PALAEOLIMNOLOGY AND HOLOCENE ENVIRONMENTAL CHANGE FROM ENDOREIC LAKES IN THE EBRO BASIN, NORTH-EAST SPAIN

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by

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Abstract

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Lake sediments from inland endoreic (saline) lakes in the semi-arid Ebro Basin, NE Spain have been analysed to provide a history of lake level, vegetation, catchment erosion and anthropogenic activity over the last 10,000 years. Analysis was undertaken for pollen, macrofossils (seeds, Cladocera ephippia, Chironomid head capsules *etc*), charcoal, geochemistry (total cations/trace metals, sulphate, carbonate & LOI) and sediment composition. Fourteen AMS radiocarbon dates provide dating control.

Seven cores were investigated from 4 seasonal playa lakes, 1 shallow (<1.5m) semi-permanent salt lake, 1 deep (5.0m) permanent salt lake and 1 Medieval-age reservoir. Over 40 surface samples were also taken to investigate modern analogue environments.

A review of the use and interpretation of saline lake macrophytes (seeds & pollen), Cladocera and Chironomids in palaeolimnology is provided, with special emphasis on those found in Spanish salt lakes. Taphonomic problems and nearshore-offshore facies were also investigated using a surface sample transect across a small playa lake. A surface sample pollen data set from 30 lakes in the Ebro Basin is presented and the implications for palaeo-interpretation discussed. The sensitivity of the pollen record as a climate indicator is investigated using 6 sites across a climatic gradient from sub-humid to semi-arid.

Lake level reconstruction is based on an 8 stage semi-quantitative palaeohydrological model, developed from a surface sample data set from 32 lakes ranging from temporary to permanent, and hypersaline to freshwater. A simple hydrological model for groundwater fed lakes is also discussed which can be used to quantify these palaeohydrological changes.

The early Holocene (<9.3-8.6Kyr BP) was characterised by semi-arid extreme continental conditions in the Ebro Basin, with an extensive *Juniper thurifera* woodland. Lake levels rose to their highest point in the Holocene between 8.6-7.2Kyr BP when evergreen oak and pine forest dominated. This is interrupted by a short recession in lake level between 8.2-7.6Kyr BP. A distinct regional early-Neolithic fire and clearance event occurs between 7.7-7.3Kyr BP. A drop in lake level and development of a monospecific pine forest (*P.halepensis*) indicates warmer and drier conditions in the mid Holocene (7.2-5.4Kyr BP).

Evergreen oak reappears as forest cover declines after 5.4Kyr BP, although this is not marked by any increase in charcoal or cultivation indicators. Low groundwater but moderate lake levels (4.0-2.7Kyr BP) may be linked to high summer storm frequency and low winter rainfall. This coincides with catchment erosion and valley floor alluviation.

Lake level rises again significantly between 2.7-1.8Kyr BP during Iberian and Roman times when archaeological evidence indicates a peak in population. Agriculture changes from small scale pastoral to small scale arable without any further decline in woodland cover. A rapid fall in lake level at *ca.*1.8Kyr BP is followed by complete forest recovery (*P.halepensis*) and depopulation, until major deforestation around 1.4Kyr BP marks the arrival of the Visigoths/Arabs and extensive nomadic pastoralism.

Intensive grazing pressure or lower temperatures resulted in *Juniperus* increasing again between 1.4-0.4Kyr BP. This also coincides with a second period of catchment erosion and valley floor alluviation. After *ca.*0.4Kyr BP, lake levels have increased along with extensive olive cultivation and the development of modern (irrigated) arable agriculture.

Acknowledgements

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Chapter 1

Introduction

1.1 Background

This research project was initiated as part of a multi-proxy investigation into Holocene environmental change in the Ebro Basin, NE Spain, in cooperation with the Taller de Arquelogía y Prehistoria de Alcañiz, Teruel, Spain. The strength of this approach has been in combining the archaeological, alluviation and lake sediment record to provide an integrated environmental reconstruction encompassing as many different lines of evidence as possible. The main challenge of this thesis has been to provide a lake sediment-based record that would reveal information on vegetation (pollen), fire history (charcoal), lake level (pollen, macrofossils, geochemistry & sediment composition) and catchment erosion (geochemistry & sediment composition). This analysis was undertaken on cores taken from a series of previously uninvestigated saline endoreic (mainly playa) lakes in the semi-arid basin of the Rio Ebro, NE Spain.

1.2 Palaeoenvironmental research in Iberia

Core-based palaeoenvironmental research in Iberia has been almost entirely dominated by pollen-based studies. Of this work, the majority of Holocene palynology has been undertaken on valley mire systems. Due to the high aridity of much of the continent, these are largely confined to high mountain areas or areas of impeded drainage along the coast. Most of the main published radiocarbon dated pollen sites for Spain and Portugal are shown in *figure 1.1* p14 and *table 1.1* p15 (some major cities are shown in *figure 1.2* p16 for reference). Full sequences for the entire Holocene are limited by a number of factors. Many coastal sites only started to accumulate sediment after sea levels stabilised in the past 4.5Kyr (*eg*. sites 1-3, 7-8, 30-31, 35). Large numbers of inland sites also only started to accumulate sediment relatively recently in the late Holocene, particularly in the Gredos & Guadarrama Mountains (sites 14-22). Other sites with longer sequences have been disturbed in later years, either through desiccation, drainage or peat cutting. Many sites have been analysed with a wide sampling interval and poor dating control, resulting in a record of low resolution. Furthermore, interest has often been focused on the Würm-late glacial transition, while neglecting the later Holocene sequence. Part of the reason for this is perhaps the fact that many of the high altitude sites that contain the best sequences show only slight changes during the Holocene compared to earlier periods. As this research shows, the geographical bias of palynological site location towards pluvial coastal and upland sites may have helped create an image of limited Holocene climate change within Iberia, particularly within the last 5.0Kyr. This may have lead to archaeological and geomorphological evidence of environmental change within the semi-arid lowland interior being interpreted in terms of anthropogenic action rather than changes within the prevailing

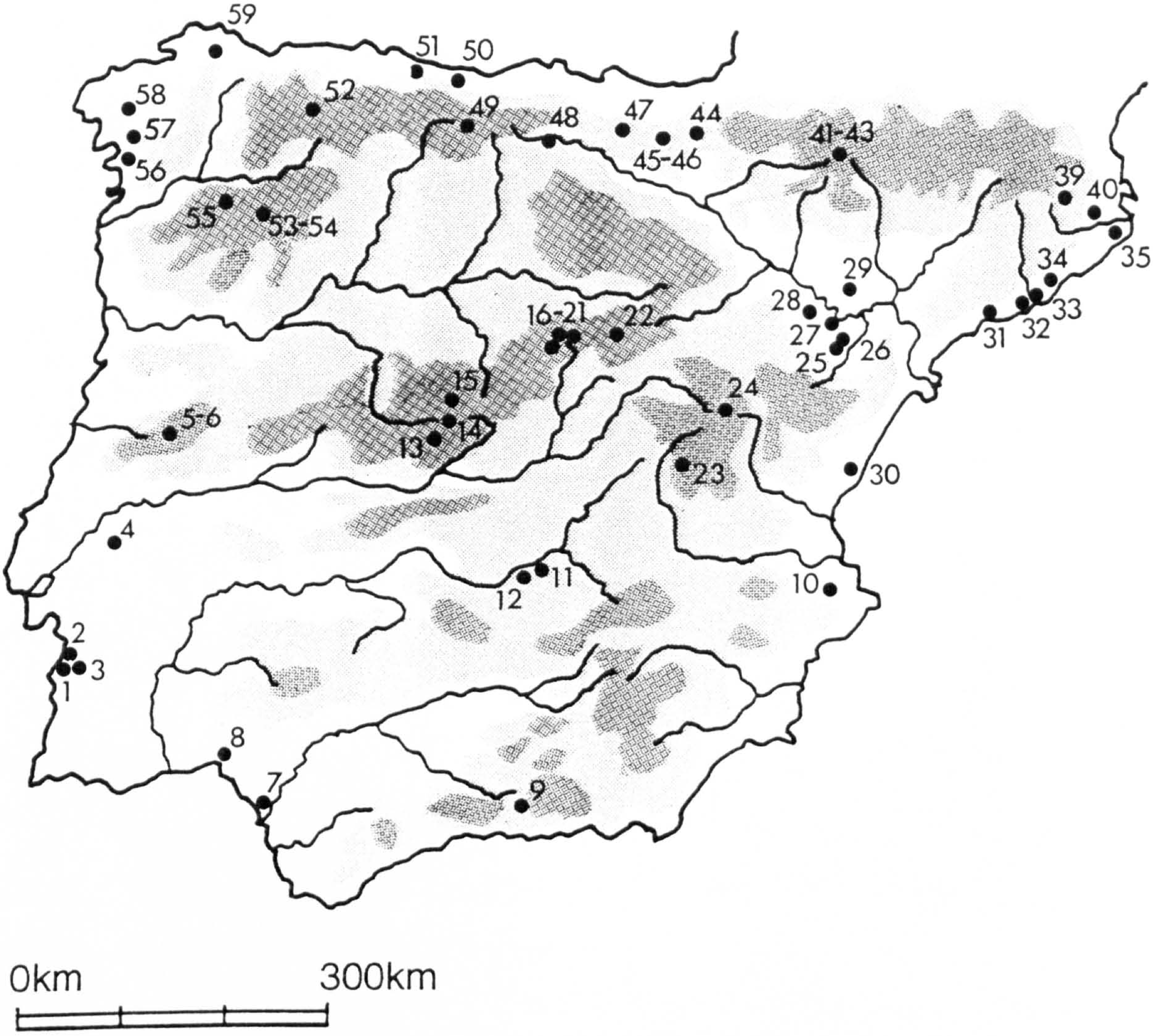
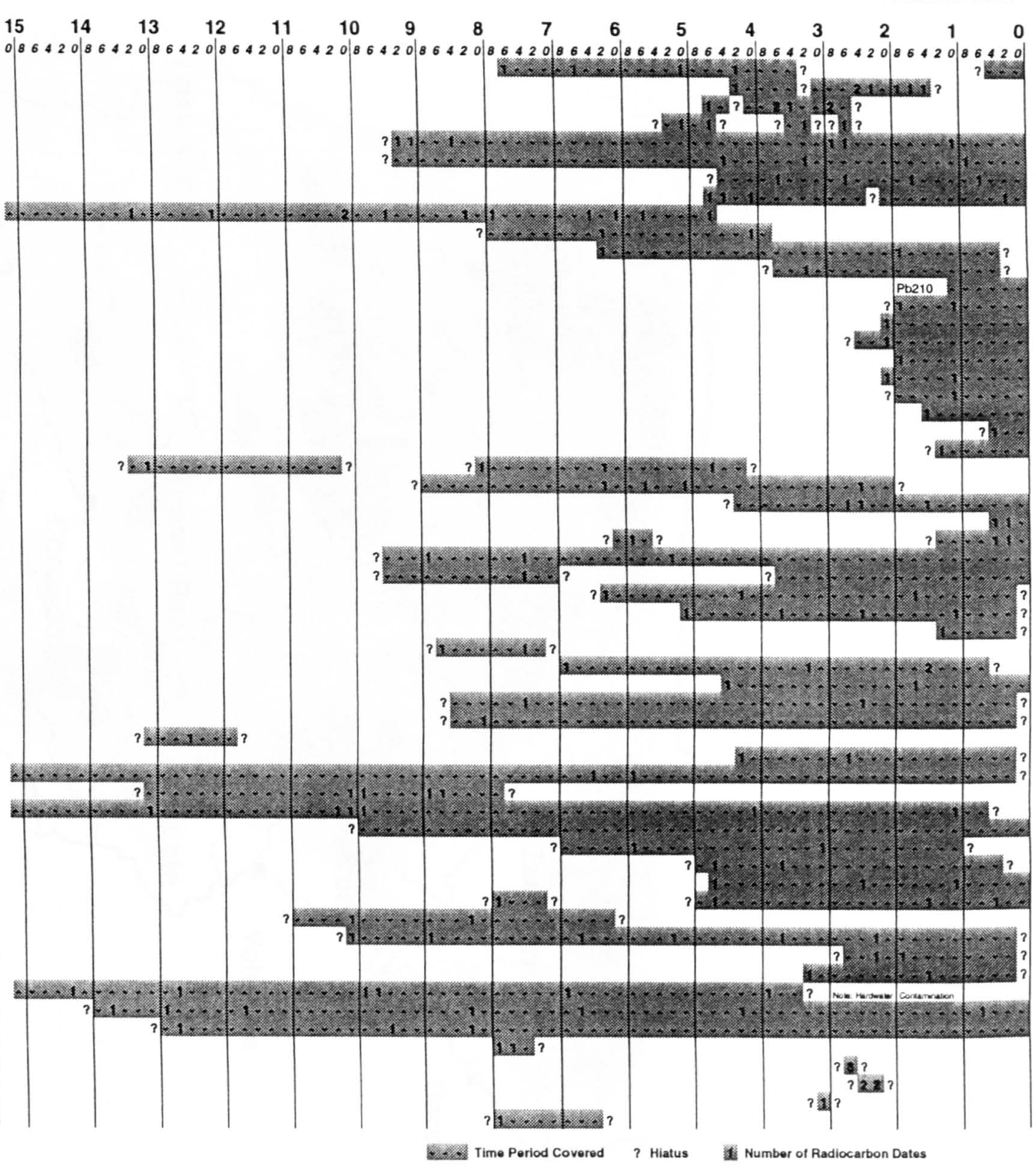


Figure 1.1 **Map of locations of late glacial and Holocene radiocarbon dated pollen diagrams from the Iberian Peninsula**

Late-Glacial & Holocene radiocarbon dated pollen diagrams from the Iberian Peninsula

Ref No	Site	Author/s	Location	Altitude	Site Type
1	Lagoa Travessa I	Mateus (1992)	Setubal	1.8m	Peat Bog
2	Lagoa Travessa II	Mateus (1992)	Setubal	1.7m	Peat Bog
3	Figueira Baixo	Mateus (1992)	Setubal	2.9m	Peat Bog
4	Alpiarca II	Van Leeuwaarden & Janssen	Setubal	80m?	Peat Bog
5	Lagoa Comprida I	Janssen & Woldringh (1981)	Serra da Estrela	1600m	Peat Bog
6	Lagoa Comprida 2A	Van den Brink & Janssen (1985)	Serra da Estrela	1600m	Peat Bog
7	Laguna de las Madres	Stevenson & Harrison (1992)	Jerez	20m	Peat Bog
8	El Acebron	Stevenson & Harrison (1992)	Huelva	25m	Peat Bog
9	Padul	Pons & Reille (1988)	Sierra Nevada	785m	Peat Bog
10	Ereta del Pedregal	Menendez Amor (1961)	Valencia	200m?	Peat Bog
11	Castillo de Caltrava	Garcia et al (1986)	Ciudad Real	600m	Peat Bog
12	Daimiel II	Menendez Amor (1961)	Ciudad Real	620m	Peat Bog
13	Laguna Grande de Gredos	Toro et al (1992)	Sierra de Gredos	1960m	Lake
14	Navaredonde	Franco Mujica (1994)	Sierra de Gredos	1580m	Peat Bog
15	Navalguijo	Franco Mujica (1994)	Sierra de Gredos	1500	Peat Bog
16	Hoya de Pepe Hernando	Gomez (1992)	Sierra Guadarrama	2020m	Peat Bog
17	Lomo de Penas Creciente	Gomez (1992)	Sierra Guadarrama	1775m	Peat Bog
18	Majadas de los Hoyas	Gomez (1992)	Sierra Guadarrama	1840m	Peat Bog
19	Puerta de Morcuera PMVIII	Garcia (1992)	Sierra Guadarrama	1740m	Peat Bog
20	Puerta de Morcuera PMIII	Garcia (1992)	Sierra Guadarrama	1740m	Peat Bog
21	Puerta de Morcuera PMVII	Garcia (1992)	Sierra Guadarrama	1190m	Peat Bog
22	Pico de Lobo	Garcia (1992)	Sierra Guadarrama	2125m	Peat Bog
23	Verdelpino	Lopez Garcia (1977)	Cuenca	1600m?	Peat Bog
24	Ojos del Tremedal	Stevenson (unpublished)	Montes de Universales	1650m	Peat Bog?
25	Salada Pequena	Davis (1994)	Central Ebro Basin	357m	Lake
26	La Estanca	Davis (1994)	Central Ebro Basin	342m	Lake
27	Laguna Salada	Davis (1994)	Central Ebro Basin	160m	Lake
28	Hoya del Castillo	Davis (1994)	Central Ebro Basin	260m	Lake
29	Laguna Guallar	Davis (1994)	Central Ebro Basin	336m	Lake
30	Torreblanca	Menendez Amor & Florschutz (1961b)	Castellon	10m?	Peat Bog
31	Cubelles	Rierra-Mora & Esteban-Amat (1994)	Tarragona	1.0m	Peat Bog
32	Murtrassa	Rierra-Mora & Esteban-Amat (1994)	Barcelona	4.0m	Peat Bog
33	Drassanes	Riera Mora (in print)	Barcelona	7.0m	Peat Bog
34	Besos	Rierra-Mora & Esteban-Amat (1994)	Barcelona	7.0m	Peat Bog
35	Ullastret	Rierra-Mora & Esteban-Amat (1994)	Gerona	15m	Peat Bog
36	Les Palanques	Pérez-Obiol (1988)	Olot	440m	Peat Bog
37	Sidera	Pérez-Obiol (1988)	Olot	440m	Peat Bog
38	Pla de Llancs-I	Pérez-Obiol (1988)	Olot	430m	Peat Bog
39	Pla de l'Estany	Pérez-Obiol (1988)	Olot	520m	Peat Bog
40	Banyoles	Perez-Obiol & Julia (1994)	Gerona	173m	Peat Bog
41	Le Paul de Bubal	Montserrat Martí (1992)	Pyrenees	1115m	Peat Bog
42	Ibon de Tramacastilla	Montserrat Martí (1992)	Pyrenees	1682m	Lake
43	Ibon de las Ranas	Montserrat Martí (1992)	Pyrenees	2092m	Lake
44	Belate	Peñalbe (1988)	Navarra	847m	Peat Bog
45	Saldropo	Peñalbe (1988)	Navarra	625m	Peat Bog
46	Saldropo	Garcia-Anton et al (1989)	Navarra	625m	Peat Bog
47	Los Tornos	Peñalbe (1988)	Navarra	920m	Peat Bog
48	Valle de la Nava	Menendez Amor (1968)	Burgos	>1000m?	Peat Bog
49	Puertos de Riofrio	Menendez Amor & Florschutz (1963)	Santander	1700m	Peat Bog
50	Buelna	Menendez Amor & Florschutz (1961a)	Santander	230m	Peat Bog
51	Llano Ronanzas	Mary et al (1973)	Asturias	200m?	Peat Bog
52	Lago de Ajo	McKeever (1984)	Asturias	1570m	Lake
53	Laguna de las Sanguijuelas	Menendez Amor & Florschutz (1961a)	Zamora	1050m	Peat Bog
54	Sanabria Marsh	Hannon (1985)	Zamora	1050m	Peat Bog
55	Sierra de Queija	Menendez Amor (1971)	Orense	1320m	Peat Bog
56	Torroso	Aira Rodriguez & Saa Otero (1988)	Pontevedra	410m?	Peat Bog
57	Trona	Aira Rodriguez & Saa Otero (1988)	Pontevedra	410m?	Peat Bog
58	Penalba	Aira Rodriguez & Saa Otero (1988)	Pontevedra	410m?	Peat Bog
59	Montes del Buyo	Menendez Amor & Florschutz (1961a)	Galicia	500m	Peat Bog



▨ Time Period Covered   ? Hiatus   ▨ Number of Radiocarbon Dates

Table 1.1

Table 1.1 List of late glacial and Holocene radiocarbon dated pollen diagrams from the Iberian

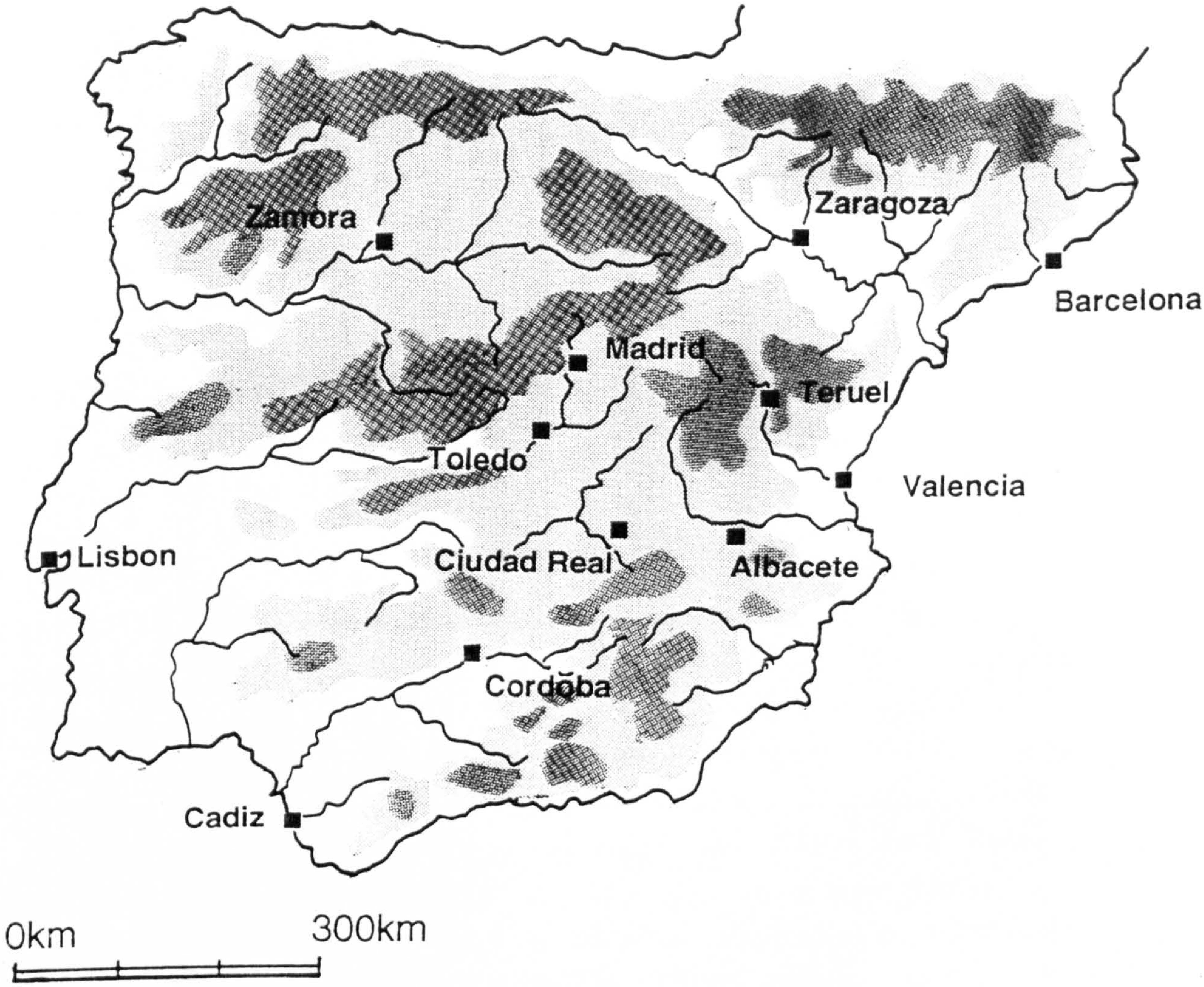


Figure 1.2 Map of some major cities in Iberia

climate (*cf.* Gilman & Thornes, 1985; Hempel, 1987). Or alternatively, being based on ideas of climate change extapolated from the experience of northern Europe (*cf.* Gutíerrez-Elorza & Peña-Monne, 1989; Julian *et al*, 1991). An important aspect of this current study has been to greatly strengthen the case for an environmental determinist interpretation to human development in the Western Mediterranean.

The semi-arid interior of Iberia has seen relatively few palaynological investigations, with only the Daimiel marshland so far investigated in detail (García *et al.*, 1986: site 11, ***Figure 1.1*** p14). This inland area, at low to mid altitudes (100-700m), comprises the major part of Spain, including the North and South Meseta and Ebro and Guadalquivir valleys. A large number of endoreic lakes can be found in these regions (***Figure 1.3*** p13) that provide sediment records comparable with valley mire systems, as well as a potential record of lake level change. As far as is known to the author, this project is the first to provide a full radiocarbon dated Holocene pollen record from this type of lake system, as well as providing a unique record of lake level change. Short sediment cores have previously been investigated for mineralogy at Laguna Gallocanta (Comín *et al*, 1990) and for pollen at some lakes in the Los Monegros area (Perez-Obiol & Roure Nolla, 1991). These cores were, however, relatively short (less than 100cm) and were not dated.

A two metre core from Laguna Gallocanta, dating back to the late glacial, is currently being investigated using a full range of palaeoenvironmental techniques by Prof. F.Comín and colleagues at Barcelona University (pers. comm.). Work is also being undertaken by J.Reed (University College London) and Dr A.C.Stevenson (Newcastle University) on long cores from karst lakes in Andalucia involving ostracod chemistry and pollen.

