, semi-transparent	0.0121	0.0031
2	1.08	♂ RV, transparent	0.0126	0.0033
3	1.18	♀ LV, transparent	0.0152	0.0044
4	0.97	♀ LV, transparent	0.0154	0.0035
5	1.09	♀ LV, transparent	0.0205	0.0031
6	1.07	♀ RV, transparent	0.0170	0.0032

7.4.2.2 Implications for analysis of fossil assemblages

The variability does not derive from temporal variation or from taphonomic processes such as post-depositional dissolution, since the ostracods can be assumed alive, or recently dead, at the time of sampling. Spatial variation is minimised since they were collected from the same sampling point at the edge of a small salt pan of dimensions c. 2 x 10m.

Variation in Mg/Ca due to the analysis of juveniles rather than adults (Chivas *et al.*, 1986a) is unlikely since shell lengths fall within the range of 0.93-1.16mm given for adults in the type description, whereas the largest, juvenile-1 instars are c. 0.75mm long (Kilenyi & Whittaker, 1974).

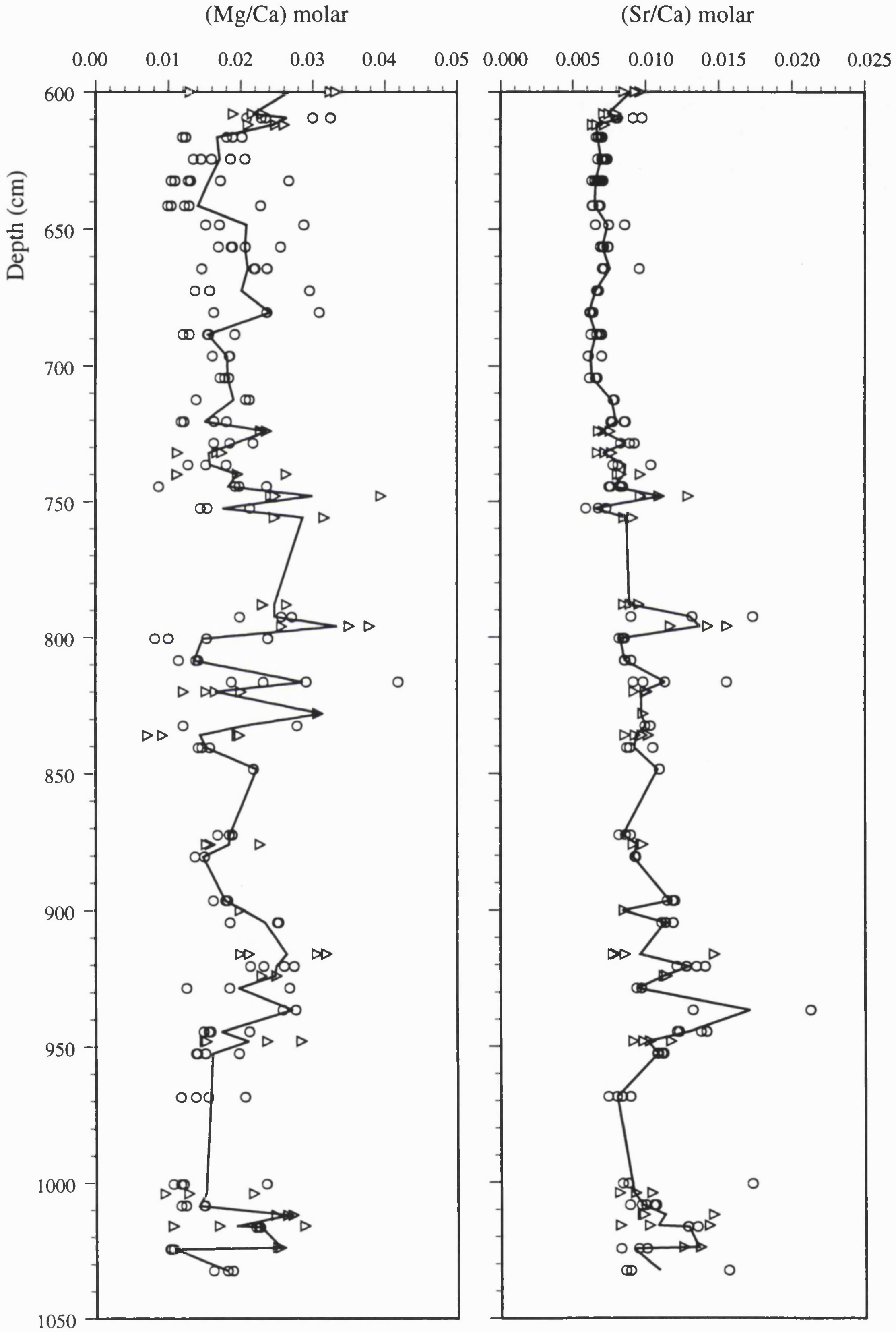
In summary, the variation appears to derive from unknown or random variation. A larger data-set would be necessary to determine whether there was significant variation according to any of the factors mentioned above. However, the results indicate that minor fluctuations in sediment-core profiles are unlikely to be significant.

7.4.3 Trace-metal analysis of fossil *Cyprideis torosa* from the Laguna de Medina

7.4.3.1 Results

Stratigraphic profiles of corrected Mg/Ca and Sr/Ca molar ratios are given in Figure 7.3 for the part

Figure 7.3 The Laguna de Medina: corrected results of ostracod shell-chemistry analysis, showing individual measurements (○ = first run, △ = second run) and mean.



of the core sequence from 1033-600cm depth in which *C. torosa* was preserved. Gaps indicate samples devoid of adults or the largest, juvenile-1 instars. The results for rare valves preserved around 300cm depth are not displayed, but are given below.

Depth	*Mg/Ca (molar)*	*Sr/Ca (molar)*
306-304cm	0.0114	0.0091
"	0.0118	0.0096
298-296cm	0.0193	0.0081

In the lower part of the core sequence, Mg/Ca values range from 0.00721-0.04190 and Sr/Ca values from 0.0592 to 0.02127. Mg/Ca values for individual samples are highly scattered compared to Sr/Ca values, particularly above 744cm depth where Sr/Ca values within each sample are very close. The overall Sr/Ca profile also shows a significant change at 744cm to a phase with very little variability from 744-600cm depth. This is less evident in the Mg/Ca profile, but there are no marked peaks in this section.

From the core-base to 744cm depth, a sustained and relatively well-defined peak common to the two profiles occurs at 1025-1012cm depth. Above this depth there are numerous gaps in the record, or samples with only 1-2 adults. The curves fluctuate but show a common trend towards higher values from 943-916cm depth; the main peak in both at 937-936cm depth may not be reliable since it derives from only two valves and the ostracod is absent in surrounding levels. A peak in Mg/Ca only at 829-828cm depth derives from a single valve and is not reliable, but another phase of fluctuating, higher values may be indicated by two peaks at 817-816cm and 797-792cm depth, the first of which is not prominent in the Sr/Ca profile. A relatively well-defined minimum in both is followed by a smaller peak at 753-752cm and 749-748cm depth respectively.

In other respects the profiles show only minor variation and values are similar to those of the phase above 744cm depth.

7.4.3.2 Variation in ostracod valve characteristics

All valves of *Cyprideis torosa* are smooth-shelled or punctate. They are transparent or a mixture of transparent and semi-transparent over most of the sequence, and are consistently transparent from 752-672cm depth. A few samples are dominated by white, opaque valves, which comprise 1008-1000cm, 953-952cm, 935-936cm, 827-828cm and 819-820cm depth.

A scatter plot of valve length:nominal shell weight against depth is given in Figure 7.4 for a random

Figure 7.4 **The Laguna de Medina: scatter plot of fossil ostracod valve length:nominal shell weight ('NSW') against depth. [NSW = (ppm Ca in solution)(acid volume).100/(relative atomic mass Ca).]**

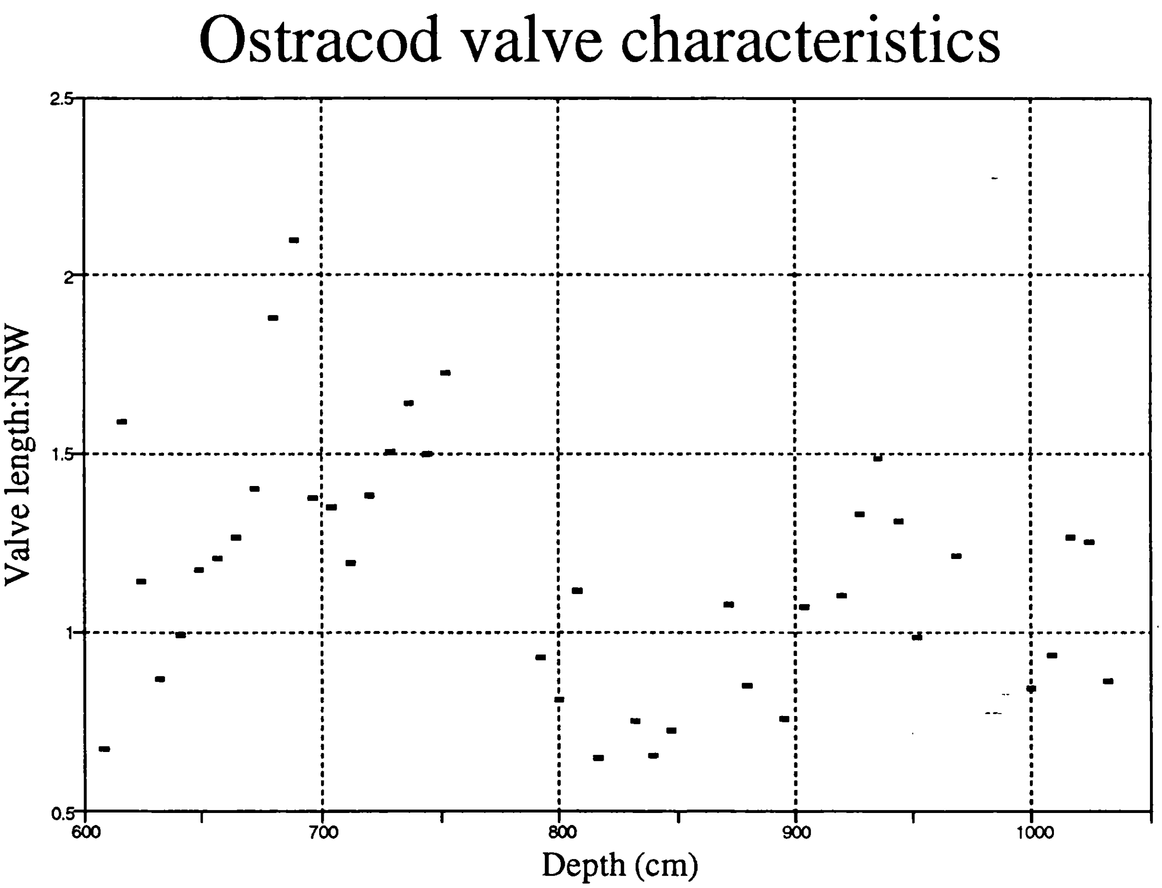
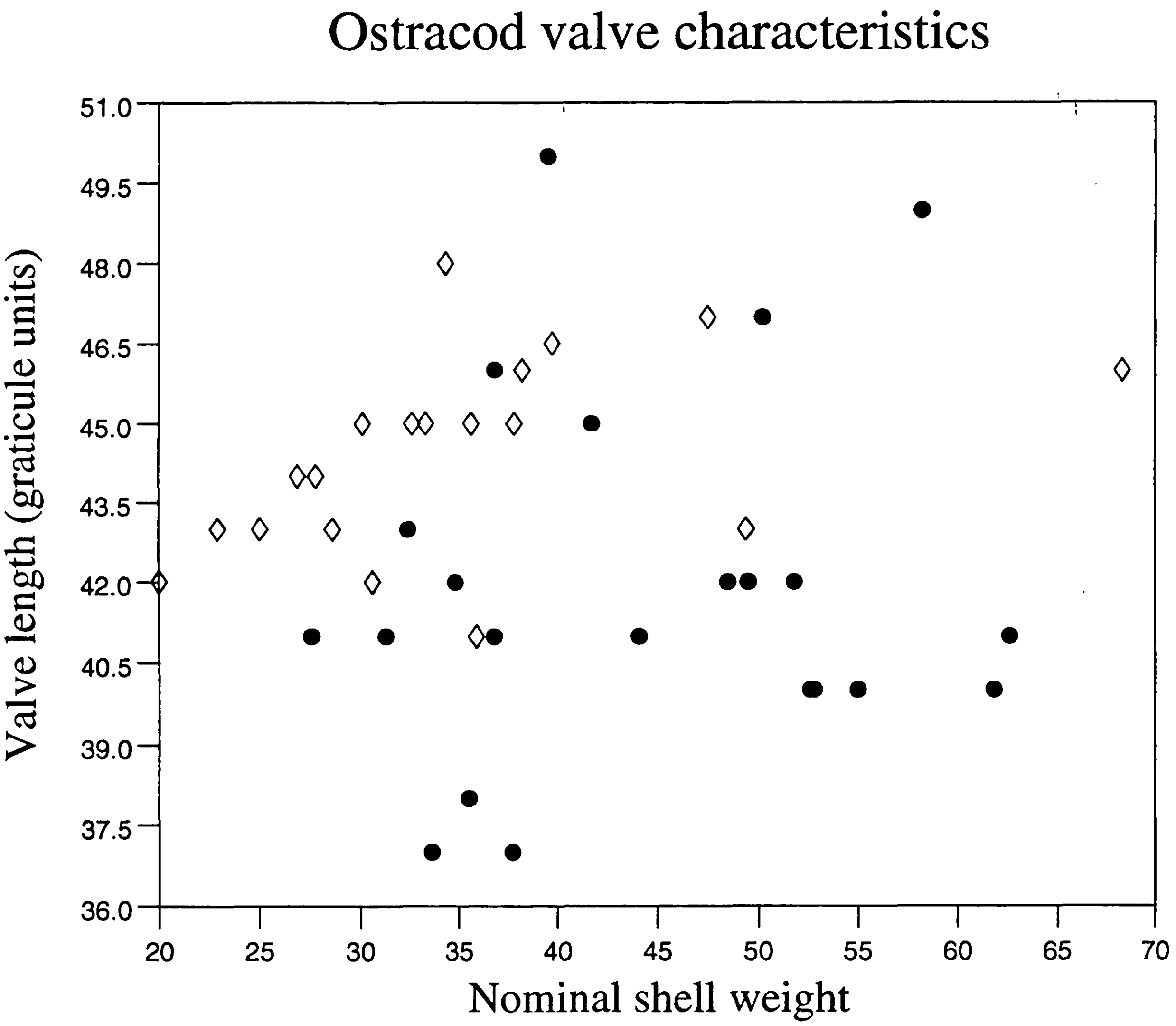


Figure 7.5 The Laguna de Medina: scatter plot of fossil ostracod valve length against nominal shell weight, classed by depth range. [• = 1032-792 cm depth, ◇ = 752-600cm depth.]



selection of ostracod valves analysed in the first run at 8cm intervals, selected as a progression from the first measured valve in one level, to the second measured valve in the next, and so on. Nominal shell weight ('NSW') indicates the relative calcium content of the shell; the ratio therefore reflects the relative shell thickness, or calcification. From Figure 7.4, the ratio for samples above 752cm depth tends to be higher than that for samples below 792cm depth. The relationship is clearer in a scatter plot of valve length against NSW (Figure 7.5 above) in which these two parts of the sequence are displayed as different symbols. With few exceptions, valves above 752cm depth show the approximately linear relationship to be expected of valves of uniform composition, and are lighter than those below 792cm depth. Below 792cm depth, valves are highly variable in composition and tend to be shorter and heavier.

7.4.4 Discussion

Various factors can affect the reliability of palaeosalinity reconstruction. Firstly, Mg/Ca values may be too high if poorly-calcified shells are used, since Mg is laid down preferentially at the start of calcification (Chivas *et al.*, 1986a). There is no evidence for this since the light, transparent valves of the section 752-600cm depth show no trend towards higher Mg/Ca values compared to the levels below. There is also no evidence that the results are affected by the chemical composition of surface (?carbonate) concretions, since the samples dominated by heavy, white valves listed above do not produce consistently higher or lower ratios.

The increased variability in shell chemistry profiles below 792cm depth is matched by increased variability in ostracod valve characteristics. *C. torosa* is a euryplastic species which exhibits considerable morphological variation according to the ambient environmental conditions. Valve thickness and ornamentation (smooth, punctate or reticulate in oligosaline-hypersaline waters) is thought to vary with the carbonate equilibrium at the sediment-water interface, which is itself controlled by the rate of degradation of organic matter (Carbonel, 1988). Thus, the tendency for a greater diversity of morphotypes in samples below 792cm depth indicates more marked seasonal or longer-term fluctuations in parameters such as pCO_2 (Gasse *et al.*, 1987).

Although the relationships are complex, variations in valve characteristics and carbonate equilibria often correlate indirectly with the Mg:Ca ratio of the host waters (Peypouquet *et al.*, 1983). Thus, in a general sense, the correlation between increased variability in valve morphology and Mg/Ca values supports the significance of salinity in driving the shell-chemistry signal.

Mg:Ca ratios are also dependent upon temperature, and the most likely explanation for the scattering of Mg/Ca values compared to Sr/Ca values is that it reflects seasonal temperature variation. Marked seasonal and longer-term temperature variation has been suggested as an explanation for the lack of covariance of *C. torosa* shell chemistry profiles from Pleistocene deposits in Spain (Anadón *et al.*, 1994). The degree of seasonal variation represented depends on the life-cycle of the ostracod analysed since the occurrence of adult ostracods varies by genus from a single season to their presence throughout the year (Horne, 1983). The shell ratio itself is related to the time of shell secretion, that is, to periods of active growth.

In a 4-year study of its life-cycle in saline ponds of Belgium, Heip (1976) found that *Cyprideis torosa* has one generation per year which is effectively split into two, and results in the presence of adults throughout the year. Development is temperature-dependent and no development occurs in winter, such that the overwintering population comprises adults and large larvae of the same generation. New larvae are produced from the spring onwards and mature at different times up to the autumn, with a peak in the summer months. Since calcite is laid down rapidly when moulting occurs (Turpen & Angell, 1971), it can be deduced that the shell chemistry of overwintering adults is representative of the autumnal environment, and the shell chemistry of fossil *C. torosa* assemblages would reflect the chemistry of host waters in the period from spring to autumn, rather than the entire annual cycle as suggested by Anadón *et al.* (1994). The pattern of development is likely to be the same in Mediterranean Europe; Heip (1976) noted that a cold late summer was sufficient to cause the growth of larger larvae to be halted significantly earlier. Thus, although no critical temperature was calculated, Mediterranean winter temperatures are unlikely to be sufficiently high in comparison to alter this period of dormancy. This is supported by a general observation by Horne (1983) that Mediterranean brackish water ostracods tend to reproduce only in the warmer months. In Mediterranean climes salt lakes show highest variation in salinity during these months and it is feasible that significant seasonal variation is reflected in the scattering of Mg/Ca values, and may explain in part the greater variation overall of the Mg/Ca profile compared to the Sr/Ca profile.

The marked scattering of Sr/Ca values in some of the lower levels (1025-1012cm, 1001-1000cm, 937-936cm and 913-912cm depth) compared to levels above 744cm depth could indicate rapid salinity fluctuation in an unstable environment. Since each of the samples represents a time period of several years, the fluctuation could reflect seasonal or slightly longer-term variation in salinity, although spatial variability may also be incorporated since it occurs in parts of the sequence where *C. torosa* is relatively rare and less likely to be *in situ* than a sample from a fossil assemblage where it is abundant.

The reduced variability of the Sr/Ca profile overall could be partly a function of its truncation by the co-precipitation of Sr with aragonite. This has been inferred in other studies of fossil assemblages from lakes whose water chemistry is dominated by minerals other than NaCl (De Deckker & Forester, 1988, Chivas *et al.*, 1993 in Australia, Engstrom & Nelson, 1991, Fritz *et al.*, 1994 in North America, Anadón

& Julià, 1990 in Spain) and has been supported in some cases by mineralogical analysis of carbonate species.

Kelts & Hsü (1978) suggest the Mg/Ca ratio of the lake water controls the carbonate phase precipitated in freshwater lakes, and Mg/Ca ratios tend to rise with salinity. For a ratio of c. 2-12, Mg-calcite or aragonite are the primary precipitates and correspond to Mg-calcite or dolomite sedimentary phases, whilst at ratios >12 aragonite is the primary precipitate and dominant sedimentary constituent. Aragonite precipitates at salinity >10 gl^{-1}, Mg/Ca >12, in Lake Valencia, Venezuela (Bradbury *et al.*, 1981).

The brine composition of the Laguna de Medina is currently $Na-Mg-Cl-SO_4$. From patterns of brine evolution (Eugster & Hardie, 1978), this type of brine tends to be associated with gypsum precipitation in Mg+Ca-rich systems where Mg>>Ca. The Mg/Ca ratio of the lake waters is currently only c. 2, but a major change in sediment accumulation patterns has occurred, and the abundance of gypsum and carbonate in levels below perhaps suggests the greater likelihood here of aragonite precipitation, either as an inorganic precipitate or in molluscan aragonite. The pale yellow lamina at 934-932cm, for example, corresponds to a carbonate peak and is a typical product of aragonite precipitation in salt lakes where gypsum is precipitating (Last & Schweyen, 1985, Kennedy, 1994). This could be determined absolutely by X-ray diffraction, which would also establish whether the record is affected by other changes in mineral phases. A Sr mineral, celestine, is a common precipitate in saline lakes of La Mancha, for example (Marfil *et al.*, 1975).

The reliability of palaeosalinity reconstruction can also be affected by the ecological tolerance range of the ostracod. Engstrom & Nelson (1991) suggested the profiles for *Candona rawsoni* in the Great Plains of North America were truncated in portions of the sequence where the salinity tolerance of the ostracod had been exceeded. *Cyprideis torosa* can tolerate fresh waters but tends to be found only at salinities of > 5 gl^{-1} in both Europe and Algeria, so it is possible that evidence for low-salinity phases is missing. In other respects it has the advantage of being extremely euryhaline; it occurs in European waters of salinity up to 60 gl^{-1} (De Deckker, 1981) and in Algerian waters up to c. 30 gl^{-1} (Gauthier, 1928b).

7.4.5 Interpretation

Despite these complicating factors, the main trends are common to both profiles and may therefore reflect palaeosalinity change. This has not been the case in some other studies where palaeosalinity interpretation may be less reliable (e.g. Anadón & Julià, 1990, Anadón *et al.*, 1994, Palacios-Fest *et al.*, 1994).

The sequence overall is characterised by more marked salinity fluctuation below 792cm depth, particularly in the samples where Sr/Ca values are scattered; this is supported by the increased variability in ostracod valve morphology in this section, which is indicative of short-term fluctuations in chemical conditions, including salinity.

When the likelihood of Sr/Ca truncation is taken into account, the relatively minor peaks at 1025-1012cm, 943-916cm, fluctuating high-low values between 817-792cm depth, and a minimum and smaller peak at 753-752cm and 749-748cm respectively can be interpreted tentatively in terms of relative salinity change.

7.5 PALAEOECOLOGY OF CALCAREOUS MICROFOSSILS, MOLLUSCS AND PLANT MACROFOSSILS

7.5.1 Introduction

This section deals with the palaeoecological interpretation of ostracods, foraminifera, molluscs and plant macrofossils. As in Chapter 6, criteria for palaeosalinity interpretation are dealt with separately prior to other palaeolimnological inferences which are relevant to the independent reconstruction of lake levels.

7.5.2 Results

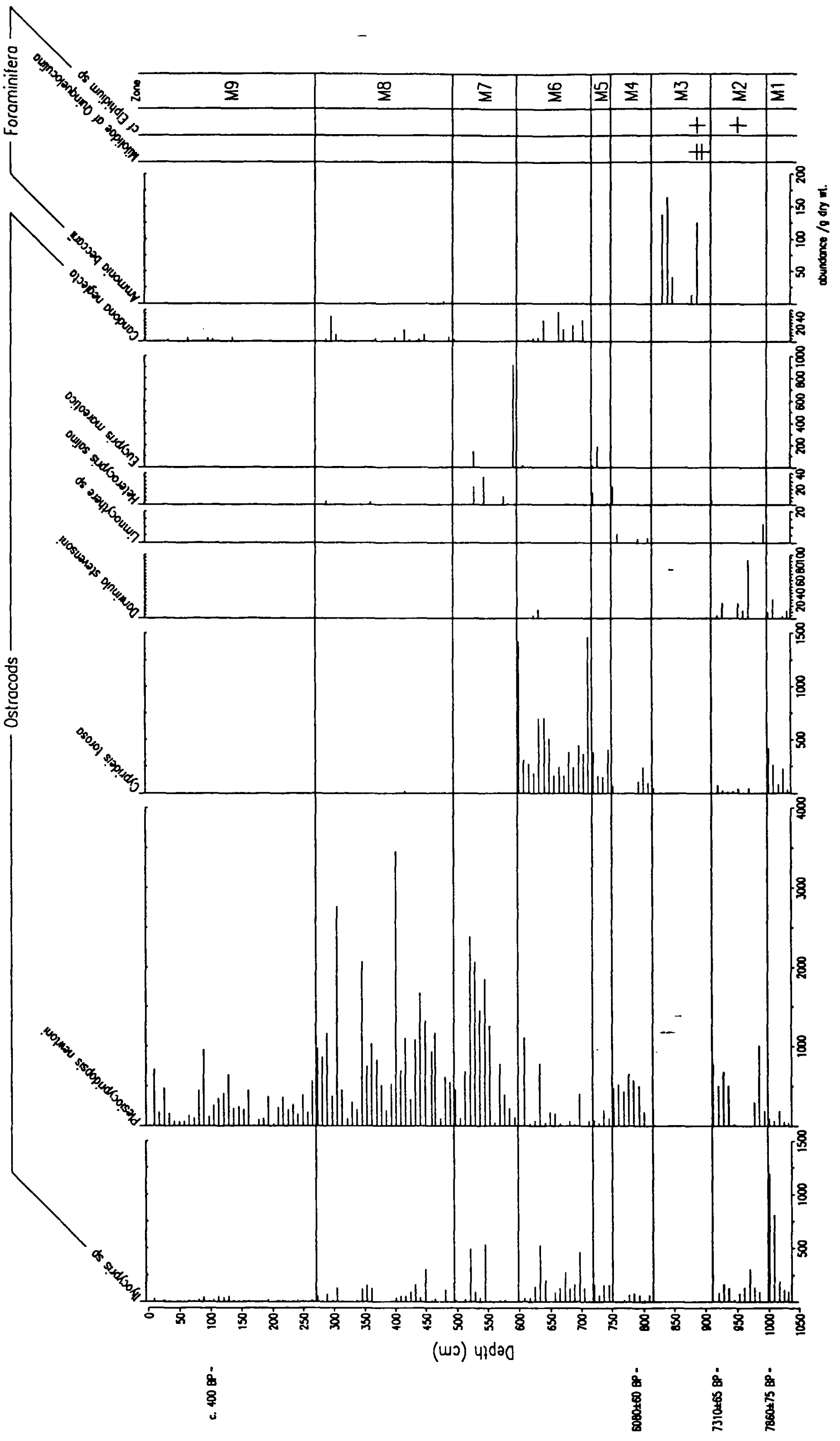
The abundance diagram for ostracods and foraminifera is given in Figure 7.6, and the diagram for molluscs and plant macrofossils in Figure 7.7. Taxa are ordered according to their first appearance from the base of the sequence upwards. Abundance is expressed as the number of single valves or shells per g dry weight for ostracods, foraminifera and molluscs, and seed abundance as the number per 5g dry weight.

The diagrams are considered together and are divided into 9 biostratigraphic zones on the basis of changes in the fauna and flora, as follows.

***Zone M1:** 1033-1000cm (to c. 7860 BP)*

Zone M1 is dominated by the ostracods, *Ilyocypris* sp. and *Cyprideis torosa*, with low frequency of *Plesiocypridopsis newtoni* and *Darwinula stevensoni*. Other remains are rare; seeds of *Potamogeton pectinatus* occur sporadically and a charcoal-rich lamina at 1001-1000cm depth contains abundant chenopod seeds.

Figure 7.6 The Laguna de Medina: ostracod and foraminifera percentage abundance diagram.



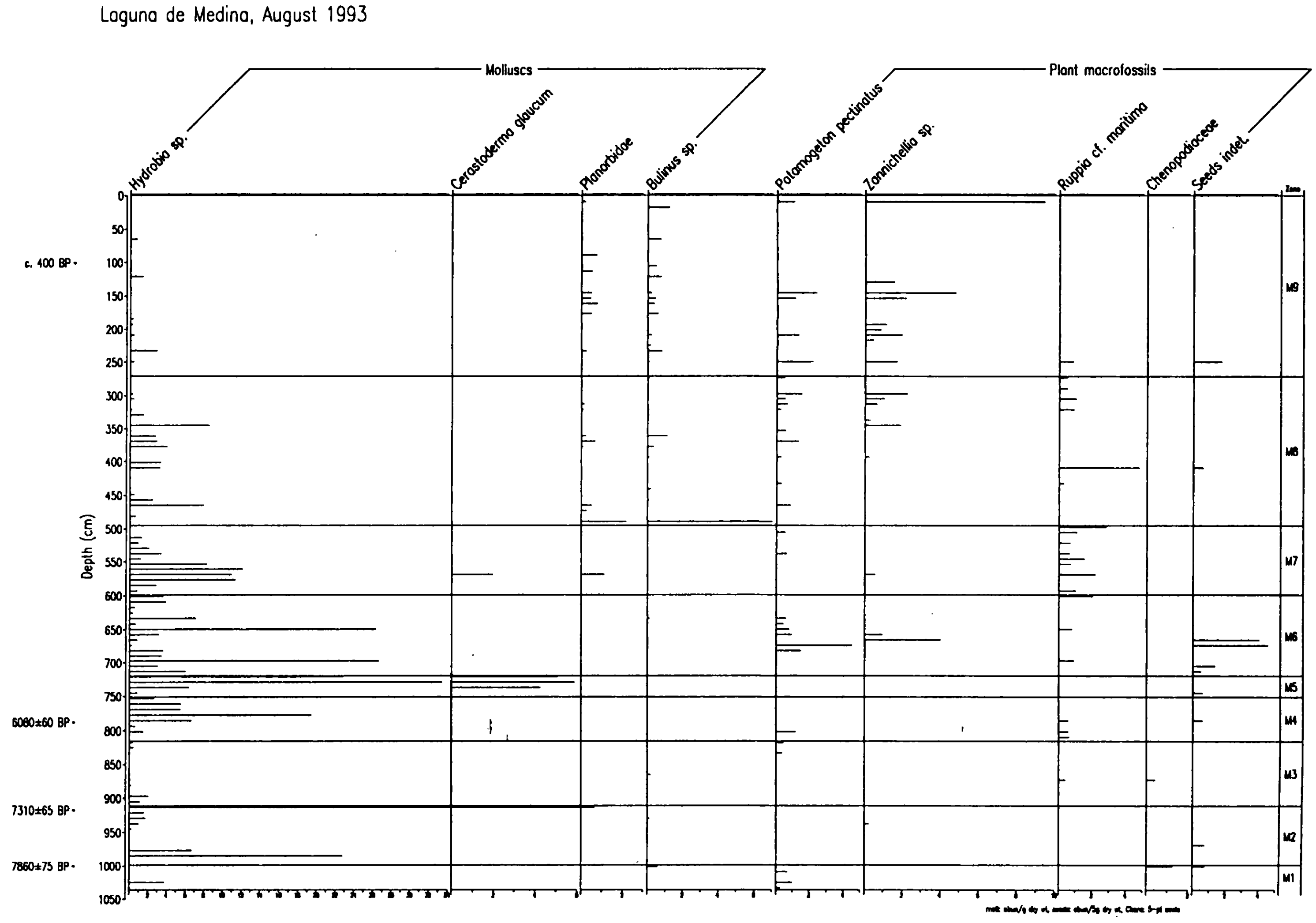


Figure 7.7 The Laguna de Medina: mollusc and plant macrofossil abundance diagram.

Zone M2: 1000-912cm (c. 7860-7310 BP)

Zone M2 is variable. The ostracod, *Ilyocypris* sp. continues to be relatively abundant throughout, whilst the lower and upper zone is dominated by *P. newtoni*. *D. stevensoni* reaches its maximum abundance in the middle zone, where *P. newtoni* is absent and *C. torosa* relatively rare. Juveniles of the gastropod, *Hydrobia* sp., occur sporadically but at high abundance in the 'mollusc lamina' at 986-985cm and in the white lamina at 913-911cm depth.

Zone M3: 912-816cm (c. 7310 at base)

Ostracods are absent in Zone M3. Two peaks of the foraminifera, *Ammonia beccarii*, occur between 889-880cm and 849-824cm depth and they are rare from 905-896cm. Remains of wood or ligneous roots c. 0.5cm wide are abundant from 921-916cm depth. All other organic remains are rare.