The continuous record of environmental change often provided by lake and mire sediments provides a valuable point of reference against which other discontinuous records can be compared. Archaeological evidence represents an invaluable snapshot of human occupation and society at various time intervals, and the abundance of archaeological remains are one of the great assets of working in the Mediterranean region. A large part of the work undertaken in Iberia, however, remains site specific (*cf.* Harrison, 1980; Harrison, 1988; Keay 1988) and only now is becoming to be seen as forming part of a broader picture of regional environmental change (Gilman & Thornes, 1985; Cuenca & Walker, 1986; Benavente *et al.*, 1991; Stevenson & Harrison, 1992, Harrison, 1994). The importance of determining the level and type of human impact is vital in understanding the interaction of climate and vegetation on environmental stability, particularly with respect to erosion and fluvial systems. Archaeology has also been employed as a dating control in studies of slope and fluvial geomorphology (Van Zuidam, 1975; Burillo *et al.*, 1986; Gutiérrez-Elorza & Peña-Monné, 1989), as well as in investigations of land use and erosion (Gilman & Thornes, 1985). Increasing dating control of alluvial histories by absolute techniques such as radiocarbon and thermoluminesence will no doubt increase the detail of the alluvial record, and continue to reveal the original ideas of Vita-Finzi (1969) as too simplified. The opportunity to integrate these discontinuous record with the more continuous record provided by endoreic lakes (Macklin *et al*, 1994) perhaps offers one of the best opportunities to isolate the relative roles of climate and anthropogenic action in determining the environmental development of the Mediterranean landscape.

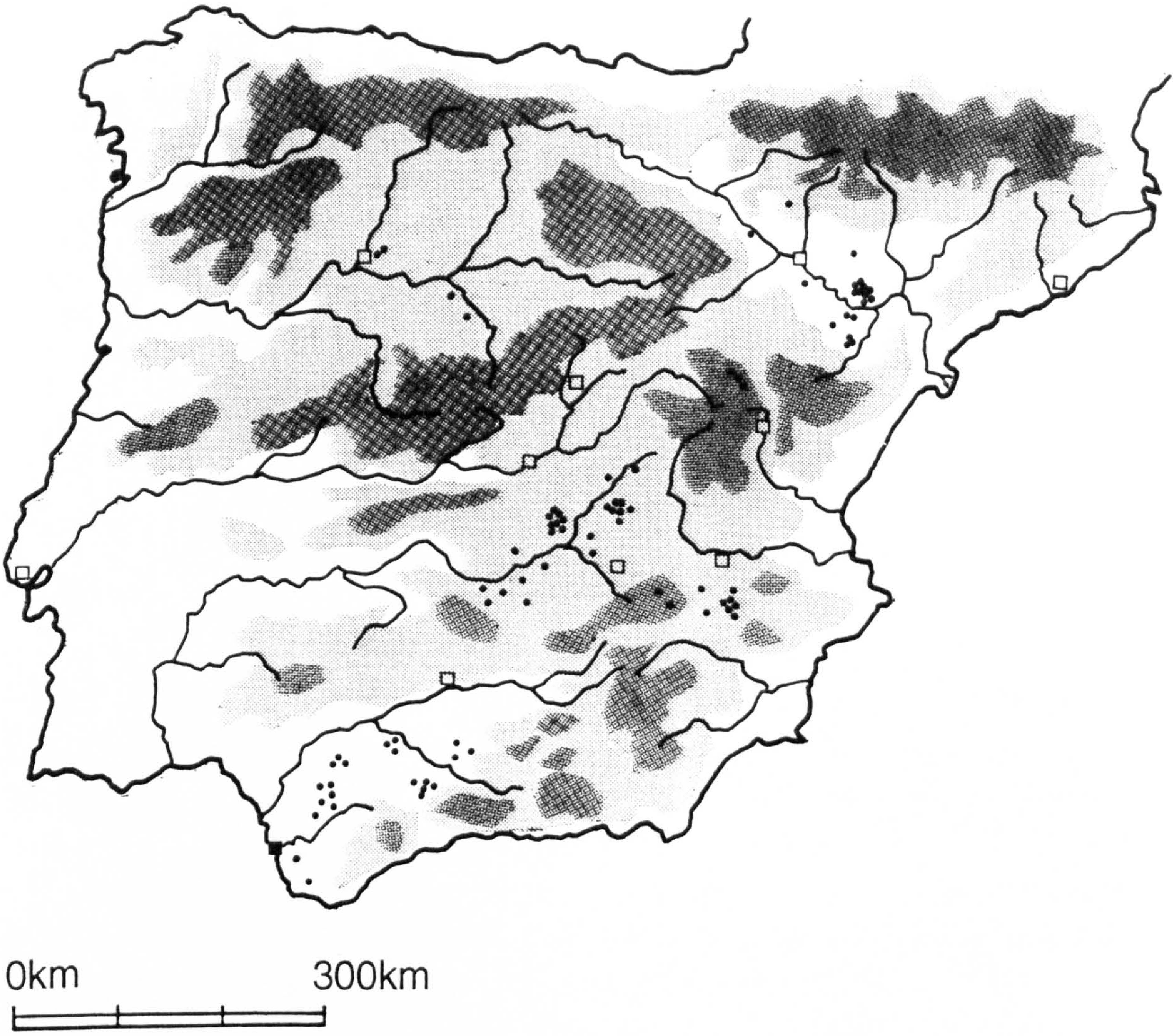


Figure 1.3 **Map of the main endoreic lakes in Iberia**

1.3 Palaeoenvironmental reconstruction from Spanish endoreic lakes

Endoreic lakes (lakes without a surface outflow) have been widely investigated as potential palaeoclimate (lake level) indicators in most of the major continents of the world where they are found (Street & Grove, 1979; Street-Perrott & Harrison, 1985). Endoreic lakes in Spain occupy a highly sensitive semi-arid climate, positioned between Mediterranean, Atlantic and continental climate influences. Their proximity to northwest Europe also allows close comparisons to be made with one of the most intensively studied areas of the world.

Lake level studies in the Western Mediterranean region have been undertaken in Southern Europe (Harrison & Digerfeldt, 1993), Morocco (Lamb *et al.*, 1991; Roberts *et al.*, 1994) and North Africa (*cf.* Fontes *et al*, 1985; Gasse *et al*, 1987; Fontes & Gasse, 1991). Apart from sites in North Africa which contain only a discontinuous record for the late Holocene, all other lakes studied have not been endoreic, although those in Morocco may have been so during periods of low lake level. Work by Harrison & Digerfeldt (1993) in Southern Europe, including Iberia, has been based on the reinterpretation of published stratigraphic and aquatic pollen data from valley mire sediments in open basin systems.

No previous palaeo lake level investigations have been undertaken on Spanish endoreic lakes, although a number of studies have been made of their contemporary ecology, mineralogy, geochemistry and hydrology (*cf.* Montes & Martino, 1987; Comín & Alonso, 1988; Montes, 1988; Comín *et al.*, 1990).

Four main areas of inland endoreic salt lakes can be distinguished in Spain, concentrated within the Duero (northwest), Ebro (northeast) and Guadalquivir (south) river basins, and between the watersheds of the Guadiana, Segura and Jucar rivers (centre). These regions are generally flat and semi-arid, falling within the rainshadow of surrounding high mountains (*Figure 1.4* p20). Rainfall is low (330-500mm per year) (*Figure 1.5* p21) and evaporation high (>1000mm per year) resulting in a large number of shallow, seasonal lakes, with many of the remainder sustained by high inputs of groundwater rather than runoff.

Research in this study was mainly confined to the Ebro Basin (*Figure 1.6* p22) where endoreic lakes are largely composed of seasonal playas due to the high aridity of the area (*Figure 1.5* p21). Such lakes present a number of difficulties in palaeoenvironmental reconstruction and have generally been neglected in palaeoenvironmental studies in favour of deeper, more permanent lakes (*Table 1.2* p23). Periodic desiccation can favour deflation and interruption of the sediment record, while oxidising conditions may present preservation problems for many biotic indicators.

In general, the nature of the preserved record dictated the analysis techniques adopted in the research. A large number of methods have been used to reconstruct the palaeoenvironment of endoreic lakes (*Table 1.2* p23), although not all were available in this study. Diatoms, ostracods and molluscs were found to be poorly preserved except in the most recent sediments. The lack of identifiable autocthogenic carbonate also restricted the application of oxygen isotopes (for palaeothermometery, evaporitic concentration *etc* (Fontes *et al.*, 1985; Gasse *et al.*, 1987; Last & Slezak, 1988; Gasse & Fontes, 1989; Rosen & Warren, 1990; Benson *et al.*, 1991; Fontes & Gasse, 1991; Hickman & Schweger, 1993; Van Campo & Gasse, 1993; Van Stempvoort *et al.*, 1993)) or carbon isotope studies (Gasse *et al.*, 1987; Last & Slezak, 1988; Gasse & Fontes, 1989; Fontes & Gasse,

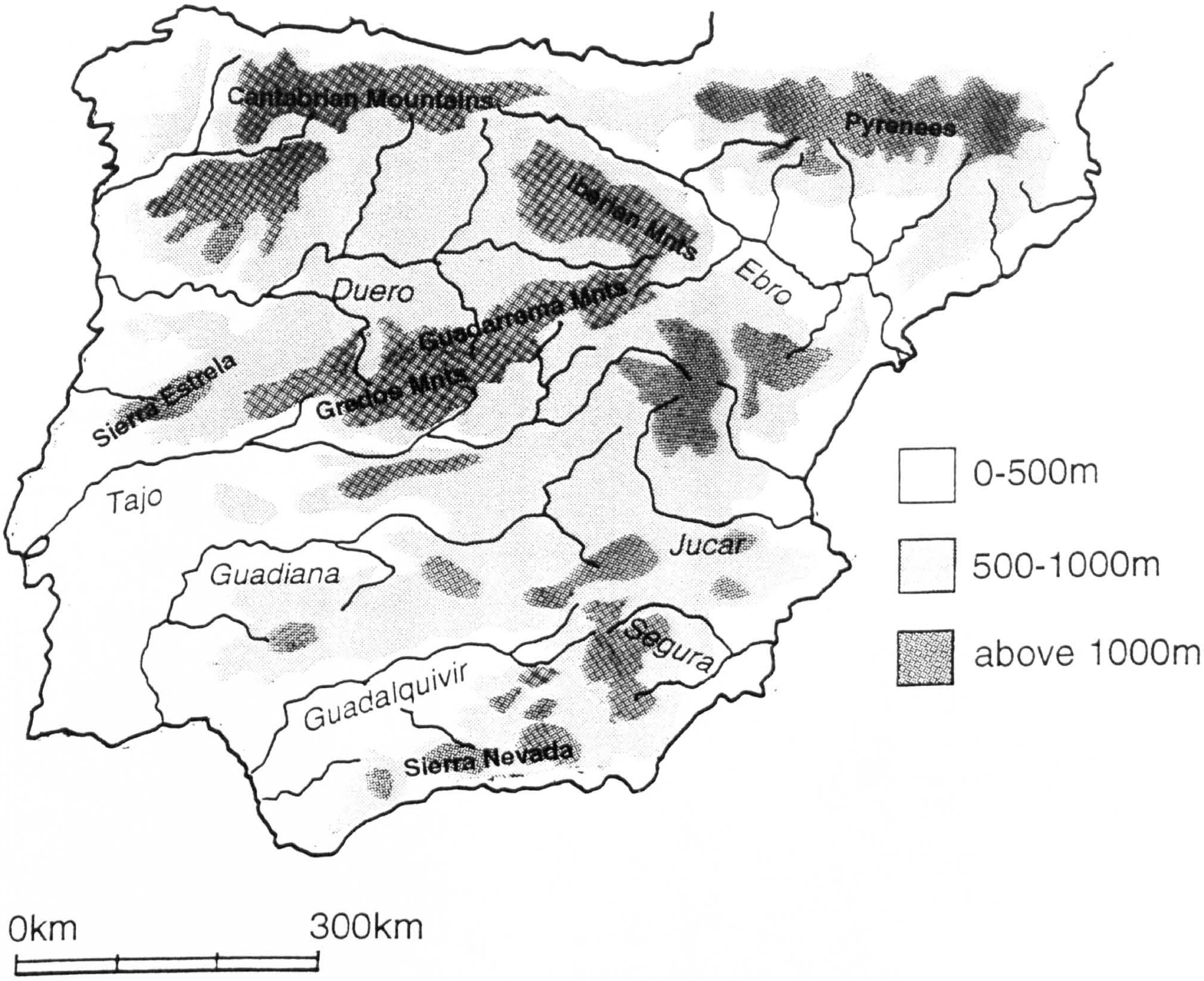
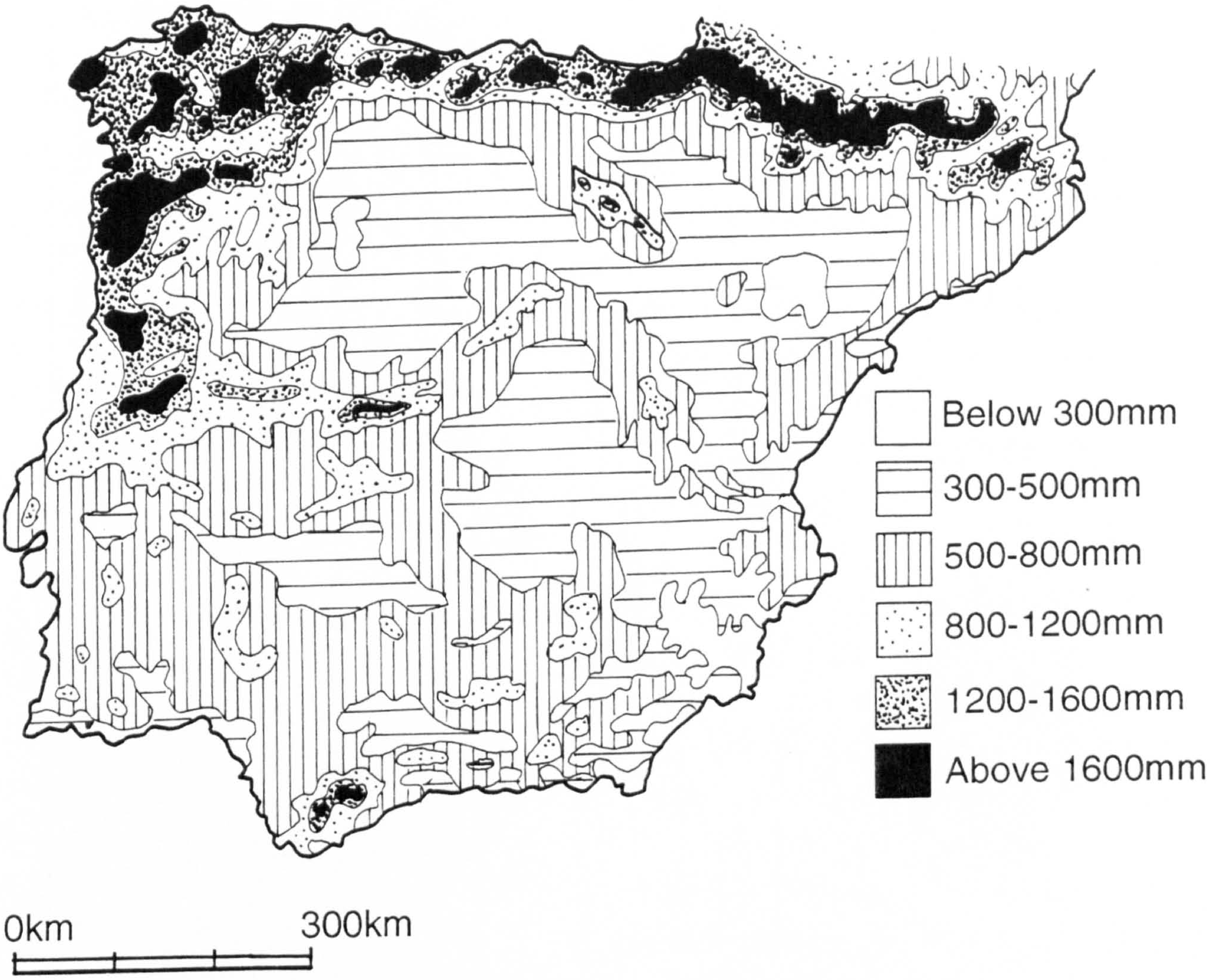


Figure 1.4 **Map of mountain ranges and major rivers in Iberia**



From *Polunin & Smythies* 1973

Figure 1.5 **Map of mean annual precipitation in Iberia**

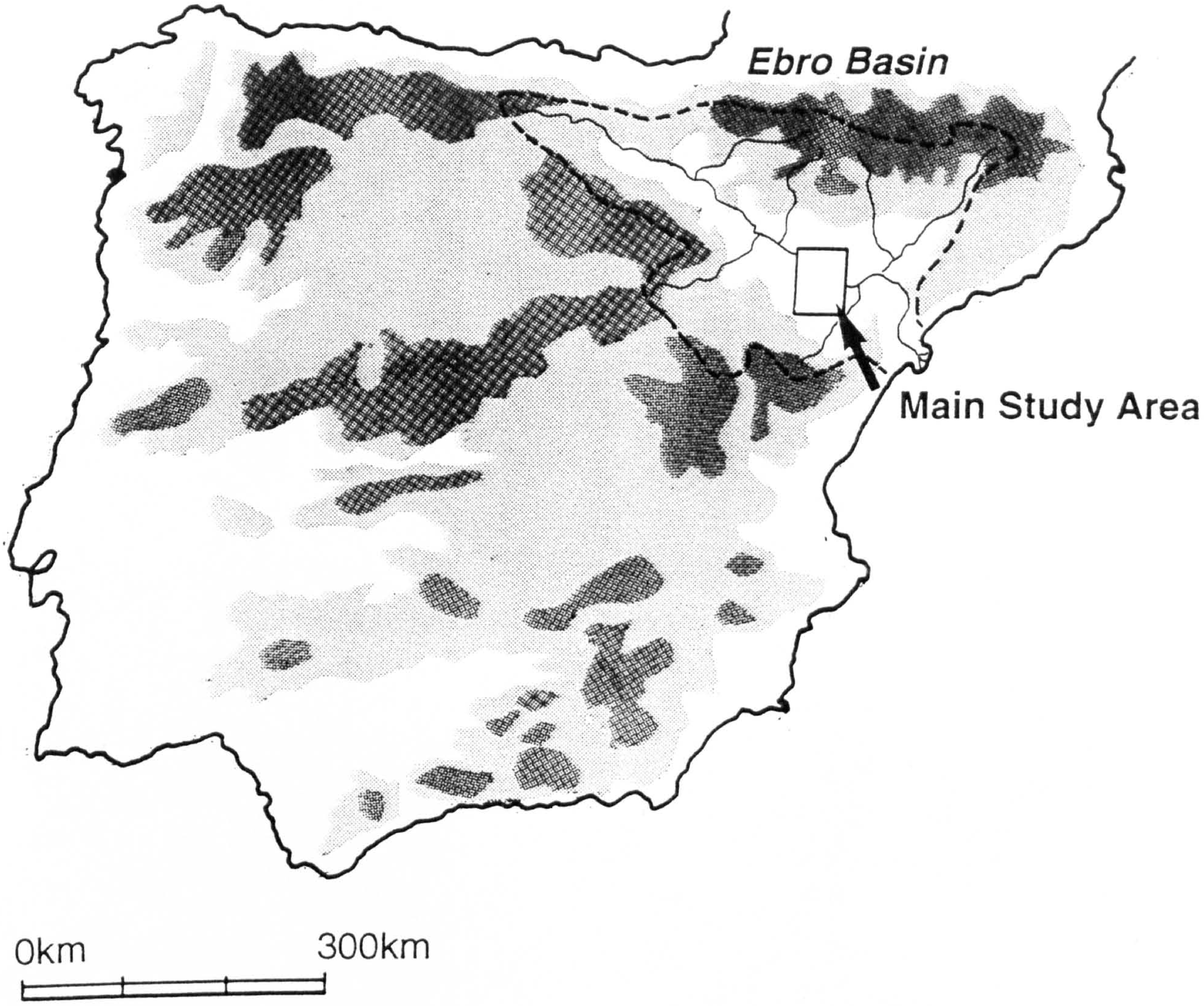


Figure 1.6 **Location map of Iberia showing the Ebro Basin and the main study area**

Palaeolimnological studies on endoreic lakes

					Analysis Technique																														
Author/s	Site	Location	Country	Lake Type (Depth)	Pollen	Diatoms	Plant Macros	Ostracods	Molluscs	Foramin.	Lithology	X-ray Diff.	Organic Content	Oxygen 18O/16O Isotope	Carbon 13C/14C Isotope	Carbonate	Sulphate	Al	Ca	Cd	Cl	Cu	Fe	K	Mg	Mn	Na	P	Pb	Sr	Ti	Zn	Textural Analysis	Magnetic Susceptibility	Others
Benson, Meyers & Spencer (1991)	Walker Lake	California/Nevada	USA	Permanent Saline (34.0m)	▨	▨					▨			▨																			▨		Magnesium Carbonate in Magnesian Calcite
Platt Bradbury, Forester & Thompson (1988)	Walker Lake	California/Nevada	USA	Permanent Saline (34.0m)	▨	▨		▨																											Artemia Pellets
Digerfeldt, Almendinger & Bjorck (1992)	Parkers Prairie	Minnesota	USA	Permanent Mineralised (1.0-5.9m)	▨		▨				▨		▨			▨																	▨	▨	
Stine (1990)	Mono Lake	E California	USA	(Section)							▨																								
Radle, Keister & Battarbee (1989)	Medicine Lake	S Dakota	USA	Permanent Saline (9m)	▨	▨					▨					▨	▨		▨						▨										
Winkler, Swain & Kutzbach (1986)	Lake Mendota	Wisconsin	USA	Permanent Mineralised (24.0m)	▨						▨																								
Barnosky (1989)	Guardipee Lake & Lost Lake	NW Montana	USA	Permanent Saline (2.2 & 7.2m)	▨		▨				▨																								Chenopod Artemisia Gramineae ratio
Fritz, Juggins, Battarbee & Engstrom (1991)	Devils Lake	N Dakota	USA	Permanent Mineralised		▨																													Interpretation based on surface sample transfer function
Rosen & Warren (1990)	Bristol Dry Lake	California	USA	Playa							▨			▨																					Deuterium
Van Campo & Gasse (1993)	Sumxi Co Basin	W Tibet	Tibet	Permanent Mineralised (8.0m)	▨	▨		▨			▨			▨																					Artemisia Chenopod Ratio
Metcalfe, Street-Perrott, Perrott, Harkness (1991)	Upper Lerma Basin	Estado de Mexico	Mexico	Drained Basin		▨					▨		▨					▨	▨				▨	▨	▨	▨	▨	▨			▨			▨	
O'Hara, Street-Perrott & Burt (1993)	Lake Patzcuaro	Michaocan	Mexico	Permanent Saline (4.6m)							▨		▨			▨												▨						▨	
Wasson, Smith & Agrawal (1984)	Didwana Lake	Thar Desert	India	Playa							▨	▨																							
Last & Slezak (1988)	Waldsea Lake	Saskatchewan	Canada	Permanent Saline (8.1m)	▨						▨	▨			▨																				
Hickman, Schweger & Habgood (1983)	Lake Wabamun	Alberta	Canada	Permanent Mineralised (10.0m)	▨	▨					▨		▨			▨							▨	▨	▨	▨	▨	▨	▨	▨					Water Content, Pigments
Van Stempvoort, Edwards, Evans & Last (1993)	Redberry Lake	S Saskatchewan	Canada	Permanent saline (17.0m)								▨	▨	▨	▨																				Pigment Abundance (Chlorophyll a & Phaeophytin)
Last & Teller (1983)	Lake Manitoba	Manitoba	Canada	Permanent Saline (3.6m)								▨																					▨		Magnesium Carbonate in Magnesian Calcite
Last (1982)	Lake Manitoba	Manitoba	Canada	Permanent Saline (3.6m)								▨	▨																						
Last & Slezak (1988)	Lake Manitoba	Manitoba	Canada	Permanent Saline (3.6m)										▨	▨																				
Hickman & Schweger (1993)	Goldeye & Moore Lakes	Alberta	Canada	Permanent Saline & Fresh (14.0 & 26.0m)	▨	▨					▨			▨	▨																				
Last & Slezak (1988)	Deadmoose Lake	Saskatchewan	Canada	Permanent Saline (9.7m)	▨						▨	▨		▨	▨																				
Vance, Mathewes & Clague (1992)	Chappice Lake	SE Alberta	Canada	Permanent Saline (0.9m)	▨		▨				▨	▨																							
Vance, Clague & Mathewes (1993)	Chappice Lake	SE Alberta	Canada	Permanent Saline (0.9m)	▨		▨				▨	▨	▨			▨		▨	▨					▨	▨		▨			▨			▨		
Last (1989)	Ceylon Lake	S Saskatchewan	Canada	Small Playa							▨	▨	▨				▨																		Na Sulphates, Mg & MgNa Sulphates, Salt solubility
Last (1990)	Ceylon Lake	S Saskatchewan	Canada	Small Playa								▨				▨	▨		▨	▨	▨				▨		▨								
Last & Slezak (1988)	Ceylon Lake	S Saskatchewan	Canada	Small Playa							▨	▨	▨																						
Vance, Emerson & Habgood (1983)	Central Alberta	Alberta	Canada	Permanent Saline (2.6-8.0m)	▨						▨																								Charcoal
Last & DeDeckker (1990)	West Basin Lake	S Victoria	Australia	Volcanic Maar Lake (5.8m)							▨	▨				▨																			
Magee (1991)	Prungle Lakes	New South Wales	Australia	Small Playa							▨	▨					▨																▨		
Bowler & Teller (1986)	Lake Tyrrell	NW Victoria	Australia	Large Playa							▨	▨	▨				▨																▨		
Bowler (1981)	Lake Keilambete	S Victoria	Australia	Volcanic Maar Lake (11.0m)	▨						▨	▨				▨																	▨		
Teller & Last (1989)	Lake Beeac	S Victoria	Australia	Small Playa							▨	▨																							
Xiang Yang Chen, Bowler & Magee (1991)	Lake Amadeus	E Western Australia	Australia	Large Playa							▨						▨																		Moisture content, Unit Density
Last & DeDeckker (1990)	East Basin Lake	S Victoria	Australia	Volcanic Maar Lake (4.5m)							▨	▨				▨																			
Watson (1988)	S Tunisia & Namib Desert	Tunisia & Namibia	Africa	Playa							▨					▨	▨								▨		▨			▨			▨		
Watson (1988)	S Tunisia & Namib Desert	Tunisia & Namibia	Africa	Playa							▨																						▨		
Ritchie, Eyles & Haynes (1985)	Oyo depression	Sudan	Africa	(Section)	▨						▨																								
Fontes et al (1985)	NNW Sahara	NNW Sahara	Africa	(Sections)		▨	▨	▨	▨	▨	▨			▨																					Charophytes
Gasse et al (1987)	N Sahara	N Sahara	Africa	(Sections)		▨	▨	▨	▨	▨	▨			▨	▨																				Charophytes, Sr Ca Ratio, Mg Ca Ratio
Fontes & Gasse (1991)	N Africa	N Africa	Africa	(Sections)		▨	▨	▨	▨		▨			▨	▨																				Charophytes
Gasse & Fontes (1989)	Lake Asal	Djibouti	Africa	Permanent Saline (7.4m)				▨	▨		▨			▨	▨																				Cyanobacteriae
Petit-Maire & Riser (1981)	Central Sahara	Central Sahara	Africa	(Section)			▨	▨	▨		▨			▨																					Fish, Charophytes
Davis (1994)	Ebro Basin	NE Spain	Spain	Playa & Permanent (1.0-5.0m)	▨		▨		▨		▨		▨			▨	▨		▨	▨		▨	▨	▨	▨	▨	▨		▨			▨	▨		Charcoal, Charophytes, Chironomids, Cladocera

Table 1.2

Table 1.2 **List of selected palaeolimnological studies on endoreic lakes**

1991; Van Stempvoort *et al.*, 1993), while X-ray diffraction (for mineral composition (*cf.* Van Stempvoort *et al.*, 1993; Vance *et al.*, 1993) suffered from the lack of available equipment and money. Alternatively, Cladocera (ephippia) and Chironomids (head capsules) were analysed which had previously been largely neglected in such studies.