Zone M4: 816-752cm (undated transitions; top <6000 BP)

Ostracod assemblages of Zone M4 are dominated by *P. newtoni*. *Ilyocypris* sp. occurs at low frequency throughout, and *C. torosa* in the lower zone. The ostracod, *Limnocythere* sp. is present in this zone. *Hydrobia* sp. is relatively abundant throughout.

Zone M5: 752-720cm

Ostracod assemblages of Zone M5 are dominated by *C. torosa*, relatively high abundance of *Ilyocypris* sp., and low frequency of *Heterocypris salina*. *P. newtoni* is relatively rare throughout. The gastropod, *Hydrobia* sp. and juvenile shells of the bivalve, *Cerastoderma glaucum*, are abundant in well-defined bands in this zone.

.Zone M6: 720-600cm

There is no significant change in the dominant ostracods of Zone M6 compared to Zone M5, but there is a change to the absence of *H. salina* and the consistent presence of *Candona neglecta*. *Hydrobia* sp. is again very abundant in some samples. In contrast to Zone M5, *Cerastoderma glaucum* is absent and seeds of *Potamogeton pectinatus* are abundant in the mid-zone.

Zone M7: 600-496cm

Above the basal sample, which is dominated by the abundant ostracod, *Eucypris mareotica*, Zone M7 is characterised by well-preserved and abundant assemblages of *P. newtoni*, with the sporadic occurrence of *Ilyocypris* sp. and *H. salina*. *C. torosa* is absent. The abundance of the mollusc, *Hydrobia* sp. decreases towards the top of the zone. In contrast to the rest of the sequence, seeds of *Ruppia* cf. *maritima* are present consistently at relatively high abundance.

Zone M8: 496-272cm

The dominant ostracod fauna is unchanged compared to Zone M7, but *C. neglecta* rather than *H. salina* is present at low frequency. *Hydrobia* sp. is present at low frequency, along with the sporadic occurrence of the molluscs, planorbs and *Bulinus* sp. *R.* cf. *maritima* occurs sporadically in this zone, whilst *P. pectinatus* and, in the upper zone, *Zannichellia* sp., are present consistently.

Zone M9: 272-0cm

Ostracods are less abundant and poorly-preserved compared to Zone M8, particularly above 100cm depth where few biogenic remains are preserved. Ostracods other than *P. newtoni* occur intermittently at very low frequency. *Hydrobia* sp. is rare; planorbs and *Bulinus* sp. are also rare but are present more consistently than in Zone M8. *Zannichellia* sp. and *P. pectinatus* are relatively abundant to c. 150cm depth.

7.5.3 Criteria for palaeolimnological interpretation of palaeosalinity and ionic composition

7.5.3.1 The use of published ecological data

The apparent salinity preferences of different taxa are geographically variable. In discussing ostracod ecology, De Deckker (1981) suggests this is due to the connection between salinity tolerance and osmoregulation, since the latter depends on a variety of parameters such as temperature which differ between regions. There is also strong evidence that ostracod salinity tolerances are dictated more by brine composition than by salinity *per se* (Forester, 1983, 1986, Carbonel & Peypouquest, 1983, Cohen *et al.*, 1983, Santamaría *et al.*, 1992, Smith, 1993) which, again, shows significant regional differences. For other biota, the literature points to marked differences in salinity tolerances of apparently identical plant species between Europe and Australia, for example (Hammer, 1986).

Since palaeosalinity interpretation is based on reported salinity preferences, emphasis is given, as for diatom analysis, to ecological data derived from Spain and similar environments of North Africa (or, where necessary, Europe) rather than from geographically-remote regions. In the case of ostracods, this is supported by the status of the Iberian fauna as transitional between that of North Africa and Europe (Baltanás, 1992). Since salinity tolerance is related to brine composition, the interpretation of ionic preferences is also included here.

7.5.3.2 Taphonomy

Calcareous microfossils and molluscs are well-preserved in many samples from all zones except Zone M9. In Zone M9 valves of the fragile ostracod, *Plesiocypridopsis newtoni*, are highly fragmented, which indicates a relatively high-energy environment or exposure prior to deposition (De Deckker, 1988b). As a corollary, the preservation of abundant, intact carapaces of *P. newtoni* in Zones M4-M8 in particular indicates they are likely to reflect deposition from an *in situ* population in a low-energy environment which underwent rapid burial after death. The valve hinge of *Cyprideis torosa* is robust and intact carapaces were found wherever they occurred. *In situ* deposition is indicated similarly for the bivalve, *C. glaucum*, whose narrow-hinged shells were intact, and for the foraminifera, *Ammonia beccarii*, due to its abundance and good preservation.

For *Hydrobia* sp., studies in Australia have shown that mollusc shells tend to accumulate on or near the shoreline and may be reworked, but are usually sparse on dry lake-beds (Chivas *et al.*, 1986c).

Although ostracod instars were not counted separately, a full range including adults occurs in many samples, of the dominants, *P. newtoni*, *C. torosa* and *Ilyocypris* sp.; this supports their status as derived from *in situ* populations (Whatley, 1988). The extreme rarity of *C. torosa* valves in Zone M3 (such that they are not represented on the diagram), is combined with an absence of adults and indicates selective transport from elsewhere. Adults of other ostracods are rare or absent, and of the molluscs, *Cerastoderma glaucum*, *Bulinus* sp. and planorbids. This indicates either selective transport, or sub-optimal conditions for growth. In the case of ostracods, all except *Candona neglecta* are relatively fragile and their good preservation suggests that if they had undergone transport, it would not have been far (or for long), and supports the interpretation of assemblages as representative of local palaeoenvironmental conditions over a short timespan.

Rapid seasonal fluctuations in water chemistry or other limnological variables are indicated if conditions for growth were sub-optimal for these ostracod taxa. Although *Darwinula stevensoni* has a 3-4 year life-cycle (McGregor, 1969), most ostracods of inland lakes reproduce rapidly in the warmer months and produce 2-3 generations per year (Horne, 1983).

Ostracod abundance is difficult to interpret in other respects since it depends also on other factors such as sediment accumulation rate and the rate of shell moulting. Ostracods are more abundant (often >1000 valves/g) in assemblages dominated by *P. newtoni*, whereas well-preserved microfossil assemblages dominated by other taxa tend to reach a maximum abundance of around 500 valves/g.

Seed abundance also depends on the production and dispersal patterns of different plants. Davis (1994) observes that most aquatics of saline lakes can reproduce vegetatively; sexual reproduction is thought to be an adaptation to stress, and seeds may be most abundant when a lake dries or when other limnological conditions are not optimal for growth, within the span of their life-cycles which in this study is 3-5 months.

7.5.3.3 Interpretation of characteristic assemblages

Table 7.3 gives a summary by region of reported salinity tolerances and optima, and ionic preferences, for the taxa found in the Laguna de Medina core. Since seeds are not abundant in the core, and their palaeosalinity ranges are not well-defined, the emphasis is on the interpretation of assemblages of calcareous microfossils and molluscs. Characteristic fossil assemblages can be interpreted as follows.

Table 7.3 **Regional comparison of reported salinity tolerance ranges ('TOL'), optima ('OPT') and ionic preferences of Laguna de Medina fossil ostracods, foraminifera, molluscs and plant macrofossils. [Salinity ranges translated from conductivity; fr=fresh, oligo=oligosaline.]**

SPECIES	**REPORTED SALINITY TOL. [OPT.] IN gl^{-1} TDS**			**SUMMARY**	**IONIC COMP.**	**COMMENTS**	**REFERENCES**
	Spain	**N. Afr./ Canaries**	**Europe/Russia/ (other)**				
Ilyocypris sp.				?	?NaCl-rich	Camargue salt pan c. 50 gl^{-1}; at low frequency with abundant foraminifera; ?allochthonous	Zaninetti & Tetart (1982)
Plesiocypridopsis newtoni	<0.5-15.7 g/l [<10]	[fr-oligo]	0.3-15.7	euryhaline	high SO_4:Cl		Marazanof (1967), Armegnol *et al.* (1975), Gasse *et al.* (1987), Bronshtein (1947), De Deckker (1981)
Cyprideis torosa	6.7-140		6->60 (140)	extremely euryhaline	Na-Mg-Cl	Euro. tolerance range for smooth-shelled morphotypes	Carbonnel & Truc (1983), Neale (1988), Anadón *et al.* (1986), Carbonel & Peypouquet (1983)
Darwinula stevensoni	[0.75 gl^{-1} Cl]		0.6-15 [0-2]	fresh water	CO_3-rich	tolerates higher salinity, but reproduction only at 0-2 gl^{-1} TDS	Margalef (1953), De Deckker (1981), Carbonel & Peypouquet (1983)
Heterocypris salina	opt. in 'saline' water	0.4-6.2 [oligo]	<0.5-60 [5-10]	euryhaline	NaCl-rich	least tolerance to fresh waters; abund. at >25 gl^{-1} in Germany	Margalef (1953), Meisch & Broodbakker (1993), Ganning (1971), Hammer (1986)
Eucypris mareotica	10-80	5-30	2.8-110	extremely euryhaline	NaCl-rich		Martino (1988), Baltanás *et al.* (1990), Baltanás (1992), Gauthier (1928b), De Deckker (1981)
Candona neglecta	8-15.7		0-15				Marazanof (1967), Neale (1988)
Ammonia beccarii		2-70 [13-40]		euryhaline	NaCl-rich	reproduction at 13-40 gl^{-1}	Bradshaw (1957)
Hydrobia sp.		0.5-25		euryhaline			Hammer (1986)
Cerastoderma glaucum		3-90 [25-45]		extremely euryhaline	NaCl-rich, tol's Ca:Mg variation		Gaillard & Testud (1980), Rosso & Gaillard (1982), Gasse *et al.* (1987)
Planorbs/*Bulinus* sp.				fresh water		can tolerate oligosaline waters	Gasse *et al.* (1987), Anadón *et al.* (1994)
Myriophyllum spicatum	?to 20		0-4	?		low reported Euro salinity tol., but abund. in BCCA in Spa. data-set	Ubierna León *et al.* (1992), Stevenson *et al.* (1993)
Potomageton pectinatus	3-40 [<20]		0-55 [<20]		cosmopolitan		Davis (1994), Hammer (1986)
Ruppia maritima	<20->100 [20]		0-66 (global)		NaCl-rich		Cirujano *et al.* (1990), Comín & Alonso (1988), Hammer (1986)
Zannichellia sp.	c. 7->30 [<20]^1		c. 2-15 (N. Am)^2			^{1} *Z. obtusifolia*, ^{2} *Z. palustris*	Davis (1994), García Murillo (1991), Birks (1973)

Assemblage 1: dominated by *Cyprideis torosa*

Cyprideis torosa rarely occurs as the dominant of monospecific assemblages. It tends to be accompanied by other taxa at low frequency, which comprise the entire range of ostracods other than *Eucypris mareotica*, or is a co-dominant with *Ilyocypris* sp. The taxon is extremely euryhaline, but the smooth- or punctate-shelled morphotypes tend to be restricted to saline waters of >6 gl^{-1} (Anadón *et al.*, 1986), in estuarine or limnic environments undergoing seasonal salinity fluctuation. Its single dominance probably indicates relatively higher salinity (mesosaline-eusaline) than its co-dominance with *Ilyocypris* sp.; this is supported by its co-occurrence with the extremely euryhaline bivalve with a preference for polysaline-eusaline waters, *Cerastoderma glaucum*, but for which conditions were sub-optimal.

Its co-dominance with *Ilyocypris* sp. probably indicates oligosaline-mesosaline conditions. The salinity tolerance of the latter is unknown, but other species of the genus tend to be restricted to fresh or slightly saline (<5 gl^{-1}) waters (De Deckker, 1981); it also reaches highest relative abundance in assemblages with low frequency of *Darwinula stevensoni*, a fresh water species found in fresh or slightly oligosaline waters. This is supported by the occurrence of *C. torosa*, *Ilyocypris*, *Darwinula stevensoni* and *Limnocythere* in assemblages of the oligosaline Lake Tiberias, Israel (Neale, 1988). Most other taxa have optima or tolerance ranges not exceeding c. 15-20 gl^{-1}, which is more suggestive of mesosaline conditions, however. A mixture of species with differing salinity tolerances is common in salt lake assemblages (Anadón *et al.*, 1994); as noted above, this could reflect selective transport, but is more likely a reflection of a seasonal succession of ostracods responding to rapid salinity change caused by brine concentration during the summer months, or by the influx of fresh waters during storm events, for example.

The taxa in these assemblages all have a preference for NaCl-rich waters. Anadón (1992) suggests *Cyprideis torosa* and *Cerastoderma glaucum* (with *Ammonia beccarii*) tend to occur together where $Cl:SO_4 > 2\text{-}27$.

Assemblage 2: dominated by *Ammonia beccarii*

The foraminifer, *Ammonia beccarii*, is abundant in monospecific assemblages which are virtually devoid of all other palaeoecological remains. The taxon is extremely euryhaline but tends to be abundant when salinity approaches that of seawater, in the eusaline range (De Deckker & Geddes, 1980, Cann & De Deckker, 1981). It is taken as an indicator of mesosaline-eusaline waters rich in NaCl.

Table 7.4 Regional summary of relevant ecological data, other than salinity preferences, for common Laguna de Medina fossil ostracods, foraminifera, molluscs and plant macrofossils.

SPECIES	LIFE-CYCLE (generations per yr/time)	TOLERANCE TO ANNUAL DESICCATION	TURBIDITY TOLERANCE	OTHER HABITAT PREFERENCES	LIFE-HABIT	REFERENCES
Plesiocypridopsis newtoni	2 /yr	High	?High	Oxygen >25%, slow-flowing or still waters (lakes, reservoirs, wells, muddy swamps)	Benthic grazer on vegetation, or free-swimming at water surface	Gauthier (1928a), Margalef (1953)
Cyprideis torosa	1 /yr	Low		Slack, unstable waters (marine estuarine, coastal lagoons and inland salt lakes, ditches etc.). Mud, sandy mud (or on algae).	Grazer to max. c. 30m depth in marine environments	Kilenyi & Whittaker (1974)
Darwinula stevensoni	3-4 yrs	Low	Very low	Still, clear water. Soft muddy sediment rich in detritus eg. marginal reed-beds	Shallow benthos, grazer and burrower	Bronshtein (1947), Griffiths & Butlin (1994)
Heterocypris salina	2-3 /yr	Low		Coastal lagoons, rockpools and inland lakes (and slow-flowing rivers)	Shallow benthos, grazer	Ganning (1971), Meisch & Broodbakker (1993)
Eucypris mareotica		High		Coastal marshes, inland salt lakes	Shallow benthos, grazer	Gauthier (1928b)
Candona neglecta		Very high		Slow-flowing water, esp. lakes fed by springs. Fine substrate rich in detritus.	Shallow benthos, grazer (subterranean in other assemblages)	Bronshtein (1947), Absolon (1973), Holmes (1992)
Ammonia beccarii	<< 2 months	Low		Marine estuarine, coastal lagoons and inland salt lakes		Cann & De Deckker (1981)
Hydrobia sp.				Shallow, swampy environments	Grazer in littoral zone	Gasse *et al.* (1987)
Cerastoderma glaucum				Marine estuarine, coastal lagoons and inland salt lakes	Littoral benthos	Plaziat (1991, 1993)
Planorbs/*Bulinus* sp.				Shallow, swampy environments	Grazers in littoral zone	Gasse *et al.* (1987)
Pot. pectinatus	5 months		Very high	Depth range c. 0.4-4m; tendency to produce seed only in waters <2m deep		Review in Davis (1994)
Ruppia maritima	3-4 months	Low	Low	Depth range c. 0.1-1.5 (7) m		Review in Davis (1994)
Chara sp.	3 months		Low	Depth range c. 0.1-6 (10) m	Pioneer species	Review in Davis (1994), Gasse *et al.* (1987)

Assemblage 3: dominated by *Plesiocypridopsis newtoni*

This ostracod dominates assemblages where *C. torosa* is absent. It has a lower salinity optimum (<10 gl^{-1}) and tolerance range and is often found in oligosaline waters. Based on patterns of brine evolution, an interpretation of relatively low salinity (oligosaline-mesosaline) is supported by its preference for waters higher in sulphate than chloride, and also by its dominance in the Laguna de Medina today.

7.5.4 Criteria for independent interpretation of lake-level change

The biotic remains provide other palaeoecological information, which is summarised in Table 7.4. In general, most of the biota are characteristic of the littoral zone, which indicates conditions were relatively shallow (<c. 10m depth) throughout (Gasse *et al.*, 1987). The ostracods are grazers apart from *P. newtoni*, which can swim freely at the water surface (Margalef, 1953) and could be distributed more widely in lake waters.

Ostracods, foraminifera and aquatic plants can be indicators of lake permanence, which may correlate with lake level. Eggs of the ostracod superfamilies, Darwinuloidea and Cytheroidea, cannot withstand desiccation, whereas those of the other group inhabiting inland waters, the Cypridacea, are drought-resistant and are dominant in ephemeral lakes (De Deckker, 1988b). In this data-set indicators of permanent waters comprise *D. stevensoni*, *C. torosa* and *Limnocythere* sp; all others are cyprids. *D. stevensoni* has been found rarely in seasonal waters (Bronshtein, 1947). Although *C. torosa* can recolonise a lake rapidly after its refilling (E. Robinson, pers. comm.), and has some resistance to desiccation due to the brood-care of eggs (Kilenyi & Whittaker, 1974), this interpretation is supported by the restriction of *C. torosa* to permanent water bodies in the Spanish data-set, and by a comprehensive survey of ephemeral, inland waters of Spain which showed them to be inhabited entirely by cyprids (Baltanás *et al.*, 1990). *C. torosa, Eucypris mareotica* and *Heterocypris salina* tend to inhabit permanent salt lakes of Algeria, whereas temporary waters are inhabited solely by *Eucypris* spp. (Gauthier, 1928b). *Ammonia beccarii* is similarly indicative of permanent waters (Cann & De Deckker, 1981).

Carbonel (1988) also notes shallow, unstable waters are characterised by subrectangular to elongate, slightly sub-triangular species, whereas permanent waters tend to be inhabited by rectangular species, a distinction which applies in separating *C. torosa* (permanent) from *Plesiocypridopsis newtoni* (ephemeral).

As a continuing theme, the separation is unlikely to be absolute; *P. newtoni*, a cyprid, is known to inhabit permanent waters (Bronshtein, 1947). It is feasible that 'semi-permanent' waters which retain water for several years at a time could contain ostracods of any superfamily, although *P. newtoni* dominates in the semi-permanent conditions currently prevailing in the Laguna de Medina. *P. newtoni* and *C. torosa* have already been identified as indicators of sulphate versus chloride waters, and it is possible water chemistry variables are more important in determining their relative proportions.

Of the aquatic plants, *Ruppia maritima* has a life-cycle of 3-4 months and in Spain tends to inhabit permanent or semi-permanent water bodies which retain water for several years at a time, whereas it is outcompeted by another species, *R. drepanensis*, in ephemeral waters (Cirujano Bracamonte, 1990). The third *Ruppia* species of Spanish waters, *R. cirrhosa*, is worthy of note since the identification of *R.* cf. *maritima* is tentative pending comparison with reference material, but this taxon is also confined to permanent or semi-permanent waters (Amat, 1984). In general, all these plants can colonise lakes successfully in a single season (Fernández-Palacios, 1990) and the presence of seeds does not necessarily indicate extended high-stands; their tendency to produce seed in times of stress as a lake dries was mentioned above and suggests the record can be ambiguous on its own.

Bands of *Cerastoderma glaucum* are preceded in all cases by thin gypsum bands in the core. They tend to occur in the littoral zone, with salt-tolerant gastropods (Plaziat, 1991), as in this study, and are an indicator of temporary low-stands. Very abundant *Hydrobia* laminae could be interpreted similarly, but their occurrence is not linked to gypsum bands and the massive mortality may reflect other rapid changes in limnological conditions.

An interpretation of *P. newtoni* as indicative of more ephemeral waters is supported to some extent by its reported tolerance to turbidity, which correlates with lake permanence in this study. It is common in muddy swamps and artificial water bodies of North Africa (Gauthier, 1928b). Its preference for well-mixed, oxygen-rich waters (Lindroth, 1956 in Gasse *et al.*, 1987) is supported by Margalef (1953), who found it restricted to still or slow-flowing Spanish waters with relatively low levels of organic matter and high oxygen (>25%). Its occurrence in the lake today indicates it can support relatively high levels of turbidity. It was interpreted as indicative of more turbid waters in comparison with *D. stevensoni* in a fossil sequence from Lake Bogoria, Kenya (Carbonel & Peypouquet, 1983), although in this case the very low tolerance of *D. stevensoni* to water agitation (Griffiths & Butlin, 1994) suggests the comparison cannot necessarily be extended to other ostracods in the Laguna de Medina sequence. The turbidity tolerance of *Cyprideis torosa* is not known.

Davis (1994) notes a reported difference in turbidity tolerance between the aquatics, *Potamogeton pectinatus* (very high), and *Ruppia maritima* (low).

7.5.5 Interpretation of palaeosalinity and lake-level change

As in the diatom analysis, the sequence is interpreted both in terms of palaeosalinity and lake level (high versus low). As noted above, it is inferred that the lake was relatively shallow (<10m depth) throughout.

Zone M1 **(1033-1000cm; to c. 7860 BP)**

Salinity: OLIGOSALINE-MESOSALINE

Lake level: HIGH, FOLLOWED BY DRY EPISODE

The *Cyprideis* + *Ilyocypris* assemblages, with associated *D. stevensoni*, indicate oligosaline-mesosaline and permanent waters. The peak in chenopod seeds at the top of the zone indicates the drying-out of the lake, since this family comprises terrestrial genera such as *Salicornia* species which inhabit damp ground on the lake margins. *Salicornia* species occupy permanently an extensive, flat shoreline to the southwest of the modern lake, and colonise the entire lake-bed during the summer months in drought years. It is likely that during periods of higher lake levels in the past, the southwestern shoreline was much reduced in extent.

Zone M2 **(1000-912cm; c. 7860-7310 BP)**

Salinity: ?OLIGOSALINE-MESOSALINE

Lake level: LOW-?-LOW

Zone M2 is variable; the dominance of *P. newtoni* at the base and top of the zone indicates oligosaline-mesosaline salinity. Assemblages at the centre of the zone are dominated by *Ilyocypris* sp., with the highest abundance of *D. stevensoni* encountered, for which salinity interpretation is uncertain. An interpretation of lowered salinity is not supported by the low abundance and diversity of the assemblages (cf. De Deckker & Forester, 1988) and, in this case, it is possible valves were transported from elsewhere such as a marginal swamp environment.

Increased ephemerality is inferred from the *P. newtoni* samples but the centre of the zone is difficult to interpret. This is supported by the 0.5cm-diameter ligneous fragments within the section 921-916cm depth, which probably derive from the stems or roots of shoreline plants and could indicate the drying of the lake at the top of the zone; roots of aquatics such as *Ruppia* are much thinner in comparison (<5mm; De Deckker, 1988b).

***Zone M3* (912-816cm; c. 7310 at base)**

Salinity: MESOSALINE-EUSALINE IN MID-ZONE
Lake level: ?LOW WITH ABRUPT HIGH STANDS

Zone M3 is characterised by assemblages of abundant, monospecific *Ammonia beccarii*; these are not present consistently, and are therefore interpreted in terms of intermittent mesosaline-eusaline salinity in short-lived high-stands of 'permanent' waters. The zone otherwise is remarkably devoid of ostracods, molluscs and plant macrofossils throughout. Since the absence of biota from the littoral zone is unlikely to reflect a state of extreme, deep waters, the zone is interpreted highly tentatively in terms of predominantly low lake levels and prolonged exposure.

***Zone M4* (816-752cm)**

Salinity: OLIGOSALINE-MESOSALINE
Lake level: LOW

Zone M4 is dominated by *P. newtoni*, which is interpreted as above in terms of oligosaline-mesosaline salinity in a relatively ephemeral environment.

***Zone M5* (752-720cm)**

Salinity: MESOSALINE-EUSALINE
Lake level: HIGH, WITH PERIODIC DESICCATION

The dominance of *Cyprideis torosa* and bands of the bivalve *Cerastoderma glaucum* in Zone M5 indicate mesosaline-eusaline conditions. This indicates a phase of predominantly permanent waters and relatively high lake levels, with periodic desiccation indicated by the mollusc beds.

***Zone M6* (720-600cm)**

Salinity: PREDOMINANTLY MESOSALINE; FLUCTUATING OLIGOSALINE-MESOSALINE, MESOSALINE-EUSALINE
Lake level: HIGH

C. torosa reaches maximum abundance in Zone M6. Fluctuations in the relative proportions of *C. torosa* and *Ilyocypris* sp. (and *Candona neglecta*) probably indicate fluctuations in salinity between mesosaline, and oligosaline-mesosaline. Its intermittent dominance in monospecific assemblages indicates temporary phases of higher salinity. This is supported in mid-zone by the consistent presence of the aquatic plant, *Potamogeton pectinatus*.

On the basis of *C. torosa*, permanent waters and relatively high lake levels can be inferred.

Zone M7 **(600-496cm)**

Salinity: OLIGOSALINE-MESOSALINE

Lake level: ?INTERMEDIATE BETWEEN ZONES M6 and M8

Salinity interpretation is based on the dominance of *P. newtoni*. This could indicate increased ephemerality and turbidity compared to Zone M6, but is contradicted by the consistent presence of the permanent-water aquatic with a low tolerance to turbidity, *Ruppia* cf. *maritima*. The terms 'ephemeral' and 'turbid' are not defined quantitatively, and the zone is best interpreted in comparison with Zone M8 as part of a longer-term trend, as given below.

Zones M8 & M9 **(496-0cm)**

Salinity: OLIGOSALINE-MESOSALINE

Lake level: LOW

The ostracod fauna is little changed in Zones M8 and M9, and salinity is interpreted as for Zone M7. The replacement of *R.* cf. *maritima* by *Potamogeton pectinatus* indicates increased turbidity relative to Zone M7. When combined with the fragmentation of valves in Zone M9, the evidence supports a long-term trend in Zones M6-M9 of increasing ephemerality.

7.5.6 Summary

A phase of relatively low salinity (oligosaline-mesosaline) and high lake levels characterises the start of the sequence, in Zone M1 (1033-1000cm depth, c. 7860 BP at upper transition).

Zones M2-M4 (1000-752cm depth, c. 7860 BP to <6000 BP) are interpreted in terms of low, fluctuating lake levels. Zones M2 and M4 are oligosaline-mesosaline, and higher salinity (mesosaline-eusaline) is exhibited in Zone M3. The interpretation of assemblages of mid-Zone M2 and of M3 is tentative due to unusual ostracod species assemblage composition on the one hand, and scarcity of remains on the other.

There is a transition to high salinity (mesosaline-eusaline) and lake levels in Zone M5 (752-720cm depth). An overall trend towards decreasing salinity and lake levels is exhibited thereafter, to oligosaline-mesosaline salinity and low lake levels in Zones M8 and M9, and plant macrofossil and taphonomic evidence for increased ephemerality in Zone M9.

7.6 THE POLLEN RECORD

7.6.1 Introduction

In this section, additional palaeolimnological data provided by the pollen of shoreline and aquatic taxa is considered, but the main emphasis is on palynological evidence for human impact on the catchment vegetation derived from the terrestrial pollen and charcoal records.

It is often a matter for debate as to whether past vegetation changes are related primarily to climate change, anthropogenic disturbance, or a mixture of both. However, pollen analysis is not a priority in this study, and terrestrial pollen is used here mainly as an indicator of the possible impact of human disturbance on the system, independent of climate change. In the Mediterranean region, charcoal could derive from either natural or human-induced burning, and is used as supporting evidence.

Thus, the pollen record is used as a means of identifying parts of the palaeolimnological sequence where palaeoclimatic inferences based on past lake-level change may be least reliable.

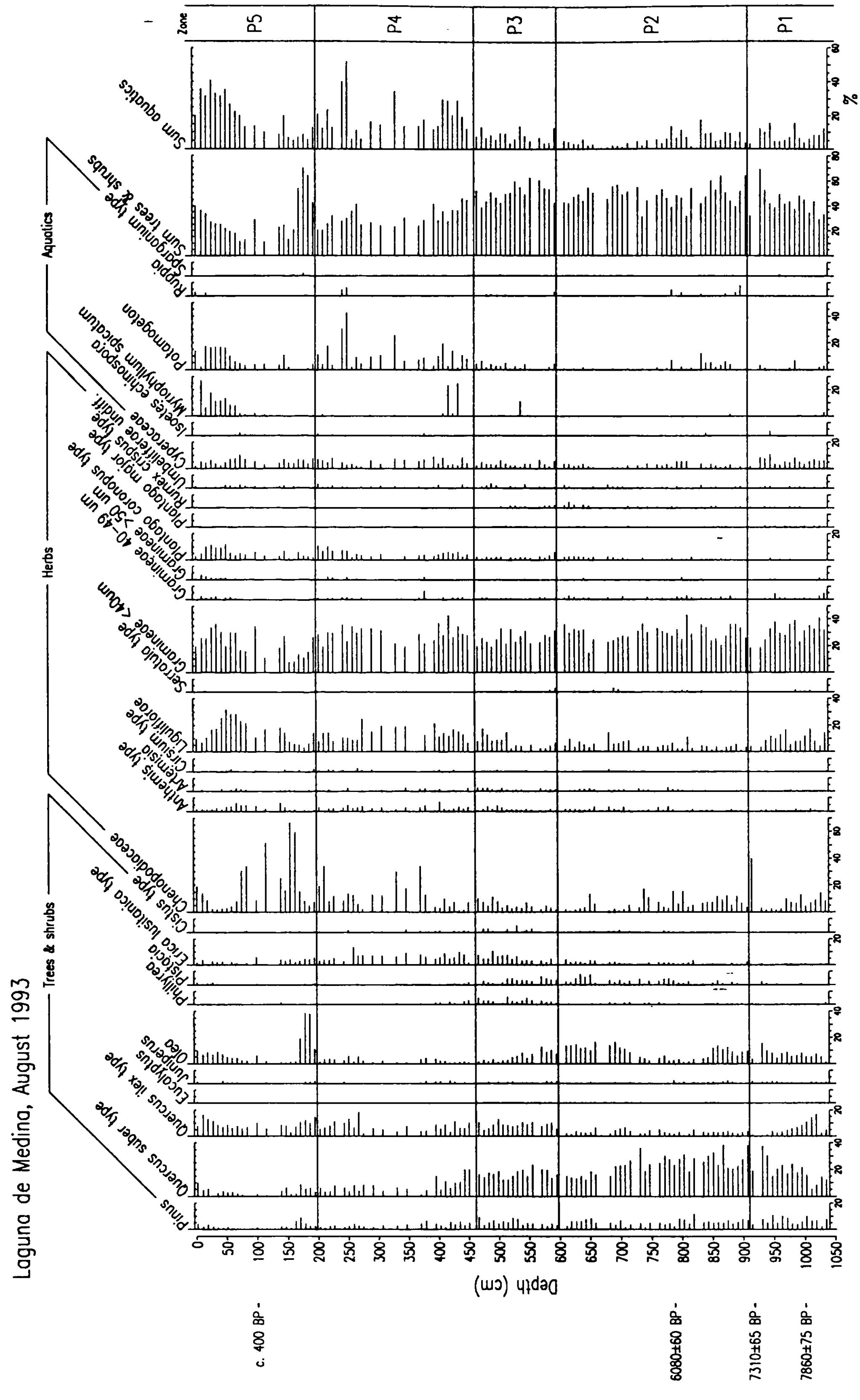
7.6.2 Results of pollen analysis

The pollen diagram is given in Figure 7.8. Trees, shrubs and herbs are expressed as a percentage of their total, and aquatics as a percentage of the total pollen. The diagram is divided into 5 major biostratigraphic units on the basis of changes in terrestrial pollen.

For the sake of brevity, an interpretation of the types of plant communities represented is given in the description. The interpretation of terrestrial vegetation relies almost entirely on the published work of Stevenson (1985), Stevenson & Moore (1988), Stevenson *et al.* (1992), and Stevenson & Harrison (1992) in similar environments of southern Spain and North Africa. This provides the ideal basis since it focusses on the identification of anthropogenic disturbance, including subtle vegetational change which could be related to woodland management, and has been carried out in the same region as this study.

In this respect it should be noted that '*Quercus* cf. *suber*' and '*Q.* cf. *ilex*' are taxonomically distinct, but their identification to species level is uncertain and interpretation relies in part on a knowledge of modern Spanish plant communities (Prof. Stevenson, pers. comm.).

Figure 7.8 The Laguna de Medina: summary pollen diagram.



Zone P1: 1033-914cm

At the base of the sequence, the arboreal pollen assemblage indicates a semi-arid woodland dominated by *Quercus* cf. *ilex* (max. 17%), the holly oak, which is replaced progressively by semi-humid *Q.* cf. *suber* (cork oak) woodland with relatively high frequency of *Olea* (olive, c. 5-10%) and low frequency of *Pinus* (pine, c. 5-10%) and *Juniperus* (juniper,<2%) throughout. *Olea* increases towards the top of the zone, to 16%. As discussed in Section 7.2.2, *Olea* is endemic and was an important constituent of the natural woodland. Pine pollen is far-travelled, and its presence at low frequency indicates regional input or its occurrence as a minor component of the woodland, possibly as *P. pinaster*. Indicators of anthropogenic disturbance such as *Plantago* and *Phillyrea* are rare.

Chenopodiaceae and Liguliflorae are families which contain common shoreline halophytes such as *Salicornia*. Their high abundance is typical of a disturbed, lagoonal system (Stevenson *et al.*, 1992). As noted above (Section 7.5.5) the zone also contains a peak in chenopod seeds and, in the modern lake, these plants have colonised the shoreline and grow across the lake bed in dry years. The high abundance of Gramineae throughout the core is likely to derive from fringing belts of *Phragmites australis* which still occur today. Aquatic pollen is at low abundance (<10%).

Zone P2: 914-602cm

Pollen of *Q.* cf. *suber* reaches a maximum (39%) in Zone P2, where *Pistacia* now forms a component of the semi-humid woodland, and *Q.* cf. *ilex* is rare (<5%). The *Olea* curve fluctuates; olive percentages fall to <4% above 834cm depth, followed by a progressive increase above 746cm to a sustained peak of up to 16% from 690-602cm depth, at the expense of *Q.* cf. *suber*. *Q.* cf. *suber*, *Pistacia* and *Olea* are characteristic of natural, 'Monte Negro' woodland, within which, as here, *Erica* spp. tend to occur at <10% abundance. Pollen of ruderals and other disturbance indicators are still rare, but a slight rise in the pollen of *Plantago coronopus* type to <3% above c. 650cm depth indicates some opening of the vegetation. There is a very slight rise in the fire-indicator, *Cistus*, from 778-674cm depth which could reflect either natural or artificial burning.

Liguliflorae pollen percentages decrease in Zone P2. Other aquatic and shoreline indicators are similar to Zone P1, with a decline in *Potamogeton pectinatus* at 800cm and disappearance of *Ruppia* at 762cm depth.

Zone P3: 602-466cm

Q. cf. *suber* woodland still dominates in Zone P3, with higher percentages of *Q.* cf. *ilex* (c. 10%) which could reflect either an increase in aridity, or other factors such as burning or disturbance. *Olea* decreases progressively to its virtual disappearance at the top of the zone. This is matched by a rise in the pollen of disturbance indicators, *Phillyrea* (to its maximum of 6%), *Erica lusitanica* type (5-10%) and, to a lesser extent, *Cistus* (1-5%) above c. 550cm depth. The ruderal curves are similar to Zone P2. *E. lusitanica* type probably derives from *E. scoparia*, which tends to develop with *Phillyrea* as the understorey vegetation of lightly-managed woodlands (*alcornales*) which are not grazed. This is supported by the frequency of *Cistus* pollen; as noted, the genus is a good indicator of fire, and grazing would tend to lead instead to a grassland understory. Thus, while the evidence is in accord with some woodland management, there is no evidence for dramatic forest clearance.

Ruppia is present consistently in this zone.

Zone P4: 466-202cm

There is the first strong evidence for forest clearance in this zone, indicated by the decline in *Q.* cf. *suber* to <10% above 392cm depth, along with the pollen of other tree species comprising *Pinus*, *Q.* cf. *ilex* and *Juniperus*, and, at the start of the zone, *Olea*. *Q.* cf. *ilex* increases again at the top of the zone, to >10%. The ruderal, *Plantago coronopus* type declines at the start of the zone, but reaches a peak of 11% at the top of the zone. *Erica* frequency is unchanged, and other disturbance indicators are rare.

The interpretation of the woodland flora is complicated by the dominance in this zone of Chenopodiaceae and Liguliflorae, which may have masked the signal for arboreal pollen, and probably indicates the expansion of shoreline halophytic plant communities related to a fall in lake level. Two chenopod peaks of >30% at the centre of the zone may reflect the periodic spread of taxa such as *Salicornia* spp. across the lake bed. There is also a major increase in aquatic pollen, comprising a peak in *Myriophyllum spicatum* at the base of the zone, and a rise in the pollen of *Potamogeton pectinatus* to 43%; *Ruppia* is rare.

Zone P5: 202-0cm

The dramatic rise in *Olea* pollen at the start of Zone P5, followed by its decline and consistent rise above c. 100cm depth was discussed in Section 7.2.2 in regard to chronostratigraphic dating, and at c. 100cm depth is interpreted tentatively in terms of changed agricultural activity around c. 400 BP. The terrestrial pollen record is similar in other respects to Zone P4, with *Q.* cf. *ilex* at greater abundance than *Q.* cf. *suber* and relatively high percentages of *Plantago* pollen.

The continued expansion of an open shoreline is suggested by the increase in Chenopodiaceae and Liguliflorae at the expense of Gramineae; chenopods reach their maximum abundance in this zone (peaks of >40%) which may indicate a trend towards a reduction in lake levels compared to Zone P4. *P. pectinatus* percentages are still relatively high, and a rise in *Myriophyllum spicatum* to 27% occurs at the top of the zone. *Ruppia* is absent.

7.6.3 Results of charcoal analysis

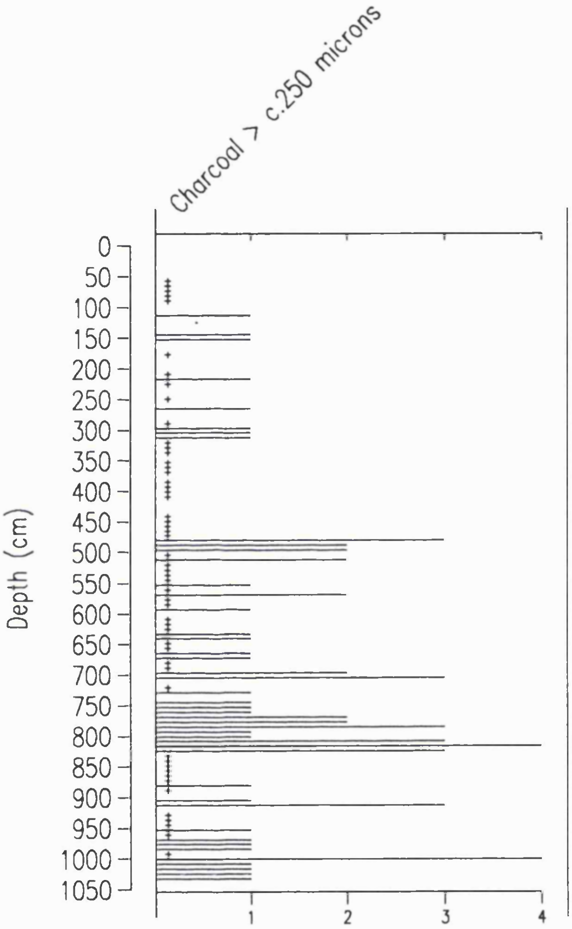
Macrofossil charcoal (>c. 250μm) was probably too rare for accurate estimation of relative abundance, since the thin fragments (<1mm wide) were often obscured by sediment. Samples with high abundance used for dating contained only 0.02-0.3 μg charcoal per g wet weight. In spite of this, the results give a general indication of trends in charcoal content and are presented in Figure 7.9.

Charcoal is present throughout most of the sequence, but in the 'rare' class, only 1-2 fragments were found. The main trend is towards a decrease in charcoal above c. 475cm depth (Pollen Zones P4 and P5). Peaks occur at 1000-999cm (charcoal lamina) and 920-912cm, and there is generally increased abundance between 824-768cm depth, and a minor peak at 496-480cm depth.

7.6.4 Interpretation of the pollen record for aquatic/shoreline vegetation

The relatively high abundance of the pollen of shoreline halophytes such as *Salicornia* is typical of disturbed lagoonal systems and provides support for an interpretation of relatively low lake levels throughout the sequence. Its increased abundance in the upper sequence is in accord with the inferred trend towards decreased lake levels inferred from other palaeoecological remains, above c. 500cm depth.

Figure 7.9 The Laguna de Medina: charcoal abundance diagram.



Assuming *Ruppia* pollen derives from *Ruppia maritima*, the same criteria for palaeoecological interpretation of aquatic pollen apply as for the plant macrofossil record (Sections 7.5.3 and 7.5.4). The increased abundance of *Potamogeton pectinatus* in the upper sequence is in accord with reduced salinity and increased turbidity compared to units with a higher abundance of *Ruppia*. In other respects, however, the aquatic pollen curves do not correlate well with changes in the plant macrofossil record reported in Section 7.5.2, and the interpretation is at odds with inferences made on the basis of ostracods and other remains. In particular, the consistent presence of *Ruppia* in levels corresponding to Zone M3 (912-816cm depth) contradicts the inferred phase of low lake levels and prolonged exposure in this zone.

There is evidence from other studies that the aquatic pollen record can be unreliable, and greater emphasis is given in this study to inferences made on the basis of other palaeoecological remains. The source area of pollen is less well-defined than plant macrofossils, which undergo less extensive transport (Birks & Birks, 1980).

Contradictions between the pollen and plant macrofossil record may also arise from the shorter time necessary for successful pollen production (Davis, 1994), such that the pollen of 'permanent lake' indicators could be produced during a seasonal infilling of the lake. As in this study, inferences drawn from aquatic pollen in salt lake studies have been known to contradict those drawn from a range of other palaeolimnological indicators (e.g. Stevenson *et al.*, 1993).

7.6.5 Interpretation of pollen and charcoal evidence for human impact

The pollen record shows a trend towards increased evidence for human impact over time. There is little evidence for anthropogenic disturbance prior to c. 7300 BP (Zone P1); the lack of vegetation change consequent upon the burning episode indicated by a charcoal peak at 1000-999 cm depth suggests it was not a product of sustained management practices. On the contrary, the inferred shift from *Quercus ilex* to *Q. suber* woodland suggests a trend towards a more humid climate at around this time.

There is little change in Zone P2, where the evidence points similarly to a natural, Monte Negro woodland dominated by *Q. suber*. The increased charcoal frequency and very slight rise in *Cistus*, a fire-indicator, in the mid-zone indicates increased burning, either natural or artificial. It is interesting to note that this correlates broadly with a fall in *Olea* pollen, but there is no other prolonged effect on the vegetation to suggest sustained human impact.

The first clear evidence for disturbance appears in Zone P3 (602-466cm depth). Stevenson *et al.* (1992) identified three types of managed plant community which can all be degraded to an open *dehesa*; the community represented here is the least disturbed woodland, with little or no grazing. *Cistus* pollen reaches its maximum in this zone, although it is not abundant, and again correlates with higher charcoal frequency. It could indicate human impact, but it correlates also with an increased abundance of *Q.* cf. *ilex.* It grows in the xeric communities surrounding the lake today (Fernández-Palacios, 1990) and could equally reflect a response to a drier climate.

There is strong evidence for a reduction in forest cover and increase in disturbance indicators in Zones P2-P1, above 466cm depth, which is likely to indicate significant human impact on the system in the more recent past. This includes evidence for an olive rise which, as noted previously, is consistent above c. 100cm depth and is assigned a highly tentatively date of c. 400 BP on the basis of regional chronostratigraphic correlation.

The implications for interpretation of Holocene climate change are considered in Chapter 8, where the results of separate analyses are consolidated, and lake-level and climate change in the Laguna de Medina are discussed.

CHAPTER 8

THE LAGUNA DE MEDINA III: DISCUSSION

8.1 INTRODUCTION

In the first part of this chapter, the Laguna de Medina results are consolidated and interpreted in terms of Holocene lake-level and climate change. The separate palaeosalinity and lake-level reconstructions derived in Chapter 6 from the fossil diatom record are compared with those derived in Chapter 7 from other palaeoenvironmental indicators.

The strength of the diatom record for palaeosalinity and independent lake-level reconstruction is assessed on the basis of the agreement between different lines of evidence. For palaeosalinity, this is limited to an evaluation of the qualitative reconstruction since, as discussed in Chapter 6, diatom dissolution is too far advanced for successful application of a quantitative transfer function.

Separate, unified palaeosalinity and lake-level curves are established from the multiple proxy data, and the relationship between past salinity and lake level is explored. The degree to which lake-level change may be driven by human impact rather than climate is assessed by reference to the pollen and charcoal evidence, which was discussed in Chapter 7.

In the second part of the chapter, the Laguna de Medina lake-level record of Holocene climate change is compared with similar data from other regions relevant to the study. The emphasis is on a detailed comparison with evidence from salt lakes in similar climate regions of Spain and northern Africa. The extent to which patterns of Holocene lake-level change in these African regions are similar, time transgressive or influenced by independent climatic forcing functions, or whether they are driven by factors other than climate, is open to debate (Gasse *et al.*, 1990, Roberts *et al.*, 1994). Some of these issues might be resolved by comparison with evidence from the Iberian Peninsula, due to its important geographic location between Africa and the rest of Europe, but this has never been done due to the lack of data.

Conflicting interpretations which have been made of the existing African data are assessed in the light of the new data from southern Spain. To assess evidence for regional versus global climate change, reference is made also to lake-level data from lakes in similar climate zones of the eastern Mediterranean, from the temperate mountains of North Africa, and from Atlantic northwestern Europe.

8.2 CONSOLIDATION OF THE LAGUNA DE MEDINA RESULTS

8.2.1 Palaeosalinity reconstruction

Summary palaeosalinity reconstructions based on different indicators, and an interpretation of the combined evidence, are given in Figure 8.1 for diatom and other palaeoecological biostratigraphic zones and for the ostracod trace-metal record.

The diatom, and combined microfossil and macrofossil palaeosalinity reconstructions differ in detail, but overall trends are common to both.

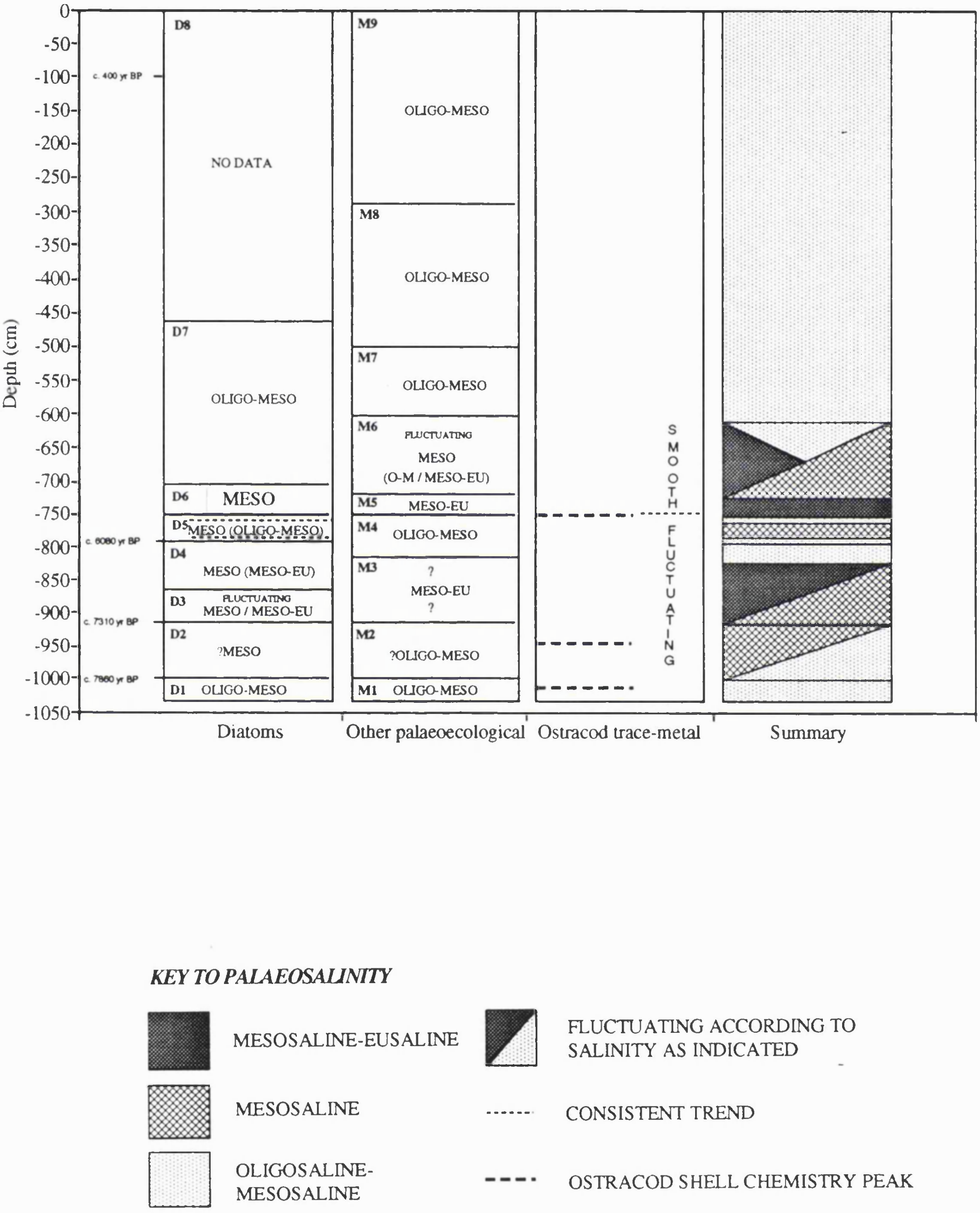
Zones D1 (diatoms) and M1 (ostracods, foraminifera, molluscs and plant macrofossils) both extend from the core base to 1000cm depth (c. 7860 BP), and the inferred salinity of Diatom Zone D1, as close to the oligosaline-mesosaline boundary, is supported by evidence from ostracod species assemblage composition. The significant change in both at 1000cm depth indicates major palaeolimnological change at c. 7860 BP.

The upper zone boundaries of zones D2 and M2 (916cm depth) also coincide and indicate a second major transition at c. 7310 BP. Palaeosalinity reconstructions were tentative; diatoms were sparse and ostracod assemblages were a mix of species with salinity preferences ranging from fresh to mesosaline. Taxa characteristic of eusaline waters were absent, however. The evidence supports an interpretation of rapid salinity fluctuation between oligosaline and mesosaline but is too weak for detailed reconstruction.

Diatom Zones D3-D5 correspond to Zones M3-M4, such that the upper boundary of Diatom Zone D5 coincides with that of Zone M4, at c.756cm depth (<6000 BP). In the section 916-756cm depth, there is a common trend towards decreasing salinity from initial fluctuation between mesosaline-eusaline and mesosaline, to predominantly mesosaline, to oligosaline-mesosaline, but the position of the salinity shift does not match at the top of the section, in Diatom Zone D5. In Zone D5, diatom preservation was good and the inferred salinity of full mesosaline (based mainly on the occurrence of *Cyclotella choctawhatcheeana*), with a transition to lower salinity at the top of the zone, is contradicted by the abundance in these samples of *Plesiocypridopsis newtoni*, an ostracod with a preference for oligosaline waters.

Similarly, there is a common trend above 756cm depth (<6000 BP to present) towards decreasing salinity, but the reconstructions do not match in detail. The diatom reconstruction shows a transition from predominantly mesosaline to oligosaline-mesosaline, which contrasts with the trend inferred from

Figure 8.1 Diagram showing palaeosalinity reconstructions based on different indicators and a summary interpretation from the combined evidence.



other fossil remains from mesosaline-eusaline, to predominantly mesosaline, to oligosaline-mesosaline. The other microfossil and macrofossil data record is probably stronger here. The initial high-salinity phase was based both on ostracod species assemblage composition and on the occurrence of the bivalve, *Cerastoderma glaucum*, and the apparent contradiction in the transition to oligosaline-mesosaline (c. 700cm depth in the diatom record compared to 600cm depth in the other) could be explained by the discontinuity and poor preservation of diatoms in Zone D7, above 700cm depth.

In respect to the ostracod trace-metal record, the inferred reduction in salinity fluctuation above 700cm depth is in accord with other lines of evidence. Individual peaks do not correlate with phases of maximum salinity inferred from other indicators, however. This indicates fluctuations in shell chemistry are not a simple response to salinity change, and the record is unreliable.

8.2.2 Lake-level change

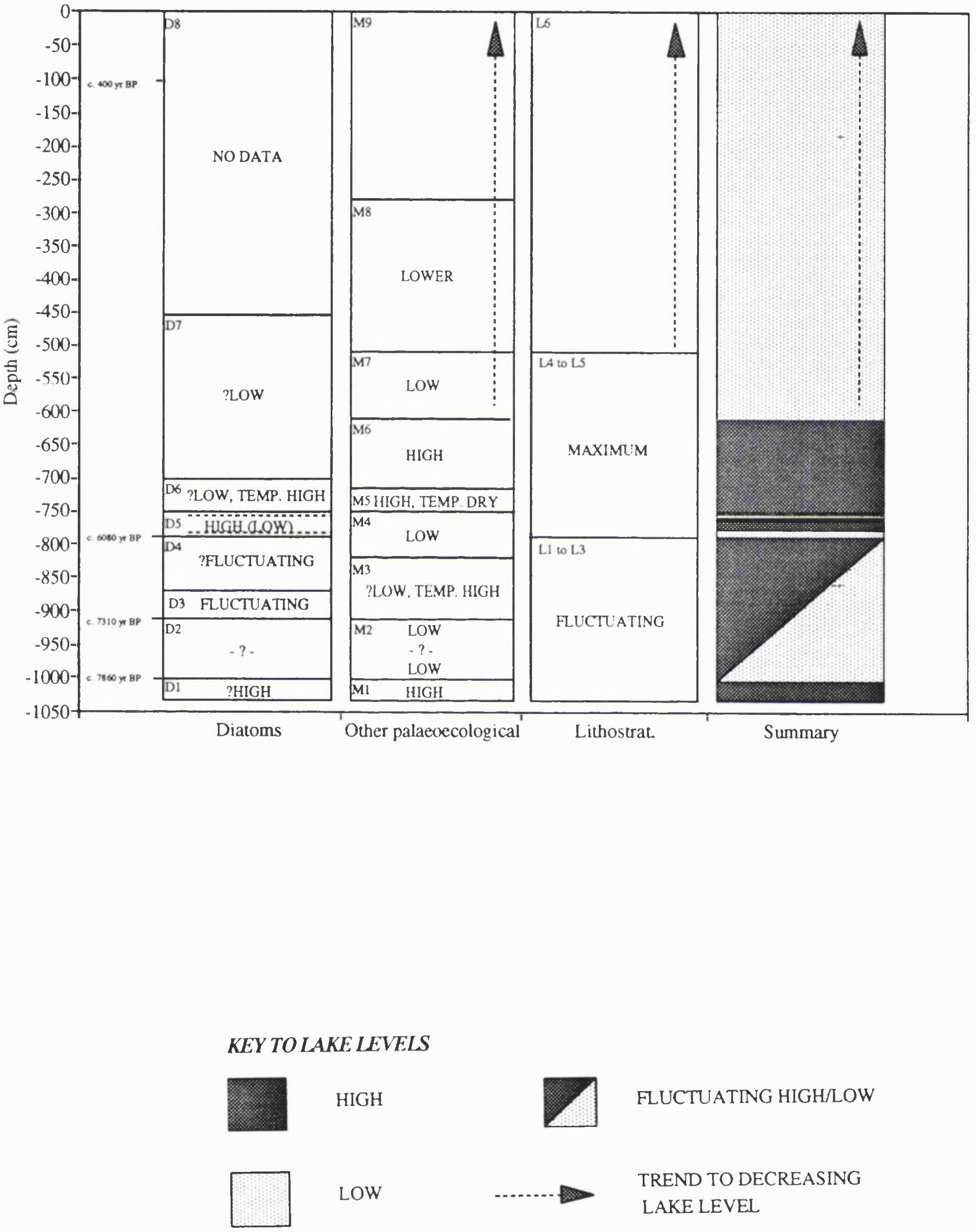
Summary lake-level reconstructions based on different indicators, and an interpretation of the combined evidence, are given in Figure 8.2 for diatom and other palaeoecological biostratigraphic zones, and for lithostratigraphic zones.

The tentative interpretation of the diatom record as indicative of a relatively shallow lake throughout on the basis of the abundance of benthic taxa is supported by other palaeoecological data which, as discussed in Chapter 7, indicate that lake levels did not exceed c. 10m maximum water depth.

In Diatom Zone D1, the diatom-based interpretation of permanent and, by inference, relatively high lake levels from 1033-1000cm depth (prior to c. 7860 BP) was tentative due to the preferential preservation of benthic taxa, but is supported by the Zone M1 ostracod data (assemblages dominated by *Cyprideis torosa*, indicative of permanent waters).

Both diatoms and other remains were poorly preserved or absent over parts of the sequence covered by Diatom Zones D2-D4, from 1000-786cm depth (c. 7860-6080 BP). From 1000-916cm depth in particular (c. 7860-7310 BP), in Zones D2 and M2, the low lake levels inferred at the sequence base and top derive only from the abundance of *P. newtoni*. This is supported by strong evidence for low lake levels at the start of the sequence, however, which is provided by the peak in chenopod seeds indicating extension of the shoreline and the drying of the lake. In Zone D3, from 916-864cm depth, it is noteworthy that the diatom record is more continuous than other palaeoecological records, including the ostracod record, and provides a more sensitive record of changing lake levels. The inference of rapid lake-level fluctuation from the diatom data is strengthened by the lithological evidence for multiple gypsum banding and intermittent laminated sediments which indicate periodic drying out and

Figure 8.2 Diagram showing lake-level reconstructions based on different indicators and a summary interpretation from the combined evidence.



the renewal of short-term stable, permanent phases, and, to a lesser extent, by the temporary high stands indicated by the presence of foraminifera in Zone M3 (912-816cm depth). Taken in combination, the evidence for the period c. 7860-6080 BP indicates an unstable environment throughout, with rapidly fluctuating lake levels and periodic drying out of the lake.

Following a transition common to all records at 786cm depth (c. 6080 BP), the diatom, other microfossil, macrofossil and lithological data all indicate a trend towards maximum lake levels. As in the palaeosalinity reconstruction, the zone boundaries do not coincide. The diatom evidence is strong for an earlier high-stand from c. 6080 BP in Diatom Zone D5 (786-752cm depth), based on the abundance of plankton, but is again contradicted by the abundance of the ostracod *P. newtoni* until the transition to Zone M5 at 752cm depth, after which *C. torosa* dominates.

The diatom reconstruction is weak or missing in Diatom Zones D7 and D8, above 700cm depth, and there is stronger evidence both in the other palaeoecological data (virtually monospecific assemblages of *P. newtoni*, the absence of *C. torosa* and a trend from *Ruppia* to *Potamogeton* and *Zannichellia* seeds in Zones M6 to M9), and in the lithostratigraphic data (compact sediments low in organic content characterised by lenticular gypsum) for a decline in lake levels over time above c. 600cm depth (undated) to the surface.

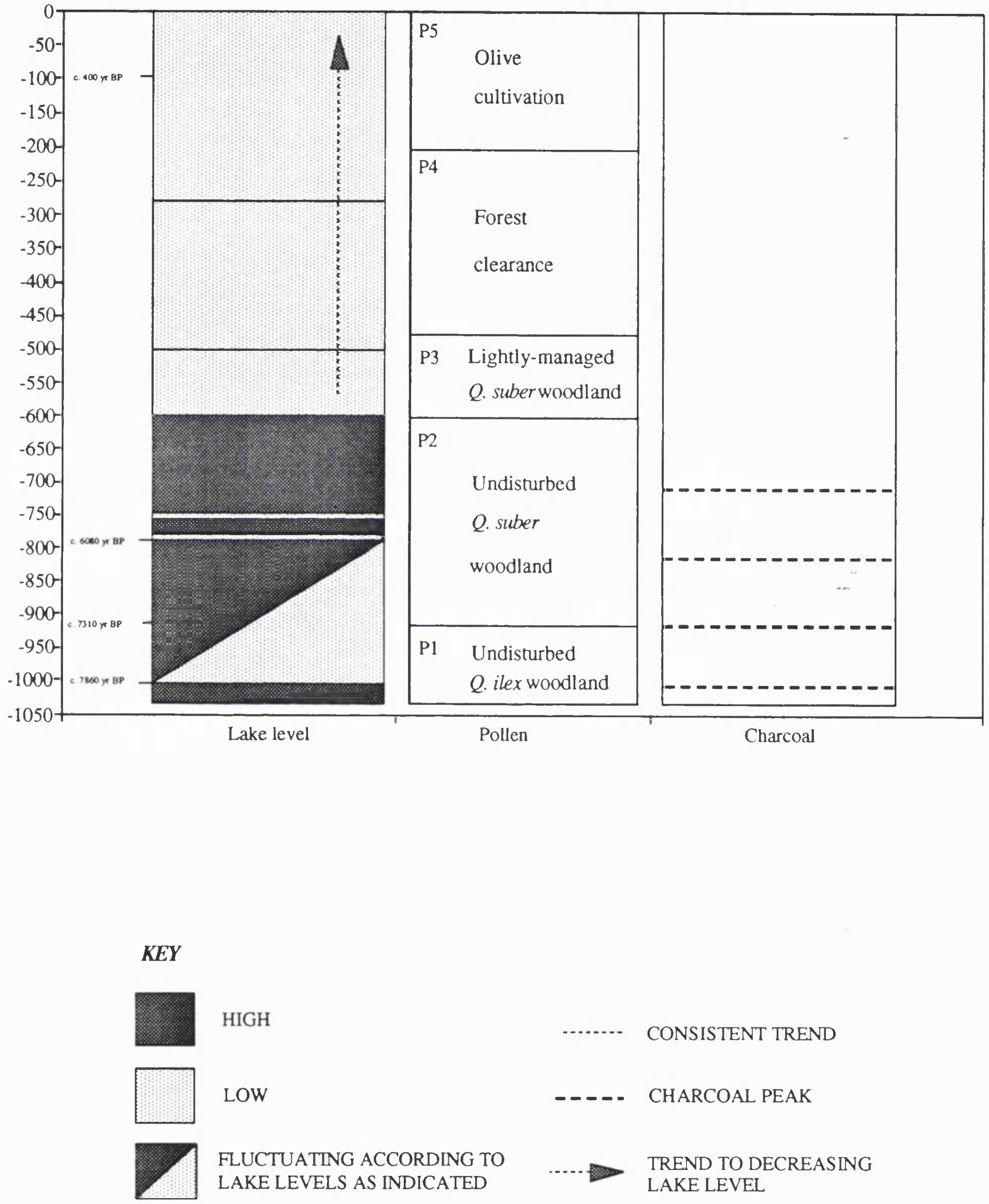
In respect to the relationship between palaeosalinity and lake-level change, the above interpretation of the combined evidence is summarised in the final columns of Figures 8.1 and 8.2 and indicates that relatively high lake levels correspond to lower salinity at the very start of the sequence, prior to c. 7860 BP (1000cm depth). This is in accord with a simple model of increased dilution with lake-level rise . Both are unstable and fluctuate rapidly in an inferred phase of generally low lake levels ending at c. 6080 BP.

The relationship is the reverse of that expected for the rest of the sequence, however. Maximum lake levels correspond to a phase of high salinity, and an inferred trend towards decreasing salinity thereafter is paralleled by a decrease in lake levels. This indicates that the direct record of lake-level change is a more reliable indicator of Holocene palaeoclimate change than the palaeosalinity record, and it is used for final interpretation of the sequence.

8.2.3 Influence on past lake levels of human impact on the catchment and regional vegetation

The Laguna de Medina lake-level record is compared in Figure 8.3 to a summary of palynological and charcoal evidence for the influence of human impact on the catchment vegetation, which was discussed in Chapter 7. This is used to assess the possible influence of human-induced catchment disturbance on

Figure 8.3 Comparison of inferred lake-level change with pollen and charcoal evidence for human impact.



the lake-level record. In addition, where a climatic influence on vegetation is inferred, the coincidence of pollen and lake-level change lends further support to a palaeoclimatic interpretation of the latter.

Within Pollen Zone P1 (1033-914cm, c. 7310 BP) the palaeolimnological transition at the top of biostratigraphic zones D1 and M1 coincides with a charcoal peak resulting from the 'charcoal lamina' at 1001-999cm depth (c. 7860 BP). The pollen indicates little vegetational change in a zone of semi-arid *Quercus ilex* woodland with no evidence for human interference other than charcoal evidence for burning. This could relate either to Mesolithic activity or to natural burning but was not sufficient to cause long-term vegetational change. Thus, the palaeolimnological evidence for a transition here from relative stability to a phase of fluctuating salinity and lake levels is interpreted in terms of an increase in aridity or seasonality at c. 7860 BP, a transition which is not registered by the pollen data.

The transition to Pollen Zone P2 at 914cm depth (c. 7310 BP) indicates a climatic shift to semi-humid *Q.* cf. *suber* woodland and coincides with a charcoal peak and with a major transition in all palaeolimnological indicators. Within this zone (914-600cm depth), charcoal peaks coincide with palaeolimnological transitions from M3-M4, and from D6-D7/L4-L5, but an anthropogenic influence is unlikely since the zone is dominated by pollen typical of an undisturbed Monte Negro woodland (Stevenson & Harrison, 1992). The evidence for maximum lake levels in the upper part of this zone is in accord with a response to increased humidity, although it does not coincide with the pollen shift registered at the start of the zone.

The first evidence for significant human impact is in the transition at 600cm depth to Pollen Zone P3, interpreted as a lightly-managed woodland. This coincides with the transition to Zone M7 and the start of an inferred trend towards decreasing salinity and lake levels.