Perhaps the most important development that differentiates this study from similar ones undertaken throughout the world is in the use of surface samples to establish a firm interpretive basis to the palaeoenvironmental record. The use of surface samples from both within and between different lake environments has allowed the semi-quantification of lake level from previously qualitative indicators. This has been possible through the integration of a number of different qualitative indicators (such as pollen, macrofossils, geochemistry and textural analysis) and their correlation with a large number of different lake environments. Although the resolution (depth/salinity) of the record is lower than for other similar quantification techniques using diatoms (*cf.* Fritz & Battarbee, 1986; Fritz *et al*, 1991) and ostracods (*cf.* De Deckker, 1988; De Deckker & Forester, 1988), it is nevertheless possible to apply the technique to previously unsuitable environments. In particular, it can be used in playa lake environments that compose the widest distribution and largest number of endoreic lakes in the world.

Other lake systems in the Ebro Basin also include one natural permanent lake (the Laguna Salada), and one semi-permanent lake (the Laguna Gallocanta), as well as a number of freshwater, artificially flooded reservoirs/hunting reserves. The diversity of lake systems provides both a useful collection of contemporary modern analogues for interpreting the palaeoenvironmental record, as well as a number of recent historical analogues within the sediment record where documented historical changes in lake level *etc* can be examined.

1.4 Study aims and thesis outline

This study has two principle aims:

1) ***To investigate the utility of endoreic lakes and their sediments in the Ebro Basin (and by default, other similar lakes within Spain and further afield) for palaeolimnological and palaeoenvironmental reconstruction.***

2) ***To then provide a palaeoenvironmental reconstruction for the Ebro Basin over whatever timescale the sediments permit (the Holocene?). This would then be compared with the broader picture of environmental change within the Western Mediterranean, including archaeological and fluvial-geomorphological evidence.***

Study Aim 1:

Chapters 2 & 3 consist mainly of a literature review of the potential use of commonly found biotic remains in Spanish salt lakes (and comparable lakes throughout the world) for palaeolimnology. **Chapter**

deals with the seeds and pollen of saline tolerant aquatic (and some terrestrial) plants. **Chapter 3** looks at the potential and problems of Chironomid head capsules and Cladocera ephippia.

Chapter 4 sets the scene for the study by reviewing the main physical characteristics of the study area and lake systems.

Chapter 5 defines the techniques used in analysing the sediments extracted from the lakes studied.

Chapters 6, 7 & 8 develop the methodology in interpreting the palaeorecord through the use of surface samples to establish modern analogues and test theoretical concepts. **Chapter 6** looks at variation between lake centre and shore. **Chapter 7** looks at variation between different lakes and develops a model to interpret the palaeohydrological record. **Chapter 8** looks at the regional vegetation and climate and how it is reflected in the pollen record.

Study Aim 2:

Chapter 9 sets the scene for each site and looks at the record provided by each sediment core.

Chapter 10 combines all the evidence from the sediment cores to provide a general reconstruction of the Holocene environment of the Ebro Basin. This is then compared with other studies throughout the Western Mediterranean and beyond.

Chapter 11 concludes with a discussion of the nature of the palaeoclimate and history of vegetation development and anthropogenic disturbance. This is also compared with the record of erosion in the area.

Chapter 2

Saline lake macrophytes and palaeolimnology: with special reference to Spanish salt lakes

2.1 Abstract

The fossil remains of saline lake macrophytes can provide a rich source of palaeolimnological information, particularly in ephemeral lakes where the preservation of other more commonly used indicators such as ostracods and diatoms are more problematic. Information on plant-environment relations of the main submerged, emergent and terrestrial taxa is reviewed and their application in palaeolimnology discussed. Problems of identification, preservation and interpretation are explored.

2.2 General Concepts

2.2.1 *Introduction*

Increasing attention is currently being directed at deriving climate histories from proxy sources in response to growing concern over climate change. Lake level studies within endoreic basins have long been shown to provide a means of climate reconstruction reflecting changes in rainfall and/or evapotranspiration (Street-Perrott & Harrison, 1985). The fossil remains of lake macrophytes preserved within lake sediments reflect the lake environment at the time of their deposition. This information can be used to reconstruct the palaeolimnology of a lake, including past changes in lake level.

The use of fossil aquatic macrophyte remains as environmental indicators has been widely applied in palaeolimnology (Birks, 1973; Watts, 1978; Kershaw, 1979; Digerfeldt, 1986; Collinson, 1988), although their application to salt lake research has been much more restricted. The greater resolution afforded by ostracods and diatoms has meant other palaeoecological indicators have often been neglected. Many problems exist in the use of macrophyte remains, not least in the balance between well preserved seeds and pollen formed by sexual reproduction, and poorly preserved vegetative buds and turions formed during asexual reproduction. However, it is an adaptive response for many salt lake macrophytes to invest heavily in sexual reproduction, leaving abundant resistant fossil remains, particularly in ephemeral lake environments where ostracod and diatom remains are often poorly preserved (Fritz & Battarbee, 1986; Fritz *et al.*, 1991; Reed & Juggins, pers.comm.).

The seed and pollen remains of salt lake macrophytes can be deposited in considerable quantities within lake sediments, providing a rich source of additional palaeoenvironmental information for multi-proxy studies, as well as often providing the only palaeoecological record in ephemeral lake environments. Information from macrophyte remains in closed basin salt lakes can be used to interpret lake depth, lake permanence and lake water salinity, as well as water temperature and turbidity (*Figure 2.1* p28 & *Table 2.1* p29). These environmental inferences can in turn be compared with those obtained from other palaeolimnological indicators such as geochemistry, mineralogy and stratigraphy to form a multi-proxy based interpretation (*eg*. Digerfeldt *et al*., 1992).

2.2.2 *Palaeolimnological information*

2.2.2.1 *Salinity*

The close relationship between aquatic plant communities and lake salinities has been shown by many authors (cf. Birks, 1973; Stewart & Kantrud, 1971; Miller, 1976) (*Figure 2.1* p28). Three main categories of salinity tolerance can be distinguished: i) those taxa that only live in freshwaters (0-3‰ TDS) ii) those that prefer freshwaters but can tolerate low salinities (*ca*.3-20‰ TDS) iii) those that thrive in highly saline environments (*c*.>20‰TDS) (Williams *et al*., 1990). Species diversity declines through each category, with the final category, the true 'halophilics' representing only a few species with a very broad tolerance range. The breadth of this range means that only very general statements can usually be made about lake water salinities from interpretation of the macrophyte palaeoenvironmental record.

Lake salinity can fluctuate considerably both between different seasons and between different years. Changes on a year to year basis are usually of a sufficiently long timescale to allow succession in line with the optimum salinity of particular plant species. Salinity changes on a shorter timescale, that is, less than the length of the life-cycle of any particular competing species, does not allow time for succession and must be within the physiological tolerance of the plants living within the lake for them to remain viable. Hypersaline lakes are particularly prone to large changes in salinity hence plants adapted for these conditions are able to tolerate wide salinity variations. Where plants are unable to tolerate the particular saline conditions, or indeed when threatened with desiccation, macrophytes may disappear altogether from the lake, but survive by a variety of perennating mechanisms, including seed.

Salinity tolerance varies not only between species, but also between different stages of the life-cycle. Lower salinities are often required for germination and fructification than during peak photosynthetic growth. Species such as the Charophyte, *Lamprothamnium papulosum*, which have been found growing under extreme hypersaline conditions, nevertheless require a short period of much lower salinity for successful germination (Burne *et al*., 1980; Soulie-Marche, 1991). Many species require a change in salinity (usually dilution) before seed dormancy can be broken (Brock, 1982).

2.2.2.2 *Water Depth/Permanence*

Water salinity, depth and permanence are often so closely linked in salt lake environments that they are difficult to distinguish. Permanent, deep, saline lakes often have much lower water salinities than shallow, seasonal lakes. A change in water depth of only 1m in a shallow ephemeral lake is likely to cause a much

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Environmental variables of some Spanish salt lake macrophytes

	Germination to Seed	Germination to flowering	Minimum Depth	Maximum Depth	Normal Depth Range	Germination Temperature	Reproduction Temperature	Maximum Temperature	Turbidity Tolerance	Turbulence Tolerance
Ruppia	3 months	2 months	0.1m	7.0m	0.1-1.5m	10-15°C	15-19°C	30°C	Low	Low
Althenia	5 months	.	.	.	.	.	.	.	High	.
Potamogeton pectinatus	5 months	.	0.4m	4.0m	0.4-2.0m	10-15°C	15-20°C	.	High	Low
Chara sp.	3 months	.	0.1m	6.0m+	0.1-2.0/6.0m+	.	.	.	Low	Low/High
Lamprothamnium papulosum	3 months	.	0.1m	3.0m	0.1-2.0m	.	.	.	Low	.
Typha sp.	.	.	0.0m	2.0m	0.5-2.0m	.	.	.	High	Low
Scirpus maritimus	.	.	0.0m	0.4m	0.2m	.	.	.	.	.

Table 2.3

Table 2.3 **Selected environmental limits of some saline lake macrophytes** greater change in salinity than the equivalent displacement in a much deeper lake. Nor is the relationship between depth and salinity for any one lake necessarily constant through time. Losses of salts through precipitation, deflation and flushing can change the net availability of salts to the lake system as water levels fluctuate (Wood & Ward, 1990). This is particularly so for shallow, ephemeral lakes, since desiccation and exposure to deflation can cause a particularly rapid loss of salts (Comín *et al.*, 1990).

Basin morphometry is also an important factor since this dictates the relationship between water volume and potential shallow water habitat. For example, a doubling in water volume will cause an approximate halving of water salinity whether a basin is large and shallow or small but deep. The horizontal expansion of water for the same doubling of volume however, is likely to differ considerably between the two basins. The area of a lake less than 2m deep is particularly important since this provides the main habitat for macrophyte growth. Below this depth light becomes restricting and stratification (chemical or thermal) can cause anoxia or sulphide build-up.

The production of seeds and pollen is critical since it is these that allow us to interpret the palaeoenvironment. An absence of such remains does not necessarily imply an absence of aquatic macrophytes since they may well have existed in the lake but reproduced vegetatively or existed at the lake margins, far away from the central sampling point. Alternatively, lake waters may be so ephemeral as to allow insufficient time for aquatic plant growth. In the latter case, aquatic macrophytes are likely to be replaced by terrestrial species invading the lake basin during prolonged periods of desiccation.

The minimum length of life-cycle for any particular macrophyte found within the lake sediments provides a minimum time period for lake flooding (*Table 2.1* p29). This flooding period, however, is likely to be longer than the life-cycle since other requirements may need to be met, such as a minimum water depth and salinity. These requirements dictate the 'environmental window' within which plant growth and reproduction will be successful. It is the maximum and minimum parameters for this window which form the basis for reconstructing the palaeoenvironment.

2.2.2.3 *Temperature, Turbidity and Turbulence*

Lake water temperature provides both an upper and lower limit for germination, growth and reproduction. Salt lakes are often characteristically shallow with large diurnal and seasonal variations in water temperature. Intense insolation in summer can raise water temperatures to over 40°C at low latitudes, while in winter at higher latitudes, lakes can become supercooled to temperatures well below freezing (Hammer, 1986). In deeper lakes at low latitudes, thermal stratification can develop for much longer periods than is common in lakes at mid-latitudes (Finlay *et al.*, 1991; Prat *et al.*, 1992). Intense insolation in early spring starts to heat the upper layers, preventing mixing until late autumn except by physical turbulence. With inherently low dissolved oxygen concentrations and high sulphide levels, stratification in saline lakes can quickly lead to anoxia and toxic sulphide levels below the thermocline or chemocline, forming an effective lower limit to submerged macrophyte development (Heseltine, 1976).

Shallower salt lakes tend to be less stratified due to physical turbulence as a result of wind and wave action. Exposure to physical turbulence can, however, have a damaging effect on macrophyte growth, although some species are better adapted than others for this type of high energy environment. Windward shores of large, open lakes with plenty of fetch are particularly vulnerable to wave action, enhanced further by the high mean wind speeds often encountered on the treeless steppes associated with many salt lake landscapes.

Physical turbulence can also lead to increased turbidity as a result of continued resuspension of inorganic particulate matter within the water column. Inorganic minerals, together with organic nutrients and a well oxygenated environment can provide favourable conditions for algal growth and hence further turbidity. Submerged macrophyte growth is particularly vulnerable to high turbidity, although again, some species such as *Potamogeton pectinatus* show better adaptation than others (Blindow, 1992a) (*Table 2.1* p29).

2.2.2.4 *Colonisation and Dispersal*

Obligate aquatic plants are generally perennials, with a tendency towards asexual, vegetative reproduction. This factor reduces the usefulness of such plants in palaeolimnology, since it is the more resilient seeds and pollen resulting from sexual reproduction that preserve best within lake sediments. It is a useful characteristic of salt tolerant taxa that as an adaptive response to the environmentally marginal conditions, greater emphasis is placed on sexual reproduction and the use of resistant and abundant seeds for perennation.

The occurrence of pollen and seeds at the coring site will be determined by the proximity of vegetation and the production and dispersal of the resistant reproductive parts. Taphonomic problems can occur through differences in production and dispersal mechanisms between species and between different lake environments. Pollen is generally the most widely dispersed agent, however, differences can occur between above or below water dispersal. In the case of the former, pollen may enter the pollen rain falling on adjacent lakes to contaminate a dissimilar environment and flora (Davis, 1994). Similar problems may arise with seed dispersal, particularly with emergent macrophytes which tend to favour wind dispersal. Many salt lakes are shallow with a low relief, causing only weak sediment focusing. Exposure to wind and wave action can result in accumulation along windward shores rather than at depth. Focusing may also be seasonal in ephemeral lakes, with strongest focusing during the summer desiccation when storm run-off can wash surficial material into the lowest areas of the basin.

Dispersal and perennation are important colonisation mechanisms. Interpretation of the palaeolimnological record requires the assumption that the lake biota and the lake environment are in equilibrium. A change in lake salinity from fresh to saline conditions would therefore be reflected in a change from fresh to salt tolerant species, assuming the change to be over a sufficiently long time period for the new generation to replace the old. Rapid changes in lake environment may fail to be recorded if succession and colonisation from the seed bank, seed rain or vegetative parts cannot occur fast enough.

2.3 Submerged macrophytes

2.3.1 *Ruppia*

2.3.1.1 *Introduction*

Ruppia has a broadly cosmopolitan distribution, occurring in salt lakes throughout the world (Hammer, 1986), although its taxonomy at species level is poorly understood (den Hartog, 1981). In Europe, two main species have been identified from permanent coastal habitats, *R.cirrhosa* and *R.maritima* (den Hartog, 1971). *R.maritima* is thought to have a world-wide distribution, also occurring in North America, along with *R.occidentalis* (Mason, 1967), as well as in Australia and parts of Asia. Further species include *R.truncatifolia* in Japan and *R.tuberosa*, *R.megacarpa* and *R.polycarpa* in Australia, with the latter two also occurring in New Zealand.

Three different species of *Ruppia* occur in the Iberian Peninsular, *R.maritima* var *maritima*, *R.drepanensis* and *R.cirrhosa*. *R.maritima* var *brevirostris* has been recorded in the Balearic islands, but not on the mainland (Cirujano *et al*, 1990). The species *R.drepanensis* does not occur elsewhere in Western Europe and is unique to Iberia and parts of North Africa. Only *R.drepanensis* and *R.maritima* var. *maritima* occur in inland salt lakes, with *R.cirrhosa* confined to the coasts (Cirujano *et al*, 1990, Fernández Casas, 1990).

2.3.1.2 *Identification from fossil remains*

Seeds

The seeds of *Ruppia* are highly adapted to survive desiccation, being both resistant to decay and prolific in number. Preservation within the sedimentary record is therefore generally very good. The identification of *Ruppia* seeds within saline lake sediment records has, however, been made by relatively few authors (*eg*. Vance *et al*., 1992), and no previously known attempt has been made to differentiate seed remains to species level.

In America, seed morphology was employed (together with penducle and podogyn length) as a taxonomic indicator by Fernald & Wiegand (1914) to subdivide *R.maritima* s.l. into 10 separate varieties. Similarly, in Australia, Brock (1982) lists two contrasting seed forms in differentiating the 'annual' *R.tuberosa* & *R.polycarpa* from the 'perennial' *R.megacarpa*. Information on seed morphology for many of the main *Ruppia* species has been reviewed by Brock (1980), and appears to show sufficient variety to provide a good guide to species identification.

Other references to seed morphology as a taxonomic indicator in the Ruppiaceae (*eg*. Valentine, 1980) have concentrated on the exocarp morphology which is rarely preserved within the fossil record and shows much less morphological variation than the endocarp. In addition, in common with all studies in the Ruppiaceae, the substantial disagreement in the nomenclature and taxonomic subdivision of the genus (Verhoeven, 1979) can provide confusing comparisons, particularly since many *Ruppia* taxa have simply been recorded as *Ruppia maritima* L.

Analysis of macrofossil remains in sediments from the Ebro basin revealed two distinct *Ruppia* seed morphologies. These forms are the same as those identified by Cirujano (1986, 1990) as taxonomic indicators for both *R.maritima* L. var *maritima* and *R.drepanensis* Tineo in La Mancha, Spain. Fossil material was identified in line with this division (*Figure 2.2* p34) with asymmetric, 'comma' types with a pronounced 'beak' being assigned to *R.drepanensis*, and only slightly asymmetric 'tear drop' types being assigned to *R.maritima* var *maritima*. Type material consulted at the Natural History Museum, London, appeared to confirm this categorisation, although only their European material has so far been re-catalogued in line with modern views on the genus. Immature seeds appeared to retain the characteristics of more mature examples, while morphotypic variation reflected the clear division apparent in the fossil material, with only limited variation within populations from the same species. The seed morphology of the three Australian species identified by Brock (1982) is comparable with that of *R.maritima* var *maritima* but not *R.drepanensis*. Morphological variation of the endocarp between the Australian species is much less than that between the two Spanish species. This would suggest that environmental, rather than genetic, factors are not significant in dictating seed shape since the 'perennial' *R.megacarpa* occupies similar environments to *R.maritima* var. *maritima*, and the 'annual' *R.drepanensis* occupies similar environments to *R.polycarpa* and *R.tuberosa*.

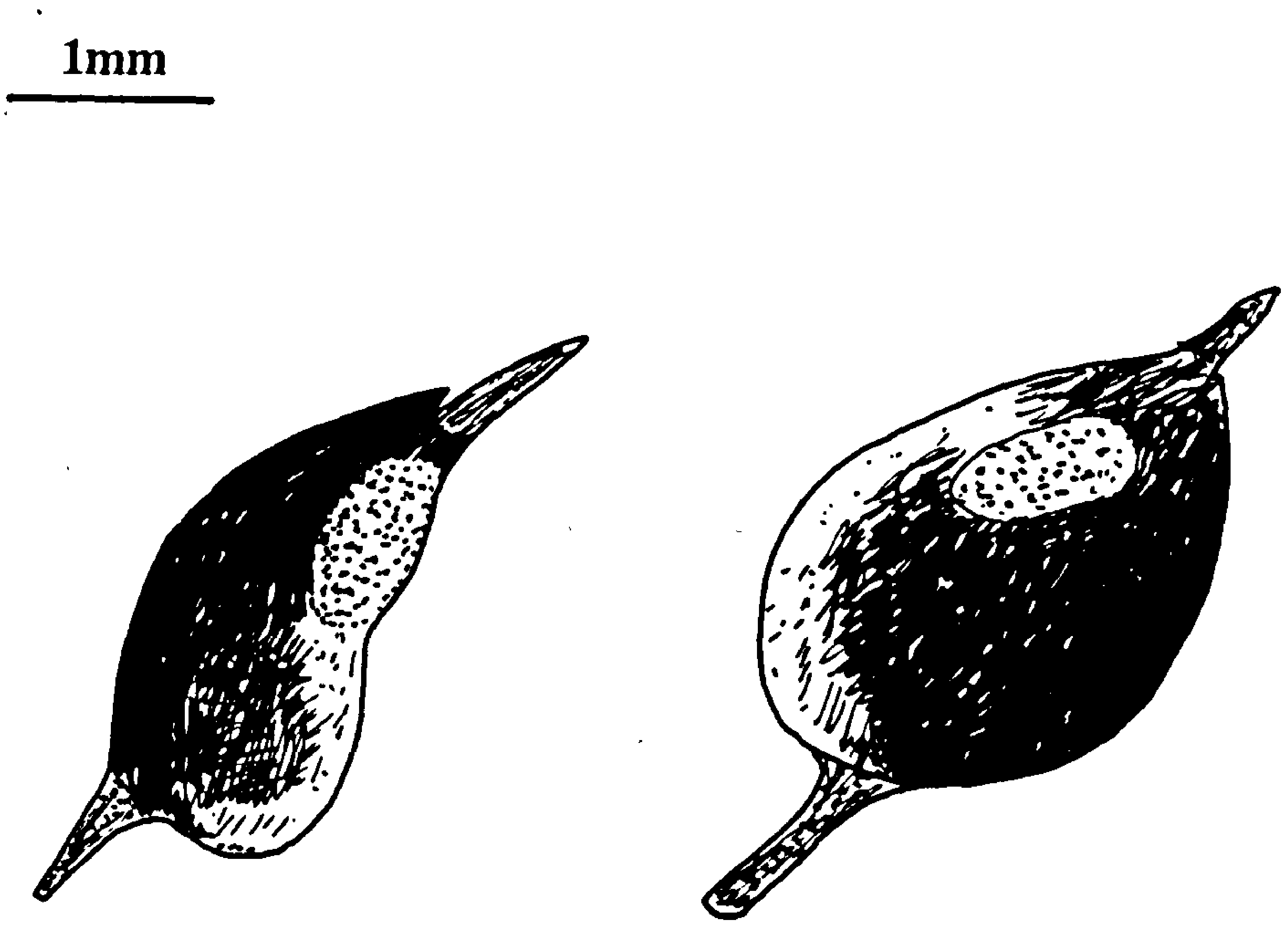
Pollen

The pollen of *Ruppia* has been identified far more frequently than *Ruppia* seeds in palaeolimnological studies (*eg*. Dodson, 1974; Hickman *et al.*, 1983; Barnosky ,1989; Radle *et al.*, 1989; Platt Bradbury *et al.*, 1989; Vance *et al.*, 1992) reflecting the greater use of palynology as an analytical tool.

Ruppia pollen has a particularly distinctive large boomerang shape, together with a delicate reticulate surface patterning. It is easily identified under the microscope, although its fine structure means that it is readily broken and distorted and poorly preserved under certain conditions, including acetolysis (Diez *et al.*, 1988). Schwanitz (1967) undertook an extensive study of *R.maritima* and *R.cirrhosa* in Europe but could find no morphological difference between their pollen grains apart from size. Slight differences in pollen morphology between 3 Australian species have been identified by Brock (1982), although Cirujano (1986), Valdes *et al.* (1987) and Cirujano *et al.* (1990) do not note any differences in the pollen of species occurring in Iberia. Independent of species, differences in pollen size have been noted by Valdes *et al.* (1987), and Brock (1982) notes significant differences in pollen grain length between habitats. Unfortunately, insufficient information is available on the likely environmental significance of pollen size and pollen identification is best confined to genus level.