Above this depth, the pollen evidence for major deforestation coincides with the continued trend towards progressively lower lake levels. It is possible processes of natural infilling of the lake basin were accelerated after this date due to increased erosion consequent upon the opening of the vegetation on the terraces surrounding the lake. This cannot be tested until more radiocarbon measurements are made since the upper sequence is undated, and sediment accumulation rates cannot be calculated. The evidence for deforestation indicates, however, that the palaeolimnological record above 600cm depth, that is, some time well after 6000 BP, cannot be interpreted with confidence in terms of climate change.

8.2.4 Summary of Holocene palaeoclimate change

In this study, the strongest palaeoclimatic evidence is provided by the direct lake-level record rather than the palaeosalinity record since the relationship between palaeosalinity and lake-level change is not straightforward.

Lake-level change and palaeoclimatic interpretation is summarised as follows. The start of the sequence represents a high-stand prior to c. 7860 BP, followed by a phase of unstable, fluctuating, relatively low lake levels. Maximum lake levels were attained at around 6000 BP.

This is in accord with an initial humid phase, a phase of fluctuation in a seasonal and possibly less humid climate, and a phase of maximum humidity. The gradual decrease in water depth some time well after 6000 BP (at 600cm depth) cannot be interpreted with confidence in terms of palaeoclimate change due to evidence for human impact.

8.3 COMPARISON WITH OTHER REGIONS

8.3.1 Introduction

As discussed in Chapter 2, Holocene palaeoenvironmental research in the Iberian Peninsula has been limited to date. Most of it is palynological and has been interpreted only in terms of an increase in humidity with the onset of the Holocene at c. 12-10,000 BP and little change thereafter, or in terms of human impact in the later Holocene (after c. 4000 BP). Harrison & Digerfeldt (1993) have reviewed existing data from the Iberian Peninsula and suggest there is additional evidence for a regional fall in lake levels after c. 5000 BP which is related to increasing aridity. This is based on only four studies, however, which were intended more for assessment of vegetation change and human impact, and two of which do not have clear evidence for lake-level change after c. 5 ka; the record of the Laguna de las Madres, Huelva, (Stevenson, 1985) is more recent than 5 ka and that of Padul, Granada (e.g. Pons & Reille, 1986a, 1986b) ends at c. 4450 BP.

The pollen and lake-level study of Davis (1994) on Holocene sequences from seven salt lakes in the Ebro Basin, northeast Spain, is the only work on the Iberian Peninsula with which the results of this study can be usefully compared. Lake levels were reconstructed from multiple proxy indicators (aquatic pollen, plant macrofossils, cladocera and mineralogy) and evidence is presented for significant lake-level and climate change throughout the Holocene.

The regions of North Africa known collectively as the Maghreb (Morocco, Algeria and Tunisia on the northern margins of the Sahara) border on southwestern Spain and the semi-arid climate is similar to southwestern Spain. In contrast to the Iberian Peninsula, extensive lake-level research has been carried out on Holocene lacustrine sequences here, to the south in the more arid regions of the central Saharan and northern Sahelian climatic zones of Mali, Chad, Niger and Libya, and to the east in the Rift Valley of East Africa. Together with the work of Davis (1994), these lake-level studies form the focus for an assessment of evidence for regional Holocene climate change.

Reference is made also to data from other geographic regions in the discussion which follows, where inferences concerning regional patterns of Holocene climate change which have been made on the basis of existing data from northern Africa, Spain and other parts of the Mediterranean and northwest Europe are assessed against the new data provided by the Laguna de Medina record.

8.3.2 Comparison with Spain and northern Africa

Limnological characteristics are summarised in Table 8.1 relating to 18 Holocene palaeoclimate studies in arid or semi-arid regions of Spain and northern Africa with which the Laguna de Medina lake-level record is compared in detail. The sites are selected for their geographic spread, their long sequences with relatively reliable dating control, and the use of multiple proxy indicators. In Table 8.1 they are ordered approximately by latitude and longitude from the Ebro Basin in northeastern Spain and the Laguna de Medina in the south, sites from west to east across the Maghreb, from west to east across the central and southern Sahara, and sites southeast of the Sahara in East Africa.

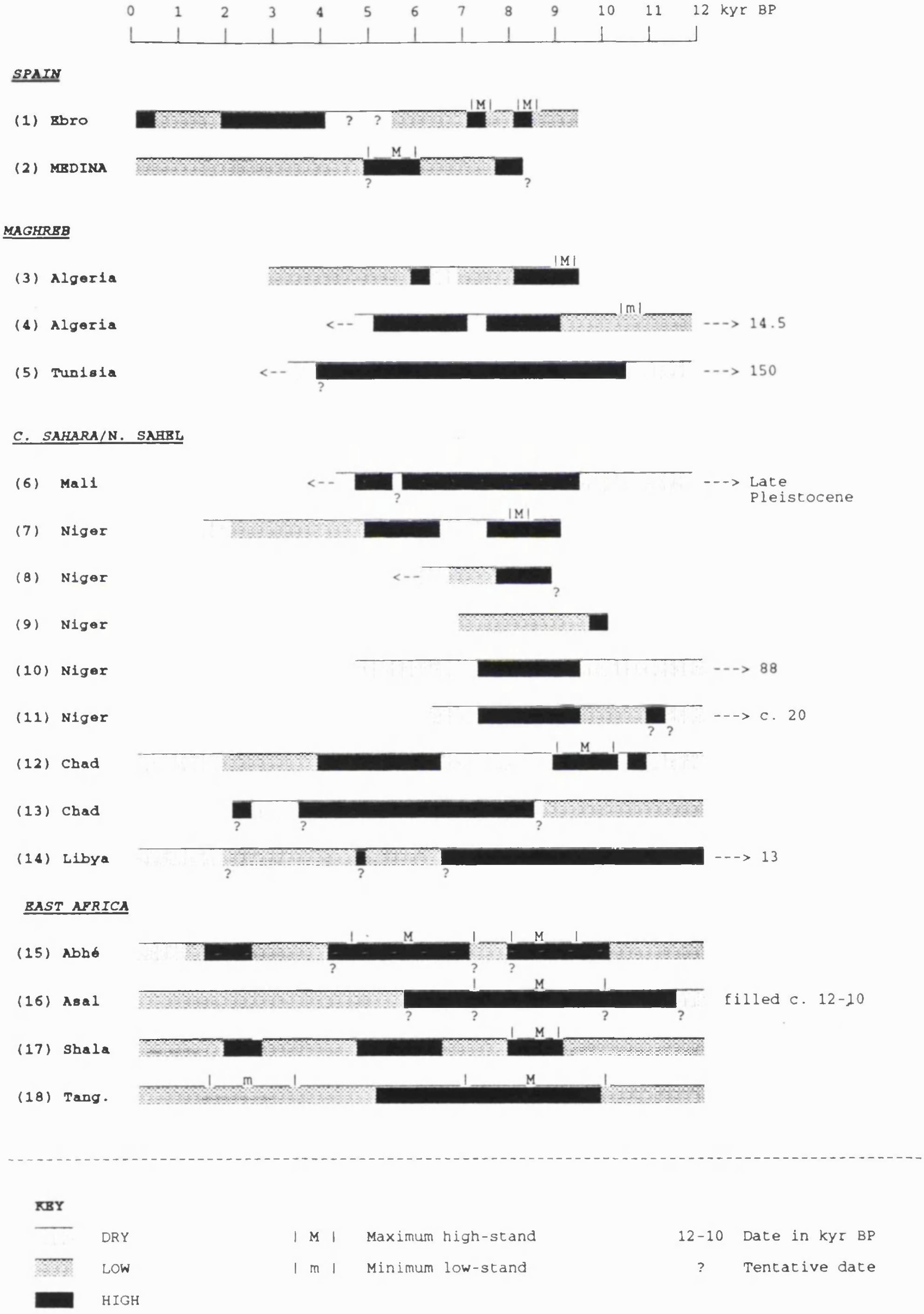
Reconstructed lake levels for these sites are summarised in Figure 8.4. Since the results of the present study and many others cannot be presented as a continuous lake-level curve, the data are summarised in terms of high and low lake levels, and dry phases, with an indication of inferred maxima or minima. For studies where the results were presented as continuous lake-level curves (studies 15, 16, 17 and 18), this was achieved by reference to the text, wherein patterns of lake-level change were also discussed in these terms.

In respect to radiocarbon dating, many studies are based on sediment sequences from alkaline, groundwater-fed lakes. Fontes & Gasse (1991a, 1991b) discuss the problems of radiocarbon dating in these environments. The ^{14}C content of aquatic invertebrates or plant macrofossils is often contaminated by older carbon from the groundwater supply. In the Laguna de Medina study this was overcome by dating terrestrial material, but suitable material is often not preserved. Radiocarbon dates from studies by Fontes and co-workers are based on aquatic organic matter and carbonates, adjusted to take account of groundwater contamination using an 'exchange-mixing' model (Fontes *et al.*, 1983). For groundwaters with low ^{13}C content (e.g. studies in Fontes & Gasse, 1991a) the reliability of the dates has been tested by comparison with the ^{13}C record; dates were considered valid where the ^{13}C content was high and, by inference, in equilibrium with atmospheric CO_2 (Fontes & Gasse, 1991a). In other cases such Lake Asal, Djibouti (Gasse & Fontes, 1989), the ^{13}C test could not be used and dates are more tentative. The reliability of carbonate dating has also been improved by selecting authigenic rather

Table 8.1 Summary of limnological characteristics for 18 Holocene palaeoclimate studies of salt lakes in Spain and northern Africa.

REGION	SITE(S)	SITE CHARACTERISTICS	REFERENCES
SPAIN	(1) Ebro Basin (c. 40°N))	Aquifer-fed dissolution basins, detailed hydrology unknown	Davis (1994)
	(2) Laguna de Medina (37°N)	Aquifer-fed dissolution basin, detailed hydrology unknown	Reed (1995)
MAGHREB	(3) N Algeria: Hassi el Mejna, Gt Western Erg (32°N)	Interdunal depression, spring-fed by unconfined aquifer, negligible runoff	Fontes *et al.* (1985), Gasse *et al.* (1987)
	(4) N Algeria: Sebkha Mellala, Gt Western Erg (32° N)	Spring-fed interdunal depression, negligible runoff but confined aquifer fed by Atlas and M'zab mts	Fontes *et al.* (1985), Gasse *et al.* (1987, 1990)
	(5) S Tunisia: Wadi El Akarit (34°N)	Coastal wadi, spring-fed by deep aquifer, influenced by sea-level change	Fontes *et al.* (1983), Fontes & Gasse (1991a)
C. SAHARA/ N. SAHEL	(6) NE Mali: Erg Ine Sakane (20-21°N)	Interdunal depression, aquifer-fed; influenced by floods of R. Niger	Petit-Maire & Riser (1981), Hillaire-Marcel *et al.* (1983), Fontes & Gasse (1985)
	(7) E Niger: Kawar (19°N)	Aquifer-fed depressions in Erg of Bilma, N. margin of L. Chad basin	Baumhauer (1991)
	(8) E Niger: Seggedim (20°N)	Aquifer-fed depression, as above	Baumhauer (1991)
	(9) E Niger: Dibella (18°N)	Spring-fed interdunal depression, as above	Baumhauer (1991)
	(10) N Niger: Adrar Bous (20°N)	Desert basins in rainshadow of Aïr Mts, fed by surface and groundwater flow	Fontes & Gasse (1991a)
	(11) N Niger: Tin Ouaffadene (20°N)	Desert basins in rainshadow of Aïr Mts, fed by groundwater only	Fontes & Gasse (1991a)
	(12) S Niger: Ari Koukouri & N'Guigmi (14°N)	Interdunal depressions depending on water level of Lake Chad	Gasse (1987), Fontes & Gasse (1991a)
	(13) Chad: Kadzell (14°N)	Interdunal depression in alluvial plain of Yobe River (tributary of Lake Chad), fed by local runoff and rain	Fontes & Gasse (1991a)
	(14) S Libya: Sarir Tibisti (24°N)	Aquifer-fed desert basins in forelands of Tibisti Mts	Pachur (1980)
EAST AFRICA	(15) Djibouti: Lake Abhé, Afar (12°N)	Stable tectonic basin fed by Ethiopian Plateau via River Awash	Gasse & Street (1978), Gasse (1977, 1991)
	(16) Djibouti: Lake Asal, Afar (12°N)	Unstable, spring-fed basin within marine evaporites; marine influence	Gasse & Street (1978) Gasse & Fontes (1989), Gasse (1991)
	(17) Ethiopia: Galla lakes, Ziway-Shala basin, Central Rift (c. 10°N)	Stable basins in highest Rift floor; high runoff	Gasse & Street (1978)
	(18) Tanganyika: L. Tanganyika, W. Rift	Deep, stable tectonic basin until volcanism after c. 5 ka	Haberyan & Hecky (1987), Vincens *et al.* (1993)

Figure 8.4 Summary of Holocene lake-level change in the Laguna de Medina and for 18 other palaeoclimate studies in Spain and northern Africa.



than bulk carbonates in studies where contamination from detrital carbonates could occur (Fontes & Gasse, 1991b). In other studies the internal consistency of a series of dates has been used as an indicator of reliability (e.g. Haberyan & Hecky, 1987). In general, parts of sediment sequences where dating is tentative have been identified by authors and are marked on Figure 8.4.

The Laguna de Medina record does not extend as far back as the Late-Glacial transition, but shows evidence for a high-stand at its start, prior to 8k years ago ('ka' hereafter). In the African sequences spanning a longer timescale there is consistent evidence, in all cases, that lakes filled or lake levels increased at the start of the Holocene, after a dry phase in the Late Glacial. The date of the transition varies from >12 to 9.3 ka, but in 14 of the 16 studies lakes were high at 9 ka. By 9 ka in the Dibella sequence, eastern Niger (study 9), lake levels were fluctuating at a lower level than the maximum attained around 10 ka, whilst in the basins of the Kadzell Plain, Chad (study 13), lakes filled at >10.8 ka, but were relatively low until some time after 8.4 ka. In the Ebro Basin, lakes were full in the early Holocene but did not reach a maximum until c. 8.6 ka.

The drier phase of fluctuating lake levels in the Laguna de Medina sequence from c. 7.9-6 ka matches a dry phase centred around c. 7.5 ka, and lasting in most cases over 1000 years, in 6 of the African studies (3, 6, 7, 12, 15 and 17). The remaining African salt lakes vary in their behaviour, although none has a short-lived high-stand at this time. They were either undergoing a prolonged high-stand, had dried out or were permanently lowered earlier, or had a later phase of low lake levels. In contrast, the Ebro Basin sites show an opposite pattern; there is a phase of high lake levels from c. 8.6-7.2 ka but it is interrupted by a low phase from c. 8.2-7.6 ka.

Many African lakes were also high at 6 ka but, in detail, the pattern of maximum lake levels initiated at around 6 ka in the Laguna de Medina is not common to most studies. The 6 African studies with a dry phase around 7.5 ka subsequently show a renewed high phase, but the date of its onset in most cases is around 7.0-6.5 ka. The Hassi el Mejna, Algeria (study 3), with a maximum around 6.2-6.0 ka, is a close parallel. In contrast, lake levels fell prior to 7 ka in the Ebro and were low at 6 ka.

The lake levels of most African lakes had started to decrease by around 5 ka, and lakes were dry or permanently lowered by around 4-3 ka. Lake-level changes in the Laguna de Medina are currently undated for the period <6 ka to present, but appear to follow the same pattern, with a gradual lowering to the present. The Ebro Basin is the only study to show a prolonged high phase in the later Holocene, from c. 4.0-1.8 ka, within which a significant rise was inferred for the period c. 2.7-1.8 ka.

8.4 DISCUSSION

8.4.1 The Laguna de Medina

Despite the effects of diatom dissolution on fossil assemblages, inferences based on the diatom, ostracod, foraminifera, mollusc, plant macrofossil and lithological data match sufficiently to allow the construction of consistent palaeosalinity and lake-level curves. If, as in this study, the likely effects of dissolution are taken into account in interpreting fossil assemblages, this supports the potential of diatoms as valuable palaeosalinity and lake-level indicators even in poorly-preserved sediment sequences.

The continuous ostracod shell-chemistry record was shown to be unreliable. Similar problems were encountered in a study of the Pleistocene Baza Basin, southeast Spain (Anadón & Julía, 1990), and a possible explanation is that the shell chemistry record also reflects different phases of carbonate precipitation. The reasons for this could be explored further using oxygen isotope analysis of ostracod valves to uncouple the effects of salinity, temperature and groundwater on the system (e.g. Hodell *et al.*, 1991, Chivas *et al.*, 1993, Curtis & Hodell, 1993), or X-ray diffraction analysis to determine different mineral phases in the sediment record. Using multiple indicators, De Deckker *et al.* (1988), for example, were able to interpret the ostracod shell chemistry record of the Gulf of Carpentaria, Australia, in terms of salinity change by identifying phases where peaks in the molar ratios occurred with a shift to calcite precipitation.

In respect to Holocene palaeosalinity and lake-level reconstruction, the lack of absolute correlation between inferences based on different palaeoecological and lithological indicators is not surprising. In palaeosalinity reconstruction, the salinity range involved is limited and does not include the ecologically significant transition to fresh waters. The biota are euryhaline or extremely euryhaline, and salinity reconstruction is perhaps less likely to be accurate than in systems which alternate between fresh and saline conditions. The range of lake-level change is also limited, and its independent interpretation relies on the identification of relatively subtle shifts in a system which appears to have been shallow (<10m deep) throughout the last c. 8k years. The techniques used rely on an assumed relationship between the poorly-defined 'permanent' state of the lake and water depth, and the threshold for a state of permanence is likely to vary between different indicators. The results indicate that more detailed interpretation of short-term palaeoenvironmental change would be unreliable.

A direct rather than inverse relationship between salinity and lake level was exhibited over much of the sequence. In other words, a simple relationship between salinity, lake level and climate does not apply and in this study lake-change cannot be inferred indirectly from palaeosalinity data. A similar phenomenon has been found in studies of shallow, groundwater-fed interdunal depressions of the northern Sahara which employed the range of palaeoenvironmental indicators used here, together with stable-isotope analysis as an indicator of groundwater influence (Gasse *et al.*, 1987). The authors argue substrate permeability is one of the most important factors controlling salt concentration in these lakes. If permeability is reduced by the production and deposition of organic detritus on the lake bed after flooding by saline groundwaters and colonisation by macrophytes, then leaching of salts is prevented and a high-salinity phase results; assuming lake levels do not rise sufficiently to result in surface outflow, lake-level rise will only cause dilution if there is a high seepage rate through the lake-bed. As discussed in Chapter 2, the Laguna de Medina is thought to be less strongly controlled by groundwater flow than other lakes of Andalucía, but it is aquifer-fed and salts are also likely to be introduced by runoff over saline outcrops. In the sediment sequence, the inferred high-salinity phase of maximum water depth was associated with high organic content, and it is possible that similar processes have operated in this lake.

Thus, the record of Holocene palaeoclimate change was derived directly from inferred changes in lake level rather than indirectly from the palaeosalinity record. Whether based on palaeosalinity or direct lake-level data, the additional step to palaeoclimate reconstruction rests on the assumption that changes in lake level (ie. water depth) are driven solely by fluctuations in effective moisture. This approach has the disadvantage that processes of sediment infilling may lead to a decrease in water depth over time independent of climate change, and to changes in lake bathymetry and habitat distribution which further complicate the relationships involved. In this study, the lower part of the sequence showed an increase rather than decrease in water depth to a maximum around 6 ka, which supports a palaeoclimatic interpretation. The inferred trend towards decreasing water depth in the upper part of the sequence, however, may be partly a function of sediment infilling (either natural or human-induced) and does not necessarily indicate increased aridity.

The palaeoclimatic interpretation of this sequence would be strengthened greatly by comparison with data from other lakes in southwestern Spain, since regionally synchronous changes in lake level are more likely to be driven by climate change than human impact, local hydrological or topographic factors. A range of lakes suitable for such a study was identified in Chapter 5.

8.4.2 Comparison with other regions

The record of lake-level change in the Laguna de Medina has more in common with the circum-Mediterranean and Saharan records of northern Africa than those of the Ebro Basin, where, apart from a humid phase in the early Holocene which is common to all sequences, the timing and pattern of lake-level change is very different. It is reasonable to conclude that the Ebro Basin has been subject to different climatic influences, and may have more in common with other parts of northwestern or continental Europe. Regional patterns of lake-level and climate are probably highly complex and driven by different climatic forcing functions. Data from southern Sweden (e.g. Digerfeldt, 1975, 1988), for example, bear little relationship to any of these studies. Lakes were high but falling at the start of the Holocene, and were low at c. 9 ka (Harrison & Digerfeldt, 1993). The Iberian Peninsula is influenced today by both Mediterranean and Atlantic climatic regimes and exhibits complex local variation in climate (Font Tullot, 1983). Clearly, further palaeoclimatic research across the Iberian Peninsula is necessary to elucidate patterns of Holocene climate change in more detail.

The results of the Laguna de Medina study make an important contribution to the understanding of early to mid-Holocene climate change. It has been suggested by some on the basis of lake-level data that the onset of humid conditions in the Holocene was time transgressive between the Equator and North Africa, and that humid conditions established prior to 10-12 ka in East Africa and other more southerly regions were not fully in evidence in the Maghreb until around 6 ka (Street & Grove, 1979, Rognon, 1987). This supports the argument that climate change over the Northern Hemisphere regions of Africa was driven primarily by the northward shift of the tropical monsoon belt bringing summer rains, which has been linked to enhanced monsoonal activity consequent upon global changes in the orbital parameters of the Earth (Kutzbach, 1983, Street-Perrott *et al.*, 1990).

The main basis for the argument was Rognon's contention that early Holocene humid events in the Maghreb identified by Fontes, Gasse and co-workers were local, and has been strongly disputed by them (Fontes & Gasse, 1989, Gasse *et al.*, 1990). Although lake levels did not peak until c. 6 ka in the Laguna de Medina, they were high by at least as early as 8 ka and have much in common with the North African sequences. The results of the Laguna de Medina study therefore strengthen the argument for an early Holocene humid phase extending as far north as southwestern Spain, and for the synchroneity rather than time-transgressive nature of early Holocene climate change.

This has implications for the interpretation of the causal mechanisms for climate change which are fed into General Circulation Models. Although there is some pollen and isotopic evidence for time-transgressive change further south (Lézine *et al.*, 1990), the assumption that climate change in North Africa was driven simply by the influence of the monsoon belt may be an over-simplification. Mediterranean Europe is under the influence of westerly depressions today. Since the Laguna de Medina data are similar to North African data, it is possible that patterns of climate change in North Africa have been more complex, and possibly driven by either one or both of Atlantic and subtropical climate systems.

The second major event is the desiccation or lowering of lake levels after c. 5 ka. The change was dramatic in deep lakes of the Rift Valley and in some other lakes such as in Libya (Pachur, 1980). A lowering of lake levels also occurred in the Laguna de Medina, which again supports an interpretation of large-scale regional climate change, although both this and the North African systems have always been relatively shallow and, as noted, it is possible their desiccation was related to a greater or lesser extent to natural or human-induced processes of sediment infilling.

In respect to other regions, Harrison & Digerfeldt (1993) have reviewed evidence for lake-level change across the Mediterranean. As in Spain and Africa, there is evidence for an early Holocene phase of high lake levels by c. 11 ka in Greece and the former Yugoslavia (based on 7 studies e.g. Bottema [1974]) and between c. 12-11 ka in Turkey (Roberts, 1983) and southern Arabia (Roberts, 1982).

Harrison & Digerfeldt (1993) also suggest there is evidence for a lowering of lake levels after c. 5 ka throughout the Mediterranean, but that the pattern was less abrupt in the east than the west. The latter argument is not supported by the results of the present study, where a gradual rather than abrupt fall in lake levels thereafter was inferred. High lake levels in the western Mediterranean until well after 5 ka are also indicated by the results of the Ebro Basin study (Study 1). As noted above, the authors' inferences concerning palaeoclimate change in the western Mediterranean relied on a very limited amount of data from four previous studies in Spain, and their conclusions are perhaps premature.

The results of the Laguna de Medina study also contribute to a debate concerning abrupt, global Holocene climate change derived from African lake-level data. Climate modellers have suggested that the dry phase centred around 7.5 ka in many African lakes, and outlined above, was a response to the suppression of warm North Atlantic Deep Water oceanic circulation. Causal mechanisms invoked range from the continued influence of the melting of the North American Laurentide Ice Sheet, which may have led to an earlier arid phase in Africa possibly equated with the 'Younger Dryas' cold phase of western Europe during the Late-Glacial transition (Street-Perrott & Perrott, 1990), to salinity oscillations of the Atlantic on a periodicity of 2.0-2.5 kyr (Broecker *et al.*, 1990, Roberts *et al.*, 1994). Roberts *et al.* (1994) favour the latter hypothesis and use lake-level data from studies 4, 15 and 17 detailed here, a tropical lake in West Africa, Lake Bosumtwi, Ghana (Talbot & Delibrias, 1980), and a karstic lake high in the Atlas Mountains, Lake Tigalmamine, Morocco (Roberts, 1990, Lamb *et al.*, 1995) as evidence for widespread arid phases throughout northern Africa at c. 10.2 ka, 7.4 ka and in the later Holocene. It is suggested that the lack of evidence for further oscillations in most African lakes after 5 ka is more a function of reduced sensitivity to climate change consequent upon their desiccation. The synchroneity of change in the Atlas Mountains, where a temperate Atlantic climate prevails, is taken as evidence that both monsoonal and Atlantic climate regimes were affected, indicative of global climate change.

This is supported by the evidence for a dry phase in the Laguna de Medina from c. 7.8-6.0 ka. It is tempting to conclude that this supports the argument for global climate change, but in essence the interpretation still relies on a very small data-set of lakes. Data from other parts of Africa are insufficient; in their research on interdunal depressions of the Maghreb and East Niger, Gasse *et al.* (1987) and Baumhauer (1991) argue that while there is consistent evidence for major changes in Holocene lake level, as outlined above, minor fluctuations are instead a product of local topography and hydrology. Interdunal systems in particular are subject to local changes in topography which can cause lake-level or salinity change independent of climate (Gasse *et al.*, 1987). As detailed in Table 8.1, many of the lakes are groundwater-fed and influenced by factors such as changes in river flow which do not necessarily relate simply to climate change. In its favour, the Sebkha Mellala, Algeria (study 4), Lake Abhé, Djibouti (study 15) and the Galla lakes in the Ziway-Shala Basin, Ethiopia (study 17) used to support the argument are all regarded as being reliable recorders of climate change, but Lake Tanganyika (study 18) is also regarded as climate-sensitive until volcanism at around 5 ka, and shows no evidence for similar lake-level fluctuations. Thus, the results of the study support the widespread occurrence of a dry phase around 7.5 ka but it is again clear that further research in stable basins is necessary to corroborate inferences of global climate change.

8.4.3 Summary

In summary, the Laguna de Medina and other lakes throughout the western and eastern Mediterranean, and in North Africa, show clear evidence for high lake levels in the early Holocene which is equated with a widespread humid phase. Within the Iberian Peninsula, the record of the Laguna de Medina differs in other respects to that of lakes in northeastern Spain and complex local or regional variability in climate change is inferred which demands further research in other systems across Spain. The results support the synchroneity of early Holocene climate change across northern Africa and southwestern Spain, and indicate that inferences concerning the overriding influence of the tropical monsoon belt across the region may have been over-simplistic.

A lowering of lake levels after c. 5ka is also common to these regions, but the evidence from the Laguna de Medina does not agree with postulated regional differences in the timing of this event, which were inferred from too limited a data-set of lakes.

An inferred arid phase of low lake levels around 7.5 ka in African sequences is common to the Laguna de Medina record. This may reflect the influence of abrupt, global climate change in the Holocene, but to err on the side of caution it is again suggested that further research should be carried out before regional patterns of climate change are interpreted in detail.

CHAPTER NINE

CONCLUSIONS

9.1 THE MODERN DATA-SET

9.1.1 Diatom-salinity transfer function

Variables reflecting total salinity, brine composition, turbidity and water depth/permanence make a significant and independent contribution to the variance in the modern diatom data-set. Conductivity is the strongest of the two salinity variables, and a transfer function has been developed successfully with simple WA ($r^2 = 0.91$) from a data-set of 70 samples from 55 lakes after removal of four outliers.

While the apparent predictive ability using simple WA is high compared to other transfer functions ($r^2 = 0.83$-0.89 for Africa and North America), performance under jackknifing is poor due to the heterogeneity and relatively small size of the data-set. The freshwater and hypersaline ends of the salinity spectrum are least well-represented, and would be the most useful salinity ranges to concentrate upon in enlarging the data-set. Low-salinity, endorheic lakes are very rare in Spain and sampling of fresh waters would rely instead on open systems. Many hypersaline, ephemeral lakes were dry when sampled for this project, and representativity of the upper salinity range could be improved by sampling in a different season. Equally, it could be improved by sampling coastal lagoons, which would also improve coverage of chloride-dominated systems and may provide additional modern analogues for fossil taxa.

From a comparison with African and North American data-sets, the Spanish flora has strong affinities with that of North Africa. For cosmopolitan taxa, an assumption that salinity optima are globally applicable appears to be valid. Salinity optima at the fresh/oligosaline end of the salinity spectrum are lower for Africa than for Spain or North America, which is probably due to the more comprehensive coverage of freshwater systems in the large African data-set. The move towards combining regional data-sets is aimed at improving representativity of the salinity range, allowing the reconstruction of other environmental gradients such as brine composition, and improving modern analogues for fossil taxa which are rare or absent in the modern flora of a given region (Juggins *et al.*, 1994). However, it is intuitively possible that salinity in the oligosaline range may in fact be underestimated using a large data-set with many freshwater samples, and it would be a useful exercise to compare the predictive ability of different sized data-sets over different parts of the salinity range.

9.1.2 The influence of other environmental gradients

TWINSPAN was used to group samples according to diatom species assemblage composition in a further assessment of the influence of other environmental gradients. Potential indicator species for chloride-rich systems have been identified, but there are no clear indicators for sulphate or carbonate systems. Indicator species for carbonate lakes are found elsewhere and their absence in the Spanish data-set is a function of the rarity of carbonate lakes in this region.

The interpretation of changes in planktonic:benthic ratios in terms of lake-level change relies on many assumptions. The validity of the approach is supported in this study by the increased abundance of planktonic taxa relative to benthic and aerophilous taxa in groups of samples from permanent and semi-permanent lakes, which correlates in this study with water depth.

9.2 STUDIES OF DIATOM PRESERVATION

From an assessment of diatom preservation in the recent sediments of >50 lakes throughout Spain, and of preservation in Holocene sequences from 21 lakes, it is clear that lakes of southern Spain are of greater potential for diatom analysis than those of central or northeastern Spain. Many of the lakes of La Mancha and the Ebro Basin are ephemeral and do not preserve diatom records either in the recent sediments or, from an assessment of 8 long cores from the Ebro Basin and 2 from La Mancha, on a Holocene timescale.

With the exception of the Laguna de Medina, the preservation of diatoms in the more permanent systems of Andalucía (and artificial systems elsewhere) is restricted to the upper part of the sediment record and it is inferred that human impact rather than climate could have driven palaeoenvironmental change. This underlines the extreme importance of the Laguna de Medina as a study site for Holocene palaeoclimate reconstruction.

The results of PCA indicate that the correlated variables water depth and lake permanence, and salinity, are the most important factors influencing preservation. The better preservation of diatoms in permanent systems of relatively low salinity is a useful predictor for studies of recent environmental change. It is not a useful predictor for Holocene studies; in addition to the possibility that lake levels have changed significantly over the last 10,000 years, human impact on these systems has been such that, in Spain at least, the current state of lakes is probably very different to their past 'natural' state.

9.3 THE LAGUNA DE MEDINA

9.3.1 Application of the diatom transfer function

A primary aim of the thesis was to assess the potential of diatoms in Spanish salt lakes for Holocene quantitative palaeosalinity reconstruction, by the application of a salinity transfer function to the fossil diatom sequence of a selected study site.

The representativity of fossil diatoms in the training set was assessed from abundance and diversity indices for individual fossil taxa, and from the results of modern analogue matching for fossil assemblages. The dominant fossil taxa are very poorly represented in the training set due to the effects of diatom dissolution on the one hand, which has resulted in the abundance of robust taxa which are rare in the surface set, and to a lack of modern analogues on the other, whereby other fossil assemblages are dominated by taxa which are completely absent in the surface set.

The transfer function was modified to include partially-dissolved 'dissolved modern analogue' or '*DMA*' assemblages from the recent sediments of lakes. This is a novel, *ad hoc* technique for improving palaeosalinity reconstruction for assemblages affected by dissolution and involves a process of screening to eliminate samples from lakes where significant environmental change is likely to have occurred since their deposition. Modern analogue matching techniques showed a good match between dissolved fossil assemblages and the modified training set assemblages, but the two dominant fossil taxa, *Campylodiscus clypeus* and *Mastogloia braunii*, are each abundant in only one *DMA* assemblage and the estimated optima in this study are again unreliable.