2.3.1.3 *Palaeoecological information*

Ruppia occurs widely throughout the world in fresh to hypersaline wetland habitats, and is often the only submerged angiosperm present in lakes of high salinity (Brock, 1982b). Its occurrence in freshwaters is only likely to be limited by competition from freshwater taxa (Brock & Lane, 1983). Its wide tolerance of



Ruppia drepanensis Tineo
Annual
Found in temporary saline waters

Ruppia maritima L. var *maritima*
Perennial
Found in permanent saline waters

Figure 2.2 **Illustration of the different endocarp seed morphologies of *Ruppia maritima* L. var *maritima* and *Ruppia drepanensis* Tineo (from Cirujano, 1986)** extreme fluctuations in salinity and prolonged periods of desiccation have made it a particularly good coloniser of ephemeral habitats. Only 3-4 months of flooding to shallow depths are sufficient for it to complete its life-cycle (Brock & Lane, 1983).

Salinity

Ruppia occurs in waters of widely ranging salinity from fresh to hypersaline. Brock (1982) reports the occasional occurrence of *R.tuberosa* in waters upto 230%oTDS in Australia, although at these extreme salinities there appeared to be little active plant growth. In most cases under these conditions, any growth is vegetative and fructification inhibited, although the effect of high salinity is usually complicated by high water temperatures and limited water depth. Brock (1982) found only *R.tuberosa* flowering in water above 50%oTDS, although Cirujano (1986) reports that development and fructification in Laguna de Pétrola is not difficult for *R.drepanensis* in water greater than 82000µS/cm (*ca.*58%oTDS). *R.drepanensis* has not been observed in extremely hypersaline (>140%oTDS) lakes in Spain (Montes & Martino, 1987).

Apart from artificial salt pans, *R.maritima* occurs in only permanent salt lakes in Spain; Laguna Salada (Ebro basin, northeast Spain) and Laguna Mata (southeast Spain) (Comín & Alonso, 1988). These permanent salt lakes (*ca.*67-120%oTDS) have a much more restricted seasonal salinity range than temporary salt lakes (*ca.*7-300%oTDS). Hammer (1986) has reviewed the evidence for the salinity tolerances of these species world-wide and reports a range of 0-66%oTDS for *R.drepanensis* and 0-72%oTDS for *Ruppia maritima*. It is perhaps interesting to note that in Australia, *R.maritima* is not a saline lake species and is confined exclusively to freshwaters (Brock & Lane, 1983). Martino (1988) notes the occurrence of *R.maritima* in permanent and semi-permanent waters in Spain in the range 68-84%oTDS, and *R.drepanensis* in temporary waters from 10-112%oTDS. The mean salinities for lakes in Iberia in which *R.drepanensis* grows is given by Cirujano *et al* (1990) as 31%oTDS, with a mean of around 20%oTDS for *R.maritima* (although this includes artificial salt pans and coastal lagoons).

The absolute concentration of ions is often the most important factor influencing submerged plant growth in saline waters (Sculthorpe, 1967 p42), however the ionic composition may be significant. In Spain *R.cirrhosa* is confined exclusively to coastal sodium-chloride waters, while *R.drepanensis* occurs only in inland waters, away from the influence of the sea, in waters dominated by magnesium-sulphate, sodium-chloride and those of mixed composition (Cirujano *et al.*, 1990). *R.maritima* lives in both coastal and inland locations, although it tends to prefer inland environments rich in sodium-chloride.

Water Depth/Permanence

The seasonal and intra-seasonal fluctuation of water level influences both water depth and salinity. Both these factors influence the environmental 'window' in which *Ruppia* can live and reproduce. The vegetative parts of *Ruppia* are rarely preserved in the fossil record, only the fruits of successful growth and reproduction. The minimum length of time needed by *Ruppia* to produce seeds gives an indication of the minimum time during which environmental conditions were favourable within the fossil record. Reproduction in *Ruppia* can be both sexual and asexual (Brock, 1982), although unlike its Australian counterparts, the production of asexual turions has not been noted in the annual *R.drepanensis* in Spain (Cirujano, 1986). In permanent environments, *R.maritima* var. *maritima* will over-winter as vegetative stems as well as by seed (Verhoeven, 1979). Seed production by perennials, although low compared to annual species, is still thought necessary as a survival strategy against possible desiccation. Laboratory trials by Brock (1982) demonstrated that the vegetative parts of the perennial *R.megacarpa* failed to regenerate following drying, although this actively promoted seed germination. Verhoeven (1979) similarly observed that resistance to desiccation by the vegetative parts of *Ruppia* was very low, resulting in death within a matter of days.

The time taken from germination to fructification under optimum conditions is commonly around 3 months for *Ruppia* (*Table 2.2*), although this may be extended for perennial species (Brock & Lane, 1983).

Table 2.2 **Minimum time for seed production in *Ruppia***

R.cirrhosa	3 month life-cycle	(Verhoeven, 1979)
R.drepanensis	3 month life-cycle	(Martino, 1988)
Ruppia spp.	3 month life-cycle	(Hammer, 1986)
Ruppia spp.	3-4 month life-cycle	(Brock & Lane, 1983)

The time taken from germination to flowering by *Ruppia* is around 2 months, though less information is available from the literature (*Table 2.3*).

Table 2.3 **Minimum time for pollen production in *Ruppia***

R.maritima	2-4 months	(Young, 1924)
R.maritima	5 weeks	(Heseltine, 1976)
R.maritima var. *maritima*	2 months	(Verhoeven, 1979)
R.cirrhosa	2½ months	(Verhoeven, 1979)

As with all flowering plants, pollen production will occur more often than fructification, implying that pollen will be produced even if seed production eventually fails.

The relative balance of ephemeral and perennial species is indicative of the existence of favourable environmental conditions in excess of this life-cycle minimum. Reproduction in the perennial species favours stable, permanent habitats where its more robust vegetative growth can out-compete the ephemeral form. *R.maritima* var *maritima* is found almost exclusively in permanent habitats in Spain, while *R.drepanensis* is confined to seasonally wet environments of 4-10 months inundation a year. This preference for vegetative reproduction in permanent waters can cause problems in the fossil record since only sexually reproducing plants

ephemeral lakes, awaiting favourable environmental conditions. The seed bank of permanent salt lakes occupied by perennial species of *Ruppia* is likely to contain lower numbers of seeds since asexual, vegetative growth tends to dominate.

Ruppia seeds do not float well and their pyrimidal shape, together the retention of their penducle, reduces seed dispersal within the lake body. Verhoeven (1979) has, however, mentioned that ripe seeds can be transported by drifting plant parts.

As with most aquatic lake species, dispersal of *Ruppia* between lakes has been the subject of much debate, particularly given the ephemeral nature of its habitat. During desiccation, Verhoeven (1979) reports that dried plant parts and attached seeds can be transported by the wind over considerable distances. A more commonly proposed idea is that birds feeding on the plant (which include flamingos in Spain) inadvertently transport vegetative parts after they become attached to a birds feet or beak, or that (more likely) after consumption, the resistant seeds are later defecated while still remaining in a viable condition. Saline lakes in Spain are important resting and feeding areas for migrating aquatic birds in an otherwise arid land. The annual South-North migration in spring when water levels and vegetative development is high, probably provides a constant "seed rain" of different species from different lake environments, such that vegetative development is in close equilibrium with the environmental potential.

Brock (1982) observed that the perennial *R.megacarpa* did not flower and fruit prolifically, although Verhoeven (1979) reports that the flowers of (mainly perennial) *R.maritima* var. *maritima* were "very abundant", and that it produced "enormous quantities of seed". Production of both seeds and pollen by the annual, *R.drepanensis*, has also been described as prolific (Cirujano, 1986; Cirujano *et al.*, 1990). A more fundamental (although not exclusive) difference occurs in the mode of pollination. Flowering by *R.drepanensis* occurs at the water surface (favouring cross-pollination), while *R.maritima* var. *maritima* flowers below the water surface (favouring self-pollination). The effect is that pollen produced by *R.maritima* will almost always enter the lake sediments directly, with little transport from its point of origin. Pollen from *R.drepanensis*, however, forms a surface scum similar to pine pollen, such that in Spring, the water of the inland salt lakes in Spain acquire a "*tonalides amarillentas*" (Cirujano, 1986; Cirujano *et al.*, 1990). A lot of this pollen is then blown by the wind to the shore where it accumulates or is further dispersed over the surrounding land (Cirujano *et al*, 1990). Pollen from *R.drepanensis* may therefore be well dispersed from its point of origin before entering the lake sediment record, and can form part of the regional pollen rain falling on nearby lakes devoid of *Ruppia*.

2.3.2 *Althenia*

2.3.2.1 *Introduction*

Den Hartog (1981) describes *Althenia* as monotypic, although its taxonomic position is somewhat controversial (Garcia Murillo & Talavera, 1986). *Althenia filiformis* occurs throughout the coastal lagoons of the Western Mediterranean and as far north as southern Brittany (Den Hartog, 1981; Valentine, 1980). In the

Iberian peninsular it also occurs in inland salt lakes, particularly in Andalucia (Martino, 1988) although here, *A.filiformis* may now have been replaced by *A.orientalis* (Garcia Murillo & Talavera, 1986).

2.3.2.2 *Identification from fossil remains*

Due to its rarity, most of the main seed key texts do not include *Althenia*. Galacia & Talavera (1986) and Den Hartog (1981) provide references to many of the main taxonomic studies on *Althenia* which include seed descriptions. SEM pictures of *Althenia* seeds are illustrated in Cirujano (1990) together with similar pictures of seeds of other taxa with which it might be confused, including *Zannichellia*.

The pollen of *Althenia* is inaperturate, with a reticulate patterning and size that make it similar to, and possibly confusable with, *Potamogeton* (Valdes *et al.*, 1987). This could be a problem were it not for the fact that, unlike *Potamogeton*, the pollen of *Althenia* does not resist acetolysis (Diez *et al.*, 1988)

2.3.2.3 *Palaeoecological information*

Althenia filiformis is an annual plant with an extended 5 month life-cycle (Martino, 1988). It occurs in both temporary and semi-permanent salt lakes and marshes in the south and centre of Spain (Montes & Martino, 1987) between 27-74‰TDS (Martino, 1988, Duarte *et al.*, 1990)). It prefers turbid saline waters, particularly where chloride is predominant (Alonso & Comelles, 1981).

2.3.3 *Potamogeton pectinatus*

2.3.3.1 *Introduction*

A wide range of *Potamogeton* species are present within the Iberian Peninsular (Valentine, 1980), including those species tolerant of base-rich conditions such as *P.lucens*, *P.coloratus*, *P.densus* and those species found in brackish water *P.filiformis*, *P.pectinatus*. However, only *P.pectinatus* is found in saline and non-permanent continental waters (Cirujano, 1990). *P.pectinatus* was the only *Potamogeton* species identified from macrofossil remains in cores taken from salt lakes in the Ebro Basin, north-east Spain (Davis, 1994).

2.3.3.2 *Identification from fossil remains*

The seeds of *P.pectinatus* can be identified using many of the main seed identification texts, although the use of seed morphology as a taxonomic discriminator in this genus is difficult. A further problem can arise in saline lakes where rapidly changing environmental conditions towards the end of the growing season can result in large numbers of immature seeds. The pollen of *Potamogeton* can be separated into the subgenera *Potamogeton* (eg. *P.natans*) and Coleogeton (*P.filiformis*, *P.pectinatus*) (Moore *et al.*, 1991). The distinction however is slight and difficult to apply consistently in the poorly preserved samples extracted from salt lake sediments.

2.3.3.3 *Palaeoecological information*

Salinity

Potamogeton pectinatus has the widest world-wide distribution of any saline lake angiosperm (Hammer, 1986). It has a wide salinity tolerance, although it generally occurs at lower salinities than *Ruppia* and *Althenia*. Hammer (1986) reviewed much of the published literature on *P.pectinatus*, giving it a range of 0-55%*o*TDS. In Spain, *P.pectinatus* is found in both hyposaline (3-20%*o*TDS) and mesosaline (20-40/50%*o*TDS) lakes (Comelles, 1981) and will out-compete *R.drepanensis* in fresh to moderately saline waters (Cirujano, 1990). Culture experiments by Van Wijk *et al.* (1988) on *P.pectinatus* from brackish coastal water environments in Europe found "a considerable decrease in biomass at 9%*o*Cl^- (*ca.*9%*o*TDS)". Hammer & Heseltine (1988) quote Huntsman (1922) as finding *P.pectinatus* abundant in Quill Lakes, Canada, at between 11-16.5%*o*TDS, and Rawson & Moore (1944) as finding *P.pectinatus* and *R.occidentalis* the only flowering plants in Saskatchewan lakes above 20%*o*TDS. In their study of salt lakes throughout the Canadian prairies, Hammer & Heseltine (1988) found only two species of *Ruppia* together with *P.pectinatus* as the submerged macrophytes in lakes over 5%*o*TDS. The salinity range of *P.pectinatus* was between 3-53%*o*TDS, although at high salinities (eg Big Quill Lake: >45%*o*TDS) it did not flower, exhibiting only vegetative growth. The modern distribution of *P.pectinatus* in lakes in Minnesota and North Dakota has been examined by Birks (1973), where it was found in all prairie lakes with conductivities between 320-2185 µmhos (*ca.*2-15%*o*TDS) (mean 1250 µmhos (*ca.*8%*o*TDS)), but not in lakes in deciduous and coniferous woodland areas. Greenhouse experimental studies by Stevenson (unpublished, but reported in Hollis (1983)) on *P.pectinatus* from Ichkuel, Tunisia, found that growth was inhibited at 20%*o*TDS and proved fatal for many plants. Seed germination was also unsuccessful at this salinity. In Australia, *P.pectinatus* is only tolerant of much lower salinities, between 1-6%*o*TDS (Brock & Lane, 1983).

One of the most detailed experimental studies has been carried out by Teeter (1965). Tolerance limits were found to depend on the stage in the life cycle at which stress was applied. At 1 week old, plants were found to tolerate upto 9%*o*TDS. This tolerance was higher at 18%*o*TDS at 8 weeks, but fell back again to only 6%*o*TDS at 12 weeks as photosynthesis declined with senescence. The maximum salinity tolerated overall was 20%*o*TDS.

Water Depth/Permanence

Reproduction in the Potamogetonaceae can take place using a number of regenerative methods, both sexual and asexual. The preference for fresher, more stable (permanent) waters tends to favour asexual strategies such as turions and persistent seedlings (Mitchell & Rogers, 1985) which do not leave a fossil record.

Flowering in populations from stable environments tends to be very irregular. Rogers (1984), found flowering and propagule development in *P.crispus* in South Africa did not appear to be in response to any particular environmental conditions. Individual plants reproduced at maturity (4-5 month life-span) regardless of time of year. A similar, but more seasonal growth pattern was observed by Hollis (1983) at Ichkuel, Tunisia. Here, growth is restricted by low temperatures until April, after which growth is rapid with flowering in June, and finally fructification in July or August.

Van Wijk *et al.* (1988) studied flowering in *P.pectinatus* from European coastal populations using culture experiments, but could find no relationship between flowering events and known stimuli. Flowering occurred at all salinities tested (1-9‰Cl^- (*ca.*1-9‰TDS)) but was most frequent around the optimum growth salinity environment (measured as the maximum total biomass) for any given population.

In less permanent environments, water depth appears to be the most important factor influencing fructification. Mitchell & Rogers (1985) explained the less frequent flowering and achene development of *P.crispus* in northern temperate lakes as a result of smaller changes in water level compared to the sub-tropics where low water levels are more frequent. In Sweden, Blindow (1992b) found high water levels were negatively correlated with *P.pectinatus* growth, while the year with the lowest July water level produced the largest quantity of seed. Correlation of low water level with high densities of plants and seeds has also been observed by Bailey & Titman (1984) for *P.pectinatus*, and Hunt & Lutz (1959) for *P.crispus*. In Lake Wabamun, Canada, Haag (1981) found that only *P.pectinatus* and *P.pusillus* in water depths less than 2.0m produced flowers and seeds. Plants at greater depths were deprived of light and time for development resulting in less successful sexual reproduction. At Delta Marsh, Manitoba, Anderson & Jones (1976) and Anderson (1978) found growth absent below 1.2m, the lower limit of photosynthetically active radiation. Maximum production occurred at a depth of 60cm.

A similar maximum depth of 1.3m was found by Hollis (1983) for *P.pectinatus* growing at Ichkeul. Optimum growth was found to occur between 1.2-0.8m, with *Ruppia* at shallower and deeper levels. A minimum depth of 40cm was found by Stevenson in experimental studies (unpublished, but reported in Hollis, 1983), below which plant biomass was severely reduced. This was suggested as relating to the need for erect growth upto 15cm as a precursor to leaf production. At depths less than 30cm, desiccation of aerial shoots can occur (Hollis, 1983).

Temperature, Turbidity and Turbulence

The influence of temperature on the life-cycle of *P.pectinatus* has not been well studied, although Hammer & Heseltine (1988) describe water temperatures alongside its phenological development in lakes in the Canadian Prairies. Growth begins in mid-May with water temperatures at around 10°C, although seeds were seen sprouting at 8°C. Flowering occurred in water at 15°C in late June, followed by fructification in mid-July with water temperatures at 20°C. Plants continued to flower and fruit into August, with the release of fruits occurring at the end of August.

The onset of growth of *P.pectinatus* at Ichkeul, Tunisia, occurs at similar water temperatures (10-11°C) to those found by Heseltine, however seed germination is reported to occur at considerably higher temperatures (20°C) (Hollis, 1983).

P.pectinatus is remarkably tolerant of high turbidity, allowing it to grow in eutrophic and polluted waters unsuitable for other species. This ability arises from the large carbohydrates stores in its tubers and achenes which allow extensive shoot growth at an early stage independent of light availability (Blindow, 1992a). Shoot length is directly correlated with decreasing light levels (Van Wijk *et al.* (1988), with foliage growth being concentrated as close to the water surface as possible. Hammer & Heseltine (1988) found *P.pectinatus* at all light levels in Canadian Prairie lakes, concluding that water pressure probably delimits its maximum depth (abundant between 1-4m).

Extensive shoot growth however, together with poor rooting, can expose *P.pectinatus* to turbulence caused by wind and wave action. Haag (1981) notes that *P.pectinatus* occurs throughout Lake Wabamun, but mainly in sheltered locations. Populations in deep water (greater than 2.0m) were heavily thinned by wave action before reaching the surface. Ice can also be a problem during low water levels in some lakes (Blindow, 1990b).

Colonisation and Dispersal

Dispersal of *P.pectinatus* seeds within lakes is limited due to their size and weight. Haag (1981) found a 90% decline in *P.pectinatus* seed within the sediment seed bank 200m away from the source population. In general, the fruits of *P.pectinatus* are only found where the plant is abundant, although even here they only occur in small quantities (Birks, 1973). Seed production is generally low, although like *Ruppia maritima*, the seeds produced are large. Seed production increases in shallow waters but overwintering is usually by asexual turions. A third of all seeds produced by *P.pectinatus* may persist through one growing season without germinating (Haag, 1981). As with the perennial *R.maritima*, seed density within the seed bank slowly increases during wet periods providing security against long term aseasonal drought.

Culture experiments by Van Wijk *et al.* (1988) found that in most cases where flowering occurred in *P.pectinatus*, achenes were produced. Watts & Winter (1962) found a close correspondence between pollen curves for *Potamogeton spp.* and their occurrence as macrofossils. This may perhaps be surprising since flowering involves semi-aquatic surface pollination similar to *Ruppia drepanensis*, allowing much greater dispersal.

The effect of salinity on *P.pectinatus* seed production was investigated by Teeter (1965) who found that salinity stress applied to young 6 week old plants produced a marked decline in the number of seeds formed later on in the life-cycle. In contrast, salinity stress applied after flowering and seed setting did not produce any change in overall seed production.

P.pectinatus is canopy forming, allowing it to out-compete other submerged macrophytes by shading (Blindow, 1992b). It is also tolerant of poor light conditions, such as those occurring at depth and high turbidities, and possesses the ability to grow upwards towards better light conditions independent of light availability. These capabilities, plus a tolerance of saline waters and drought conditions, allow it to aggressively colonise turbid, semi-permanent/permanent meso-saline lakes.

2.3.4 Charophytes

2.3.4.1 *Introduction*

A large number of palaeolimnological studies undertaken in North Africa have identified Charophyte remains, including Fontes *et al.* (1985); Gasse *et al.* (1987) and Fontes & Gasse (1991). Palaeolimnological work undertaken by Davis (1994) in Spanish salt lakes found similar remains, although only *Chara vulgaris* and *Lamprothamnium papulosum* were identified to species level. Few examples of the *Nitella* genus and *Tolypella* genus were found, although this probably reflects their preference for less saline waters.

A comprehensive catalogue of the Spanish charophyta, together with their environmental distribution, is given in Comelles (1982) and Alonso & Comelles (1984). Over 20 different species are listed, occupying habitats ranging from the fresh to hypersaline, clean to turbid and temporary to permanent. The palaeoenvironmental potential of this diversity is limited by the difficulty of identifying individual species from their macrofossil remains.

2.3.4.2 *Identification from fossil remains*

The identification of Charophyte species from oospore macrofossils remains difficult despite the detailed accounts of oosporangia included in botanical descriptions (*eg*. Wood & Imahori, 1964). This is partly related to a degree of taxonomic confusion within the genus, but mainly the limitations of the light microscope and the level of morphological variation between oospores of the same species. This has led to sometimes contradictory and misleading descriptions. Recent work using the SEM (*eg*. John & Moore, 1987; Soulíe-Märche, 1989; Leitch, 1989; John *et al.*, 1990; Leitch *et al.*, 1990; Casanova, 1991) have revealed that the surface ornamentation of oospores is indeed a good taxonomic indicator, but has often been misinterpreted under the light microscope (John *et al.*, 1990). Unfortunately, some problems of descriptive uniformity have persisted through the use of SEM's at relatively low magnifications, as well as the application of different descriptive terminology (Leitch *et al.*, 1990). Further difficulties persist for the palaeoecologist without access to type material, since published keys relate to only a few species investigated mainly for their taxonomic interest. Attempts at an 'educated guess' using the light microscope can prove reasonably reliable where the species involved is distinctive, dominant, and can be traced back through the sediment record from present day living specimens. However, the only truly reliable method of identification is through comparison of high resolution SEM's of both modern and fossil oospore material. Since fossil oospore populations potentially include examples of many different species, and SEM identification of all oospores would be impracticable, a sampling strategy would be necessary. Once the species composition and uniformity of the fossil population has been assessed, the light microscope could then be applied to speed up the counting process so long as the given species composition could be confidently differentiated.

2.3.4.3 *Palaeoenvironmental information*

Salinity

Charophytes occupy a wide range of aquatic environments but mainly alkaline, calcium rich waters, with a low phosphorus content (Forsburg, 1964; Moore, 1986). In Spain, they are mainly found in nutrient poor and moderately mineralised to hypersaline waters (Cirujano, 1990). Waters rich in nutrients tend to be dominated by angiosperms which are better adapted to higher turbidity levels from phytoplankton growth (Crawford, 1977).

C.vulgaris is a cosmopolitan freshwater species with an ability to adapt to slightly oligohaline water (Soulíe-Märche, 1991). Corillion (1957) found *C.vulgaris* together with the brackish water species, *C.canescens*, in waters upto 5‰TDS, while Brock (1981) reports *C.vulgaris* in waters upto 4‰TDS. In Spain, Alonso & Comelles (1984) found *C.vulgaris* in 4 out of 6 of their lake categories: both permanent and temporary clean freshwaters (0.5-2.0‰TDS), muddy permanent freshwaters, and permanent clean mineralized waters (this category includes lakes upto 30‰TDS). It occurred twice as often in permanent clean mineralized waters than in the other three lake environments. Of the other 2 categories, *C.vulgaris* did not occur in temporary clean mineralized waters and althalosaline waters. *C.vulgaris* has also been noted in lakes with a high proportion of calcium (Crawford, 1977; Cirujano, 1990). Hammer (1986) quotes the salinity distribution of *C.vulgaris* at between 0-16‰TDS from Academia Sinica (1979), China.

Lamprothamnium papulosum is only found in inland salt lakes in Spain and Australia (Martino, 1988). It is widely reported as being able to withstand hypersaline conditions, where it photosynthesises with greatest efficiency (Burne *et al.*, 1980). In Australia, Burne *et al.* (1980) found living plants in waters up to 70‰TDS, while Brock & Shiel (1983) noted *L.papulosum* as the only Charophyte collected from waters between 10-100‰TDS. These results are similar to Brock & Lane (1983), who observed *L.papulosum* in waters from 9-125‰TDS. Martino (1988) reports the distribution of *L.papulosum* in inland waters in Spain from 27.5-112‰TDS. *L.papulosum* is exclusive to hypersaline waters (Cirujano, 1990), while occurring in association with *C.galiodes* at moderate salinities (Cirujano *et al.*, 1988; Comin & Alonso, 1988; Cirujano, 1990). Growth experiments show that the optimum growth salinity for *L.papulosum* is between 24-28‰TDS, with a minimum salinity tolerance of 8‰TDS (Daniel, 1975, reported in Moore, 1986).