Despite this, the technique has the potential to provide a rapid means of improving palaeosalinity reconstruction for poorly-preserved fossil sequences. In this study only 9 sites contain suitable *DMA* samples, and the data-set would need to be expanded.

The Laguna de Medina record is excellent in comparison with other sites screened, which suggests that the potential of diatoms for quantitative Holocene palaeoclimate reconstruction using standard techniques is limited in Spain to studies of recent environment change, or to permanent karstic systems which are fed by major aquifers and where lake levels are less likely to be sensitive to climate change.

9.3.2 Diatom-based palaeosalinity and lake-level reconstruction

Evidence for significant palaeosalinity and lake-level change has been derived by employing traditional palaeoecological techniques based on reported salinity preferences and on changes in the relative abundance of planktonic taxa for palaeosalinity and lake-level reconstruction respectively.

For palaeosalinity, this overcomes the constraint on quantitative reconstruction of a lack of modern analogues for taxa abundant in fossil assemblages, *Cyclotella choctawhatcheeana* and *Diploneis didyma*, by reference to ecological data from other regions. By taking diatom dissolution into account, less robust taxa at low frequencies are given added significance and interpretation does not rely solely on the few dominant, robust taxa, *Campylodiscus clypeus*, *Mastogloia braunii*, *Cyclotella choctawhatcheeana* and *Diploneis didyma*. Unlike many previous studies, palaeosalinity interpretation is strengthened by reference to the large body of reliable diatom and associated water chemistry data established through the development of transfer functions in Spain, Africa and North America.

9.3.3 Palaeosalinity and lake-level reconstruction using multiple proxy indicators

With the exception of ostracod shell chemistry, inferred trends in palaeosalinity, and lake-level change, are common to different lines of evidence (diatoms, and basic sediment properties, ostracod shell chemistry analysis and the palaeoecology of ostracods, foraminifera, molluscs and plant macrofossils). Although there are weaknesses in some of the techniques, such as the use of single ostracod taxa as indicative of permanent versus ephemeral waters, the consistency of the results supports their reliability.

An important aim of the study was to assess the potential of diatoms for Holocene reconstruction. The separate rather than combined analysis of the data provides a clearer indication of the relative reliability of different techniques, and indicates that diatoms are valuable palaeoenvironmental indicators even in poorly-preserved sequences.

Whilst inferred trends are consistent, the separate analysis of the data also shows that the location of inferred transitions does not match exactly. This suggests that it may be unwise to interpret the record in detail, in terms of short-term palaeoenvironmental change.

The ostracod shell chemistry record may be affected by other factors such as the precipitation of different carbonate phases and it is necessary to apply additional analytical techniques before the record can be interpreted with confidence.

The direct rather than inverse relationship between palaeosalinity and lake-level over much of the sequence may be a consequence of groundwater flow and limnological change independent of climate, and in this study the palaeosalinity record cannot be used to infer lake-level change.

9.3.4 Holocene palaeoclimate change

Following a high-stand prior to c. 7860 BP, there is a phase of unstable, predominantly low but fluctuating lake levels. Maximum lake levels (and salinity) are attained around 6000 BP. This indicates an early Holocene humid phase, followed by an increase in seasonality or aridity, and a phase of maximum humidity. The gradual decline in lake level initiated some time after 6000 BP (currently undated) coincides with palynological evidence for human impact and cannot be interpreted with confidence in terms of climate change. It could equally reflect natural processes of sediment infilling over time.

9.3.5 Comparison with other regions

The lake-level record of the Laguna de Medina has most in common with the circum-Mediterranean and Saharan records of northern Africa, where an early Holocene humid phase of high lake levels is followed by a reduction in lake levels after c. 5ka interpreted as an increase in aridity. The new evidence from southwest Spain supports an argument for the synchroneity rather than time-transgressive nature of Holocene climate change across northern Africa and has implications for the interpretation of the climatic forcing functions involved. There is also evidence for low lake levels centred on c. 7.5ka which may be a result of abrupt, global climatic episodes, although the hypothesis currently rests on a relatively small data-set of lakes and further work is needed to establish regional patterns of climate change in more detail.

Other than the early Holocene phase of high lake levels, Holocene lake-level change in the Laguna de Medina has little in common with the inferred pattern in lakes of the Ebro Basin, northeastern Spain, which is the only other study on the Iberian Peninsula with which the results of this study can be usefully compared. The Ebro Basin has probably been subject to different climatic influences, and, again, further research is necessary across Spain to elucidate patterns of Holocene climate change.

The results (and those from the Ebro Basin) do not support the postulated more abrupt nature of lake-level lowering after c. 5ka in western Europe compared to the east, which had been based on a very limited data-set of insufficient quality for such inferences.

In all respects it is clear that further research needs to be done in these regions before patterns of Holocene climate change can be fully understood.

APPENDIX ONE

SITE NAMES AND LOCATION

SITE CODE	SITE NAME	MUNICIPALITY	PROVINCE	LATITUDE	LONGITUDE	ALTITUDE (m asl)
AAMA	L Amarga	Lucena	Cordoba	37 29' 02"N	4 41' 40"W	380
ADLC	L Dulce	Lucena	Cordoba	37 29' 01"N	4 41' 41"W	380
AHDA	L Honda	Alcaudete	Jaen	37 35' 48"N	4 07' 48"W	460
AJRL	L de los Jarales	Lucena	Cordoba	37 18' 50"N	4 34' 40"W	440
ASBL	El Salobral	Luque	Cordoba	37 35' 18"N	4 12' 00"W	420
ATSC	L de Tiscar	Puente-Genil	Cordoba	37 25' 50"N	4 49' 06"W	180
AZNR	L de Zonar	Aguilar de la Frontera	Cordoba	37 29' 02"N	4 41' 40"W	300
BCCA	L Chica	Archidona	Malaga	37 05' 55"N	4 18' 35"W	800
BCPC	L de Capacete	Campillos	Malaga	37 01' 00"N	4 50' 30"W	460
BDCE	L Dulce	Campillos	Malaga	37 03' 12"N	4 50' 00"W	460
BFNT	L de Fuente de Piedra	Fuente de Piedra	Malaga	37 06' 13"N	4 44' 48"W	410
BGDE	L Grande	Archidona	Malaga	37 06' 30"N	4 18' 10"W	800
BRTS	L de la Ratosa	Humilladero	Malaga	37 10' 48"N	4 42' 00"W	450
BSDA	L Salada	Campillos	Malaga	37 02' 18"N	4 50' 30"W	460
CALC	L de la Alcaparrosa	Utrera	Sevilla	37 03' 06"N	5 48' 48"W	20
CARJ	L de Arjona	Utrera	Sevilla	37 02' 12"N	5 49' 01"W	40
CBLL	L la Ballestera	Osuna	Sevilla	37 22' 00"N	5 10' 30"W	150
CGSQ	L del Gosque	Martin de la Jara	Sevilla	37 07' 42"N	4 56' 30"W	440
CTRJ	L del Taraje	Las Cabezas de San Juan	Sevilla	36 55' 00"N	5 54' 24"W	130
CZRR	L de Zarracatin	Utrera	Sevilla	37 02' 00"N	5 48' 00"W	50
DCMS	L del Comisario	Puerto Real	Cadiz	36 31' 24"N	6 01' 48"W	60
DDUL	L Dulce	Espera	Cadiz	36 51' 30"N	5 51' 48"W	110
DHND	L Hondilla	Espera	Cadiz	36 52' 18"N	5 51' 36"W	100
DMDN	L de Medina	Jerez de la Frontera	Cadiz	36 37' 18"N	6 02' 48"W	35
DPRA	Salinas de Belen Nuevo I	Puerto Real	Cadiz	36 31' 15"N	6 09' 05"W	2
DPRB	Salinas de Belen Neuvo II	Puerto Real	Cadiz	36 31' 15"N	6 09' 05"W	2
DSLA	L Salada	El Puerto de Santa Maria	Cadiz	36 38' 42"N	6 14' 06"W	30
DSLD	L Salada de la Zorrilla	Espera	Cadiz	36 52' 00"N	4 49' 35"W	100
DTJE	L de Taraje	Puerto Real	Cadiz	36 32' 45"N	6 03' 30"W	40

DTLL	L de los Tollos	Jerez de la Frontera	Cadiz	36 50' 42"N	6 01' 00"W	70
EACH	L de Alcahozo	Pedro Munoz	Ciudad Real	39 23' 30"N	2 52' 30"W	669
EALB	L de La Albuera	Daimiel	Ciudad Real	39 05' 00"N	3 39' 48"W	645
EALM	L de Almodovar	Almodovar del Campo	Ciudad Real	38 42' 30"N	4 10' 54"W	675
EALT	L del Altillo	Lillo	Toledo	39 41' 30"N	3 17' 48"W	680
ECHC	L Chica de Villafranca	Villafranca de los Caballeros	Toledo	39 27' 30"N	3 20' 30"W	645
ECLD	L de la Celadilla	Las Pedroneras	Cuenca	39 27' 18"N	2 45' 42"W	690
ECPL	L de los Capellanes	Belmonte	Cuenca	39 39' 00"N	2 37' 00"W	900
ECRR	L de la Carrizosa	Cabezarados	Ciudad Real	38 50' 30"N	4 14' 42"W	680
EDEH	L de la Debesilla	Las Pedroneras	Cuenca	39 26' 18"N	2 50' 12"W	680
EFTL	L de Fuentillejo	Ciudad Real	Ciudad Real	38 56' 24"N	4 03' 18"W	640
EGRA	L Grande de Villafranca	Villafranca de los Caballeros	Toledo	39 27' 12"N	3 20' 42"W	645
EHIT	L de El Hito	Montalbo	Cuenca	39'50' 00"N	2 42' 00"W	830
ELLL	L de Lillo	Lillo	Toledo	39'42' 00"N	3 19' 48"W	690
EMNJ	L de Manjavacas	Mota del Cuervo	Cuenca	39 25' 12"N	2 51' 42"W	670
ENVG	L Nava Grande	Malagon	Ciudad Real	39 10' 48"N	3 56' 30"W	620
EPBL	L del Pueblo	Pedro Munoz	Ciudad Real	39 24' 54"N	2 56' 42"W	654
EPNH	L's de Pena Hueca	Villacanas	Toledo	39 30' 48"N	3 20' 30"W	650
EPZL	L de Pozuelo	Pozuelo de Calatrava	Ciudad Real	38 54' 54"N	3 50' 00"W	620
EQU1	L Grande	Quero	Toledo	39 29' 30"N	3 15' 12"W	650
EQU2	L Grande salt pan	Quero	Toledo	39 29' 30"N	3 15' 12"W	650
ESLC	L de Salicor	Campo de Criptana	Ciudad Real	39 28' 06"N	3 10' 24"W	668
ETRY	L del Taray	Las Pedroneras	Cuenca	39 24' 30"N	2 45' 30"W	670
ETRZ	L de Tirez	Villacanas	Toledo	39 32' 12"N	3 21' 36"W	650
GCNJ	L Concejo	Ossa de Montiel	Albacete	38 55' 12"N	2 48' 36"W	860
GCRL	L Grande	Corral Rubio	Albacete	38 50' 06"N	1 27' 48"W	855
GLNG	L Lengua	Ossa de Montiel	Albacete	38 56' 30"N	2 51' 24"W	820
GMJN	L Mojon Blanco	Corral Rubio	Albacete	38 48' 06"N	1 26' 06"W	880
GNVL	L de Navalcudia	El Bonillo	Albacete	38 56' 24"N	2 27' 42"W	1080
GONT	La Ontalafia	Albacete	Albacete	38 43' 18"N	1 46' 12"W	840
GPTR	L de Petrola	Petrola	Albacete	38 50' 42"N	1 34' 00"W	860
GRSA	L de Hoya Rasa	Corral Rubio	Albacete	38 47' 18"N	1 25' 36"W	873
GSAR	L del Saladar	Corral Rubio	Albacete	38 47' 42"N	1 25' 12"W	873
GSLB	L del Salobrejo	Higueruela	Albacete	38 55' 06"N	1 27' 12"W	940
HBDP	Balsa del Planeron	Belchite	Zaragoza	41 22' 00"N	0 38' 00"W	240

HBSA	L Balsa Salada	Alcaniz	Teruel	40 59' 00"N	0 12' 00"W	325
HCAS	Hoya del Castillo	Hijar	Zaragoza	41 16' 00"N	0 30' 00"W	260
HCHI	La Estanca, Caspe	Chiprana	Zaragoza	41 14' 00"N	0 09' 00"W	150
HEST	La Estanca, Alcaniz	Alcaniz	Teruel	41 04' 00"N	0 11' 00"W	325
HGAL	L de Gallocanta	Calamocha	Teruel	40 50' 00"N	2 11' 00"W	1020
HGUA	L Guallar	Bujaraloz	Zaragoza	41 24' 30"N	0 13' 42"W	336
HLAG	La Laguna	Setiles	Teruel	40 44' 00"N	1 36' 00"W	1300
HLCA	La Lagunica	Calamocha	Teruel	40 49' 00"N	2 10' 00"W	1020
HLDP	L de La Playa	Bujaraloz	Zaragoza	41 25' 12"N	0 11' 12"W	324
HLDS	L de la Salineta	Bujaraloz	Zaragoza	41 29' 00"N	0 09' 30"W	320
HLOR	Balsa de Lor	Tudela	Navarra	41 59' 00"N	1 41' 00"W	370
HLZO	El Lagunazo	Sadaba	Zaragoza	42 18' 00"N	1 18' 00"W	1020
HPD1	Estany de la Podrida I	Llobregat	Barcelona	41 51' 00"N	2 25' 00"E	0.5
HPEQ	L Salada Pequena	Alcaniz	Teruel	41 03' 00"N	0 12' 00"W	357
HPIC	Balsas del Pico	Chiprana	Zaragoza	41 08' 00"N	0 01' 00"W	300
HPIT	L del Pito	Bujaraloz	Zaragoza	41 24' 48"N	0 08' 48'W	328
HREB	La Salina de Rebollon	Bujaraloz	Zaragoza	41 22' 48"N	0 18' 18"W	316
HSAL	L Salada de Chiprana	Chiprana	Zaragoza	41 14' 18"N	1 10' 48"W	150
HSUL	L Salada Sulfurica	Mediana	Zaragoza	41 30' 12"N	0 44' 00"W	350
HZAI	L de La Zaida	Used	Zaragoza	41 00' 30"N	1 34' 20"W	1000
IFAF	L Salina Grande	Villafafila	Zamora	41 50' 00"N	5 36' 24"W	680
IRDR	L Rodrigo	Santa Maria la Real de Nieva	Segovia	38N	5W	920
IVGZ	L de la Iglesia	Coca	Segovia	38N	5W	850
IVRN	L de las Salinas II	Villarin de Campos	Zamora	41 48' 18"N	5 38' 30"W	690

APPENDIX TWO

MODERN DATA-SET: SELECTED LIMNOLOGICAL VARIABLES

SITE CODE	DATE	MEAN AREA (km^2)	PERM	EUTR	TURB	DEPTH (m)	COND (mS cm^{-1})	pH
AAMA1	27 Mar 92	0.04	3	1	1	3.0	13	9.0
AAMA2	12 Jul 92					2.5	14	8.7
ADLC1	27 Mar 92	0.05	1	1	1	damp	e: 5	
AHDA1	11 Jul 92	0.01	1	2	2	0.1	30	8.5
AJRL1	27 Mar 92	0.03	1	1	3	dry	e: 20	
ASBL1	26 Mar 92	0.48	1	1	3	0.1	33	8.4
ASBL1'	11 Jul 92					0.5	0.38	9.2
ATSC1	27 Mar 92	0.11	1	1	2	1.0	37	7.6
AZNR1	26 Mar 92	0.38	3	2	1	9.5	4.4	6.3
BCCA1	5 Apr 91	0.04	3	2	1	1.0	23.6	9.0
BCCA2	15 Jul 92					1.5	21	9.7
BCPC1	31 Mar 92	0.04	1	2	3	0.3	44	8.5
BDCE1	31 Mar 92	0.10	2	1	3	0.2	15	8.3
BDCE2	13 Jul 92					dry		
BFNT1	31 Mar 92	12.19	2	1	3	0.1	43.5	8.3
BGDE1	5 Apr 91	0.12	3	2	1	7.0	4.3	8.3
BGDE2	16 Jul 92					8.2	0.5	8.3
BRTS1	31 Mar 92	0.17	2	2	3	0.5	46.5	8.6
BRTS2	13 Jul 92					damp		
BSDA1	6 Apr 91	0.13	2	2	3	0.5	23.9	8.4
BSDA2	31 Mar 92					0.3	90.5	8.4
BSDA3	13 Jul 92					damp		
CALC1	28 Mar 92	0.05	2	1	1	0.8	7.1	7.7
CALC2	1 Jul 92					0.6	12	7.7
CARJ1	27 Mar 92	0.02	2	2	2	0.9	15	8.3
CARJ2	30 Jun 92					0.6	18	8.3
CBLL1	30 Mar 92	0.25	1	1	2	damp	e: 75	
CGSQ1	30 Mar 92	0.25	2	1	3	0.8	19	8.0
CGSQ2	14 Jul 92					0.6	25.5	9.7
CGSQ3	16 Aug 93					0.02	350	8.3
CTRJ1	28 Mar 92	0.03	2	1	2	2.0	5.3	8.2
CTRJ2	1 Jul 92					1.6	7.6	8.5
CTRJ3	11 Aug 93					0.5	25.6	8.5
CZRR1	29 Mar 92	0.55	2	1	2	0.03	338	6.6
CZRR2	3 Jul 92					damp		

DCMS1	30 Mar 92	0.21	2	2	2	1.5	7.8	8.9
DDUL1	29 Mar 92	0.09	2	1	1	2.0	5.3	7.7
DDUL2	2 Jul 92					1.3	9.2	7.3
DHND1	29 Mar 92	0.04	2	1	2	0.6	5.1	7.6
DMDN0	30 Mar 92	1.40	2	1	1	0.8	12.1	7.0
DMDN1	4 Jul 92					0.7	15.66	8.2
DMDN2	13 Aug 93					dry		
DPRA1	5 Aug 93	0.01	3	1	1	1.0	77.7	8.3
DPRB1	5 Aug 93	0.01	3	1	1	1.0	71.8	8.3
DSLA1	5 Jul 92	0.32	1	1	2	dry	e: 30	
DSLD1	29 Mar 92	0.19	1	1	2	1.0	17	7.4
DSLD2	2 Jul 92					0.3	27	8.1
DTJE1	11 Aug 93	0.19	3	1	2	0.3	10.25	8.4
DTLL1	29 Mar 92	0.71	1	1	3	0.04	36	8.0
DTLL2	29 Jun 92					dry		
EACH1	7 Apr 92	0.71	1	3	1	0.1	40	8.9
EALB1	5 Apr 92	0.80	1	1	1	0.3	5.15	7.7
EALM1	5 Apr 92	0.26	1	2	1	0.3	12.5	9.9
EALT1	7 Apr 91	0.14	1	1	1	0.05	56.6	8.0
ECHC1	16 Sep 91	0.25	3	2	1	1.09	e: 3.8	8.3
ECHC2	6 Apr 92					0.9	3.8	8.3
ECLD1	7 Apr 92	0.06	3	3	1	1.0	2.1	8.4
ECPL1	9 Apr 92	0.08	1	3	1	1.5	2.2	7.7
ECRR1	5 Apr 92	0.10	1	3	1	0.02	0.15	7.5
EDEH1	7 Apr 91	0.17	1	1	2	0.02	51.3	8.0
EDEH2	8 Apr 92					dry		
EFTL1	5 Apr 92	0.05	1	1	3	0.04	4.6	9.8
EFTL2	7 Jul 92					dry		
EGRA2	16 Sep 91	0.10	3	2	1	1.5	e: 7.7	8.2
EGRA1	6 Apr 92					1.0	7.7	8.2
EHIT1	9 Apr 92	1.50	1	1	2	0.04	7.1	8.3
EHIT2	18 Jul 92					dry		
ELLL1	8 Apr 92	0.96	1	3	1	0.1	38	9.3
EMNJ1	7 Apr 92	1.06	1	3	2	0.15	22	7.8
ENVG1	5 Apr 92	0.50	1	1	1	0.05	14	8.0
EPBL1	7 Apr 92	0.38	2	3	2	2.0	5.5	7.7
EPNH1	6 Apr 92	1.18	1	2	2	0.04	73	8.4
EPZL1	5 Apr 92	0.46	1	3	1	0.1	14.5	8.8
EQU11	6 Apr 92	0.01	1	2	2	0.25	46	8.8
EQUE1	6 Apr 92	0.001	1	2	1	0.1	38	8.5
ESLC1	6 Apr 92	0.44	1	3	3	0.03	49	8.3
ETRY1	8 Apr 92	0.03	3	2	1	0.2	1.7	8.0
ETRZ1	6 Apr 92	0.62	1	2	1	0.02	350	8.9
GCNJ1	12 Apr 92	4.64	3	1	1	4.0	0.67	7.8

GCRL1	10 Apr 92	1.22	1	3	3	0.05	34	8.6
GLNG1	12 Apr 92	1.84	3	1	1	2.7	0.55	8.1
GMJN1	10 Apr 92	0.06	1	1	1	0.09	49	7.8
GNVL1	11 Apr 92	0.01	1	1	2	0.03	0.21	9.3
GONT1	10 Apr 92	3.84	2	1	3	0.8	4.85	8.0
GONT2	10 Jul 92					1.5	0.5	9.7
GPTR1	10 Apr 92	1.74	1	3	1	0.7	10	9.0
GRSA1	9 Jul 92	0.12	1	2	1	0.1	61.5	8.3
GSAR3	6 Apr 91	0.25	2	1	2	0.5		
GSAR1	10 Apr 92					0.7	23	8.2
GSAR2	9 Jul 92					0.2	50	8.9
GSLB1	9 Apr 92	0.36	2	3	2	0.8	18.5	8.7
GSLB2	9 Jul 92					0.5	25	8.9
HBDP1	23 Jul 90	0.30	1	1	2	0.5	6.6	6.9
HBSA1	23 Jul 90	0.05	1	1	3	dry	e: >50	
HCAS1	21 Jul 91	0.20	1	1	3	dry	e: >50	
HCHI1	19 Jul 90	0.50	3	1	1	1.2	3.2	7.2
HEST1	23 Jul 90	1.00	3	1	1	8.0	0.8	7.4
HGAL1	24 Jul 90	13.30	2	1	1	0.5	205	9.2
HGUA1	22 Jul 90	0.13	1	1	3	damp	e: >50	
HLAG1	8 Apr 91	0.01	3	2	2	3.0	0.723	7.0
HLCA1	24 Jul 90	0.15	1	1	2	0.3	3	7.5
HLDP2	1 Dec 91	1.92	1	1	2	0.05	40	7.3
HLDS2	22 Jul 90	0.17	2	1	2	damp	e: >50	
HLDS1	1 Dec 91					0.05	e: 200	8.0
HLOR1	24 Jul 90	0.13	3	2	3	0.5	1.2	7.3
HLZO1	23 Jul 90	0.14	3	1	3	1.5	0.6	8.9
HPOD1	24 Aug 92	0.01	3	2	1	0.2	e: 30.9	9.0
HPEQ1	18 Jul 91	0.09	1	1	3	dry	e: >50	
HPIC1	18 Jul 91	0.01	1	1	3	dry	e: >50	
HPIT1	15 Jul 90	0.40	1	1	3	dry	e: >50	
HREB1	16 Jul 91	0.11	1	1	3	dry	e: >50	
HSAL1	15 Jul 90	0.23	3	1	1	5.0	e: 54	8.5
HSAL2	17 Jul 91					5.0	54.00	8.5
HSUL1	1 Jul 90	0.08	1	1	3	dry	e: >50	
HZAI1	24 Jul 90	2.04	1	1	3	dry	e: >50	
IFAF1	13 Apr 92	0.01	1	1	3	0.5	22	8.8
IRDR1	13 Apr 92	0.10	1	1	1	dry	e: 20	8.0
IVGZ1	13 Apr 92	0.15	1	1	1	dry	e: 30	8.0
IVRN1	13 Apr 92	0.02	1	2	2	0.15	14	9.4

KEY: See text (Chapter 4, Section 4.3, 'Quality and range of environmental variables'), for explanation of water classification.

General lake characteristics: Mean Area; Perm = Permanence (1=ephemeral, 2=semi-permanent, 3=permanent.
Eutr = Eutrophication (1='low', 2='moderate', 3='high'); Turb = Turbidity (1='transparent', 2='moderate turbidity', 3='high turbidity')

Field data: 'Damp' and 'dry' refer to the state of lakes without a measurable water depth. Conductivity estimates denoted by 'e'.

APPENDIX THREE

MODERN DATA-SET: MAJOR IONS

SITE CODE	TDS (g l^{-1})	Na (meq l^{-1})	K (meq l^{-1})	Mg (meq l^{-1})	Ca (meq l^{-1})	Cl (meq l^{-1})	SO_4 (meq l^{-1})	CO_3+HCO_3 (meq l^{-1})	CATIONS (Na+K: Mg+Ca)	ANIONS (CO_3+HCO_3: Mg+SO_4)
AAMA1	11.76	101.19	1.18	86.33	48.09	96.18	78.26	3.41	0.76	0.020
AAMA2	12.35	579.42	5.36	92.37	48.63	105.55	85.99	0.92	4.16	0.005
ASBL1	62.12	596.43	2.98	391.05	47.14	684.56	310.34	3.42	1.37	0.003
ASBL2	3.50	33.34	0.84	17.29	12.61	32.75	21.10	1.00	1.14	0.018
ATSC1	42.32	543.19	0.71	78.82	59.12	578.66	80.08	1.17	3.94	0.002
AZNR1	2.98	41.54	0.45	3.09	0.55	40.21	4.24	5.29	11.51	0.119
BCCA2	21.92	145.72	3.88	137.04	52.63	121.97	167.23	0.86	0.79	0.003
BCPC1	101.46	559.62	47.24	335.23	34.43	709.51	274.98	11.87	1.64	0.009
BDCE1	13.63	121.42	0.76	54.69	53.09	132.37	89.00	2.06	1.13	0.009
BFNT1	93.35	1156.56	3.68	336.44	55.75	1389.98	116.69	2.02	2.96	0.001
BGDE1	3.97	11.38	1.07	18.18	36.70	9.81	47.86	1.19	0.23	0.021
BGDE2	3.97	11.38	1.07	18.18	36.70	9.81	47.86	1.19	0.23	0.021
BRTS1	63.55	624.83	0.93	262.89	66.05	873.35	144.77	4.17	1.90	0.004
BSDA2	103.57	1058.97	1.73	638.85	54.76	1494.60	288.70	6.54	1.53	0.004
CALC1	5.71	67.26	0.72	16.13	20.01	68.60	13.32	6.31	1.88	0.077
CALC2	7.40	82.39	3.75	22.07	24.47	89.45	17.86	5.38	1.85	0.050
CARJ1	18.15	178.34	4.12	55.98	74.02	236.18	54.93	2.05	1.40	0.007
CARJ2	18.15	178.34	4.12	55.98	74.02	236.18	54.93	2.05	1.40	0.007
CGSQ1	15.22	228.65	0.23	33.75	1.07	228.09	28.51	7.05	6.57	0.027
CGSQ2	25.83	327.42	3.92	54.40	3.63	334.73	39.21	6.31	5.71	0.017
CGSQ3	217.56	813.45	28.70	206.33	2.31	4111.36	1020.40	6.50	4.04	0.001
CTRJ1	4.66	33.38	1.78	35.60	15.90	36.16	29.91	3.98	0.68	0.060
CTRJ2	5.47	36.45	2.18	44.38	18.65	46.16	34.93	3.37	0.61	0.042
CTRJ3	27.44	154.70	4.26	179.63	28.01	232.65	195.21	4.61	0.77	0.011
CZRR1	333.02	3872.38	4.00	673.10	121.28	6219.23	135.20	2.87	4.88	0.000
DCMS1	5.15	26.63	0.34	26.78	25.84	59.09	30.77	1.85	0.51	0.021
DDUL1	5.32	16.82	3.33	29.58	28.85	23.02	59.86	3.39	0.34	0.041
DDUL2	7.68	29.96	5.62	51.84	44.19	33.67	80.69	2.72	0.37	0.024

DHND1	2.13	9.53	0.62	10.32	13.28	13.68	16.40	4.38	0.43	0.146
DMDN0	10.61	87.89	4.00	65.80	34.96	84.46	78.28	3.20	0.91	0.020
DMDN1	9.40	45.02	1.77	83.12	35.68	110.43	51.81	3.22	0.39	0.020
DPRA1	59.67	383.98	33.07	158.42	26.17	546.59	52.88	4.35	2.26	0.007
DPRB1	53.06	370.17	32.10	154.85	24.87	472.00	87.46	3.67	2.24	0.007
DSLD1	16.00	89.05	1.84	99.90	43.86	92.64	104.73	4.06	0.63	0.021
DSLD2	28.57	180.07	6.05	216.19	38.39	212.06	202.18	4.53	0.73	0.011
DTJE1	7.18	49.17	1.66	35.70	30.81	42.33	63.90	1.07	0.76	0.010
DTLL1	43.41	487.88	1.99	123.42	36.42	550.04	145.60	2.74	3.06	0.004
EACH1	107.12	408.30	12.49	1425.54	22.11	816.95	1036.46	13.69	0.29	0.007
EALB1	4.80	11.02	2.76	27.96	30.77	19.40	54.60	2.40	0.23	0.032
EALM1	8.46	122.84	0.67	0.44	0.53	84.73	13.56	32.45	127.22	0.330
ECHC1	4.11	7.52	2.65	30.26	26.67	9.39	50.24	2.65	0.18	0.044
ECHC2	4.11	7.52	2.65	30.26	26.67	9.39	50.24	2.65	0.18	0.044
ECLD1	2.06	0.84	0.92	4.81	21.60	2.36	26.18	2.98	0.07	0.104
ECPL1	2.24	2.43	0.10	5.26	22.55	0.69	31.36	2.24	0.09	0.070
ECRR1	0.14	0.53	0.45	0.66	1.33	0.26	0.48	0.83	0.49	1.137
EFTL1	3.13	40.81	2.73	3.35	0.99	20.38	4.07	21.08	10.05	0.860
EGRA1	11.18	39.59	1.59	121.61	29.87	43.74	131.44	3.06	0.27	0.017
EHIT1	8.09	28.36	4.47	76.05	27.89	31.61	94.79	2.00	0.32	0.016
ELLL1	13.16	166.09	4.00	166.16	20.00	171.83	181.24	3.40	0.91	0.010
EMNJ1	28.87	168.57	12.38	263.43	30.86	243.65	181.58	3.17	0.61	0.007
ENVG1	9.84	81.69	3.95	46.10	54.57	109.15	39.82	1.27	0.85	0.009
EPBL1	4.83	22.12	5.46	22.26	21.15	29.70	43.11	4.02	0.64	0.055
EPZL1	12.42	79.34	31.35	86.25	16.92	64.54	103.39	2.75	1.07	0.016
EQUE1	81.03	451.43	13.72	1030.83	22.35	454.87	851.76	1.16	0.44	0.001
ESLC1	184.29	786.20	61.01	2169.88	20.23	1468.09	1765.30	27.03	0.39	0.008
ETRY1	1.77	2.35	1.12	9.84	14.98	2.87	19.99	1.64	0.14	0.072
GCNJ1	0.40	0.22	0.31	0.07	3.11	1.08	1.77	3.29	0.17	1.156
GCRL1	45.59	335.94	4.69	392.64	72.99	596.99	209.04	3.01	0.73	0.004
GLNG1	2.03	0.97	0.60	1.75	2.77	1.35	1.75	1.90	0.35	0.612
GMJN1	173.34	998.66	29.78	1994.59	21.95	1346.83	1467.65	34.78	0.51	0.012
GNVL1	0.43	0.87	0.45	1.05	1.74	0.37	0.45	1.96	0.47	2.405
GONT1	3.40	22.60	4.58	34.29	5.83	34.23	14.60	1.01	0.68	0.021
GONT2	3.26	22.74	1.38	30.84	3.06	33.59	15.44	4.01	0.71	0.082

GPTR1	27.39	196.74	10.97	332.30	17.17	219.54	206.10	6.26	0.59	0.015
GRSA1	95.31	364.46	7.40	1200.02	33.01	487.30	980.10	24.33	0.30	0.017
GSAR1	61.05	205.62	7.01	917.97	27.73	367.45	641.06	9.94	0.22	0.010
GSAR2	70.27	202.12	8.74	901.94	30.44	341.50	716.98	9.68	0.23	0.009
GSLB1	22.06	89.15	5.49	323.28	3.59	90.83	229.90	16.93	0.29	0.053
GSLB2	29.46	102.83	6.92	400.17	4.96	116.89	303.99	0.00	0.27	0.044
HCHI1	4.72	28.12	0.30	10.00	35.00	2.95	63.33	1.84	0.63	0.028
HEST1	0.60	1.77	0.20	1.00	6.00	0.53	5.41	2.83	0.28	0.476
HLDP2	212.74	2812.28	487.20	592.56	24.95	3061.39	567.84	10.59	5.34	0.003
HLDS1	233.30	2344.65	46.59	1762.87	10.48	3223.26	850.72	14.99	1.35	0.009
HPD11	21.38	300.14	6.83	68.36	22.76	309.90	37.70	2.40	3.37	0.007
HSAL1	67.63	452.40	4.10	584.33	30.94	439.92	690.56	10.99	0.74	0.010
HSAL2	67.63	452.40	4.10	584.33	30.94	439.92	690.56	10.99	0.74	0.010
IFAF1	20.63	284.62	2.49	21.74	15.14	315.56	41.35	4.22	7.79	0.010
IVRN1	10.49	167.21	3.78	6.29	0.73	117.06	20.16	19.60	24.35	0.143