While *L.papulosum* thrives at high salinities, lower salinities are required for germination (Burne *et al.*, 1980, Soulíe-Märche, 1991). For instance, culture experiments by Burne *et al.* (1980) showed that germination occurred in freshwater and sea-water (35‰TDS), but not at higher salinities (53‰ and 70‰TDS). A low salinity phase is therefore required before *L.papulosum* can start its life-cycle, the lack of *L.papulosum* perhaps indicative of constant high salinities, without even a short period of freshwater input (Soulíe-Märche, 1991).

Water Depth/Permanence

Charophytes generally tolerate much greater depths than macrophytes (Collinson, 1988), often being distributed in the deep central area and shallow margins of lakes, while being outcompeted by macrophytes in the middle depths, between 2-6m (Moore, 1986). Ice and wave action in the shallow margins restricts this zone to smaller species (0.5-1.0mm shoot diameter), including *C.vulgaris* (Blindow, 1992a). In coastal locations, *L.papulosum* is usually found in waters less than 2m deep (Moore, 1986).

Charophytes are ideally suited to temporary waters, producing a large number of resistant propagules (oospores) which can survive desiccation, often remaining viable for many years while unfavourable conditions persist (Olsen, 1944). Under stable conditions however, some perennial species may propagate using bulbils which are not preserved within the fossil record. The presence of oospore remains indicates submersion for a minimum of 3 months, this being the minimum time of a single life-cycle (Soulíe-Märche, 1991).

L.papulosum and *C.vulgaris* occur in both permanent and ephemeral (seasonal and aseasonal) waters (cf. Brock & Lane, 1983; Moore, 1986; Comin & Alonso, 1988; Cirujano, 1990). *L.papulosum* occurs in temporary lakes of at least 3 months inundation (Brock & Lane, 1983), with an annual life-cycle synchronised with its ephemeral habitat (Brock, 1986). On refilling, reproduction can occur within 4-6 weeks following germination and the onset of growth (Brock, 1986).

Temperature, Turbidity & Turbulence

The influence of temperature on the development of Charophytes has been little studied although Moore (1986) notes that, "high temperatures often induce rapid and massive spore formation", while gametangia development may be inhibited by low temperatures (Hutchinson, 1975).

Charophyte lakes have generally low turbidity and phytoplankton productivity (Forsberg, 1965). In clear lake waters, Charophytes dominate over angiosperms at depth, while in turbid lakes, macrophytes tend to dominate (Blindow, 1992a). Charophytes utilize light better than canopy forming macrophytes and typically form dense meadows which restrict the capacity of angiosperms to invade. Reduced light intensities promote falling plant densities (Hutchinson, 1975) and hence greater invasion by canopy forming macrophytes. Growth in most Characeae is inhibited when shaded by floating leaved aquatics (Moore, 1986). Unlike some other macrophytes (eg. *P.pectinatus*), Charophyte propagules do not possess sufficient carbohydrate stores to allow growth to the surface of turbid lakes in spring (Blindow, 1992a) and Crawford (1977) notes succession from *C.vulgaris* by *Najas* and *Potamogeton* in farm ponds as a result.

Turbidity may be increased initially by phytoplankton blooms relating to enhanced phosphate levels and eutrophication (Crawford, 1977). Loss of submerged vegetation then increases turbidity as a result of wave action on the exposed sediment substrate. Alternatively, Characeae meadows can be seriously reduced by snail and crayfish grazing (Crawford, 1977), as well as by birds (Moore, 1986). This can effectively increase turbidity by sediment exposure, or by encouraging phytoplankton growth directly by the liberation of nutrients

(Blindow, 1992b), or indirectly, by preventing the buffering of phosphates by marl precipitation (Otsuki *et al*, 1972).

Smaller Charophytes can often be found dominating lake margins as a result of their greater resistance to wave and ice action (Blindow, 1992a). These tend to have a condensed and bushy form and may have a larger bulbil to act as an anchor, in addition to their usual rhizoidal network (Moore, 1986).

Colonisation and Dispersal

Charophytes are aggressive pioneering plants of newly created aquatic environments, often acting to stabilise the sediment allowing the establishment of other macrophytes which may then come to cause their decline through the action of succession (Moore, 1986). The density and speed by which Charophytes can dominate a lake system is partly related to their prolific production of resistant propagules. A single plant can easily produce over 100 oospores to contribute to the seed bank (Soulíe-Märche, 1991). These oospores can then remain viable for over 4 years, even after drying (Proctor, 1967). The dispersal of these oospores within the water body before entering the sediment seed bank is partly related to their propensity and degree of calcification. Calcified oospores (gyrogonites) (eg. *C.vulgaris*) do not float, hence dispersal is limited and in-situ deposits can easily be identified by their abundance of oospores (Soulíe-Märche, 1991). Non-calcified oospores (eg. *C.baltica, C.horrida, C.galiodes, C.connivens*) can float or be easily transported by wave action to become widely dispersed (Birks, 1973). Large accumulations of oospores can often occur on the windward shore of shallow playa lakes (De Decker, 1988; Pueyo, 1978).

Dispersal of Charophytes between lakes is thought to occur through the action of birds, with oospores and plant remains having been found in the stomachs of wildfowl (Moore, 1986). Oospores have been found to remain viable even after passage through the digestive tracts of ducks (Proctor, 1962).

2.3.5 Others

2.3.5.1 *Introduction*

Other submerged macrophytes that also appear in Iberian saline waters include the angiosperms in the Ranunculaceae, *Najas*, *Zannichellia*, *Myriophyllum*, and the bryophyte *Riella helicophylla*.

2.3.5.2 *Identification from fossil remains*

Riella helicophylla is a bryophyte whose distinctive spores frequently appear on pollen slides from Iberian salt lakes. Detailed descriptions of spore morphology, including SEM photographs, can be found in Cirujano *et al.* (1988b). The seeds of *Najas* and *Zannichellia* also often occur in abundance but the pollen of these taxa are rarely encountered in palynological work due to their poor resistance to acetolysis (Díez, 1988). This is in contrast to *Myriophyllum* which has a resistant and distinctive pollen morphology which can be readily identified to species level (Valdes *et al*, 1987; Moore *et al*, 1991; Reille, 1992b). Pollen of *Ranunculaceae* is of limited use in palaeolimnology since it is too easily confused with that of terrestrial species, although its seeds can be relatively easily identified.

2.3.5.3 *Palaeoenvironmental information*

Salinity

Najas flexilis was found by Birks (1973) living in virtually all lakes sampled in Minnesota and North Dakota upto 1240µmhos Conductivity (*ca.*8‰TDS), although the average value was nearer 200µmhos (*ca.*1‰TDS). Water conductivity ranges for other macrophytes included 325-2185µmhos (*ca.*2-15‰TDS) (1250µmhos mean (*ca.*8‰TDS) for *Zannichellia palustris*. Hammer (1986) notes the salinity tolerances of *Myriophyllum propinquum* (0-5‰), *Myriophyllum spicatum* (0-5‰) and *Riella capensis* (5-23‰). In Spain, Cirujano *et al* (1988) found *Riella helicophylla* in environments from 2.6-74‰ salinity, although there was a preference for sodium-chloride waters above 10‰. Spore germination, however, required much lower salinities, in the range 0-7‰. In the Doñana coastal marsh of southern Spain, Duarte *et al.* (1990) classified *Zannichellia obtusifolia* in the upper class of conductivity, between 47-10mS, while *Myriophyllum alterniflorum* was distributed in the lower 2-1mS class. García (1991) reports *Z. obtusifolia* as preferring relatively low salinities in Spain compared to *Ruppia drepanensis* which gradually displaces *Z.obtusifolia* as water salinities rise as lake levels fall.

Water Depth/Permanence

Riella helicophylla is one of the fastest growing macrophytes found in seasonal salt lakes in Spain, requiring less than 3 (Garcia Murillo, 1991) or 4 (Cirujano *et al.*, 1988) months in shallow waters to complete its life cycle.

Other plants are more typical of deep permanent waters, including *Myriophyllum spicatum* and *Najas marina*, although species characteristic of temporary environments, such as *Zannichellia obtusifolia* and *Ranunculus peltatus*, may colonise the ephemeral areas around the shores of permanent lakes (García Murillo, 1991).

Colonisation and Dispersal

Zannichellia, *Riella* and *Najas* have hydrophilous pollination or spore production mechanisms, while many others are anemophilous.

Seed production varies depending on the preferred perennation mechanism, with annuals such as *Najas* and *Zannichellia* producing considerable numbers (Birks, 1973; Grillas *et al.*, 1993) in comparison with perennials such as *Myriophyllum*. Vegetative reproduction can still occur, however, in *Zanichellia* by means of stem or rhizomes, or by turions in the case of *Myriophyllum* (Sanchez *et al*, 1992).

In surface sample studies, Birks (1973) found seeds of *Najas* were widely dispersed, with many samples containing seeds but with no plants growing nearby. This contrasts with the results of Grillas *et al* (1993) for *Zanichellia*, where seed occurrence generally reflected the distribution of living plants.

2.4 Emergent macrophytes

2.4.1 *Introduction*

The shallow basin shape of many salt lakes often encourages the development of a marginal emergent vegetation. Fluctuating water levels and extreme salinities often result in poor growth, particularly where the deep rooting system is unable to reach less saline groundwaters. Most emergent species grow best in freshwaters, with few being truly halophilic. Declining salinity is often marked by an increase in emergent vegetation, particularly at the very lowest salinity levels in shallow waters with a fairly stable water level.

In common with many salt lakes throughout the world, the margins of saline lakes in Spain are typically colonised by emergents such as *Typha*, *Phragmites* and *Scirpus*. A north-south distribution appears to occur within the country between *Typha angustifolia* and *T.domingensis*, with *T.domingensis* more associated with lower latitudes, similar to that observed in North America.

2.4.2 *Identification from fossil remains*

The pollen of *Typha latifolia* is tetrad and easily distinguished from the monoporate *Typha angustifolia* pollen. Most species of *Sparganium* however share the same monoporate pollen morphology as *T.angustifolia* and are in most cases indistinguishable, often being combined to form the pollen taxon, *T.angustifolia* type (Moore *et al.*, 1991). The pollen of *T.domingensis* shares many of the morphological characteristics of pollen from *T.angustifolia*, and although the two have been distinguished (Valdes *et al.*, 1987), this is difficult to do reliably.

T.minima and *T.shuttleworth* similarly share much the same pollen morphology as *T.latifolia* (Punt, 1976), with the three often combined under the *T.latifolia* type taxon (Huntley & Birks, 1983).

There are few distinguishing features between the pollen of the Cyperaceae and Gramineae making identification to species level almost impossible. It is therefore not possible to differentiate *Scirpus* and *Phragmites* pollen from other members of their respective families. Differentiation can only achieved by examining their seed morphologies or possibly stem structure.

2.4.3 *Palaeoenvironmental information*

Salinity

Typha is normally found in freshwaters, although it can tolerate moderately saline conditions, along with *Phragmites australis* (Cirujano, 1990). As with most emergents, growth is generally negatively affected by increasing salinities (Whigham *et al.*, 1989; Goldsmith, 1984). *Scirpus* is generally found occupying waters and marshes of higher salinities and shallower depths, which are liable to dry out for longer periods.

Birks (1973) found *Typha* and *Scirpus acutus/S.validus* in all lakes sampled in Minnesota & North Dakota from 30-2185µmhos (*ca.*0-15%*o*TDS), with a mean of 500µmhos (*ca.*3%*o*TDS). *T.angustifolia*, however, was confined only to Prairie Lakes (320-2185µmhos (*ca.*2-15%*o*TDS)). Hutchinson (1957) describes both species of *Typha* as often ocurring together in the same lakes with the same water chemistry environment. Substratum differences appeared to be the main factor affecting their distribution, with *T.angustifolia* growing on the more organic sediments in comparison with *T.latifolia*. Hammer (1986) has reviewed the salinity tolerances of many of the main emergent macrophytes found in salt lakes. *T.angustifolia* was generally found occupying waters of slightly higher salinities (0-9%*o*TDS), than *T.latifolia* (0-6%*o*TDS). *Phragmites australis* can be found in waters of still higher salinities from 0-15%*o*, while *Scirpus* species range from the mainly freshwater *S.litoralis* (0-5%*o*) to hypersaline *S.maritimus* (0-60%*o*). *T.angustifolia* does not occur in Canadian prairie salt lakes and Hammer & Heseltine (1988) found *T.latifolia* restricted to only 2 lakes with a salinity range of 3-10%*o*.

It is important to note that the salinity tolerance of emergents, with their deep and extensive rooting system, is often related more to the salinity of the subsurface groundwater than that of the lake waters themselves. Thus it may be possible to find emergents with their roots in relatively low salinity groundwaters able to withstand periodically hypersaline lake waters. This is often the case at the margins of seasonal lakes, where the deep rooting of *Typha* often allows it to survive the summer desiccation in sheltered locations by drawing on the groundwater below. Exceptions to this rule are likely to occur during germination and seedling survival when conditions within the lake waters are correspondingly more important.

Water Depth/Permanence

Typha can generally grow to greater water depths than other emergents, usually occupying the range 0.5-2.0m (Hutchinson, 1975). Differences in depth range between *Typha* species have been noted by Grace & Wetzel (1981) who observed that *T.domingensis* was able to outcompete *T.latifolia* at depths greater than 0.8m due to the lower resource allocation required for its narrower leaves. *T.latifolia* dominated at shallower depths where its broader leaves could outcompete *T.domingensis* for light. Experiments by Stevenson (reported in Goldsmith, 1984) showed that *Scirpus maritimus* from Ichkeul, Tunisia, preferred water levels in the region of 20cm, while *S.litoralis* was found to prefer deeper, but more saline conditions. The maximum depth *S.maritimus* was found to colonise was 40cm.

Temperature, Turbidity and Turbulence

Typha is generally more sensitive to turbulence and exposure to wind and wave action than *Phragmites australis*. This can result in *Phragmites* replacing *Typha* on the lake side of reed beds in exposed positions, in reverse to the usual zonation (Hutchinson, 1975).

Emergents are typically more tolerant of high turbidity and eutrophication than submerged macrophytes due to their aerial leaves. *Typha* in particular responds well to anoxic substrate conditions, deriving most of its oxygen from the above surface parts of the plant (Mitchell & Rodgers, 1985). Hutchinson (1975) notes differences between species of *Typha* found by Maristo in Finnish lakes, where *T.latifolia* replaced *T.angustifolia* in shallow, highly eutrophic waters.

Colonisation and Dispersal

Most emergents perennate as buds attached to rhizome networks. Seeds are generally dispersed by the wind and few are generally found in lake sediments away from the lake margins. Identification is therefore often confined to pollen analysis, although reed stem litter can be found preserved under certain circumstances.

Typha is wind pollinated and produces abundant pollen, although it appears to be poorly dispersed. Surface sample studies by Ayyad *et al.* (1992) showed poor representation outside reedswamp areas (<5%TP), but where *T.domingensis* was dominant in the local vegetation (upto 100%), it made up a mean value of 87%TP of the pollen rain. Kershaw (1979) found very little pollen of *Phragmites australis* in surface samples from *Phragmites* swamp. He concluded this was either due to low pollen productivity or the oxidation of pollen as it lay on the thick litter layer on the water surface. Lieffers & Shay (1981, 1982) mention that seed production in *S.maritimus* varied according to the inundation environment, with higher seed production occurring in deeper water.

2.5 Terrestrial Plants

2.5.1 *Introduction*

During periods of low water, terrestrial halophytes typically colonise saline lake margins along a gradient according to salinity and inundation period. Prolonged desiccation can allow terrestrial vegetation to colonise the entire basin of shallow ephemeral lakes, although this is usually limited in seasonal salt lakes by the existence of a thick layer of precipitated minerals. Declining soil salinity and flooding period higher up the shore increases competition from less tolerant species and the replacement of halophytes by more diverse species. The seeds and pollen of these plants can readily become incorporated into the palaeoenvironmental record, particularly in the case of weedy annuals which can produce prolific remains (Watts & Winter, 1966)

2.5.2 *Palaeoecological information*

Among the most highly adapted plants to high salinity conditions are members of the Chenopodiaceae. The margins of hypersaline and mesosaline lakes in Spain are readily colonised by annual species of Chenopodiaceae such as *Salicornia ramosissima* and *Sarcocornia herbacea* (Montes & Martino, 1987; Bourrut, 1991). These annual species have a poor resistance to drought and require almost permanently wet root conditions in comparison with woody perennials such as *Suaeda* and *Arthrocnemum glaucum* that colonise the outer margins (Bourrut, 1991). Prolonged drying is liable to favour the replacement of annuals by perennials (Watts & Winter, 1966).

Declining inundation period is often connected with a lowering of the groundwater table. This allows free drainage by meteoric waters into the sub-soil causing the leaching of accumulated salts and a decline in surface sediment salinity. Colonisation of the entire lake basin by halophytes may follow, along with the onset of pedogenic processes. Further loss of surface salts will result in growing species diversity as lesser halophytes begin to colonise, often attracted by the damper conditions found at the centre of endoreic basins.

2.6 Conclusions

Saline lakes represent particularly unstable ecosystems, susceptible to rapid and large scale changes in environmental conditions. Such lakes are responsive indicators of past environmental fluctuations, including climate change, wherever the records of such fluctuations have been preserved by lake sediments and biotic remains.

Plants adapted to these lake systems are, by necessity, tolerant of a broad range of environmental conditions. Interpretation of the palaeolimnological record through the use of macrophyte remains is therefore restricted by their low resolution in comparison with other palaeoenvironmental indicators such as ostracods and diatoms which show greater species diversity and niche occupancy, and more rapid reproductive cycling. Quantitative estimates of limnological conditions such as lake salinity or water permanency may however be possible through the examination of seed or oospore morphology (Brock, 1982; Soulié-Marche, 1989).

In this sense, macrophytes are more comparable with geochemical and stratigraphic indicators, providing a qualitative basis for interpreting the palaeo-environment. Integration of these records, however, may provide a basis for semi-quantitative reconstruction that cannot be obtained from their individual independent analysis (chapter 7). Thus the greatest strength of macrophyte analysis is as part of a multi-proxy based approach to palaeoenvironment reconstruction.

Chapter 3

Cladocera and Chironomid remains and saline lake palaeolimnology: with special reference to Spanish salt lakes

3.1 Abstract

Cladocera ephippia and Chironomid head capsules preserve well in salt lake sediments, providing an additional proxy record for palaeolimnological studies. Chironomids can provide information on the benthic environment including the development of deep water stratification. Cladocera can be used to follow changing lake salinities when identifiable to species level, as well as nutrient release from lake macrophyte breakdown at a more aggregate level.

3.2 Introduction

Palaeolimnological analysis of saline lake sediments is best achieved through the use of multiple-proxy indicators which provide information on as many different aspects of the lake system as possible. Palaeoecological analysis of lake biota can be particularly useful due to the sensitive relationship that exists between organisms and their environment. Cladocera ephippia and Chironomid head capsules are often found well preserved in saline lake sediments and can form an additional proxy of limnological conditions, particularly in ephemeral lakes where problems of dissolution and differential preservation restrict the use of ostracods and diatoms. Little palaeolimnological work has been undertaken using Cladocera and Chironomids in saline lake systems despite their proven utility in freshwaters. Work on Spanish salt lakes has shown that a number of useful interpretations can be made from their preserved remains, suggesting that more widespread use might be made from their application.

3.3 Cladocera

3.3.1 *Introduction*

The use of Cladoceran remains as palaeoenvironmental indicators has been widely documented (Frey, 1962; Crisman, 1978; Frey, 1986; Whiteside & Swindoll, 1988; *etc*) although few studies have been applied to saline lake systems (Kokkinn & Williams, 1987). The taxonomy and contemporary distribution of the Spanish Cladocera are well documented (Alonso, 1985; Alonso, 1991; *etc*), providing a useful basis for palaeoenvironmental studies within the Iberian Peninsular. As in Australia (Williams, 1986), the most predominant Cladocera within saline lakes in Spain are the Daphniidae and Moinidae (Montes & Martino, 1987; Comín & Alonso, 1988; Martino, 1988; *etc*). Unfortunately these are often the least useful families for Cladoceran analysis due to the difficulty of species identification from their commonly preserved remains (Frey, 1962). Evidence of Cladocera from lake sediments in the Ebro Basin (Davis, 1994) were confined entirely to the ephippia of Daphniidae and Moinidae.

3.3.2 *Identification from fossil remains*

Introduction

Analysis of Cladoceran fossil assemblages primarily relies on the identification of littoral Cladocera using their disarticulated exoskeletal remains such as the shell, head shield, postabdominal claws, antennal segments and mandibles. Planktonic Cladocera such as the Daphniidae and Moinidae produce few such remains and as a result are difficult to identify beyond the generic level. Relatively few studies have identified planktonic Cladocera (with perhaps the exception of *Bosmina*) although they are often predominant amongst the salt lake fauna and their ephippia preserve well. Unfortunately little work has been undertaken on the identification of species from ephippial morphology, although this has been proven to be possible (Williams, 1986; Kokkinn & Williams, 1987). At present, no comprehensive diagnostic key is available for the Cladocera based on ephippial characteristics and any identification must be restricted to particularly distinctive species or else confined to the generic level.

Ephippia

Ephippial production in the Cladocera is primarily confined to the Sididae, Holopediidae, Daphniidae and Moinidae (Frey, 1986). Reproduction in the Cladocera is predominantly parthenogenic. Sexual reproduction generally occurs under environmental stress when parthenogenetic egg production starts to fall and an increasing number of eggs develop as males. These males then mate with sexual females which have started to produce haploid eggs. Following fertilisation, the brood pouch thickens to enclose the egg (or eggs) in a resistant ephippium (Wetzel, 1983). The ephippium allows the Cladocera to endure unfavourable conditions such as a declining food supply, as well as being resistant enough to survive desiccation, extreme salinity and freezing. In sediments from extreme environments such as salt lakes, ephippia are often the most abundant animal remains and the most conspicuous of Cladoceran remains (Kokkinn & Williams, 1987).

The use of ephippia in palaeolimnology has been restricted by the lack of work concerning the taxonomic role of ephippial morphology. The use of ephippia as taxonomic indicators have only recently been shown to be important (Williams, 1986; Kokkinn & Williams, 1987), despite the early identification of the palaeolimnological potential of species identification in the Daphniideae related to the diversity of its habitat niches (Frey, 1962).

The gross structure of ephippial eggs can take two main forms. The *Daphnia* and *macrocopa* group of *Moina* produce ephippia containing pairs of eggs, while the *Ceriodaphnia, Scapholeberis, Simocephalus* and *brachiata* group of *Moina*, contain only one egg in each ephippia (Hutchinson, 1967). A key to species in the *brachiata* group of *Moina* based on ephippial characteristics is given in Alonso (1985), but otherwise published references for identification purposes are extremely limited. Drawings of ephippia of Daphniidae are also available in Alonso (1985), however confident identification of Daphniidae species would probably require reference to comparative type material and further identification of key taxonomic discriminating features. Only *M.mongolonica* was found to be sufficiently distinctive to be confidently identified to species level by Davis (1994) in Spain.

Other references available include limited line drawings of *Daphnia* ephippia in Smitt (1861) and Frey (1962), and SEM photographs of *Daphniopsis* ephippia in Williams (1986), and Kokkin & Williams (1987). The latter studies identify extreme morphotypic variation of ephippia between populations of *Daphniopsis* which they conclude is taxonomic rather than environmental. Importantly, ephippial morphology is shown to remain constant between seasons, changing little with variations in salinity and other environmental factors (Kokkin & Williams, 1987).

3.3.4 *Palaeoenvironmental information*

Introduction

Palaeolimnological investigations using Cladoceran remains have been mainly used to interpret water chemistry and trophic state, as well as environmental fluctuations related to variations in community structure, size-selective predation and littoral v planktonic species distributions (eg. Frey, 1962, 1969, 1976, 1986; Crisman, 1978; Whiteside & Swindoll, 1988). Cladoceran studies in saline environments have been limited despite the widespread occurrence of ephippial remains in salt lake sediments (De Deckker, 1982, 1986). Palaeolimnological interpretation of these remains has been mainly limited to water salinity reconstructed from contemporary tolerances (Williams, 1986).

Salinity

The salinity tolerances of the Spanish Daphniidae have been investigated by Alonso (1988, 1990) and Comín & Alonso (1988). Within the family, species occupy a broad range of salinities from fresh to hypersaline. The maximum salinity is recorded by *Daphnia (Ctenodaphnia) mediterranea* Alonso which was found to occur in saline waters in the range 10-60‰ (Alonso, 1990). Of the Moinidae, *Moina mongolica* (*M. salina*) was found in the most saline environments, between 22-60‰ (Alonso, 1990).

Hammer (1986) has reviewed much of the world evidence on the salinity tolerances of Cladocera species. Of the six hypersaline species, two are Daphniidae and three are Moinidae. The highest recorded salinity is for *D.similis* from Little Manitou Lake (Alberta) at 103‰, and within the Moinidae, *M.mongolonica* has been found in lakes upto 73‰.

Water Depth & Permanence

Apart from salinity, Cladocera analysis provides only circumstantial evidence of water depth. The balance between littoral and planktonic species can give some idea of changing depth, particularly in a shallow sloping basin where small changes in depth can produce large changes in the extent of littoral macrophytes (Whiteside & Swindoll, 1988). The use of littoral:planktonic ratios has however generally been used as an indicator of lake productivity (and littoral extent) on the basis of constant water depth (Crisman, 1978).

The Daphniidae and Moinidae are predominantly limnoplanktonic (Hutchinson, 1967; etc) and therefore likely to increase with a decrease in littoral macrophytes and concurrent increase in limnetic habitat. Megard (1964) found *Daphnia* was associated with a lack of vegetation at Dead Man Lake, New Mexico. This relationship however can often be complicated, given that an increase in algal productivity can lead to both a reduction in macrophytes through algal shading, as well as an increase in algal food supply (Crisman, 1978). Similarly, in saline environments with fluctuating water levels, littoral development is often limited and changes in the limnetic environment (such as food supply) are likely to dominate.

In Spain, both Daphniidae and Moinidae can be found in temporary and permanent waters, although *M.mongolonica* lives only in shallow, periodically dry waters, generally poor in vegetation (Alonso, 1985).

Turbidity & Temperature

Since Daphniidae and Moinidae are generally planktonic, they often show a close positive relationship with organic turbidity. This relationship depends however on the ability of different species to filter and digest different algae of different sizes and concentrations. Increasing organic turbidity due to planktonic algae therefore leads to an increased abundance of planktonic Cladocera, but at the same time, a decreased species diversity (Whiteside & Swindoll, 1988). Hence for example, the rapid filtering abilities of *M.brachiata* and *D.pulex* allow them to live in waters containing high amounts of bacterial seston which would block the filtering apparatus of other species (Hutchinson, 1967). On the other hand, some algae are simply too big to be filtered, such as some of the filamentous algae and blue-greens. These algal forms often increase with increasing lake fertility (Moss, 1988). For instance, Hutchinson (1967) reports that *Chlamodomonas*, *Mallomonas*, *Cryptomonas* and small *Euglena* are all easily digested by *Daphnia* and *Moina*, while *Trachelomonas*, *Lepocinclis*, *Phacus* and *Glenodinimium* are poorly digested.

In general, planktonic Cladocera abundance will depend on phytoplankton production (organic turbidity) which will in turn depend on lake nutrient status. High organic turbidity might therefore be implied by abundant Daphniidae and Moinidae remains. This situation may be more complex since Schoenburg & Carlson (1984) found that grazing by *Daphnia* in enclosures within a hypereutrophic Scandinavian lake actually kept the water clear.

Increasing inorganic turbidity is generally considered to lead to decreased abundance and decreased species diversity (Whiteside & Swindoll, 1988). Certain hypersaline species however seem to be able to cope successfully with the high inorganic turbidity often encountered in shallow salt lakes. Alonso (1985) reports that *M.mongolonica* favours waters with abundant inorganic (clay/marl) material in suspension. These lakes are characteristically influenced by water birds such as flamingoes whose wading and feeding habits disturb the bottom sediments. It is not known to what extent *M.mongolonica* is favoured in such circumstances, either directly, due to its ability to cope with inorganic particulate matter, or indirectly, by the enhancement of food supply, by either resuspension of bottom debris or the increased nutrient supply to lake waters caused by bird guano. *D.mediterranea* is similarly more frequent in shallow muddy waters with high turbidity (Alonso, 1985).

Ephippial production can also be related to organic turbidity and food supply. A rapid (rather than gradual) decline in food supply can provide sufficient environmental stress to provoke the generation of males and ephippial females (Hutchinson, 1967).

Temperature is an important factor in the growth of the Cladocera, with higher water temperatures encouraging more rapid growth. Hutchinson (1967) reviews evidence of the effects of temperature on Cladocera species. The optimum and fatal maximum and minimum temperature limits for Cladocera vary not only between species but also between populations of the same species. In general, those adapted for warm waters will have higher upper and lower temperature limits and will have a selective advantage against other species at higher temperatures. Examples of the uppermost limit for life and the optimum temperature for breeding (in brackets) for warm temperature species are given as 48°C (35°C) for *M.macrocopa* and 41°C (25°C) for *D.magna.*

Dispersion & Colonisation

Cladocera ephippia are small, light and easily dispersed. In the littoral they are often attached to macrophytes to reduce the chance dispersal (Frenzel, 1983), although here they are presumably liable to be taken up by feeding birds and transported to other water bodies. In free water, ephippia either sink or float following formation, being liable to drift and accumulate along windward shorelines (Wetzel, 1983). The accumulation of ephippia is similar to that of a seed bank in that it provides for immediate development of large populations when conditions become more favourable. Little information is available on the length of time ephippia remain viable.

3.4 Chironomids

3.4.1 *Introduction*

The Chironomids or midges form the major part of the benthic fauna of most lake systems and their larval remains are often well preserved within lake sediments. The use of Chironomid larval remains in the reconstruction of palaeoenvironments has primarily been based on oxygen concentration (trophic state) in deep, stratified, lakes (Brundin, 1949, 1956; Stahl, 1969; Saether, 1979) and sediment composition, water depth, and water temperature in shallow, unstratified lakes (Walker & Mathewes, 1986; Hofmann, 1986; Walker &

Mathewes, 1989; Walker *et al*, 1991). Few studies have however been undertaken at low latitudes and within saline lake systems.

3.4.2 *Identification from fossil remains*

A number of comprehensive keys to the Chironomids are available for the palaearctic or holarctic regions (Hofmann, 1986) including Wiederholm (1983) and Hofman (1971). These are all based on head capsule or attached assemblages, which can be extracted through simple sieving of the sediment sample following disaggregation.

3.4.3 *Palaeoenvironmental information*

Salinity

Chironomids are highly adaptable and occur in almost all aquatic habitats (Hammer, 1986). Salinity tolerances at the tribal level for *Chironomus* and *Tanytarsini* are very wide, with species ranging from fresh to hypersaline waters. For instance, in Australia, *Tanytarsus barbitarsis* has been reported in lakes of 140%*o*TDS (Kokkinn, 1986), while species of *Chironomus* have been reported in salinities up to·285%*o*TDS on the Kirgiz Steppe (Cannings & Scudder, 1978). Chironomid fauna in salt lakes in Spain remain poorly studied. Comín & Alonso (1985), mention dense populations of *Baeotendipes* Kieffer, together with *Dunaliella salina* Teodorescu and *Artemia salina* at about 120%*o*TDS at La Mata, a permanent salt lake in southeastern Spain. Chironomids were also reported by Margalef (1948) in temporary salt lakes in La Mancha.

The occurrence of Chironomids in fresher waters in Spain are much better documented (Prat, 1980; Prat & Daroca, 1983; Prat *et al*, 1992). At these low levels, salinity alone is not seen as a limiting factor, although the reduction of sulphate to sulphide in profundal waters can lead to mortality in species otherwise able to cope with limited anoxia. *Chironomus* has haemoglobin, and has the ability to cope with temporary periods of anoxia, however sulphide at sufficient concentration is fatal for all invertebrates. Thus the profundal environments of lakes and reservoirs in the east of Spain, where sulphate loadings are highest, tend to be dominated by migratory species able to escape the periodically lethal concentrations of sulphide (Prat *et al.*, 1992).

Water Depth/Permanence

Chironomid larvae have been found living in both temporary (Margalef, 1947), and permanent (Comín & Alonso, 1988) salt lakes in Spain, including the Ebro Basin (Chapter 7, Chapter 9 section 9.5), although evidence in the latter case is confined to extinct head capsules and not living organisms. Macrofossil analysis of a sediment core from the permanent salt lake, Laguna Salada (Section 9.5) confirms the historical presence of a benthic fauna, however no head capsules could be found in the most recent sediments as a result of recent development of an anoxic, sulphide rich chemocline. Stratification is crucial to the development of a hypolimnion and with it the stable conditions for anoxic and sulphide degradation of the profundal environment. Shallow waters tend to be well mixed by wind and wave action, ensuring oxygenation throughout the water column. It is perhaps significant that Comín & Alonso (1986) report the abundance of the phytophagous *Baeotendipes* in La Mata not during the phytoplankton bloom of 1979, when food supply was abundant and salinity more moderate, but in 1985 when lake levels were considerably depressed and salinity much higher. The difference perhaps partly relating to enhanced mixing during the period of shallow water, maintaining suitable oxygen conditions and reducing sulphide build-up in the profundal waters. The depth of water needed before chemical stratification will occur will depend on the chemical concentration, size and exposure of the lake body, as well as the chemical concentration of the inflow waters. The Laguna Salada in the Ebro Basin is only 5m deep yet has a well defined chemocline at 2.5m (Guerrero *et al*, 1991). Deep waters in Mediterranean climates also exhibit longer periods of thermal stratification than temperate waters due to higher surface temperatures. The duration of the thermocline can typically last from April to November in eastern and southern Spain (Finlay *et al*, 1991; Prat *et al*, 1992). Development of anoxia due to thermal and chemical stratification is compounded by warmer water conditions in the hypolimnion which can cause rapid deoxygenation, even when oxygen concentrations are initially high (Moss, 1988).

The implications of all these factors leads to a higher capacity for eutrophication in Spanish waters at lower levels of primary productivity. Prat *et al* (1991) found that Saether's (1979) typology could only be applied successfully to natural lakes over 1500m in the Pyrenees and 2000m in the Sierra Nevada. The traditional classification of oligotrophic '*Tanytarsus* lakes' (Theinemann 1913, 1922; Brundin, 1949, 1956, 1958) similarly holds only at these high altitudes (Prat, 1980). Tanytarsini are rarely encountered in the majority of Spanish reservoirs, despite the low nutrient content of their recharge waters and their capacity for oligotrophy (Prat & Daroca, 1983). Prat (1980) found the geographical distribution of Tanytarsini restricted to reservoirs in the north and west of Spain, where temperatures are cooler and water level fluctuations less pronounced. No Tanytarsini were found in shallow waters between 0-10m, since these are particularly prone to eutrophication (Prat & Daroca, 1983; Prat *et al.*, 1992).

Tanytarsini are not tolerant of low oxygen concentrations, being normally associated with the shallow littoral zone of most lakes, and only the profundal zone of oligotrophic lakes. Some palaeoecological studies have applied this known relationship as a basis to interpret historical changes in water depth. Megard (1964) studied Dead Man Lake (2800m altitude) in New Mexico, finding Tanytarsini dominant both in the present lake and throughout the palaeo record. This was interpreted as reflecting little change in the current shallow (1m deep) nature of the lake, despite the existence of an outlet 16m above. It was argued by Megard that if the lake was ever this deep, a profundal zone would have developed with a sufficient seasonal depletion in oxygen to inhibit Tanytarsini. Similarly, Bryce (1962) interpreted a change from clay to calcareous sedimentation during the Boreal at Malham Tarn in England, as reflecting a fall in water depth, coincident with a change in the Chironomid fauna from *Chironomus* to Tanytarsini. Studies of *Tanytarsus barbitarsus* in Australia have demonstrated its paleolimnological value as indicative of shallow (less than 5m depth), hypersaline (35-100%.TDS) and eutrophic conditions (Kokkinn, 1986).

The dominant Chironomid fauna in shallow lakes in the Ebro Basin, however, was found to be *Chironomus* type, and not Tanytarsini (Chapter 7). Since oxygen conditions are not limiting in shallow lakes, and high sulphide concentrations would be equally fatal for all Chironomids, the main environmental factors dictating differential distribution are likely to be salinity and food supply. Little information is available on these two factors, however it would appear that salinity is not necessarily limiting given that Tanytarsini is absent from both fresh and saline shallow waters (Prat, 1980; Chapter 7). The role of food supply is discussed in the next section.

The length of the life cycle for Chironomids is extremely variable, depending on the suitability of the environment for growth. Favourable conditions can result in accelerated growth over a matter of weeks, while unfavourable conditions can delay growth over many months. *Chironomus anthracinus* larvae in Lake Esrom take 24 months to reach maturity in the hypolimnion due to annual summer deoxygenation and winter cold. Growth is suspended around the end of spring until the autumn overturn re-oxygenates the profundal waters. The same larvae in shallow waters, where there is no summer deoxygenation, can grow to maturity in less than a year (Jonasson, 1972, 1977, 1978). Chironomids are also able to survive desiccation as well as invade from neighbouring more favourable habitats (Edward, 1986).

The existence of fossil Chironomid remains is therefore not a particularly good indicator of water permanence. Other factors would appear to be equally, or more important, and indivisible given the scarcity of ecological information. Chironomids occur in both permanent and temporary (2-3 months inundation) waters in Spain, however the lack of Chironomid fauna could indicate a number of conditions not necessarily those of drought, for instance relating to anoxia, sulphide build up and food supply.

Turbidity & Temperature

Prat (1980) found a high correlation between the abundance of *Chironomus* and the concentration of chlorophyl-α in Spanish reservoirs. At high chlorophyl-α concentrations (200-700 mg Cl-α/m^2) *Chironomus* was the most abundant multicellular invertebrate in the benthos. Total Chironomid abundance was also highest at these high chlorophyl-α concentrations, with benthic productivity increasing with phytoplankton production. Shallow eutrophic waters, with a stable water level, result in the greatest quantity of phytoplankton material in the profundal zone (Prat *et al*, 1992). Fluctuating water levels restrict the development of littoral vegetation (Prat, 1980), while low water retention times restrict the build up of nutrients (Prat & Daroca, 1983). Both these factors favour oligotrophy, while water level stability and low inflow (together with low water level) favour eutrophy, and in turn, phytoplankton production and turbidity. A similar relationship between phytoplankton and benthic productivity was found by Jonassen (1964, 1972) on a seasonal basis, with high phytoplankton production in spring and autumn between winter cold and summer deoxygenation.

Periods of inorganic turbidity are often linked to rapid sedimentation related to catchment erosion. This can be particularly pronounced in reservoirs and ephemeral waters where fluctuating water levels lead to an unvegetated 'tidal' shore zone which can be easily eroded. Rapid inorganic sedimentation has been proposed by Prat *et al.* (1992) to explain the relative abundance of mobile Chironomid forms (eg *Procladius*) in some reservoirs. A relative reduction in phytophagus Chironomids is also likely, given that suspended fine sediment can reduce phytoplankton productivity by both reducing light levels and adsorbing phospates.

Dispersion & Colonisation

Chironomids are able to colonise temporary waters through two main strategies (Edward, 1986). Opportunistic species survive drying out by retreating to moist refuges, from which they re-invade when water returns. Other species are drought resistant, surviving drying out by a special stage in their lifecycle. The adult form lives for only a few days but is capable of widespread colonisation of new habitats due to its capacity for flight. Chironomid larvae are capable of tolerating a wide variety of environmental conditions and will colonise virtually any aquatic habitat free of the extremes already discussed.

Few studies have looked at the role of Chironomids in colonising new habitats, although Prat & Daroca (1983) have examined Chironomid remains from cores taken from recently constructed reservoirs in Spain. They found the time of impoundment well represented by the presence of Chironomid head capsules. During this initial phase, reservoir waters were temporarily enriched due to the release of nutrients from decaying terrestrial vegetation. Chironomid remains then declined as the water body became increasingly oligotrophic as a result of the increasing dominance of the nutrient-poor inflow waters. Importantly, Tanytarsini was well represented along with *Chironomus* during the initial eutrophic phase. Since the time period appeared sufficiently long for any stratification and deoxygentation of the reservoir waters to have already developed, this could suggest that food supply was the dominant control. In particular, the role of Tanytarsini as a detritivore could be of importance.

Within a lake body, most Chironomids occur in relation to macrophyte growth (Crisman, 1978). In the shallow Dead Man Lake, Megard (1964) found Tanytarsini larvae abundant amongst the extensive aquatic vegetation that covered the lake. Two years later the lake was absent of vegetation and almost devoid of Chironomid larvae.

3.5 Conclusions

The most commonly encountered Cladocera in salt lakes are members of the Daphniidae and Moinidae. These species produce resistant ephippia (egg sacs) which are often well preserved, but currently difficult to identify to species level due to a lack of taxonomic keys based on ephippial morphology. In general, the *Daphnia* produce ephippia containing two eggs, while the *Moina* (except the *macrocopa* group) produce single egg ephippia (Hutchinson, 1967). The *brachiata* group of *Moina* can be further distinguished according to ephippial surface patterning (Alonso, 1985).

In Spain, species from both families can be found in permanent and temporary waters upto 60*‰*, although *Moina mongolonica* has a higher lower salinity limit of 22*‰*, compared to *10‰* for *Daphnia (Ctenodaphnia) mediterranea* Alonso (Alonso, 1990). Both families are limnoplanctonic and there is evidence to suggest that algal food supply associated with macrophyte development may be the most important control on population numbers in salt lake systems. Turbidity does not appear to be a limiting factor.

Cladocera ephippia are small, light and easily dispersed, although designed to be anchored to macrophytes (Frenzel, 1983) whereupon they may be carried between water bodies by feeding birds. The resistance of ephippia to desiccation and other environmental stresses allows them to accumulate to form a 'seed' bank, permitting a rapid increase in population when favourable conditions return.

Salt lake Chironomids have been little studied in Spain, although they appear to occupy a full range of habitats from permanent to temporary waters. The head capsules of benthic larvae are well preserved within salt lake sediments and relatively easily identified from published keys. The extreme environmental conditions results in lower species diversity than in temperate and arctic lakes, reducing the resolution of the palaeoenvironmental record.

Salinity tolerances appear to be very wide for *Chironomus*, the most commonly found Chironomid in Spanish salt lakes, occurring at salinities over 120‰. Tanytarsini are not generally found even in relatively shallow waters due to the greater capacity for anoxic conditions to develop in the majority of Spanish lakes (Prat & Daroca, 1983). Seasonal thermal stratification occurs for longer periods at low latitudes than in temperate lakes and warmer water temperatures in the hypolimnia increases the risk of rapid deoxygenation. Saline lakes are further vulnerable to chemical stratification as well as sulphide build-up. While *Chironomus* can survive limited anoxia, sulphide is lethal to all invertebrates. A lack of Chironomid remains may therefore indicate depths in excess of those necessary to permit prolonged stratification (around 2.5m). At lesser depths, *Chironomus* abundance appears to be influenced by turbidity and phytoplankton productivity (Prat, 1980).

Chapter 4

Study Area: The Central Ebro Basin

4.1 Abstract

The central Ebro Basin is a large geologically controlled depression in north-east Spain, filled by Tertiary evaporites and surrounded by high mountain ranges. The climate is Mediterranean and semi-arid, with large diurnal and seasonal extremes. Vegetation forms a concentric zonation from the arid central steppe with juniper, to allepo pine and kermes oak matorral, then finally to holm oak forest in the surrounding foothills. Endoreic salt lakes occur within the arid central area, fed by groundwaters rich in sulphates. Palaeoenvironmental investigations have been centred on these lake systems.

4.2 Introduction

The Ebro Basin is a geological depression which forms the hydrological catchment of the Rio Ebro, flowing for 300km from the Cantabrian mountains on the Atlantic seaboard in the west, to the Mediterranean Sea in the east (*Figure 4.1* p63). High mountain ranges surround the basin from the Pyrenees to the north, the Cantabrian Cordillera in the west, the Iberian System in the south and the Catalonian mountains to the east (*Figure 4.2* p63). These mountains effectively intercept any rainfall from reaching the central area of the depression, forming the most northerly area of truly semi-arid climate in Europe. The little rainfall that falls during the bitterly cold winter is greatly exceeded by evaporation during the long, hot, dry summer. Vegetation is poorly developed under these harsh conditions, consisting mainly of steppe on the central plains, but changing rapidly along the sharp climate gradient from pine and evergreen oak to deciduous forest high in the surrounding mountains.

Water draining from these surrounding hills has been increasingly diverted for irrigation purposes, however drainage in the arid central area is poorly developed with large endoreic areas. Groundwater discharge and limited precipitation runoff within these areas sustain a series of small salt lakes (*Figure 4.2* p63). Nearly 100 such lakes occur in the largest area called Los Monegros, near the town of Bujaraloz (41°29'50"N 0°09'06"W), 20km to the north of the Rio Ebro. Other smaller areas occur to the south of the Rio Ebro, near the towns of Caspe, Alcañiz and Hijar.

Palaeoenvironmental investigations have mainly been centred around these lakes (*Figure 4.3* p64 & *4.4* p65). Other similar lakes occur around Zaragoza to the west but were found to be unsuitable due to recent drainage for cultivation or flooding for irrigation. The Laguna Gallocanta lies to the south of the Ebro Basin and was also investigated. This lake is the largest natural lake in Spain and lies at a higher altitude within a