APPENDIX FOUR

SUMMARY OF MODERN DIATOM SAMPLES AND SEDIMENT CORE DATA

SITE CODE	DATE	*DIATOM TRANSFER FUNCTION*			*SEDIMENT CORE DATA: DIATOM PRESERVATION STUDIES*							
		SS TYPE	SS QUAL	DEPTH (cm)	IA	IB	II	III	CORE TYPE	CORE DEPTH (cm)	DIATOM PRES'N CLASS	BELOW-SURFACE DIATOM PRESERVATION (cm subsample depths)
AAMA1	27-Mar-93	glew	wetd	.5		y		y	glew	15	2	VR 5 / A 10 / R 14
AAMA2	12-Jul-92	l/st	wetd	.5			y	y	l/st hiller	333	2	A 5 / NIL 10, 15
ADLC1	27-Mar-92	trowel	dryd	1		y		y	trowel	10	2	OCC 0, 9
AHDA1	11-Jul-92	lost	lost				y	y	(glew) l/st	273	1	NIL @ 20cm intervals
AJRL1	27-Mar-92	trowel	dry-	1		y		y	trowel	25	1	NIL 24
ASBL1	26-Mar-92	glew	wetd	.5		y		y	glew	21	1	NIL 20
ASBL2	11-Jul-92	glew	wetd	.5			y	y	glew cobra	687	1	NIL @ 50cm intervals
ATSC1	27-Mar-92	glew	wetd	.5		y		y	glew	17	1	NIL 16
AZNR1	26-Mar-92	glew	wetd	.5		y		y	glew	15	3	VA 14
BCCA1	05-Apr-91	hongve	nochem	1								
BCCA2	15-Jul-92	l/st	wetd	.5								
BCPC1	31-Mar-92	glew	wet-	.5		y		y	glew	16	1	NIL 15
BDCE1	31-Mar-92	glew	wetd	.5		y		y	glew	15	2	R 14
BDCE2	13-Jul-92	hiller	dryd	2								
BFNT1	31-Mar-92	glew	wetd	.5		y		y	glew	15	1	NIL 14
BGDE1	05-Apr-91	hongve	wetd	1								
BGDE2	16-Jul-92	l/st	wetd	.5			y	y	l/st	283	3	@ 20cm intervals: VA 0-80 / A 101-150 / R 182 / OCC 200-240 / NIL 260-282
BRTS1	31-Mar-92	glew	wetd	.5		y		y	glew	31	1	NIL 30
BRTS2	13-Jul-92	glew	dry-	.5								
BSDA1	06-Apr-91	h/ful	wet-	.5								
BSDA2	31-Mar-92	glew	wetd	.5		y		y	glew	26	1	NIL 25
BSDA3	13-Jul-92	glew	dry-	.5								
CALC1	28-Mar-92	glew	wetd	.5		y		y	glew	15	2	A 5 / R 14
CALC2	01-Jul-92	glew	wetd	.5			y	y	glew cobra	180	2	R 10
CARJ1	27-Mar-92	glew	wetd	.5		y		y	glew	21	2	A 20
CARJ2	30-Jun-92	glew	wetd	.5			y		glew l/st cobra	200		not screened

CBLL1	30-Mar-92	trowel	dryd	1		y		y	trowel	10	1	NIL 9
CGSQ1	30-Mar-92	glew	wetd	.5		y		y	glew	5	1	NIL 4
CGSQ2	14-Jul-92	glew	wetd	.5								
CGSQ3	16-Aug-93	scrape	wetd	1								
CTRJ1	28-Mar-92	glew	wetd	.5		y		y	glew	15	2	OCC 5,10 / NIL 14
CTRJ2	01-Jul-92	l/st	wetd	.5			y	y	l/st cobra	137	2	R 10
CTRJ3	11-Aug-93	glew	wetd	.5								
CZRR1	29-Mar-92	glew	wetd	.5		y		y	glew	16	1	NIL 15
CZRR2	03-Jul-92	glew	dryd	.5			y	y	glew cobra	750	1	NIL @ 50cm
DCMS1	30-Mar-92	scrape	wetd	1								
DDUL1	29-Mar-92	glew	wetd	.5		y		y	glew	7	2	A 6
DDUL2	02-Jul-92	l/st	wetd	.5			y	y	l/st cobra	380	2	@ 10cm intervals: VA 10 / A 15 /OCC 20 / R 36-120 / A 140-256 / R 280-379
DHND1	29-Mar-92	glew	wetd	.5		y		y	glew	8	2	A 3 / R 5, 7
DMDN0	30-Mar-92	glew	wetd	.5		y		y	glew	6	2	A 2 / OCC 4, 9
DMDN1	04-Jul-92	glew	wetd	.5			y	y	glew l/st cobra	750	2	VA 3 / A 4, 6, 10/ NIL 15-200 / A 250 / NIL 300-452 / variable below 452cm
DMDN2	13-Aug-93	cobra	dryd	.5				y	cobra l/st	1032	1	R 8 / NIL 16-280; see core analysis for 280-1032
DPRA1	05-Aug-93	glew	wetd	.5								
DPRB1	05-Aug-93	scrape	wetd	1								
DSLA1	05-Jul-92	trowel	dry-	2				y	trowel	20	1	NIL 19
DSLD1	29-Mar-92	scrape	wetd	1								
DSLD2	02-Jul-92	glew	wetd	.5				y	glew l/st	53	1	NIL @ 20cm intervals
DTJE1	11-Aug-93	glew	wetd	.5								
DTLL1	29-Mar-92	scrape	wetd	1								
DTLL2	29-Jun-92	hiller	dryd	2			y	y	hiller	400	1	NIL 0-162 / variable below 162cm
EACH1	07-Apr-92	glew	wetd	.5		y		y	glew	30	2	R 29
EALB1	05-Apr-92	scrape	wetd	1								
EALM1	05-Apr-92	glew	wetd	.5		y		y	glew	9	1	NIL 8
EALT1	07-Apr-91	h/ful	wet-	4								
ECHC1	16-Sep-91	hongve	wetd	1	y			y	hongve l/st	357	3	@ 5-10cm intervals: VA 10 / A 20, 25 / VA 30-50 / A 60-80 / OCC 90 / A 100 / O 110 / R 120-140 / NIL 150-357
ECHC2	06-Apr-92	glew	wetd	.5		y		y	glew	23	3	VA 22
ECLD1	07-Apr-92	glew	wetd	.5		y		y	glew	10	3	VA 9
ECPL1	09-Apr-92	scrape	wetd	1								
ECRR1	05-Apr-92	scrape	wetd	1								
EDEH1	07-Apr-91	h/ful	wet-	4								
EDEH2	08-Apr-92	glew	dryd	.5		y		y	glew	18	1	NIL 17
EFTL1	05-Apr-92	glew	wet-	.5		y		y	glew	15	1	NIL 14
EFTL2	07-Jul-92	cobra	dryd	2			y	y	cobra	750	1	NIL @ 50cm
EGRA2	16-Sep-91	hongve	nochem	1								

EGRA1	06-Apr-92	scrape	wetd	1							-	
EHIT1	09-Apr-92	glew	wetd	.5		y		y	glew	6	1	NIL 5
EHIT2	18-Jul-92	hiller	dryd	2			y	y	hiller auger	102	1	NIL @ 20cm
ELLL1	08-Apr-92	glew	wetd	.5		y		y	glew	8	1	NIL 7
EMNJ1	07-Apr-92	glew	wetd	.5		y		y	glew	13	1	NIL 12
ENVG1	05-Apr-92	scrape	wetd	1								
EPBL1	07-Apr-92	scrape	wetd	1								
EPNH1	06-Apr-92	glew	dry-	.5		y		y	glew	10	1	NIL 9
EPZL1	05-Apr-92	glew	wetd	.5		y		y	glew	7	1	NIL 6
EQU11	06-Apr-92	scrape	wet-	1								
EQUE1	06-Apr-92	scrape	wetd	1								
ESLC1	06-Apr-92	glew	wetd	.5		y		y	glew	6	1	NIL 5
ETRY1	08-Apr-92	glew	wetd	.5		y		y	glew	34	3	VA 33
ETRZ1	06-Apr-92	glew	wet-	.5		y		y	glew	16	1	NIL 15
GCNJ1	12-Apr-92	phyton	wetd									
GCRL1	10-Apr-92	glew	wetd	.5		y		y	glew	17	1	NIL 16
GLNG1	12-Apr-92	glew	wetd	.5		y		y	glew	16	3	VA 15
GMJN1	10-Apr-92	glew	wetd	.5		y		y	glew	13	1	NIL 12
GNVL1	11-Apr-92	glew	wetd	.5		y		y	glew	16	1	NIL 15
GONT1	10-Apr-92	glew	wetd	.5		y		y	glew	18	1	NIL 17
GONT2	10-Jul-92	glew	wetd	.5			y	y	glew	25	1	NIL 24
GPTR1	10-Apr-92	glew	wetd	.5		y		y	glew	22	1	NIL 21
GRSA1	09-Jul-92	glew	wetd	.5				y	glew	25	1	NIL 24
GSAR3	06-Apr-91	scrape	nochem	1								
GSAR1	10-Apr-92	glew	wetd	.5		y		y	glew	29	1	NIL 28
GSAR2	09-Jul-92	glew	wetd	.5								
GSLB1	09-Apr-92	glew	wetd	.5		y		y	glew	25	1	NIL 24
GSLB2	09-Jul-92	glew	wetd	.5								
HBDP1	23-Jul-90	kayak	nochem	1								
HBSA1	23-Jul-90	scrape	dry-	1								
HCAS1	24-Jul-90	cobra	dry-	2								
HCHI1	19-Jul-90	l/st	wetd	1	y			y	l/st	101	3	VA 0, 10, 20 / A 40 / R 60, 80 / NIL 100
HEST1	23-Jul-90	l/st	wetd	1	y			y	l/st	174	3	VA 0-70 / NIL 121-173
HGAL1	24-Jul-90	kayak	nochem	1	y			y	kayak	22	2	R 4, 9
HGUA1	22-Jul-90	hiller	dry-	2	y			y	hiller	194	1	NIL @ 20cm
HLAG1	08-Apr-91	hongve	wet-	1								
HLCA1	24-Jul-90	scrape	nochem	1								
HLDP2	01-Dec-91	scrape	wetd	1								
HLDS2	22-Jul-90	hiller	dry-	2	y			y	hiller	168	1	NIL @ 20cm
HLDS1	01-Dec-91	scrape	wet-	1								
HLOR1	24-Jul-90	kayak	nochem	1								
HLZO1	23-Jul-90	kayak	nochem	1								
HPOD1	24-Aug-92	scrape	wetd	1								

HPEQ1	18-Jul-91	hiller	dry-	2	y			y	hiller	320	1	NIL @ 50cm
HPIC1	18-Jul-91	scrape	dry-	1								
HPIT1	15-Jul-90	hiller	dry-	2	y			y	hiller	121	1	NIL @ 20cm
HREB1	16-Jul-91	hiller	dry-	2								
HSAL1	15-Jul-90	l/st	wetd	1	y			y	l/st	220	2	A 4-20 / R 20-40
HSAL2	17-Jul-91	phyton	wetd									
HSUL1	01-Jul-90	kayak	dry-	1								
HZAI1	24-Jul-90	auger	dry-	2	y			y	auger	10	1	NIL 5, 9
IFAF1	13-Apr-92	glew	wet-	.5		y		y	glew	7	1	NIL 6
IRDR1	13-Apr-92	trowel	dry-	2		y		y	trowel	10	1	NIL 9
IVGZ1	13-Apr-92	trowel	dry-	2		y		y	trowel	26	1	NIL 25
IVRN1	13-Apr-92	glew	wetd	.5								

KEY:

Diatom Transfer Function:- SS type = surface sediment from different corers, 'h/ful' [handful], 'scrape' [sediment scrape from lake-bed surface], 'trowel' [shallow section];
SS qual = surface sediment quality: wetd and wet- [wet lake, diatoms preserved, and not preserved], 'dryd' [dry/damp lake, diatoms preserved, and not preserved];
SS depth = surface sediment sample depth.

Sediment Core Data:- Studies I-III described in Chapter 5; Core types: l/st = Livingstone corer;
Diatom Pres'n Class refers to preservation at short-core bases (<50cm below surface) or at 20cm depth in long cores:-
1 = nil preservation, 2 = dissolved, 3 = full preservation;
Below-Surface Diatom Preservation refers to preservation in screened core samples:-
NIL = no diatoms, VR = very rare fragments, OCC = occasional fragments/valves, uncountable; A = abundant, dissolved assemblage, countable; VA = very abundant, full preservation.

APPENDIX FIVE

MODEL OUTPUTS FOR WA REGRESSION OF THE TRAINING SET

App. 5(a)(i) Simple WA, cross-validation by jackknifing: 74 samples, conductivity

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==================
Variable      COND
==================

Coefficients for inverse deshrinking regression equation:
xhat_final = b0 + b1 * xhat_initial

              b0          b1
 WA        -0.284422    1.27016
 WA(tol)   -0.261914    1.22772

Sample Estimates
                                                                                    WA                      WA-Tol                Cross-Val WA           Cross-Val WA-Tol
                    Ntaxa          N2         Obs       XXXXX      XXXXXX         Est        Resi         Est        Resi         Est        Resi         Est        Resi

  1  AAMA1000     32.0000     10.4718      1.1139      0.2548      0.3557      1.2952      0.1812      1.2144      0.1005      1.3126      0.1987      1.2230      0.1090
  2  AAMA2000     31.0000      8.4986      1.1461      0.2471      0.4055      1.2659      0.1198      1.1565  1.0420e-02      1.2716      0.1255      1.2064  6.0301e-02
  3     ASBL1     10.0000      4.6407      1.5185      0.1756      0.4014      1.3792     -0.1393      1.3957     -0.1228      1.2912     -0.2274      1.3527     -0.1658
  4     ASBL2      8.0000      1.2102     -0.4202      0.3336      0.4035     -0.6355     -0.2153     -0.2750      0.1453      0.9070      1.3272      0.9126      1.3328
  5     ATSC1     24.0000      8.4026      1.5682      0.2530      0.3548      1.5602 -8.0390e-03      1.6715      0.1033      1.5995  3.1284e-02      1.6993      0.1311
  6     AZNR1     41.0000      7.1987      0.6435      0.3875      0.3500      0.4914     -0.1521      0.5986 -4.4890e-02      0.4226     -0.2209      0.8503      0.2069
  7     BCCA2     21.0000      3.1876      1.3222      0.1801      0.2236      1.2735 -4.8692e-02      1.2607 -6.1562e-02      1.1211     -0.2011      1.0760     -0.2462
  8     BDCE1     20.0000      2.6897      1.1761      0.1371      0.3479      1.0985 -7.7580e-02      1.0633     -0.1128      1.0469     -0.1292      1.0028     -0.1732
  9     BPNT1     22.0000      5.3667      1.6385      0.1871      0.4824      1.7117  7.3247e-02      1.6977  5.9196e-02      1.7071  6.8600e-02      1.6750  3.6465e-02
 10  BGDE1000     11.0000      1.2651      0.6335      0 1912      0.5205 -2.5046e-02     -0.6585  5.1319e-02     -0.5821     -0.4489     -1.0824     -0 4386     -1.0720
 11  BGDE2000     13.0000      1.7516     -0.3010      0.2618      0.4944 -1.7192e-02      0.2838 -4.2716e-03      0.2968      0.3025      0.6035      0.3010      0.6021
 12     BRTS1     26.0000      3.9670      1.6674      0.2076      0.4730      1.6838  1.6353e-02      1.6168 -5.0640e-02      1.5708 -9.6636e-02      1.5452     -0.1223
 13     BSDA2     23.0000      5.5209      1.9567      0.2052      0.3470      1.5991     -0.3575      1.5404     -0.4162      1.5439     -0.4127      1.4506     -0.5061
 14  CALC1000     32.0000      4.0419      0.8513      0.2001      0.5063      0.8415 -9.7749e-03      0.8151 -3.6179e-02      0.8171 -3.4175e-02      0.8652  1.3988e-02
 15  CALC2000     30.0000      8.5172      1.0792      0.1537      0.3823      0.9051     -0.1741      0.8738     -0.2054      0.8874     -0.1918      0.7923     -0.2869
 16  CARJ1000     43.0000     12.5522      1.1761      0.2979      0.3280      1.1556 -2.0505e-02      1.1237 -5.2345e-02      1.1514 -2.4673e-02      1.1139 -6.2161e-02
 17     CARJ2     31.0000      8.1613      1.2553      0.3529      0.3259      1.0577     -0.1975      1.1541     -0.1011      1.0248     -0.2305      1.1257     -0.1295
 18     CGSQ1     33.0000      9.7282      1.2787      0.2017      0.3741      1.3842      0.1055      1.3349  5.6174e-02      1.3599  8.1154e-02      1.3446  6 5836e-02
 19     CGSQ2     19.0000      5.0043      1.4065      0.1772      0.4111      1.4610  5.4427e-02      1.3852 -2.1323e-02      1.4769  7.0328e-02      1.3640 -4.2491e-02
 20     CGSQ3     10.0000      4.6253      2.5441      0.1888      0.3550      1.7047     -0.8394      1.6506     -0.8935      1.5440     -1.0001      1.4712     -1.0728
 21     CTRJ1     29.0000      8.4720      0.7243      0.2210      0.3479      0.9821      0.2578      0.6866 -3.7704e-02      1.0340      0.3097      0.6506 -7.3698e-02
 22     CTRJ2     26.0000      8.8347      0.8808      0.2746      0.3471      0.9604  7.9573e-02      0.9496  6.8752e-02      0.9838      0.1030      1.0210      0.1401
 23     CTRJ3     29.0000      3.9461      1.4082      0.2127      0.2840      1.3256 -8.2619e-02      1.3635 -4.4721e-02      1.0872     -0.3211      1.2567     -0.1516
 24     CZRR1     15.0000      2.1410      2.5289      0.1676      0.4894      1.8894     -0.6395      1.7733     -0.7556      1.6878     -0.8411      1.6114     -0 9175
 25     DCMS1     28.0000      3.1202      0.8921      0.2617      0.3984      1.2689      0.3768      1.2144      0.3223      1.4060      0.5139      1.3035      0.4114
 26  DOUL1000     23.0000      6.6159      0.7243      0.2269      0.4570      0.9707      0.2464      0.9520      0.2277      1.0167      0.2924      1.0217      0.2974
 27  DOUL2000     27.0000      7.0047      0.9638      0.2016      0.4945      0.9943  3.0477e-02      0.9446 -1.9211e-02      1.0063  4.2492e-02      0.9538 -9.9398e-03
 28  DHND1000     37.0000     12.0845      0.7076      0.2177      0.3828      0.8676      0.1600      0.8961      0.1886      0.9150      0.2074      0.9634      0.2559
 29  DMDN0000     32.0000     12.1848      1.0828      0.2971      0.3576      1.1937      0.1109      1.1503  6.7536e-02      1.2018      0.1190      1.1818  9.9040e-02
 30  DMDN1000     19.0000      5.3771      1.1948      0.2110      0.4061      1.2414  4.6626e-02      1.1756 -1.9215e-02      1.2276  3.2767e-02      1.1276 -6.7230e-02
 31     DPRA1     27.0000     10.8048      1.8904      0.3162      0.4181      1.6614     -0.2290      2.0317      0.1413      1.4151     -0.4753      1.3657     -0.5248
 32     DPRB1     20.0000      2.5918      1.8561      0.3125      0.3633      1.8512 -4.8995e-03      2.0298      0.1737      1.4377     -0.4184      1.3796     -0.4765
 33     DSLD1     38.0000     11.6044      1.2305      0.2976      0.3941      1.1387 -9.1799e-02      1.1404 -9.0032e-02      1.1287     -0.1018      1.1229     -0.1076
 34     DSLD2     19.0000      2.7383      1.4314      0.1766      0.5931      1.3593 -7.2060e-02      1.3143     -0.1170      1.3455 -8.5827e-02      1.2691     -0.1623
 35     DTJE1     47.0000     15.0372      1.0107      0.2406      0.3812      0.9312 -7.9503e-02      0.9541 -5.6655e-02      0.4081     -0.6026      0.6067     -0.4041
 36     DTLL1     15.0000      2.1986      1.5563      0.1557      0.5275      1.4148     -0.1415      1.3999     -0.1564      1.3742     -0.1821      1.3471     -0.2092
 37     EACH1     10.0000      2.5990      1.6021      0.1259      0.3616      1.5162 -8.5823e-02      1.4346     -0.1674      1.4231     -0.1789      1.2694     -0.3327
 38     EALB1     34.0000      5.0670      0.7118      0.2002      0.3623      0.9053      0.1934      0.9130      0.2012      0.9908      0.2790      1.0144      0.3026
 39     EALM1      7.0000      2.6368      1.0969  9.6563e-02      0.4753      1.2410      0.1441      1.2126      0.1157      1.3444      0.2475      1.3505      0.2536
 40     ECHC1     21.0000      2.1609      0.5798      0.1856      0.5027      0.5971  1.7272e-02      0.5931  1.3266e-02      0.6568  7.7023e-02      0.6408  6.1040e-02
 41  ECMC2000     19.0000      1.7069      0.5798      0.1562      0.4138      0.6071  2.7273e-02      0.5951  1.5314e-02      0.6701  9.0358e-02      0.6662  8.6455e-02
 42     ECLD1     20.0000      8.9099      0.3222      0.3256      0.4028  9.5344e-02     -0.2269      0.1638     -0.1584      0.1017     -0.2205      0.2002     -0.1220
 43     ECPL1     30.0000      7.5382      0.3424      0.4300      0.3611      0.1795     -0.1629      0.2943 -4.8114e-02      0.1418     -0.2006      0.3600  1.7579e-02
 44     ECRR1     20.0000      3.6730     -0.8239      0.4455      0.3452      0.1271      0.9510      0.1274      0.9513      0.5506      1.3745      0.5073      1.3313
 45     EGRA1     18.0000      1.6143      0.8865      0.2344      0.4053      0.6777     -0.2088      0.6283     -0.2582      0.5668     -0.3197      0.4511     -0.4354
 46     EHIT1     14.0000      4.8514      0.8513      0.3261      0.3918      1.3165      0.4652      1.2212      0.3699      1.4070      0.5558      1.3403      0.4890
 47     ELLL1      9.0000      1.2348      1.5798      0.1892      0.1098      1.6700  9.0183e-02      1.6380  5.8265e-02      1.6714  9.1665e-02      1.2562     -0.3236
 48     EMNJ1     14.0000      1.6917      1.3424      0.2410      0.4846      1.6158      0.2734      1.5929      0.2505      1.6641      0.3217      1.6257      0.2832
 49     ENVG1     24.0000      3.2854      1.1461      0.4137      0.5131      0.7595     -0.3866      1.1203 -2.5816e-02      0.4492     -0.6969      1.0511 -9.5073e-02
 50     EPRL1     21.0000      5.8211      0.7404      0.3298      0.4341      1.0611      0.3207      1.0831      0.3427      1.2188      0.4785      1.2983      0.5579
 51     EPZL1      9.0000      2.9244      1.1614      0.2565      0.4147      1.2585  9.7118e-02      1.2892      0.1278      1.3537      0.1923      1.3932      0.2319
 52     EQUE1     17.0000      5.5414      1.5798      0.1988      0.5355      1.7350      0.1552      1.7051      0.1254      1.7035      0.1237      0.7641     -0.8157
 53     ESLC1      7.0000      3.1150      1.6902      0.2889      0.3819      1.4532     -0.2370      1.5793     -0.1109      1.2676     -0.4226      1.3415     -0.3487
 54     ETRY1     10.0000      1.2952      0.2304  8.7440e-02      0.5482 -2.7702e-02     -0.2582 -8.7052e-03     -0.2392     -0.2168     -0.4473     -0.1821     -0.4125
 55     GCNJ1     23.0000      8.5870     -0.1739      0.1961      0.3217     -0.1342  3.9741e-02     -0.3933     -0.2193  9.0063e-02      0.2640      0.1446      0.3185
 56     GCRL1     23.0000      6.5846      1.5315      0.3036      0.3526      1.3914     -0.1400      1.3932     -0.1383      1.3393     -0.1921      1.2580     -0.2735
 57     GLNG1     32.0000     12.3336     -0.2596      0.2768      0.4085     -0.2719 -1.2253e-02     -0.4408     -0.1812      0.1165      0.3761  5.4510e-02      0.3141
 58     GMJN1     11.0000      3.0004      1.6902      0.1391      0.2762      1.7443  5.4126e-02      1.7063  1.6078e-02      1.6994  9.1727e-03      1.6847 -5.4874e-03
 59     GNVL1     13.0000      4.7248     -0.6778      0.5965      0.3008     -0.7101 -3.2299e-02     -0.9130     -0.2352      0.9954      1.6732      1.2460      1.9238
 60     GONT1     16.0000      3.5830      0.6857      0.1875      0.4986      0.7556  6.9818e-02      0.7229  3.7161e-02      0.8579      0.1721      0.8697      0.1839
 61     GONT2      8.0000      1.1794     -0.3010      0.1444      0.5250      0.4368      0.7378      0.5125      0.8135      1.1741      1.4751      1.1638      1.4648
 62     GPTR1     13.0000      3.3826      0.4771      0.3438      0.4963      0.9505      0.4734      0.8988      0.4217      1.2277      0.7506      1.1525      0.6754
 63     GRSA1      9.0000      1.4011      1.7889      0.2084      0.2238      1.9249      0.1360      1.8597  7.0797e-02      1.9398      0.1509      1.8125  2.3596e-02
 64     GSAR1     24.0000     10.1798      1.3617      0.2538      0.4225      1.2956 -6.6146e-02      1.2877 -7.4056e-02      1.2208     -0.1409      1.2307     -0.1310
 65     GSAR2      5.0000      2.0891      1.6990      0.2278      0.2611      1.8180      0.1191      1.7832  8.4221e-02      1.8281      0.1292      1.7375  3.8546e-02
 66     GSLB1     17.0000      3.7834      1.2672      0.1800      0.5043      1.2974  3.0191e-02      1.2792  1.1987e-02      1.2843  1.7091e-02      1.2702  3.0227e-03
 67     GSLB2     12.0000      2.4480      1.3979      0.1631      0.4879      1.3923 -5.6522e-03      1.3834 -1.4492e-02      1.3240 -7.3990e-02      1.2712     -0.1267
 68  HCHI1000     21.0000      6.0082      0.5052      0.4097      0.4337      0.3934     -0.1117      0.4813 -2.3813e-02      0.3899     -0.1153      0.6105      0.1054
 69     HEST1     12.0000      2.0229 -9.6910e-02      0.1994      0.4198     -0.3514     -0.2545     -0.3116     -0.2146      0.9227      1.0196      0.9047      1.0016
 70     HLDP2      5.0000      2.6047      1.6021  2.7429e-02      0.3361      1.7058      0.1038      1.6950  9.2916e-02      1.6985  9.6409e-02      1.6868  8.4773e-02
 71     HPD11     13.0000      5.3085      1.4900      0.3496      0.4572      1.1795     -0.3105      1.3436     -0.1464      1.1266     -0.3633      1.2062     -0.2838
 72  HSAL1000      8.0000      3.3610      1.7324      0.1187      0.3021      1.8095  7.7081e-02      1.7988  6.6377e-02      1.7841  5.1746e-02      1.6799 -5.2539e-02
 73     HSAL2      7.0000      2.8815      1.7324      0.1361      0.4354      1.7644  3.1977e-02      1.7966  6.4187e-02      1.7263 -6.1090e-03      1.6457 -8.6665e-02
 74     IVRM1     23.0000      5.1848      1.1461      0.2869      0.4273      1.1337 -1.2406e-02      1.1873  4.1200e-02      1.0077     -0.1384      1.1830  3.6901e-02

                               MSE        RMSE   R-squared    Avg-Bias    Max-Bias

Simple WA                  0.07073      0.2660      0.8471           0      0.1479
Tol d/w WA                 0.06785      0.2605      0.8533           0      0.1042
Cross Val WA                0.2415      0.4914      0.4850     0.05065      0.7446
Cross Val Tol d/w WA        0.2535      0.5035      0.4548     0.03678      0.7754
```

App. 5(a)(ii) Simple WA, cross-validation by jackknifing: 74 samples, total dissolved solids ('TDS')

```
==================
Variable       TDS
==================

Coefficients for inverse deshrinking regression equation:
xhat_final = b0 + b1 * xhat_initial

                b0           b1
  WA         -0.329288    1.29622
  WA(tol)    -0.373698    1.31573

Sample Estimates
                                                                                  WA                       WA-Tol                   Cross-Val WA             Cross-Val WA-Tol
                     Ntaxa        N2       Obs      XXXXX     XXXXXX         Est        Resi          Est        Resi          Est        Resi          Est        Resi