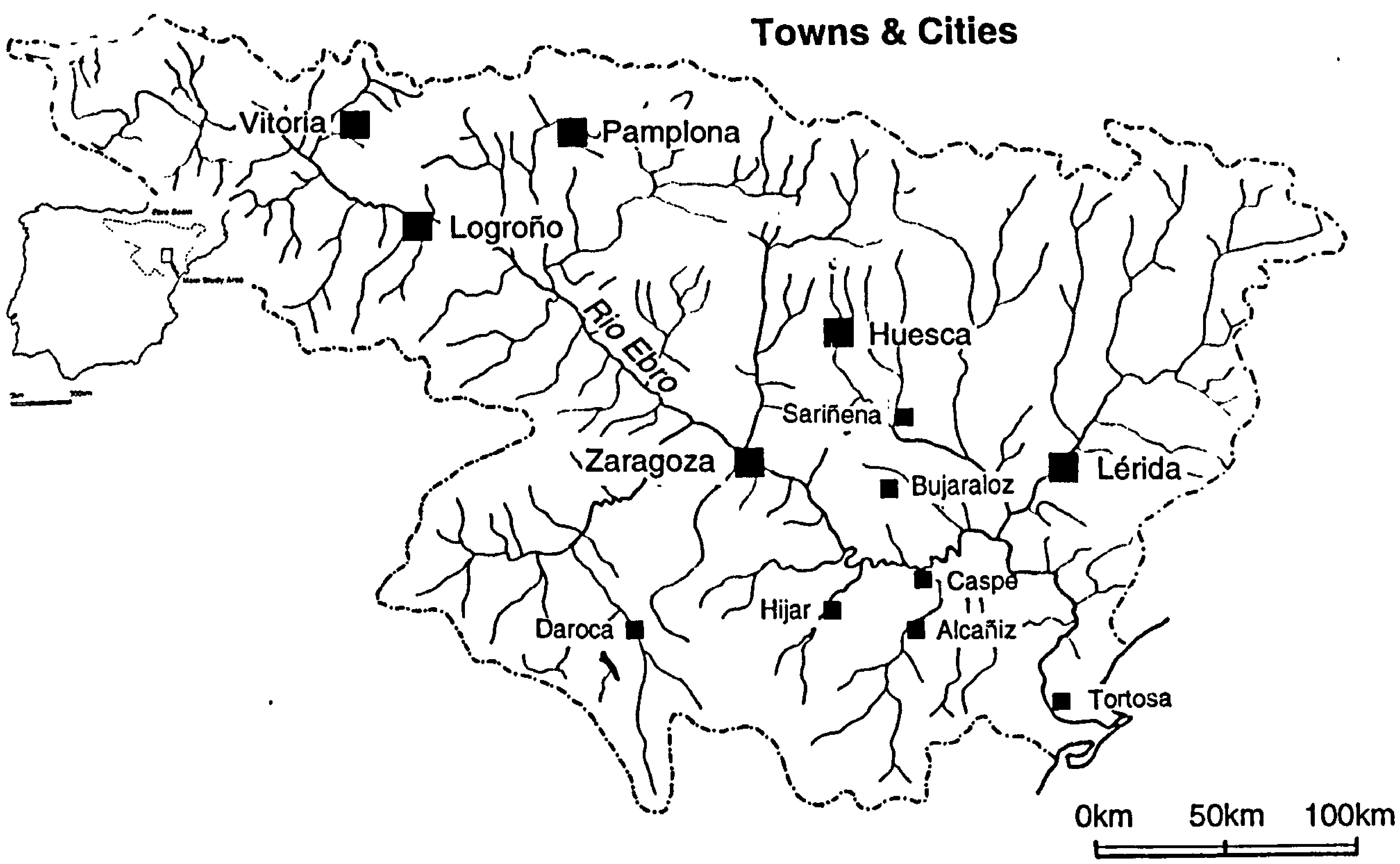


Figure 4.1 Map of the major towns and cities in the Ebro Basin

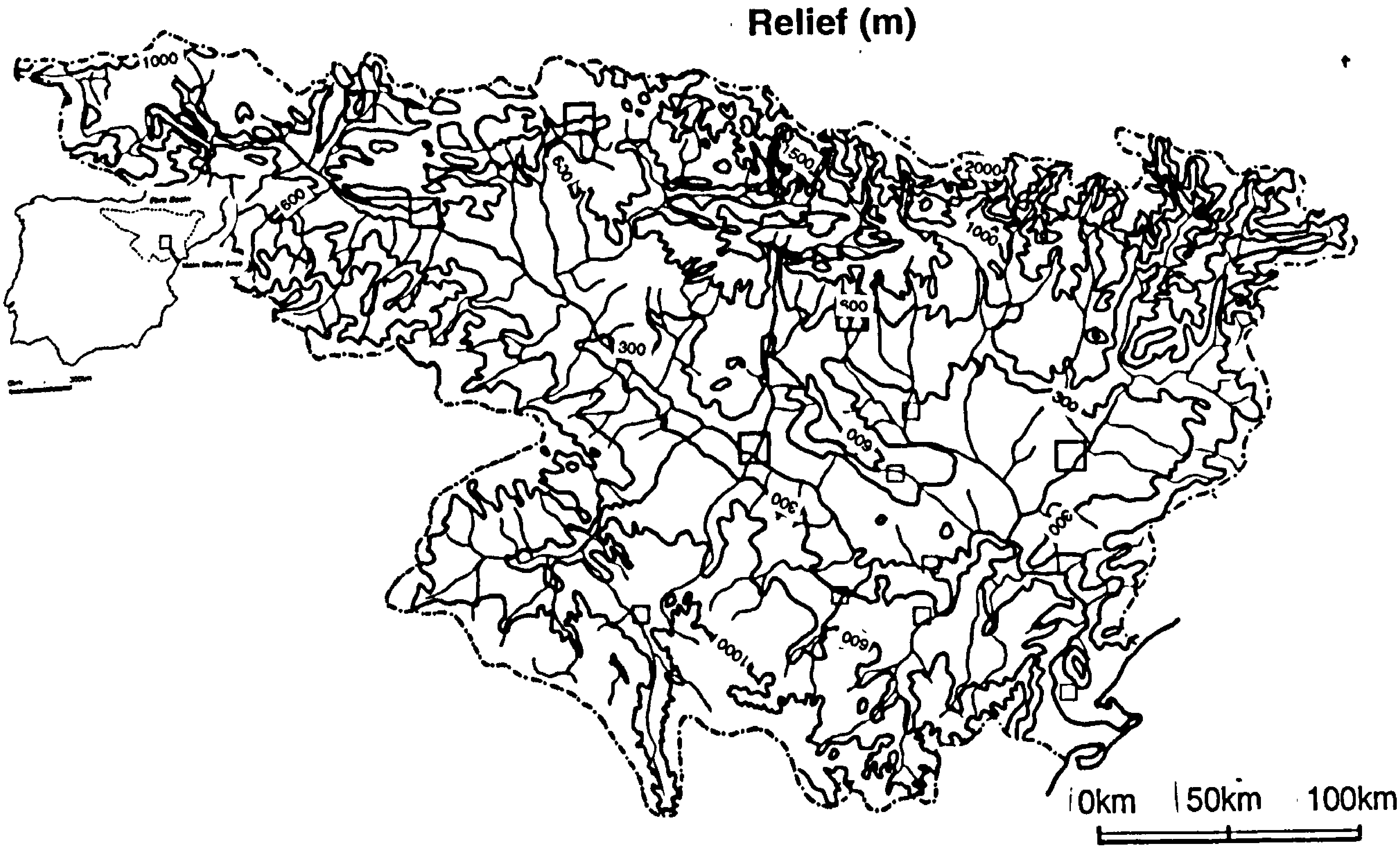


Figure 4.2 Map of the topography of the Ebro Basin

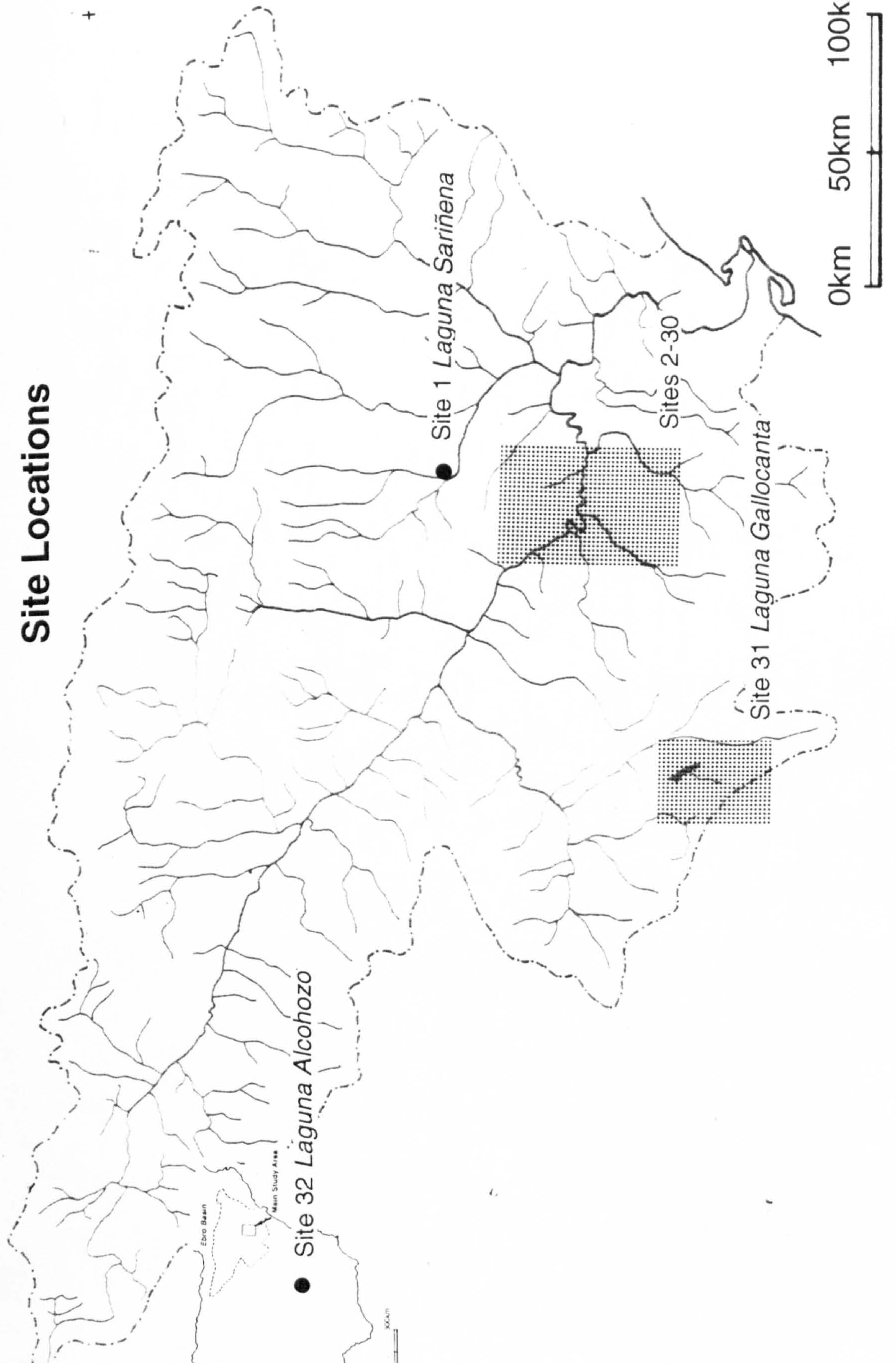
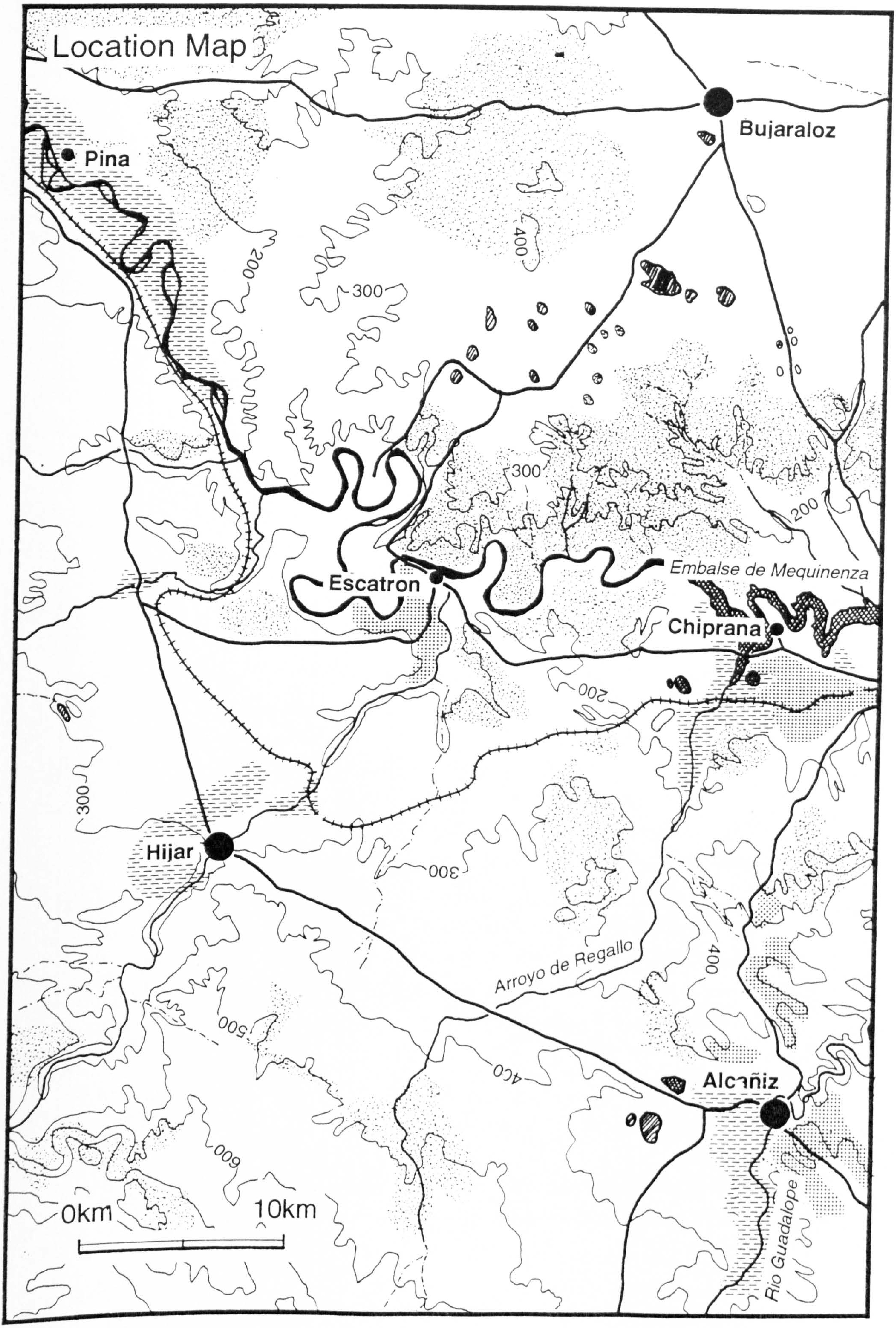


Figure 4.3 **Location map of study sites in the Ebro Basin**


Location Map
Bujaraloz
Pina
200
300
400
300
200
Embalse de Mequinenza
Escatron
Chiprana
200
300
Hijar
300
Arroyo de Regallo
400
500
400
Alcañiz
600
0km
10km
Rio Guadalope

separate tectonically formed endoreic basin, with a cooler and wetter climate. Details of this area are dealt with in chapter 9, subsection 9.7.

4.3 Geology

The geology of the Ebro Basin is dominated by Oligocene and Miocene evaporites deposited after the basin was formed as a result of subsidence early on in the Tertiary (*Figure 4.5* p67). Subsidence allowed the sea to invade, forming a shallow lagoon in which marine evaporite minerals were deposited. During the Oligocene, access to the basin by the sea became more restricted, resulting in a mixture of both marine and continental facies. By the Miocene, the basin was cut off entirely from the sea, with only continental facies deposited, consisting of lacustrine clays, marls, gypsum and limestones. Little tectonic activity has occurred since the deposition of these deposits which have retained much of their structural horizontality (Embleton, 1983).

The formation of the basin in its modern form began when the River Ebro started to discharge through the Catalonian mountains to the Mediterranean sea, some time at the end of the Tertiary and the beginning of the Quaternary. Erosion and denudation followed, giving rise to deep valleys and scattered accumulations of fluvial gravels, detritus and silts in the form of debris cones and alluvial terraces (Zuidam, 1975).

4.4 Geomorphology

Relief within the Central Ebro Basin consists largely of flat or rolling limestone capped plateaus between 300-350m a.s.l, bordered by steep escarpments. The extreme aridity of the area has resulted in an incomplete drainage network, leaving areas of endoreic drainage at the interfluves of the current river system (*Figure 4.6* p67). Ponding of waters in these areas is encouraged by impermeable clays and marls below, as well as upward groundwater flow, resulting in '*drenaje impedido*' (impeded drainage).

Within these endoreic areas are a network of playa lake systems, the origins of which were first investigated by Dantin Cerada (1942), and later by Quirantes (1965) and Ibanez (1973, 1975). Sánchez *et al* (1991) provides a summary of current thinking (*Figure 4.7* p68).

Two main processes have been used to explain the origin and evolution of depressions and playa lakes in the Ebro Basin. The first processes is common to endoreic areas in the region of Los Monegros and Hijar and involves karstification through the dissolution and collapse of limestones and gypsum. The second process involves differential erosion by deflation in areas around Alcañiz and Caspé, constrained by a network of resistant sandstone palaeocanals.

4.5 Climate

The climate of the Ebro Basin is semi-arid Mediterranean, with rainfall as low as 300-350mm/yr in the central area due to interception of precipitation by the surrounding mountain ranges (*Figure 4.8* p69). Rainfall

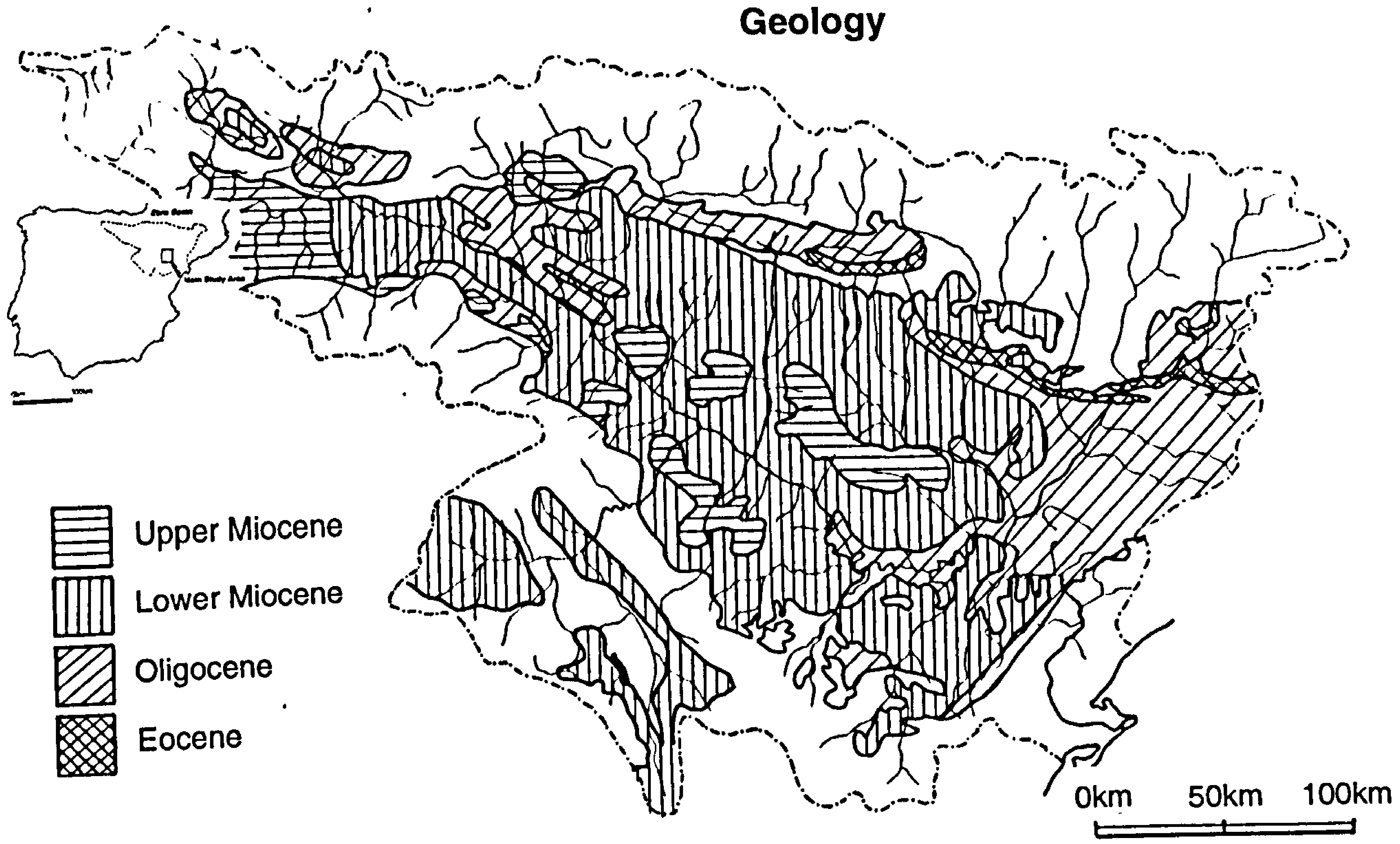


Figure 4.5 **Map of the geology of the Ebro Basin**

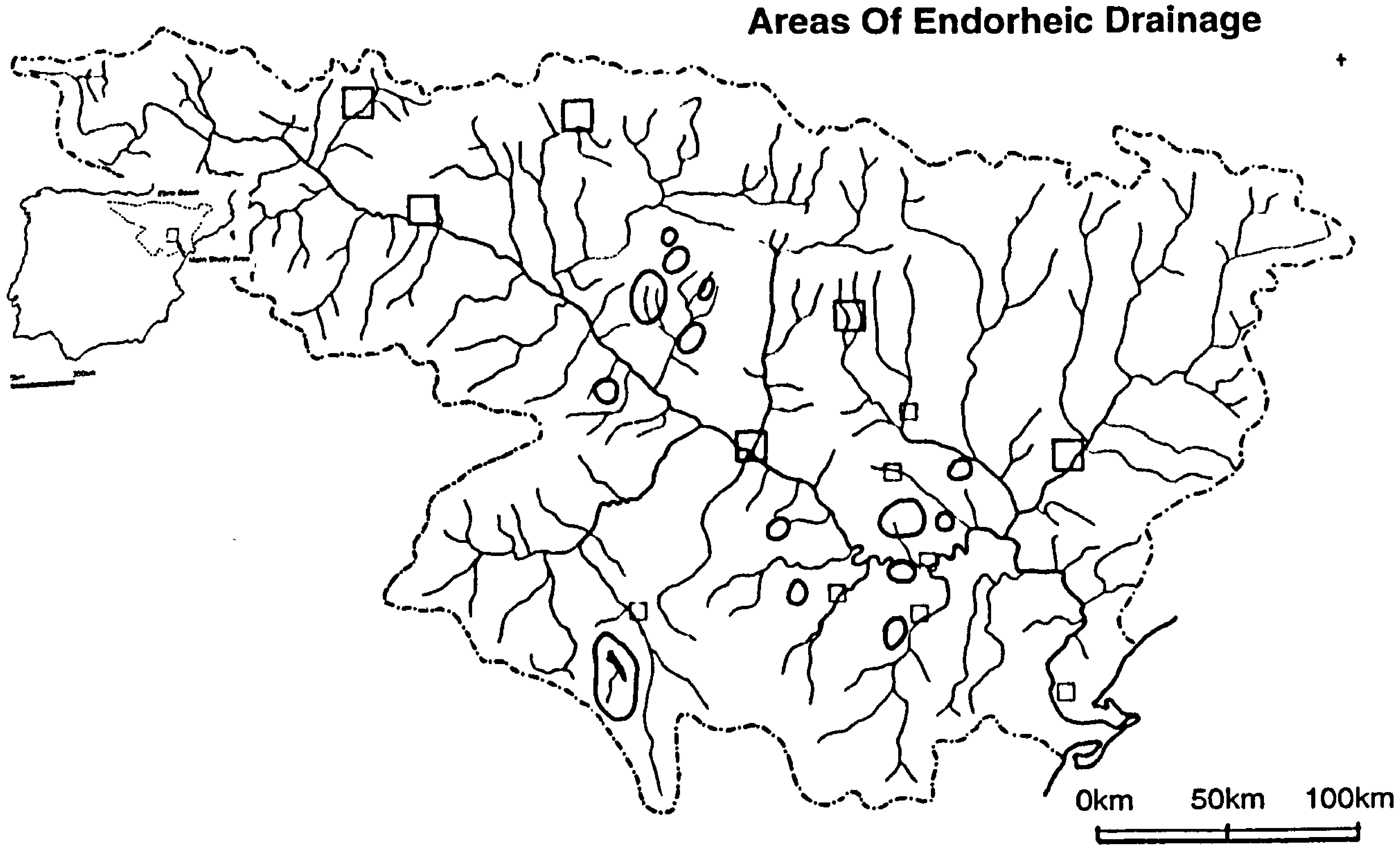
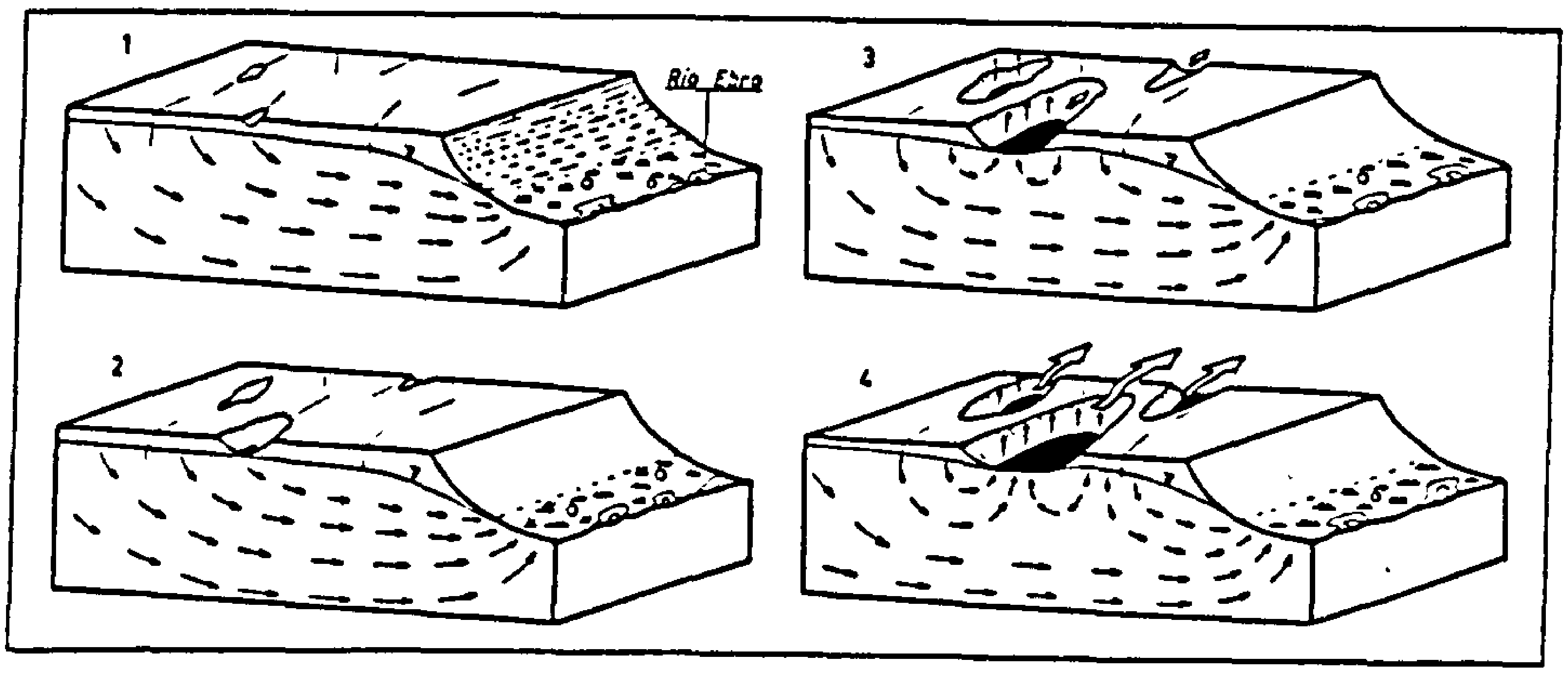
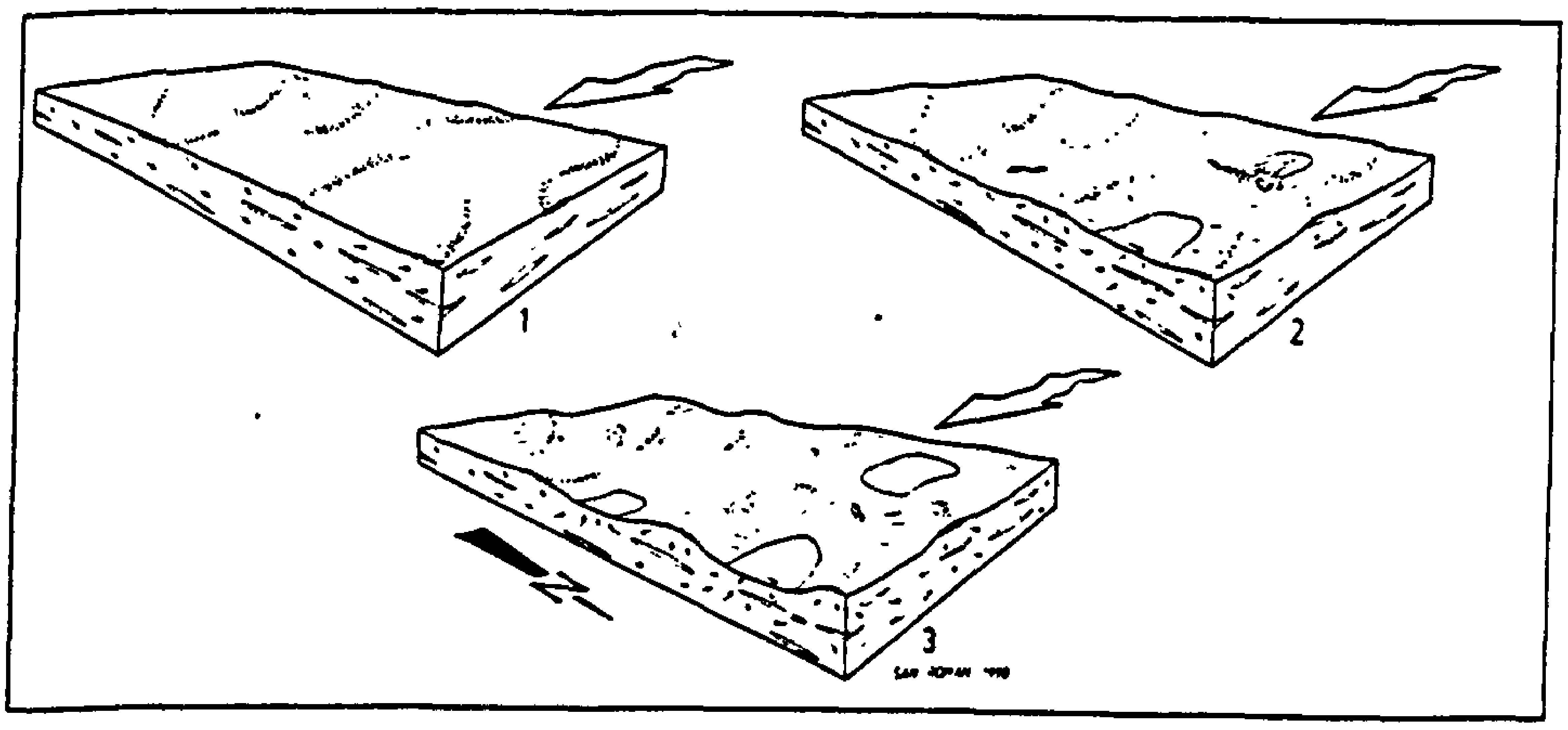


Figure 4.6 **Map of the main areas of endoreic drainage in the Ebro Basin**



Los Monegros/Hijar

1. Meteoric waters start to infiltrate in the more permeable areas, such as along the fault system. Carbonaceous and gypsiferous material is dissolved and carried in solution down to the phreatic surface where it then joins the general subterranean flow.
2. A doline-like, funnel shaped, closed depression starts to form which continues to deepen down to the phreatic surface. On reaching the phreatic surface, water inundates the depression forming a playa lake.
3. The exposed phreatic surface starts to generate evaporatic pumping, causing a water gradient around the lake similar to that formed around a well during extraction. The water gradient provokes an upward flow of groundwater preventing the infiltration of meteoric waters and resulting in so called 'impeded drainage'. The lake water becomes more saline as it becomes unable to dispose of salts through downward flow, and the ascending groundwater inputs yet more salts into the lake.
4. Evaporation of the lake waters provokes precipitation and accumulation of salts and organic remains in the depression to form an extremely flat surface morphology typical of a *sebkha* environment. Continued lateral dissolution of the depression results in yet more groundwater flow to the lake. Excavation of precipitated salts is possible by the action of the wind.