   1  AAMA1000     32.0000   10.4718    1.0704    0.2951     0.3681      1.2985      0.2280       1.2148      0.1444       1.3211      0.2507       1.8717      0.8013
   2  AAMA2000     31.0000    8.4986    1.0917    0.2953     0.4435      1.2230      0.1313       1.0336 -5.8117e-02       1.2093      0.1176       0.9433     -0.1484
   3     ASBL1     10.0000    4.6407    1.7932    0.1584     0.3457      1.4518     -0.3414       1.4527     -0.3405       1.3252     -0.4681       1.3535     -0.4397
   4     ASBL2      8.0000    1.2102    0.5437    0.1580     0.2396      0.4326     -0.1111       0.4057     -0.1380       0.9275      0.3838       0.9092      0.3655
   5     ATSC1     24.0000    8.4026    1.6265    0.2923     0.3678      1.6862  5.9651e-02       1.6931  6.6558e-02       1.7469      0.1204       1.7463      0.1198
   6     AZNR1     41.0000    7.1987    0.4736    0.3963     0.4071      0.3409     -0.1328       0.3713     -0.1023       0.3527     -0.1209       0.7467      0.2731
   7     BCCA2     21.0000    3.1876    1.3408    0.2580     0.2897      1.2369     -0.1039       1.2715 -6.9322e-02       1.0265     -0.3144       1.0464     -0.2944
   8     BDCB1     20.0000    2.6897    1.1345    0.1638     0.3721      1.0295     -0.1050       0.9975     -0.1370       0.9786     -0.1560       0.9369     -0.1977
   9     BPNT1     22.0000    5.3667    1.9701    0.2737     0.5972      1.8874 -8.2749e-02       2.0805      0.1104       1.8632     -0.1069       1.9148 -5.5310e-02
  10  BGDE1000     11.0000    1.2651    0.5987    0.1435     0.4614      0.3250     -0.2737       0.2939     -0.3048       0.2294     -0.3693       0.2215     -0.3772
  11  BGDE2000     13.0000    1.7516    0.5987    0.2031     0.4309      0.3695     -0.2292       0.3663     -0.2323       0.3084     -0.2903       0.2450     -0.3537
  12     BRTS1     26.0000    3.9670    1.8031    0.2306     0.4844      1.8655  6.2415e-02       1.8273  2.4207e-02       1.8399  3.6727e-02       1.7616 -4.1525e-02
  13     BSDA2     23.0000    5.5209    2.0152    0.2323     0.3601      1.6793     -0.3360       1.6694     -0.3458       1.6258     -0.3894       1.5739     -0.4413
  14  CALC1000     32.0000    4.0419    0.7563    0.2305     0.5769      0.8215  6.5188e-02       0.6715 -8.4851e-02       0.8279  7.1564e-02       0.7401 -1.6203e-02
  15  CALC2000     30.0000    8.5172    0.8692    0.1574     0.4174      0.8162 -5.2995e-02       0.6851     -0.1841       0.8469 -2.2292e-02       0.6581     -0.2111
  16  CARJ1000     43.0000   12.5522    1.2588    0.2928     0.3794      1.1233     -0.1356       1.1040     -0.1548       1.1072     -0.1516       1.0016     -0.2572
  17     CARJ2     31.0000    8.1613    1.2588    0.2730     0.3910      1.1377     -0.1211       1.1022     -0.1566       1.1164     -0.1425       1.0406     -0.2182
  18     CGSQ1     33.0000    9.7282    1.1823    0.2532     0.4004      1.3655      0.1832       1.2829      0.1006       1.3603      0.1780       1.3808      0.1985
  19     CGSQ2     19.0000    5.0043    1.4120    0.1935     0.4164      1.4457  3.3703e-02       1.4260  1.3984e-02       1.4558  4.3732e-02       1.4143  2.2860e-03
  20     CGSQ3     10.0000    4.6253    2.3376    0.2156     0.4192      1.7466     -0.5909       1.7827     -0.5548       1.6274     -0.7102       1.6254     -0.7122
  21     CTRJ1     29.0000    8.4720    0.6683    0.2311     0.4667      0.9214      0.2531       0.7087  4.0407e-02       0.9678      0.2995       0.4424     -0.2259
  22     CTRJ2     26.0000    8.8347    0.7383    0.2086     0.3905      0.9377      0.1994       0.8374  9.9123e-02       0.9801      0.2418       0.9407      0.2024
  23     CTRJ3     29.0000    3.9461    1.4384    0.2267     0.3260      1.3424 -9.6042e-02       1.3833 -5.5082e-02       1.0336     -0.4048       1.0691     -0.3693
  24     CZRR1     15.0000    2.1410    2.5225    0.2189     0.4798      2.0921     -0.4304       2.0866     -0.4358       1.9431     -0.5794       1.9290     -0.5935
  25     DCMS1     28.0000    3.1202    0.7114    0.2989     0.4735      1.2214      0.5100       1.1217      0.4103       1.4214      0.7100       1.0530      0.3416
  26  DDUL1000     23.0000    6.6159    0.7262    0.2465     0.4494      0.9208      0.1946       0.8495      0.1233       0.9545      0.2282       0.9088      0.1826
  27  DDUL2000     27.0000    7.0047    0.8855    0.2108     0.4845      0.9641  7.8524e-02       0.8608 -2.4752e-02       0.9871      0.1016       0.8728 -1.2686e-02
  28  DHND1000     37.0000   12.0845    0.3282    0.2647     0.4089      0.7783      0.4502       0.7184      0.3903       0.9177      0.5895       0.8804      0.5523
  29  DMDN0000     32.0000   12.1848    1.0258    0.2546     0.3755      1.1676      0.1418       1.0234 -2.4208e-03       1.1757      0.1498       1.0234 -2.4874e-03
  30  DMDN1000     19.0000    5.3771    0.9732    0.1998     0.4434      1.1764      0.2032       1.0036  3.0413e-02       1.2341      0.2609       1.0592  8.5954e-02
  31     DPRA1     27.0000   10.8048    1.7758    0.2833     0.5045      1.6043     -0.1715       1.9222      0.1465       1.4431     -0.3327       1.1476     -0.6282
  32     DPRB1     20.0000    2.5918    1.7248    0.2371     0.4272      1.7455  2.0741e-02       1.9133      0.1885       1.4485     -0.2763       1.3732     -0.3515
  33     DSLD1     38.0000   11.6044    1.2041    0.3117     0.4511      1.1152 -8.8924e-02       1.1390 -6.5139e-02       1.1005     -0.1037       1.1375 -6.6668e-02
  34     DSLD2     19.0000    2.7383    1.4559    0.1895     0.5886      1.3445     -0.1114       1.2917     -0.1642       1.3271     -0.1289       1.2350     -0.2210
  35     DTJB1     47.0000   15.0372    0.8564    0.2692     0.4195      0.7889 -6.7477e-02       0.7301     -0.1262       0.3214     -0.5350       0.4560     -0.4003
  36     DTLL1     15.0000    2.1986    1.6375    0.1222     0.6102      1.4286     -0.2089       1.4092     -0.2283       1.3718     -0.2657       1.3407     -0.2968
  37     EACH1     10.0000    2.5990    2.0299    0.3198     0.3114      1.8474     -0.1825       1.7313     -0.2986       1.6683     -0.3616       1.3455     -0.6844
  38     EALB1     34.0000    5.0670    0.6815    0.2172     0.3890      0.8577      0.1762       0.8405      0.1590       0.9388      0.2573       0.9400      0.2585
  39     EALM1      7.0000    2.6368    0.9274    0.1930     0.4358      1.2248      0.2974       1.1500      0.2226       1.5300      0.6026       1.5145      0.5871
  40     ECWC1     21.0000    2.1609   -0.8761    0.2526     0.8107      0.1246      1.0007       0.2969      1.1730       0.7512      1.6273       0.7066      1.5827
  41  ECWC2000     19.0000    1.7069    0.6142    0.1939     0.2908      0.1508     -0.4634       0.2641     -0.3501 -1.9015e-02     -0.6332       0.2436     -0.3705
  42     ECLD1     20.0000    8.9099    0.3137    0.3582     0.4855  9.8032e-02     -0.2148       0.1358     -0.1779       0.1129     -0.2008       0.2283 -8.5341e-02
  43     ECPL1     30.0000    7.5382    0.3504    0.4365     0.3381      0.1899     -0.1606       0.2366     -0.1138       0.1513     -0.1991       0.2729 -7.7506e-02
  44     ECRR1     20.0000    3.6730   -0.8416    0.5275     0.3821      0.1025      0.9442  1.2438e-02      0.8541       0.5465      1.3882       0.3979      1.2395
  45     EGRA1     18.0000    1.6143    1.0483    0.3600     0.2608      0.2299     -0.8184       0.8178     -0.2305      -0.1870     -1.2353       2.0240      0.9757
  46     EHTT1     14.0000    4.8514    0.9078    0.3939     0.4732      1.3488      0.4410       1.2080      0.3001       1.4123      0.5044       1.3869      0.4790
  47     ELLL1      9.0000    1.2348    1.1192    0.1926     0.1408      1.7558      0.6366       1.7393      0.6201       1.9266      0.8074       1.9242      0.8050
  48     EMNJ1     14.0000    1.6917    1.4605    0.2367     0.4419      1.7347      0.2742       1.6596      0.1991       1.7774      0.3169       1.6771      0.2167
  49     ENVG1     24.0000    3.2854    0.9928    0.4531     0.6970      0.7011     -0.2917       1.1019      0.1091       0.4430     -0.5498       1.1081      0.1153
  50     EPBL1     21.0000    5.8211    0.6837    0.3305     0.4876      1.0425      0.3588       1.0028      0.3191       1.2215      0.5378       1.2390      0.5553
  51     EPZL1      9.0000    2.9244    1.0940    0.2997     0.4083      1.3068      0.2128       1.3343      0.2403       1.6003      0.5063       1.5472      0.4532
  52     EQUB1     17.0000    5.5414    1.9086    0.2302     0.6795      2.0116      0.1030       2.1261      0.2175       1.9441  3.5434e-02       2.0211      0.1125
  53     ESLC1      7.0000    3.1150    2.2655    0.3851     0.5899      1.7790     -0.4865       1.9697     -0.2958       1.4063     -0.8592       1.2262     -1.0393
  54     ETRY1     10.0000    1.2952    0.2490 6.8596e-02     0.3660  2.1631e-02     -0.2273 -7.1912e-03     -0.2561       0.1861 -6.2890e-02       0.1679 -8.1067e-02
  55     GCNJ1     23.0000    8.5870   -0.3979    0.2626     0.3305     -0.1587      0.2393 -6.7238e-02      0.3307       0.2064      0.6043       0.2220      0.6199
  56     GCRL1     23.0000    6.5846    1.6589    0.3492     0.3685      1.4501     -0.2088       1.4907     -0.1683       1.3725     -0.2864       1.3013     -0.3577
  57     GLNG1     32.0000   12.3336    0.3071    0.2154     0.4063  4.8164e-02     -0.2589  4.8516e-02     -0.2586  2.6140e-02     -0.2809  4.8059e-02     -0.2590
  58     GMJN1     11.0000    3.0004    2.2389    0.1859     0.3357      2.1812 -5.7728e-02       2.1339     -0.1050       2.1174     -0.1214       2.0635     -0.1754
  59     GNVL1     13.0000    4.7248   -0.3675    0.5403     0.3838     -0.4409 -7.3325e-02      -0.6533     -0.2858       1.0342      1.4017       1.0549      1.4224
  60     GONT1     16.0000    3.5830    0.5319    0.2125     0.4726      0.7654      0.2335       0.6730      0.1411       0.9313      0.3994       0.8351      0.3033
  61     GONT2      8.0000    1.1794    0.5134    0.1007     0.4706      0.7930      0.2796       0.7501      0.2368       1.0938      0.5804       1.0624      0.5490
  62     GPTR1     13.0000    3.3826    1.4376    0.2350     0.6941      1.3389 -9.8739e-02       1.3083     -0.1293       1.0975     -0.3400       1.1145     -0.3231
  63     GRSA1      9.0000    1.4011    1.9791    0.2494     0.2768      2.1687      0.1895       2.1665      0.1874       2.1823      0.2032       2.1162      0.1371
  64     GSAR1     24.0000   10.1798    1.7857    0.2849     0.4404      1.4338     -0.3519       1.4468     -0.3388       1.2577     -0.5279       1.2537     -0.5320
  65     GSAR2      5.0000    2.0891    1.8467    0.2118     0.4473      1.9224  7.5683e-02       1.9784      0.1316       1.9090  6.2304e-02       1.9385  9.1734e-02
  66     GSLB1     17.0000    3.7834    1.3436    0.2293     0.5112      1.3348 -8.8094e-03       1.3475  3.8500e-03       1.3109 -3.2767e-02       1.2815 -6.2167e-02
  67     GSLB2     12.0000    2.4480    1.4692    0.1925     0.7845      1.4620 -7.2892e-03       1.5072  3.7923e-02       1.3861 -8.3144e-02       1.3852 -8.4099e-02
  68  HCHI1000     21.0000    6.0082    0.6742    0.4269     0.4189      0.4104     -0.2638       0.5160     -0.1582       0.3611     -0.3131       0.5558     -0.1184
  69     HEST1     12.0000    2.0229   -0.2204    0.2303     0.2865     -0.5481     -0.3277      -0.5559     -0.3355       0.7443      0.9647       0.6897      0.9101
  70     HLDP2      5.0000    2.6047    2.3279    0.1801     0.3082      2.0500     -0.2778       1.9990     -0.3289       1.9451     -0.3827       1.8540     -0.4739
  71     HPD11     13.0000    5.3085    1.3300    0.2508     0.5031      1.2287     -0.1012       1.2241     -0.1059       1.2337 -9.6313e-02       1.1913     -0.1387
  72  HSAL1000      8.0000    3.3610    1.8301    0.1345     0.3754      1.9169  8.6794e-02       1.9621      0.1320       1.8845  5.4392e-02       1.7788 -5.1380e-02
  73     HSAL2      7.0000    2.8815    1.8301    0.1547     0.3569      1.8628  3.2647e-02       1.9606      0.1305       1.8147 -1.5418e-02       1.7441 -8.6071e-02
  74     IVRN1     23.0000    5.1848    1.0208    0.3851     0.4202      1.2959      0.2751       1.2886      0.2678       1.2423      0.2215       1.4414      0.4206

                             MSE        RMSE   R-squared    Avg-Bias    Max-Bias

Simple WA                0.09391      0.3065      0.8168           0      0.2024
Tol d/w WA               0.07947      0.2819      0.8450           0       0.132
Cross Val WA              0.2462      0.4962      0.5253     0.03256      0.5832
Cross Val Tol d/w WA       0.237      0.4869      0.5408     0.04091      0.5824

Species parameters
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App. 5(b) Simple WA, cross-validation by jackknifing: 70 samples, conductivity

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Variable     COND
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Coefficients for inverse deshrinking regression equation:
xhat_final = b0 + b1 * xhat_initial

              b0          b1
 WA        -0.243543    1.22522
 WA(tol)   -0.17281     1.15895

Sample Estimates
                                                                               WA                        WA-Tol                Cross-Val WA              Cross-Val WA-Tol
                   Ntaxa        N2       Obs      XXXXX    XXXXXX         Est        Resi         Est        Resi       Est        Resi         Est        Resi

  1  AAMA1000   32.0000   10.4718    1.1100     0.2174    0.3223      1.2754      0.1654      1.2252      0.1152    1.2924      0.1824      1.2385      0.1285
  2  AAMA2000   31.0000    8.4986    1.1500     0.2146    0.3613      1.2353  8.5281e-02      1.1675  1.7485e-02    1.2382  8.8158e-02      1.2088  5.8841e-02
  3     ASBL1   10.0000    4.6407    1.5200     0.1582    0.3642      1.3389     -0.1811      1.3790     -0.1410    1.2522     -0.2678      1.3400     -0.1800
  4     ASBL2    8.0000    1.2102   -0.4200     0.3401    0.4021     -0.5766     -0.1566     -0.1731      0.2469    0.9168      1.3368      0.9422      1.3622
  5     ATSC1   24.0000    8.4026    1.5700     0.2406    0.3281      1.5212 -4.8761e-02      1.6445  7.4511e-02    1.5576 -1.2394e-02      1.6647  9.4700e-02
  6     AZNR1   41.0000    7.1987    0.6400     0.3257    0.3014      0.5524 -8.7552e-02      0.6217 -1.8286e-02    0.5131     -0.1269      0.8287      0.1887
  7     BCCA2   21.0000    3.1876    1.3200     0.1793    0.2198      1.2584 -6.1601e-02      1.2623 -5.7725e-02    1.1109     -0.2091      1.0841     -0.2359
  8     BDCE1   20.0000    2.6897    1.1800     0.1280    0.3383      1.0894 -9.0609e-02      1.0834 -9.6643e-02    1.0374     -0.1426      1.0293     -0.1507
  9     BFNT1   22.0000    5.3667    1.6400     0.1861    0.3803      1.6595  1.9533e-02      1.6706  3.0612e-02    1.6529  1.2874e-02      1.6511  1.1069e-02
 10  BGDE2000   13.0000    1.7516   -0.3000     0.3504    0.4892     -0.3249 -2.4939e-02     -0.3533 -5.3281e-02   -0.1033      0.1967 -3.8721e-02      0.2613
 11     BRTS1   26.0000    3.9670    1.6700     0.1586    0.3028      1.6260 -4.4000e-02      1.5729 -9.7087e-02    1.5118     -0.1582      1.5069     -0.1631
 12     BSDA2   23.0000    5.5209    1.9600     0.1530    0.2836      1.5318     -0.4282      1.5092     -0.4508    1.4694     -0.4906      1.4315     -0.5285
 13  CALC1000   32.0000    4.0419    0.8500     0.1728    0.4011      0.8594  9.3859e-03      0.8318 -1.8186e-02    0.8391 -1.0941e-02      0.8604  1.0429e-02
 14  CALC2000   30.0000    8.5172    1.0800     0.1510    0.3330      0.9070     -0.1730      0.9027     -0.1773    0.8892     -0.1908      0.8269     -0.2531
 15  CARJ1000   43.0000   12.5522    1.1800     0.2500    0.2736      1.1701 -9.8873e-03      1.1489 -3.1085e-02    1.1664 -1.3608e-02      1.1426 -3.7394e-02
 16     CARJ2   31.0000    8.1613    1.2600     0.1863    0.2960      1.2191 -4.0925e-02      1.1960 -6.3975e-02    1.2044 -5.5635e-02      1.1716 -8.8402e-02
 17     CGSQ1   33.0000    9.7282    1.2800     0.1816    0.3339      1.3295  4.9490e-02      1.3195  3.9520e-02    1.3019  2.1887e-02      1.3162  3.6184e-02
 18     CGSQ2   19.0000    5.0043    1.4100     0.1253    0.3130      1.3243 -8.5698e-02      1.3200 -8.9955e-02    1.2893     -0.1207      1.2736     -0.1364
 19     CTRJ1   29.0000    8.4720    0.7200     0.1761    0.2914      1.0076      0.2876      0.7170 -3.0146e-03    1.0597      0.3397      0.7290  8.9945e-03
 20     CTRJ2   26.0000    8.8347    0.8800     0.2192    0.3119      1.0290      0.1490      1.0149      0.1349    1.0563      0.1763      1.0922      0.2122
 21     CTRJ3   29.0000    3.9461    1.4100     0.1695    0.2614      1.3280 -8.1973e-02      1.3567 -5.3347e-02    1.0973     -0.3127      1.3038     -0.1062
 22     CZRR1   15.0000    2.1410    2.5300     0.1769    0.4684      1.8408     -0.6892      1.7156     -0.8144    1.6427     -0.8873      1.5742     -0.9558
 23     DCMS1   28.0000    3.1202    0.8900     0.2266    0.3402      1.2393      0.3493      1.2160      0.3260    1.3693      0.4793      1.3037      0.4137
 24  DDUL1000   23.0000    6.6159    0.7200     0.1544    0.3271      1.0118      0.2918      0.9342      0.2142    1.0647      0.3447      1.0103      0.2903
 25  DDUL2000   27.0000    7.0047    0.9600     0.1528    0.4566      1.0232  6.3225e-02      0.9900  3.0041e-02    1.0380  7.7979e-02      1.0053  4.5310e-02
 26  DHND1000   37.0000   12.0845    0.7100     0.2006    0.3352      0.9000      0.1900      0.9237      0.2137    0.9488      0.2388      0.9868      0.2768
 27  DMDN0000   32.0000   12.1848    1.0800     0.1820    0.3087      1.2118      0.1318      1.1671  8.7065e-02    1.2205      0.1405      1.1949      0.1149
 28  DMDN1000   19.0000    5.3771    1.1900     0.1141    0.3900      1.2625  7.2453e-02      1.1829 -7.0832e-03    1.2515  6.1482e-02      1.1427 -4.7279e-02
 29     DPRA1   27.0000   10.8048    1.8900     0.2926    0.3291      1.6399     -0.2501      1.9951      0.1051    1.4021     -0.4879      1.3739     -0.5161
 30     DPRB1   20.0000    2.5918    1.8600     0.2412    0.3323      1.8486 -1.1366e-02      1.9933      0.1333    1.4487     -0.4113      1.3928     -0.4672
 31     DSLD1   38.0000   11.6044    1.2300     0.2381    0.3347      1.1566 -7.3363e-02      1.1678 -6.2212e-02    1.1468 -8.3203e-02      1.1541 -7.5920e-02
 32     DSLD2   19.0000    2.7383    1.4300     0.1474    0.5412      1.3180     -0.1120      1.2973     -0.1327    1.3023     -0.1277      1.2583     -0.1717
 33     DTJB1   47.0000   15.0372    1.0100     0.2160    0.3333      0.9524 -5.7554e-02      0.9753 -3.4680e-02    0.8974     -0.1126      0.9387 -7.1331e-02
 34     DTLL1   15.0000    2.1986    1.5600 8.0993e-02    0.2558      1.3836     -0.1764      1.3725     -0.1875    1.3394     -0.2206      1.3221     -0.2379
 35     EACH1   10.0000    2.5990    1.6000     0.1438    0.3533      1.5251 -7.4880e-02      1.4735     -0.1265    1.4461     -0.1539      1.3153     -0.2847
 36     EALB1   34.0000    5.0670    0.7100     0.1896    0.3256      0.9123      0.2023      0.9376      0.2276    0.9977      0.2877      1.0326      0.3226
 37     EALM1    7.0000    2.6368    1.1000 9.4642e-02    0.4362      1.2323      0.1323      1.2182      0.1182    1.3338      0.2338      1.3457      0.2457
 38     ECHC1   21.0000    2.1609    0.5800     0.1858    0.3210      0.6137  3.3672e-02      0.6381  5.8117e-02    0.6764  9.6411e-02      0.6881      0.1081
 39  ECHC2000   19.0000    1.7069    0.5800     0.1486    0.4079      0.6313  5.1260e-02      0.6414  6.1390e-02    0.6942      0.1142      0.7087      0.1287
 40     ECLD1   20.0000    8.9099    0.3200     0.2873    0.3209      0.1985     -0.1215      0.2188     -0.1012    0.2233 -9.6739e-02      0.2472 -7.2782e-02
 41     ECPL1   30.0000    7.5382    0.3400     0.4072    0.3257      0.2851 -5.4944e-02      0.2421 -9.7938e-02    0.2802 -5.9791e-02  9.7192e-02     -0.2428
 42     EGRA1   18.0000    1.6143    0.8900     0.2345    0.3986      0.6875     -0.2025      0.6715     -0.2185    0.5796     -0.3104      1.8255      0.9355
 43     EHIT1   14.0000    4.8514    0.8500     0.2951    0.3184      1.3035      0.4535      1.2244      0.3744    1.3973      0.5473      1.3351      0.4851
 44     ELLL1    9.0000    1.2348    1.5800     0.1722    0.1068      1.5618 -1.8198e-02      1.5598 -2.0163e-02    1.5399 -4.0083e-02      1.3047     -0.2753
 45     EMNJ1   14.0000    1.6917    1.3400     0.2027    0.4786      1.5274      0.1874      1.5354      0.1954    1.5633      0.2233      1.5632      0.2232
 46     ENVG1   24.0000    3.2854    1.1500     0.2421    0.3544      1.0187     -0.1313      1.1452 -4.7848e-03    0.8126     -0.3374      1.0955 -5.4498e-02
 47     EPBL1   21.0000    5.8211    0.7400     0.2825    0.3991      1.0901      0.3501      1.1189      0.3789    1.2498      0.5098      1.3100      0.5700
 48     EPZL1    9.0000    2.9244    1.1600     0.1732    0.3733      1.2822      0.1222      1.2906      0.1306    1.3763      0.2163      1.3890      0.2290
 49     EQUE1   17.0000    5.5414    1.5800     0.2067    0.3968      1.6890      0.1090      1.6771  9.7147e-02    1.6425  6.2495e-02      0.8646     -0.7154
 50     ESLC1    7.0000    3.1150    1.6900     0.2203    0.2626      1.5089     -0.1811      1.5625     -0.1275    1.3473     -0.3427      1.2441     -0.4459
 51     ETRY1   10.0000    1.2952    0.2300 8.1823e-02    0.5027 -5.4819e-03     -0.2355  5.3295e-02     -0.1767   -0.3867     -0.6167     -0.3046     -0.5346
 52     GCNJ1   23.0000    8.5870   -0.1700     0.2329    0.3110     -0.1017  6.8323e-02     -0.2684 -9.8419e-02    0.1283      0.2983      0.1899      0.3599
 53     GCRL1   23.0000    6.5846    1.5300     0.2742    0.3176      1.3392     -0.1908      1.3899     -0.1401    1.2875     -0.2425      1.2765     -0.2535
 54     GLNG1   32.0000   12.3336   -0.2600     0.2944    0.3428     -0.2502  9.8215e-03     -0.3258 -6.5830e-02    0.1247      0.3847      0.1170      0.3770
 55     GMJN1   11.0000    3.0004    1.6900     0.1198    0.2255      1.7307  4.0736e-02      1.6722 -1.7836e-02    1.7032  1.3150e-02      1.6430 -4.7015e-02
 56     GNVL1   13.0000    4.7248   -0.6800     0.6747    0.2774     -0.5963  8.3678e-02     -0.7273 -4.7286e-02    1.2313      1.9113      1.4301      2.1101
 57     GONT1   16.0000    3.5830    0.6900     0.1441    0.4781      0.9606      0.2706      0.8127      0.1227    1.1006      0.4106      1.0033      0.3133
 58     GPTR1   13.0000    3.3826    0.4800     0.3266    0.3683      0.9355      0.4555      0.9553      0.4753    1.2020      0.7220      1.1762      0.6962
 59     GRSA1    9.0000    1.4011    1.7900     0.2037    0.2212      1.8922      0.1022      1.8112  2.1155e-02    1.9057      0.1157      1.7613 -2.8659e-02
 60     GSAR1   24.0000   10.1798    1.3600     0.1781    0.3552      1.3037 -5.6307e-02      1.3003 -5.9675e-02    1.2578     -0.1022      1.2359     -0.1241
 61     GSAR2    5.0000    2.0891    1.7000     0.2027    0.1665      1.6545 -4.5470e-02      1.6501 -4.9929e-02    1.6123 -8.7746e-02      1.5757     -0.1243
 62     GSLB1   17.0000    3.7834    1.2700     0.1689    0.4834      1.3020  3.1991e-02      1.2776  7.5604e-03    1.2949  2.4853e-02      1.2656 -4.4206e-03
 63     GSLB2   12.0000    2.4480    1.4000     0.1235    0.3240      1.4159  1.5903e-02      1.3886 -1.1439e-02    1.3927 -7.2759e-03      1.2861     -0.1139
 64  HCHI1000   21.0000    6.0082    0.5100     0.3882    0.4025      0.4432 -6.6802e-02      0.5163  6.2822e-03    0.4451 -6.4943e-02      0.6664      0.1564
 65     HEST1   12.0000    2.0229   -0.1000     0.2016    0.3993     -0.3095     -0.2095     -0.2244     -0.1244    0.9231      1.0231      0.9294      1.0294
 66     HLDP2    5.0000    2.6047    1.6000 3.8718e-02    0.3153      1.6619  6.1894e-02      1.6698  6.9754e-02    1.6572  5.7201e-02      1.6582  5.8200e-02
 67     HPD11   13.0000    5.3085    1.4900     0.2170    0.3683      1.2925     -0.1975      1.3252     -0.1648    1.2476     -0.2424      1.1696     -0.3204
 68  HSAL1000    8.0000    3.3610    1.7300     0.1182    0.2508      1.7742  4.4161e-02      1.7722  4.2209e-02    1.7490  1.9030e-02      1.6702 -5.9829e-02
 69     HSAL2    7.0000    2.8815    1.7300     0.1397    0.4243      1.7283 -1.7446e-03      1.7672  3.7239e-02    1.6909 -3.9108e-02      1.6241     -0.1059
 70     IVRN1   23.0000    5.1848    1.1500     0.2696    0.3441      1.1320 -1.7989e-02      1.2009  5.0882e-02    1.0089     -0.1411      1.1918  4.1755e-02

                             MSE        RMSE   R-squared    Avg-Bias    Max-Bias

Simple WA                0.03396      0.1843      0.9101           0      0.1523
Tol d/w WA               0.03204      0.1790      0.9152           0      0.1262
Cross Val WA              0.1667      0.4083      0.5666     0.05202        0.51
Cross Val Tol d/w WA      0.1996      0.4468      0.4790     0.05248      0.5346
```

App. 5(c) Simple WA, cross-validation by jackknifing: 71 samples, TDS

```
=================
Variable      TDS
=================

Coefficients for inverse deshrinking regression equation:
xhat_final = b0 + b1 * xhat_initial

               b0          b1
  WA      -0.347551     1.29299
  WA(tol) -0.280582     1.24515

Sample Estimates
                                                                                    WA                     WA-Tol               Cross-Val WA          Cross-Val WA-Tol
                    Ntaxa          N2         Obs       XXXXX      XXXXXX         Est        Resi         Est        Resi         Est        Resi         Est        Resi

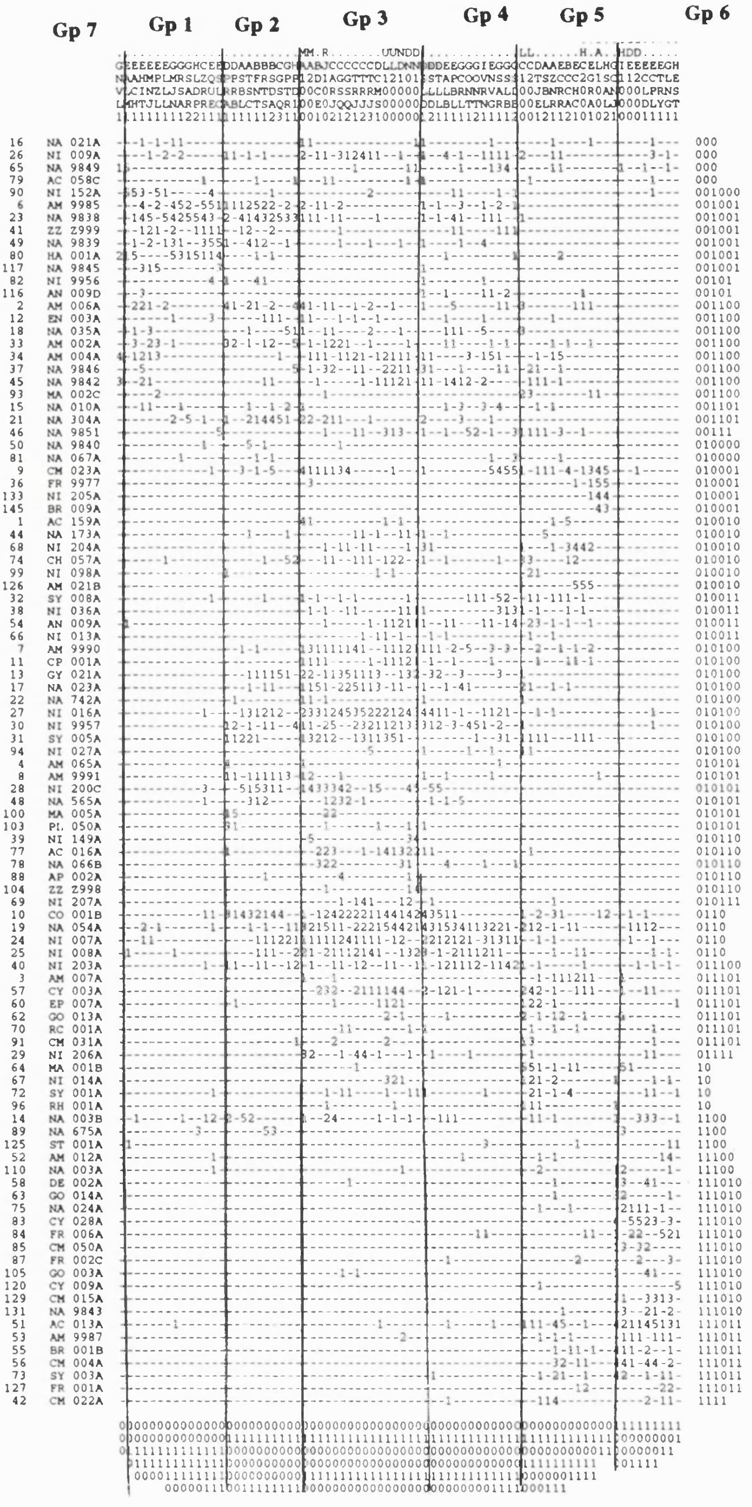
  1  AAMA1000     32.0000     10.4718      1.0700      0.2963      0.3813      1.3049      0.2349      1.2319      0.1619      1.3283      0.2583      1.8459      0.7759
  2  AAMA2000     31.0000      8.4986      1.0900      0.2935      0.4775      1.2117      0.1217      1.0552 -3.4789e-02      1.1988      0.1088      1.9852      0.8952
  3     ASBL1     10.0000      4.6407      1.7900      0.1582      0.2854      1.4323     -0.3577      1.4459     -0.3441      1.3069     -0.4831      1.3474     -0.4426
  4     ASBL2      8.0000      1.2102      0.5400      0.1517      0.2364      0.4183     -0.1217      0.4570 -8.3013e-02      0.9195      0.3795      0.9389      0.3989
  5     ATSC1     24.0000      8.4026      1.6300      0.3234      0.4650      1.7086  7.8554e-02      1.7320      0.1020      1.7699      0.1399      1.8036      0.1736
  6     AZNR1     41.0000      7.1987      0.4700      0.3649      0.4021      0.3934 -7.6610e-02      0.4207 -4.9321e-02      0.4461 -2.3943e-02      0.7838      0.3138
  7     BCCA2     21.0000      3.1876      1.3400      0.1849      0.2749      1.2657 -7.4340e-02      1.2662 -7.3766e-02      1.0689     -0.2711      1.0586     -0.2814
  8     BDCE1     20.0000      2.6897      1.1300      0.1540      0.3659      1.0228     -0.1072      1.0287     -0.1013      0.9755     -0.1545      0.9808     -0.1492
  9     BPNT1     22.0000      5.3667      1.9700      0.2761      0.4394      1.8769 -9.3094e-02      2.0732      0.1032      1.8548     -0.1152      1.9198 -5.0235e-02
 10  BGDE1000     11.0000      1.2651      0.6000      0.1402      0.4521      0.3109     -0.2891      0.3924     -0.2076      0.2131     -0.3869      0.3686     -0.2314
 11  BGDE2000     13.0000      1.7516      0.6000      0.1926      0.4225      0.3608     -0.2392      0.4227     -0.1773      0.2993     -0.3007      0.3075     -0.2925
 12     BRTS1     26.0000      3.9670      1.8000      0.2371      0.4642      1.8564  5.6421e-02      1.8331  3.3109e-02      1.8324  3.2351e-02      1.7727 -2.7326e-02
 13     BSDA2     23.0000      5.5209      2.0200      0.2259      0.3440      1.6682     -0.3518      1.6653     -0.3547      1.6143     -0.4057      1.5657     -0.4543
 14  CALC1000     32.0000      4.0419      0.7600      0.3122      0.5460      0.8875      0.1275      0.6779 -8.2124e-02      0.9033      0.1433      0.7418 -1.8182e-02
 15  CALC2000     30.0000      8.5172      0.8700      0.1628      0.4099      0.8177 -5.2256e-02      0.7004     -0.1696      0.8529 -1.7052e-02      0.6501     -0.2199
 16  CARJ1000     43.0000     12.5522      1.2600      0.2892      0.3636      1.1399     -0.1201      1.1339     -0.1261      1.1256     -0.1344      1.0371     -0.2229
 17     CARJ2     31.0000      8.1613      1.2600      0.2726      0.3605      1.1362     -0.1238      1.1238     -0.1362      1.1151     -0.1449      1.0638     -0.1962
 18     CGSQ1     33.0000      9.7282      1.1800      0.2513      0.3799      1.3604      0.1804      1.2935      0.1135      1.3569      0.1769      1.3937      0.2137
 19     CGSQ2     19.0000      5.0043      1.4100      0.1793      0.3857      1.4550  4.4985e-02      1.4415  3.1541e-02      1.4709  6.0907e-02      1.4277  1.7672e-02
 20     CGSQ3     10.0000      4.6253      2.3400      0.1962      0.3196      1.7373     -0.6027      1.7735     -0.5665      1.6183     -0.7217      1.6156     -0.7244
 21     CTRJ1     29.0000      8.4720      0.6700      0.2257      0.3701      0.9302      0.2602      0.7513  8.1302e-02      0.9772      0.3072      0.5023     -0.1677
 22     CTRJ2     26.0000      8.8347      0.7400      0.2030      0.4153      0.9382      0.1982      0.8721      0.1321      0.9814      0.2414      0.9683      0.2283
 23     CTRJ3     29.0000      3.9461      1.4400      0.2241      0.3378      1.3797 -6.0295e-02      1.4273 -1.2724e-02      1.0757     -0.3643      1.0678     -0.3722
 24     CZRR1     15.0000      2.1410      2.5200      0.2281      0.4720      2.0925     -0.4275      2.0829     -0.4371      1.9468     -0.5732      1.9231     -0.5969
 25     DCMS1     28.0000      3.1202      0.7100      0.2850      0.4711      1.2104      0.5004      1.1199      0.4099      1.4120      0.7020      1.0889      0.3789
 26  DCUL1000     23.0000      6.6159      0.7300      0.2020      0.4592      0.9673      0.2373      0.8471      0.1171      1.0095      0.2795      0.8959      0.1659
 27  DCUL2000     27.0000      7.0047      0.8900      0.1995      0.4853      0.9766  8.6640e-02      0.9100  2.0000e-02      1.0028      0.1128      0.9242  3.4237e-02
 28  DHND1000     37.0000     12.0845      0.3300      0.2852      0.4215      0.8229      0.4929      0.7564      0.4264      0.9744      0.6444      0.8976      0.5676
 29  DMDN0000     32.0000     12.1848      1.0300      0.2437      0.3718      1.1662      0.1362      1.0428  1.2758e-02      1.1751      0.1451      1.0399  9.9156e-03
 30  DMDN1000     19.0000      5.3771      0.9700      0.1950      0.4836      1.1623      0.1923      1.0222  5.2168e-02      1.2220      0.2520      1.0712      0.1012
 31     DPRA1     27.0000     10.8048      1.7800      0.2855      0.3825      1.5880     -0.1920      1.8901      0.1101      1.4248     -0.3552      1.2022     -0.5778
 32     DPRB1     20.0000      2.5918      1.7200      0.2359      0.3627      1.7191 -9.4008e-04      1.8793      0.1593      1.4282     -0.2918      1.3761     -0.3439
 33     DSLD1     38.0000     11.6044      1.2000      0.2707      0.4416      1.1707 -2.9342e-02      1.1835 -1.6508e-02      1.1632 -3.6819e-02      1.1916 -8.4467e-03
 34     DSLD2     19.0000      2.7383      1.4600      0.1764      0.5764      1.3361     -0.1239      1.3050     -0.1550      1.3182     -0.1418      1.2445     -0.2155
 35     DTJE1     47.0000     15.0372      0.8600      0.2436      0.3970      0.8310 -2.8981e-02      0.7629 -9.7148e-02      0.8601  1.3083e-04      0.7212     -0.1388
 36     DTLL1     15.0000      2.1986      1.6400      0.1183      0.4473      1.4110     -0.2290      1.4140     -0.2260      1.3537     -0.2863      1.3444     -0.2956
 37     EACH1     10.0000      2.5990      2.0300      0.3526      0.2893      1.8715     -0.1585      1.9049     -0.1251      1.7065     -0.3235      1.5067     -0.5233
 38     EALB1     34.0000      5.0670      0.6800      0.2330      0.4115      0.8944      0.2144      0.8802      0.2002      0.9910      0.3110      0.9767      0.2967
 39     EALM1      7.0000      2.6368      0.9300      0.1993      0.3235      1.2129      0.2829      1.1658      0.2358      1.5194      0.5894      1.5038      0.5738
 40  ECMC2000     19.0000      1.7069      0.6100      0.1840      0.2847      0.5176 -9.2425e-02      0.5253 -8.4698e-02      0.8707      0.2607      0.1765     -0.4335
 41     ECLD1     20.0000      8.9099      0.3100      0.3113      0.3820      0.1701     -0.1399      0.2125 -9.7538e-02      0.2001     -0.1099      0.3044 -5.5709e-03
 42     ECPL1     30.0000      7.5382      0.3500      0.3547      0.3677      0.3100 -4.0007e-02      0.2849 -6.5074e-02      0.3097 -4.0327e-02      0.3383 -1.1718e-02
 43     EHIT1     14.0000      4.8514      0.9100      0.3681      0.3256      1.3637      0.4537      1.2213      0.3113      1.4392      0.5292      1.3791      0.4691
 44     ELLL1      9.0000      1.2348      1.1200      0.1916      0.1325      1.7385      0.6185      1.7217      0.6017      1.9081      0.7881      1.8871      0.7671
 45     EMNJ1     14.0000      1.6917      1.4600      0.1909      0.4285      1.8025      0.3425      1.8051      0.3451      1.8535      0.3935      1.8485      0.3885
 46     ENVG1     24.0000      3.2854      0.9900      0.2849      0.3466      0.9772 -1.2796e-02      1.1406      0.1506      0.8766     -0.1134      1.2031      0.2131
 47     EPRL1     21.0000      5.8211      0.6800      0.3221      0.4740      1.0490      0.3690      1.0363      0.3563      1.2421      0.5621      1.2923      0.6123
 48     EPZL1      9.0000      2.9244      1.0900      0.2147      0.3577      1.3268      0.2368      1.3378      0.2478      1.6253      0.5353      1.5368      0.4468
 49     EQUE1     17.0000      5.5414      1.9100      0.2597      0.4879      2.0632      0.1532      2.1293      0.2193      2.0177      0.1077      2.0996      0.1896
 50     ESLC1      7.0000      3.1150      2.2700      0.3998      0.2567      1.9381     -0.3319      2.1786 -9.1410e-02      1.6268     -0.6432      1.2984     -0.9716
 51     ETRY1     10.0000      1.2952      0.2500  5.2828e-02      0.3600  2.1203e-02     -0.2288  8.2848e-02     -0.1672      0.1978 -5.2220e-02      0.2576  7.6345e-03
 52     GCNJ1     23.0000      8.5870     -0.4000      0.2631      0.3209     -0.1246      0.2754  3.3768e-02      0.4338      0.2646      0.6646      0.3081      0.7081
 53     GCRL1     23.0000      6.5846      1.6600      0.3561      0.3229      1.4805     -0.1795      1.5314     -0.1286      1.4129     -0.2471      1.3456     -0.3144
 54     GLNG1     32.0000     12.3336      0.3100      0.2068      0.3875      0.1053     -0.2047      0.1736     -0.1364      0.1644     -0.1456      0.4388      0.1288
 55     GMJM1     11.0000      3.0004      2.2400      0.2031      0.2157      2.2306 -9.4135e-03      2.2140 -2.6043e-02      2.1917 -4.8253e-02      2.1380     -0.1020
 56     GNVL1     13.0000      4.7248     -0.3700      0.6163      0.3109     -0.3863 -1.6327e-02     -0.4781     -0.1081      1.3037      1.6737      1.5839      1.9539
 57     GONT1     16.0000      3.5830      0.5300      0.2135      0.4587      0.8540      0.3240      0.7420      0.2120      1.0676      0.5376      0.9489      0.4189
 58     GONT2      8.0000      1.1794      0.5100      0.1182      0.4501      0.7784      0.2684      0.7885      0.2785      1.0818      0.5718      1.0857      0.5757
 59     GPTR1     13.0000      3.3826      1.4400      0.2986      0.3650      1.5987      0.1587      1.4644  2.4417e-02      1.4941  5.4073e-02      1.1352     -0.3048
 60     GRSA1      9.0000      1.4011      1.9800      0.2483      0.2693      2.1625      0.1825      2.1463      0.1663      2.1785      0.1985      2.0980      0.1180
 61     GSAR1     24.0000     10.1798      1.7900      0.2843      0.4450      1.5083     -0.2817      1.4929     -0.2971      1.3945     -0.3955      1.3248     -0.4652
 62     GSAR2      5.0000      2.0891      1.8500      0.2132      0.1825      1.9032  5.3238e-02      1.9512      0.1012      1.8886  3.8633e-02      1.8935  4.3513e-02
 63     GSLB1     17.0000      3.7834      1.3400      0.2319      0.4660      1.3326 -7.3571e-03      1.3655  2.5487e-02      1.3128 -2.7248e-02      1.3533  1.3254e-02
 64     GSLB2     12.0000      2.4480      1.4700      0.1582      0.3296      1.4946  2.4599e-02      1.5350  6.4977e-02      1.4698 -2.4104e-04      1.5042  3.4233e-02
 65  HCHI1000     21.0000      6.0082      0.6700      0.4051      0.4781      0.4279     -0.2421      0.6069 -6.3070e-02      0.3857     -0.2843      0.2608     -0.4092
 66     HEST1     12.0000      2.0229     -0.2200      0.2877      0.2520     -0.5517     -0.3317     -0.4640     -0.2440      0.7410      0.9610      0.7497      0.9697
 67     HLDP2      5.0000      2.6047      2.3300      0.2136      0.2481      2.0658     -0.2642      2.0783     -0.2517      1.9707     -0.3593      1.9172     -0.4128
 68     HPD11     13.0000      5.3085      1.3300      0.2519      0.4114      1.2275     -0.1025      1.2235     -0.1065      1.2358 -9.4220e-02      1.1693     -0.1607
 69  HSAL1000      8.0000      3.3610      1.8300      0.1339      0.2503      1.9032  7.3218e-02      1.8823  5.2344e-02      1.8762  4.6247e-02      1.7953 -3.4693e-02
 70     HSAL2      7.0000      2.8815      1.8300      0.1558      0.3230      1.8510  2.1039e-02      1.8681  3.8115e-02      1.8108 -1.9163e-02      1.7683 -6.1698e-02
 71     IVRN1     23.0000      5.1848      2.5300      0.4209      0.4212      1.8746     -0.6554      1.8419     -0.6881      1.3214     -1.2086      1.4274     -1.1026

                                 MSE        RMSE   R-squared    Avg-Bias    Max-Bias

Simple WA                     0.0619      0.2488      0.8620           0      0.2326
Tol d/w WA                    0.0509      0.2256      0.8866           0      0.1865
Cross Val WA                  0.1845      0.4295      0.5948     0.04911      0.4143
Cross Val Tol d/w WA           0.225      0.4743      0.5030     0.02623      0.5208
```

APPENDIX SIX

TWINSPAN OUTPUT, 74 TRAINING SET SAMPLES



```
                                                        ........
                ..............................MM.R.......UUNDD.............LL......H.A.HDD.....
                GEEEEEEGGGHCEEDDAABBBCGHAABJCCCCCCDLLDNNDDDEEGGGIEGGGCCDAAEBECELHGIEEEEEGH
                NAAHMPLMRSLZQSPPSTFRSGPP12D1AGGTTTC12101SSTAPCOOVNSSS12TSZCCC2G1SC112CCTLE
                VLCINZLJSADRULRRBSNTDSTD00C0RSSRRRM00000LLLLBRNNRVALD00JBNRCH0R0AN000LPRNS
                LMHTJLLNARPRECABLCTSAQR100E0JQQJJJS00000DDLBLLTTNGRBB00ELRRAC0A0LJ000DLYGT
                111111111122111111112311001021212310000012111112111120012112101021000111111

  16  NA 021A  ---1-1-11---------------11-------------11--------1-------1----1-------1---  000
  26  NI 009A  ----1-2-2-----11-1-1----2-11-312411--1--1--4-1--1111-2---11-----------3-1-  000
  65  NA 9849  15--------------------------------1-----11-----1---134-----11-------1--1--1-  000
  79  AC 058C  -----------1------1----1--11----------1-1-------------1----------------1---  000
  90  NI 152A  -553-51-----4-------1-----------2----------11----1-1-----------------1---  001000
   6  AM 9985  ---4-2-452-5511112522-2-2-11-2----------1-1--3--1-2-1---------------------  001001
  23  NA 9838  --145-5425543-2-41432533111-11----1-----1-1-41--111--1--------------------  001001
  41  ZZ Z999  ---121-2--1111--12--2--------1--------------11----111---------------------  001001
  49  NA 9839  --1-2-131--3551--412--1------1---1---1--1----1--4------------------------  001001
  80  HA 001A  215----5315114----1-1---------------------1--------1-----2----------------  001001
 117  NA 9845  ---315-------3----------------------------1-------------------------------  001001
  82  NI 9956  ------------4-1---41--------------------------1-------1--------------------  00101
 116  AN 009D  ---3----------------------------------------1--1----11-2--------1-------------  00101
   2  AM 006A  --221-2-------41-21-2--441-11--1-2--1---1---5-----11-3------111-------------  001100
  12  EN 003A  --------1----3-----111--11---1-1--1---------1----1-------1-----------------  001100
  18  NA 035A  --1-3------------1----511--11----2---1-----111--5----3---------------------  001100
  33  AM 002A  --3-23-1------02-1-12--5-1-1221--1----1----11----1-1-----1-1--1------------  001100
  34  AM 004A  4-1213----------------1--111-1121-1211111----3-151----1-15-----------------  001100
  37  NA 9846  ---5-------------------5-1-32--11--2211-31---1----11--21--1----------------  001100
  45  NA 9842  3--21---------------11-----1-----1-1112111-1412-2-----111-1----------------  001100
  93  MA 002C  -----2---------------------1-------------------------23-------11-----------  001100
  15  NA 010A  ---11---1---------1--1-2-1-------------------1-3--3-4---1-1----------------  001101
  21  NA 304A  -------2-5-1--1--214451-22-211---1------2----3---1--------------------------  001101
  46  NA 9851  -------------5-------------1---11--313--1--1--52-1--31111-3--1-------------  00111
  50  NA 9840  -----------1-----5-1---------1------------------------------------------  010000
  81  NA 067A  --------1----------1-1------------------------------1--3-----1-------------  010000
   9  CM 023A  ------------1---3-1-5---4111134-----1---1--------54551-111-4-1345---1-----  010001
  36  FR 9977  --------------------------3--------------------------------------1-155--------  010001
 133  NI 205A  ----------------------------------------------------------------144--------  010001
 145  BR 009A  -----------------------------------------------------------------43--------  010001
   1  AC 159A  -----------------------41---------1-1-----------------1-5------------------  010010
  44  NA 173A  --------------------1----141--------11-1--11-1--1-------------5-------------  010010
  68  NI 204A  ---------------------------1-11-11----1-31------------1---1-3442-----------  010010
  74  CH 057A  ------1------------1--52---11--111-122--1--1------1--13----12--------------  010010
  99  NI 098A  --------------1---------------------1-1-------------------21-----------------  010010
 126  AM 021B  --------------------------------------------------------------555----------  010010
  32  SY 008A  ------------1------1----1-1--1-1------1------111-52--11-111-1--------------  010011
  38  NI 036A  ----------------------------1-1--11-----111---------3131-1---1-1-----------  010011
  54  AN 009A  -1---------------------------1-----1-11211--11---11-14-23-1-1--1-----------  010011
  66  NI 013A  ------------------------------------1-11-1--1-1---------1--1----------------  010011
   7  AM 9990  -----------------1-1----1311111141--1112111-2-5--3-3--2--1-1-2------------  010100
  11  CP 001A  ------------------------1111------1-11121-1--1----1----1---11-1------------  010100
  13  GY 021A  -----------------111151-22-11351113--132-32--3----3--1---------------------  010100
  17  NA 023A  -----------------1-11---1151-225113-11--1--1-41------21--1-1----------------  010100
  22  NA 742A  ---------------1--------11-1------------1------------1----------------------  010100
  27  NI 016A  -----------1----131212--23312453522212444411-1--1121---1-1----------1---  010100
  30  NI 9957  --------------12-1-11--411-25--232112133312-3-451-2--1-------------1---  010100
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  94  NI 027A  -----------------------------------5------1-----1--1---11----------------------  010100
   4  AM 065A  --------------1---------1---------------------------1------------------------  010101
   8  AM 9991  --------------11-1111131 2---1----------1--1----1-----------1------------  010101
  28  NI 200C  -----------3----515311--1433342--15---45-55----------------------------------  010101
  48  NA 565A  -----------1----312-------1232-1--------1-1-5-------------------------------  010101
 100  MA 005A  --------------15-----------22------------------------------------------------  010101
 103  PL 050A  --------------31-----------1-----1---1-11-----------------------------------  010101
  39  NI 149A  ------------------------------5-----------34---------------------------------  010110
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  78  NA 066B  ---------------------------322--------31----4----1---1-----------------------  010110
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 104  ZZ Z998  ---------------------------1----------11-------------------------------------  010110
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  24  NI 007A  ---11--------------1112211111241111-12---2212121-31311-1-1----------1--1---  0110
  25  NI 008A  -1-----1----------111--221-21112141--1323-1-2111211------1--11-------1-1-  0110
  40  NI 203A  -----------1--11--11--12-1--11-12--11--11-121112-11421-1-----1------1-1-1-  011100
   3  AM 007A  ------------------------1---1--------------------------1-111211---1-------  011101
  57  CY 003A  ----------------------------232--2111144--2-121-1------242-1--111---1--11---  011101
  60  EP 007A  ---------------1-------------1----1121-------------------122-1---------------1  011101
  62  GO 013A  -------------------------------------2-1----1----------2-1-12--1----1-------  011101
  70  RC 001A  ----------------------------11-------1-1-------------1--1--1--------1---  011101
  91  CM 031A  ---------------------------1---2------2--------------------13---------------1---  011101
  29  NI 206A  -----------------------------32---1-44-1---1--1----1-------1--------------11---  01111
  64  MA 001B  ---------------------------------1-------------------551-1-11-----51------  10
  67  NI 014A  ------------------------------------321---------------121-2-------1----1-1-  10
  72  SY 001A  ------------1-------------1-11----1--111-------1-----21-1-4---------11--1  10
  96  RH 001A  ---------------------------1-------1----------------111---------1---------  10
  14  NA 003B  --1-----1--12-2-52------1--24-----1-1-1--111-----------11-1-------1--333--1  1100
  89  NA 675A  -----------3--------53--------------------------------------------3-------  1100
 125  ST 001A  -1------------------------------------------------3-----------1------------11  1100
  52  AM 012A  ------------1-------------------------------1---------1-1--------------14-  11100
 110  NA 003A  ------------1--------------------------1----------------2----------2-----1-  11100
  58  DE 002A  -------------------------------1----------------------------1--------3--41---  111010
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  75  NA 024A  ---------------------------------------------------------1---1------2111-1--  111010
  83  CY 028A  -------------------------------------------------------------------------5523-3-  111010
  84  FR 006A  ----------------------------------------------------11------------11---22--521  111010
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APPENDIX 7

PRESERVATION STUDY II: LITHOLOGICAL DESCRIPTIONS OF LONG CORES COLLECTED IN SUMMER, 1992.

Laguna Grande, Archidona, Málaga

247-226cm	Dk gr-br marly clay; very hard, with abundant gypsum crystals at base.
226-211cm	Sharp diagonal contacts between dk br clay and salt bands to 220cm. Alternating bands of dk br clays and white ?carbonate-rich sediment to 211cm.
211-143cm	Soft, mottled lt br marly clay with large gypsum crystals, laminated from 187-179cm and 156-143cm.
143-99cm	Dk-br marly clay alternating with bands of gypsum.
99-67cm	Soft, lt br marly clay.
67-0cm	Very soft gr clay.

Laguna de Zarracatín, Utrera, Sevilla

500-384cm	Dk gr 5Y 4/1 homogeneous clay; hard 500-474cm/soft 474-442cm/hard 442-384cm with tufa-rich band 426-422cm. Variable lenticular gypsum <2mm, aggregate gypsum and rounded translucent crystals.
384-334cm	Gradual transition at 380cm from gr 5Y 5/1 to olive-gr 5Y 5/2 and 4/2 soft sticky clay with abundant or occasional lenticular gypsum and occasional aggregates and tufa.
334-120cm	Variably compact dk gr 5Y 4/1 and gr 5Y 5/1 clay; no recovery 318-300cm. Occasional lenticular gypsum. Aggregates and translucent crystals variable. No tufa.
120-5cm	Soft, olive-gr 5Y 5/2 clay with transition to gr 5Y 5/1 and lt gr 5Y 6/1 clays above c.74cm. Abundant lenticular gypsum (>2mm), well formed gypsum hexagonal crystals and rare tufa, desert roses and translucent crystals.
5-0cm	c.3cm salt crust overlying black, unconsolidated anoxic sediments.

Laguna del Taraje, Las Cabezas, Sevilla

137-112cm	Hard, v compact homogeneous dk gr 10YR 4/1 clay with very rare gypsum.	
112-0cm	Soft, less compact clay, highly variable.	
	112-97:	Soft dk gr 10YR 4/1 and v dk gr 5Y 3/1 clay with abundant lenticular gypsum and aggregates <2mm diameter.
	97-79:	Ill-defined organic banding within mottled v dk gr 5Y 3/1 clay; solid band of reduced herbaceous root/stem 87-85cm. Abundant lenticular gypsum and aggregates.
	79-26:	Soft dk gr 2.5Y N4 and olive-br 2.5y 4/3 clay with hard, more friable layers @ 64-57cm and 49-47cm. Abundant lenticular gypsum and aggregates; tufa rare throughout.
	26-16:	V soft mottled v dk gr 10YR 3/1 and black 10YR N2 clay with rare lenticular gypsum and occasional tufa.
	16-0:	Very soft v dk gr 10YR 3/1 clay (oxidised since coring to red).

Laguna Dulce, Espera, Cádiz

380-374 cm	Horizontally bedded reduced root/stem remains within hard, friable v dk grey-brown 2.5Y	
374-258cm	Soft dk gr 5Y 4/1 homogeneous clay to 374-342; gradual transition to olive grey 5Y 3/2, becoming darker from 270-260. Rare lenticular gypsum.	
258-c.180cm	Variable v dk gr 10YR 3/1, dk gr 10YR 4/1, dk olive-gr 5Y 3/2, olive-gr 5Y 4/2 and black clays with high ?marl content in bands of varying thickness as follows:	
	258-224cm:	Alternation between hard, friable and soft bands of clay separated by sharp transitions. Abundant lenticular gypsum (>2mm) and root/stem remains in different bands.
	224-200cm:	Friable dk gr clay, homogeneous with occasional lenticular gypsum <2mm and aggregates.
	200-186cm:	V soft clay with abundant translucent crystals.
	186-180cm:	Bands of horizontally-bedded root/stem remains.
180-80cm	Soft clay, variable colour range as 258-180cm with occasional lenticular gypsum, more abundant from 160-148cm.	
80-43cm	Soft, mottled, olive green 2.5Y 5/4, olive-brown 2.5Y 4/3 and dk gr 2.5Y N4 clay with significant disturbance (irregular 'overturned' sediment) from 77-66cm above a gypsum band. Occasional gypsum aggregates.	
43-10cm	Very sharp transitions between bands of varying thickness:	

	43-30cm:	Organic-rich mottled dk gr 10YR 4/1 clay alternating with c.2cm bands of reduced organics; solid organic band 34-30.
	30-24cm:	Horizontal c.2cm gypsum bands alternating with dk gr or olive gr clays.
	24-10cm:	Dk gr 2.5Y N4, olive gr 5Y 4/3, 5/3 and white laminae. Occasional aggregates. Solid band of reduced organics 11-10cm.
10-0cm	V soft dk olive br 2.5Y 3/3 banded clay with abundant vegetative remains.	

Laguna de los Tollos, Jerez, Cádiz

400-91cm	Lt gr-br 10YR 6/2 calcareous silty clay with abundant lenticular gypsum (<2mm and >2mm) and occasional aggregates, translucent crystals and tufa. Hard and friable 400-376cm; soft 379-91cm (very soft to c.247cm).
91-75cm	Soft gr-br 10YR 5/2 homogeneous silty clay with abundant aggregates.
75-0 cm	Hard dk gr-br 10YR 4/2 homogeneous silty clay with abundant lenticular gypsum. Friable white clay at lake surface (top 2cm) overlain by dried remains of algal mat.

Laguna de Medina, Jerez, Cádiz

760-600cm	Organic clays alternating with gypsum bands:	
	760-674cm:	Alternation between soft olive-gr 5Y 4/2 and 5Y 5/2 clay and gypsum bands of 1-2cm thickness at c.10cm intervals between 750-711cm and a single band at 676-674cm.
	674-646cm:	Soft gr-br 2.5Y 5/2 and gr 5Y 5/1 clay. Lenticular gypsum at 674-660cm only.
	646-600cm:	Soft olive-gr 5Y 5/2 ?marl-rich clay with abundant lenticular gypsum, alternating with irregular gypsum bands of 1-4cm thickness (at 636-634, 632-628 and 614-613cm), the upper band lying above green and white laminae of c.2mm depth.
600-504 cm	Incomplete recovery (soft clays with few salt crystals recovered at the Cobra core centre). Vivianite (<180µm) in sample 540-542cm.	
504-416cm	Soft, sticky gr-br 2.5Y 5/2 clay with occasional lenticular gypsum <2mm and aggregates; harder friable band with abundant lenticular gypsum at 444-438cm.	
(416-404cm no recovery)		
404-326cm	Soft gr-br 2.5Y 5/2 clay with abundant prismatic (to 5mm) and lenticular gypsum.	
(326-316cm no recovery)		

316-290cm	Soft dk gr 2.5Y N4 clay with occasional lenticular gypsum and aggregates. Gypsum band 292-290cm.
290-26cm	Gr-br 2.5Y 5/2 clay with abundant lenticular gypsum. Rare quartz sand 216-100cm; rare tufa above 60cm. Band of very soft lt olive-br 2.5Y 5/3 clay 30-26cm with large (0.5cm) lenticular gypsum.
(26-12cm no recovery)	
12-0cm	Very soft unconsolidated gr-br 2.5Y 5/2 clay over hard horizontal laminae of reduced organics 12-10cm.

Laguna Amarga, Lucena, Córdoba

338-270cm	Highly variable banding of clay, marl and gypsum: 338-323cm: Dk gr clay 5Y 4/1 with abundant lenticular gypsum <2mm. 323-315/6cm: Gr-br 2.5Y 5/2 clay with abundant lenticular gypsum. 315/6-306cm: Narrow bands of gypsum and clays. 306-301cm: Grey 2.5Y N5 marly clay 301-289cm: Bands of gypsum (to 4cm thickness) and reduced organics, clay and marl (c.1cm). 289-283cm: Stiff, compact grey 2.5Y N5 clay with low salt content. 283-270cm: Very sharp transition to gypsum band.
(270-259 no recovery)	
259-219cm	Soft olive-br 2.5Y 4/3 marly clay with abundant small lenticular gypsum.
(219-204cm no recovery)	
204-160cm	Hard, mottled dk gr 2.5Y 4/1 and v dk gr 2.5Y N3 clay with reduced salt content. Abundant specks of reduced organics 190-171cm; gradual transition to softer olive-br 2.5Y 4/3 marly clays above clay/marl bands between 171-168cm.
160-124cm	Very sharp transitions between narrow laminae (1-2cm) of gypsum, clay, marl, white ?carbonate and root/stem remains.
124-89cm	Broader bands (5-10cm) of dk gr 2.5Y N4 clay with variable organic content and no salt crystals. Diffuse marl laminae 109-104 and 95-94cm, with very sharp transition to organic-rich gypsum band 94-89cm.
89-0cm	Soft, dk gr 5Y 4/1 clay with dk olive-gr 5Y 3/2 clay bands 76-72cm and 57-51cm. No salt. Increasing organics towards core top.

El Salobral, Luque, Córdoba

600-540cm	Soft pale yellow 2.5Y 7/3 calcareous clay with abundant small lenticular gypsum <2mm.
540-280cm	Soft mottled lt yellow-br 2.5Y6/3 and 6/2 clay with low carbonate content. Very abundant (often >50%) large gypsum crystals dominated by well-formed, prismatic crystals to 5cm length and abundant lenticular gypsum and rounded translucent crystals.
280-242cm	V pale br 10YR 7/3 and gr br 10YR 5/2 bands (c.10cm thickness) of calcareous clay with abundant lenticular and translucent crystals.
242-80cm	Hard, mottled gr-br 10YR 4/2 and 2.5Y 5/2 silty clay with abundant lenticular gypsum, occasional aggregates and rare tufa. Rare quartz sand 174-152cm.
80-10/13cm	Soft gr-br 2.5Y 5/2 and lt olive-br 2.5Y 5/3 silty clay with low salt content; occasional tufa above 20cm.
13-10cm	Irregular sharp transitions surrounding black, anoxic sandy silty clay.
10-0cm	Pale brown 10YR 6/3 unconsolidated silty clay.

Laguna Honda, Jaén

273-260cm	V compact, friable v dk gr clay.
260-209cm	Compact grey silty clay with abundant gypsum bands at 245-243cm and 215-209cm. Black anoxic clays 243-228cm.
209-72cm	Soft lt gr and gr silty clay with variable bands of olive-green and black marly clay, white ?carbonate layers and algal mats.
72-10cm	V soft, black silty clay alternating with 1-2cm bands of grey and brown clay, marly clay and remains of algal mats.

APPENDIX EIGHT

LAGUNA DE MEDINA: LOG$_{10}$ AND BACK-TRANSFORMED PALAEOSALINITY CALIBRATION RESULTS

App. 8(a) Calibration using original transfer function

SAMPLE	LOG CON	COND
0	1.8959	78.68868
465	1.0742	11.86334
489	1.2582	18.12208
521	1.098	12.53162
529	1.0245	10.58051
537	1.0696	11.73835
545	1.077	11.94007
609	1.0144	10.33729
617	1.0669	11.6656
633	1.068	11.69518
701	1.0776	11.95658
709	1.0669	11.6656
713	0.4728	2.970319
717	1.0699	11.74646
723	1.1319	13.549
725	1.0566	11.39218
727	1.0614	11.51879
729	0.9669	9.266298
737	1.0602	11.48701
739	1.067	11.66828
745	1.0809	12.04778
749	1.0199	10.46903
753	1.1009	12.61558
757	0.9249	8.41213
761	0.8456	7.008184
765	0.9047	8.029821
769	1.1385	13.75648
773	0.9973	9.938171
777	0.961	9.141263
781	1.2955	19.74733
785	1.0309	10.73759
787	1.1506	14.14515
821	1.0669	11.6656
825	0.9925	9.828934
829	0.9346	8.602131
865	0.8905	7.771516
873	0.553	3.572758
877	0.5266	3.362044
881	0.687	4.864122
885	0.6992	5.002701
889	1.0501	11.22294
901	1.0669	11.6656
905	1.224	16.74973
909	1.069	11.72214
911	1.081	12.05055
912	1.1369	13.70589
913	1.1464	14.00901
921	1.0624	11.54534
933	1.8556	71.71533
949	1.02	10.47144
1001	1.0599	11.47907
1017	1.0304	10.72523
1025	0.9509	8.931125
1033	1.0604	11.4923

SAMPLE = Sample depth (cm), LOG COND = Log-10 salinity estimate, COND = mS/cm salinity estimate

App. 8(b) Calibration using modified *DMA* transfer function

SAMPLE	LOG CON	COND
0	1.8771	75.35501
465	1.2584	18.13043
489	1.25	17.78313
521	1.2121	16.29701
529	1.4278	26.77992
537	1.2715	18.68565
545	1.2272	16.87361
609	1.5209	33.18256
617	1.1723	14.86988
633	1.1853	15.32173
701	1.172	14.85962
709	1.1716	14.84594
713	0.5292	3.382232
717	1.1867	15.3712
723	1.2976	19.84305
725	1.2815	19.1209
727	1.2548	17.98076
729	1.1575	14.37168
737	1.1694	14.77092
739	1.1825	15.22326
745	1.3413	21.94364
749	1.1716	14.84594
753	1.4638	29.0944
757	1.3138	20.59722
761	0.9963	9.915313
765	1.1811	15.17426
769	1.3296	21.36036
773	1.3269	21.22798
777	1.2538	17.93941
781	1.3973	24.96371
785	1.3329	21.52329
787	1.2442	17.54721
821	1.1737	14.9179
825	1.1753	14.97296
829	1.197	15.74011
865	0.8846	7.666652
873	0.6329	4.294416
877	1.0671	11.67097
881	0.9097	8.122802
885	0.8826	7.631426
889	1.1652	14.62876
901	1.3672	23.29211
905	1.111	12.91241
909	1.2455	17.59981
911	1.1955	15.68584
912	1.3081	20.32865
913	1.2942	19.68831
921	1.1659	14.65236
933	1.138	13.74065
949	1.1436	13.91898
1001	1.1669	14.68614
1017	1.1847	15.30057
1025	1.3751	23.71968
1033	1.1903	15.49914

SAMPLE = Sample depth (cm), LOG COND = Log-10 salinity estimate, COND = mS/cm salinity estimate

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