Alcañiz/Caspe

1. The initial surface topography is flat, inclined slightly away from the nearby mountains, with the sandstone palaeocanals entirely buried within alluvial mudrock. Superficial and subterranean meteoric waters initiate the weathering of the terrain. Wind action causes the deflation of the mudstone material, contrasting with the sandstone palaeocanals where erosion is confined to corrosion. These sub-horizontal structures impede superficial drainage, further concentrating water into large depressions.
2. Differential erosion by the wind creates depressions in the mudstone surrounded by palaeocanals. Lake formation occurs when the phreatic surface is reached.
3. Evaporitive pumping causes local groundwater flow into the lake which is then joined by other major routes providing waters rich in dissolved salts. Evaporitic concentration causes the precipitation of these salts which become deposited in the lake together with eroded mudstone. The bottom of the lake is extremely flat, typical of a sebkha environment.

Figure 4.7 **The origin and evolution of closed basins in the Central Ebro Basin**
(Sánchez *et al.*, 1991)

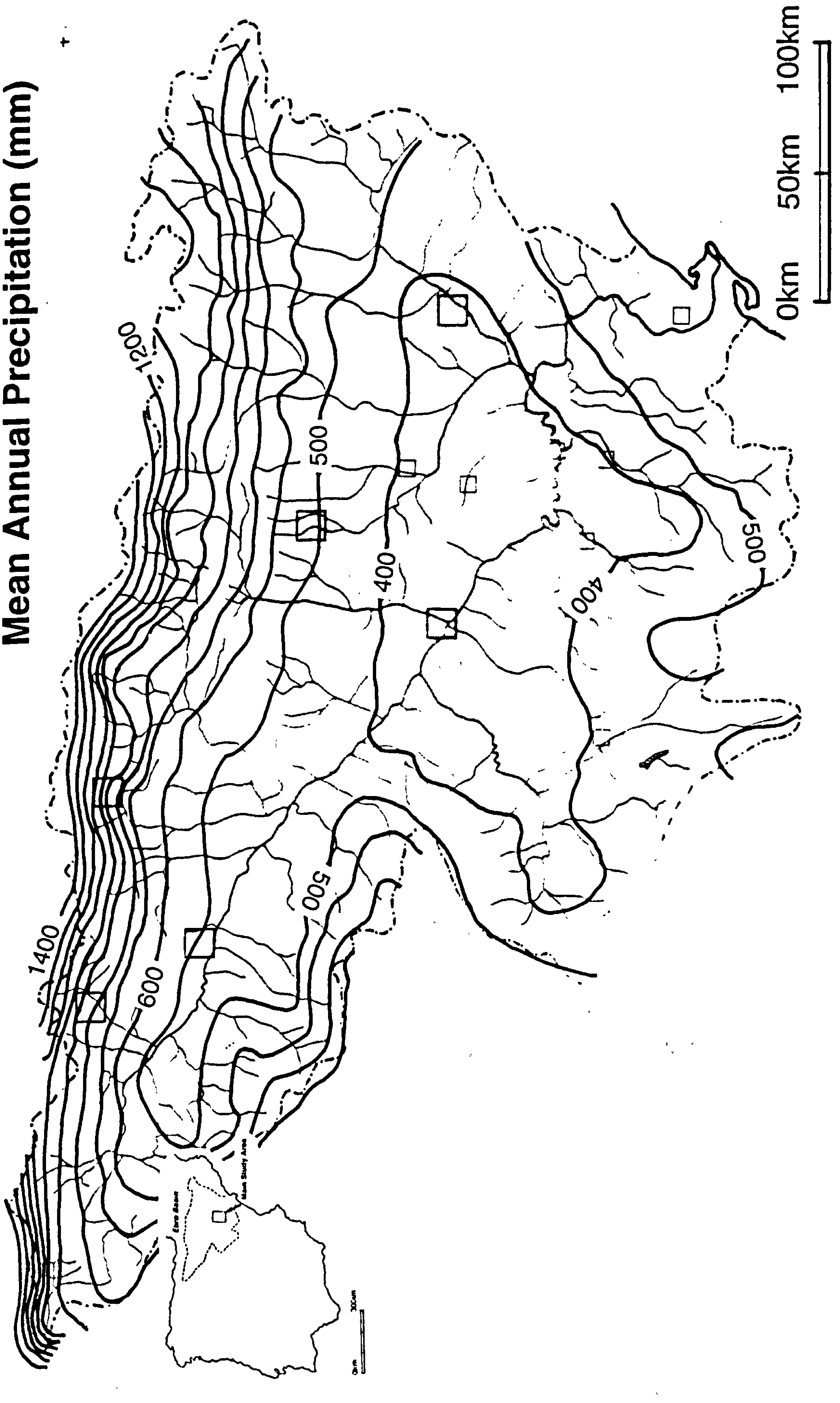


Figure 4.8 Map of mean annual precipitation in the Ebro Basin

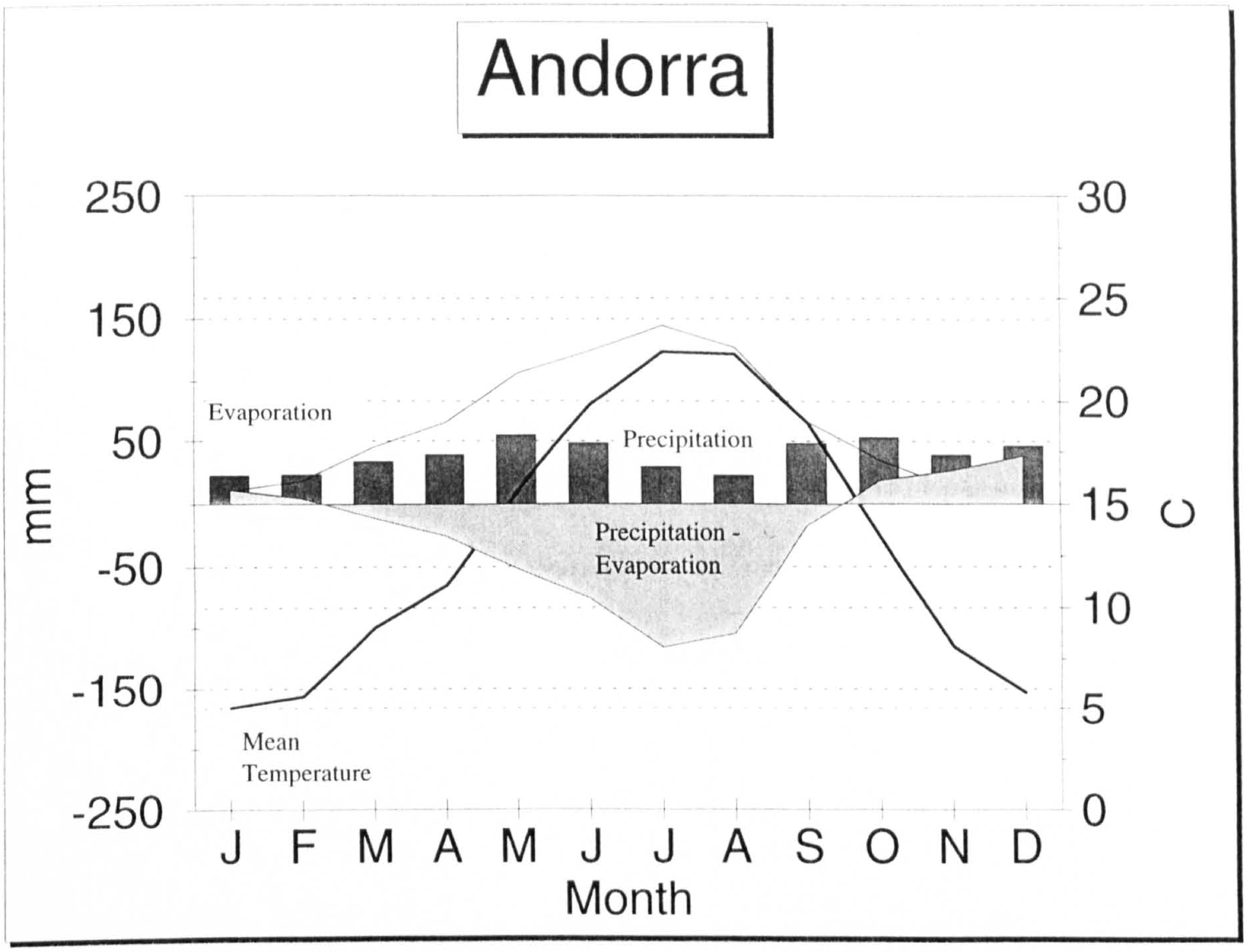


Figure 4.9A **Climogram of monthly temperature, precipitation and evaporation: Andorra**

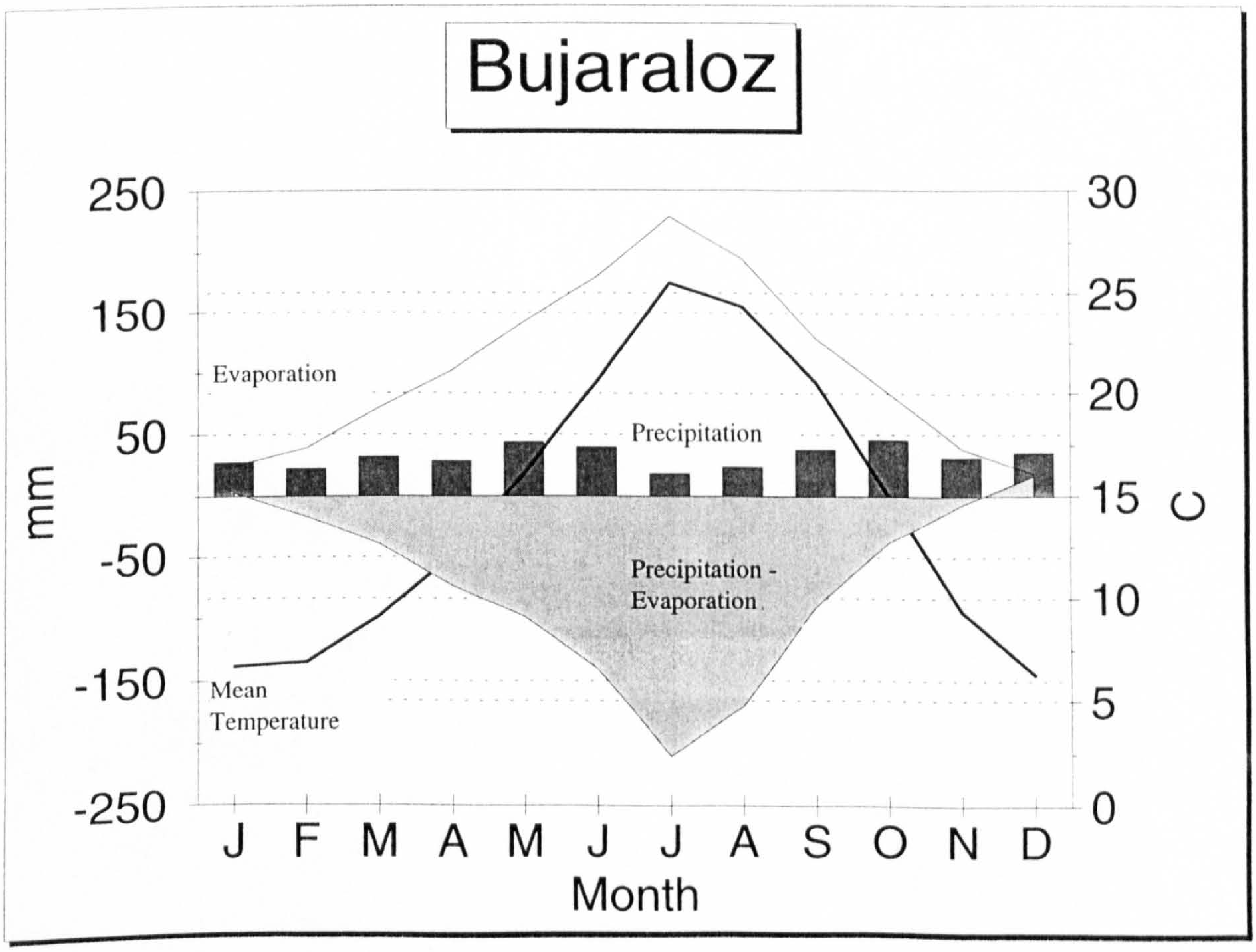


Figure 4.9B **Climogram of monthly temperature, precipitation and evaporation: Bujaraloz**

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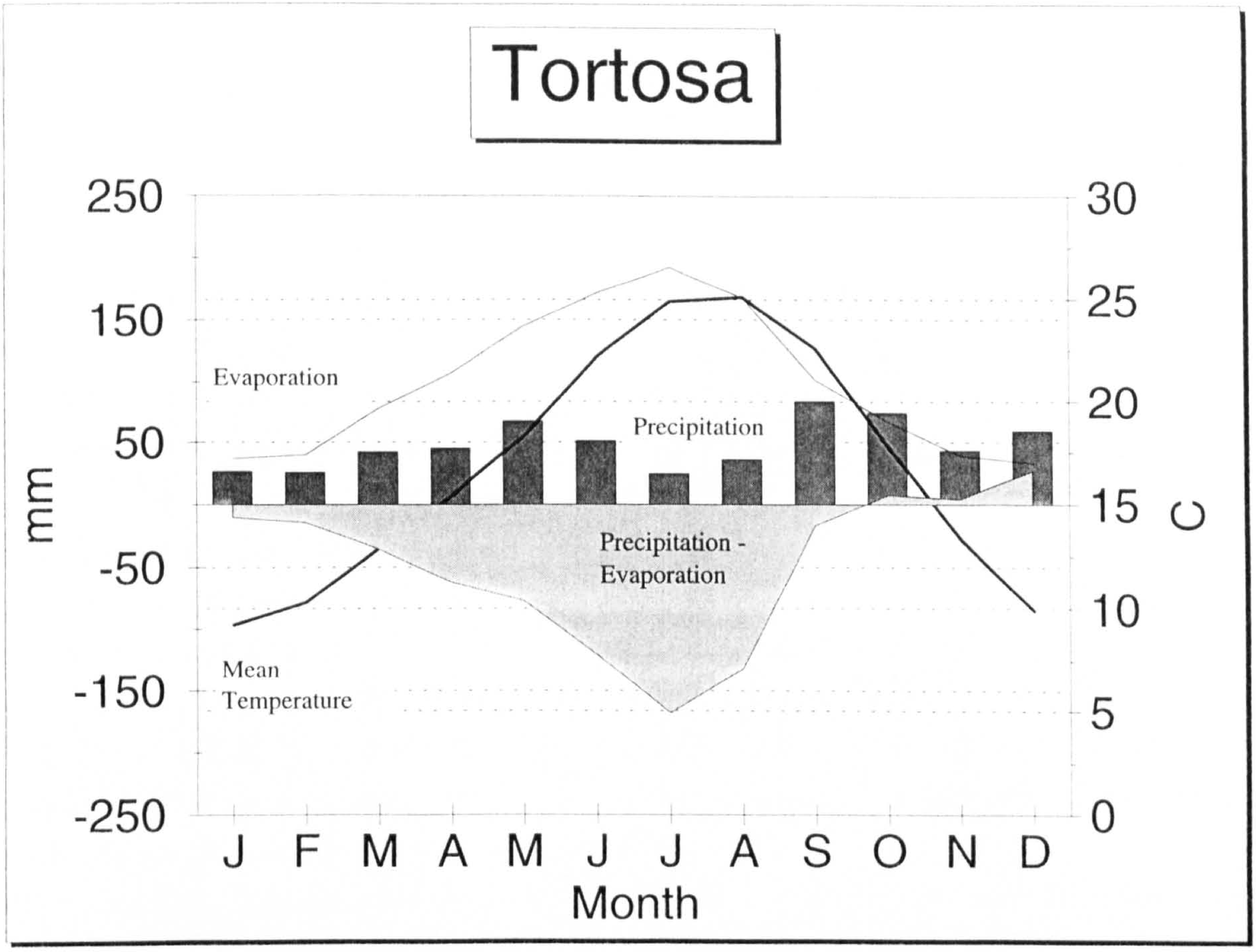


Figure 4.9E **Climogram of monthly temperature, precipitation and evaporation: Tortosa**

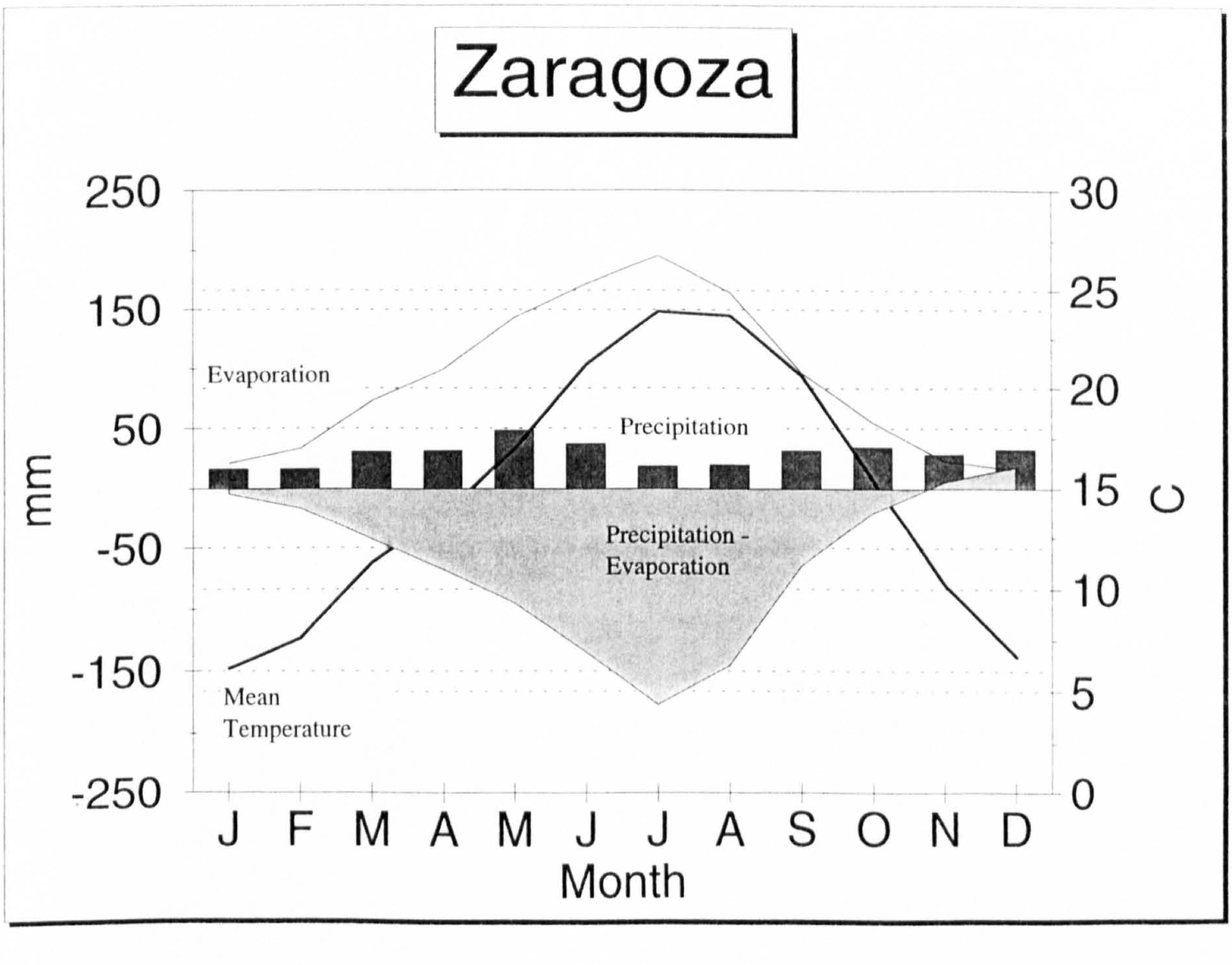


Figure 4.9F **Climogram of monthly temperature, precipitation and evaporation: Zaragoza**

increases towards the surrounding mountains to around 500mm/yr on the lower slopes, rising to over 1000mm/yr with greater altitude in the Pyrenees to the north. In common with most of the north-east of Spain, the seasonal pattern of rainfall is not typically Mediterranean (*Figure 4.9 A-F* p70-72). Instead, precipitation is bi-modal, being highest in spring and autumn and lowest in summer and winter. February is the driest month of the year at Zaragoza (*Figure 4.9 F* p72). This is due to the movement of the southern branch of the polar jet stream which lies north of the area in summer and south in winter. Depressions associated with the jet stream only affect the area in spring and autumn when the jet stream is in the process of moving north or south. In winter, when the jet stream steers depressions towards the straights of Gibraltar, the size of the peninsula is sufficient for it to form a winter anticyclone which reduces precipitation still further. The mid-winter drought is particularly important for groundwater recharge since it is at this time of the year when cool temperatures restrict evapotranspiration and permit a hydrological surplus to develop (P-Et > 0.0). The fact that this time also coincides with low precipitation clearly reduces the amount of recharge that will occur.

The inter-annual distribution of rainfall typically shows large variations. For instance annual rainfall at Alcañiz in 1966 was 287mm, while in 1969, 561mm fell (Peña & Echeverriá, 1991). Rainfall tends to be concentrated, with fewer than 60 days of rain in Lower Aragon, leading to potentially erosive, high intensity rainfall up to 110-120mm/24hrs (Peña & Echeverriá, 1991).

Mean annual temperature is around 14°C but is markedly continental with cold winters and hot summers resulting in an annual range of over 19°C. Annual temperatures decline with distance from the centre of the basin and the Mediterranean Sea in the east (*Figure 4.10* p74). Mean January temperatures are typically around 5-6°C, while mean July temperatures are between 22-25°C, rising up to 35-41°C. Extremes of temperature on the central plains of Los Monegros have been recorded as low as -15.5°C in winter and 44.1°C in summer (Blanché & Molero, 1986). This area is particularly prone to the formation of temperature inversions, giving the local climate a more montane character, together with a higher frequency of late frosts (Terradas, 1986).

Winds can be particularly strong across the bare central plains, leading to high evaporation and evapotranspiration rates when linked with insolation and high summer temperatures. The *cierzo* is a strong warm wind that blows in spring from the north or north-west, while in winter a *mistral* type wind called the *tramontano* can affect plant growth (Way, 1962). Lack of rainfall together with high potential evapotranspiration of 1000-1300mm/yr leads to a marked soil moisture deficit between May and October.

4.6 Hydrology

Endoreic lake hydrology has been studied by Sánchez *et al* (1989), Samper & Garcia (1992) and Samper *et al* (1993) in the Los Monegros region, and by Sánchez *et al* (1991) in the area around Alcañiz. Other studies concerning water chemistry and lake sediment mineralogy have been made by Pueyo (1979), Alonso & Comelles (1985), Pueyo & Inglés (1987), Martino (1988), Guerrero *et al* (1991), Peña & Echeverría (1991) and García (1992).

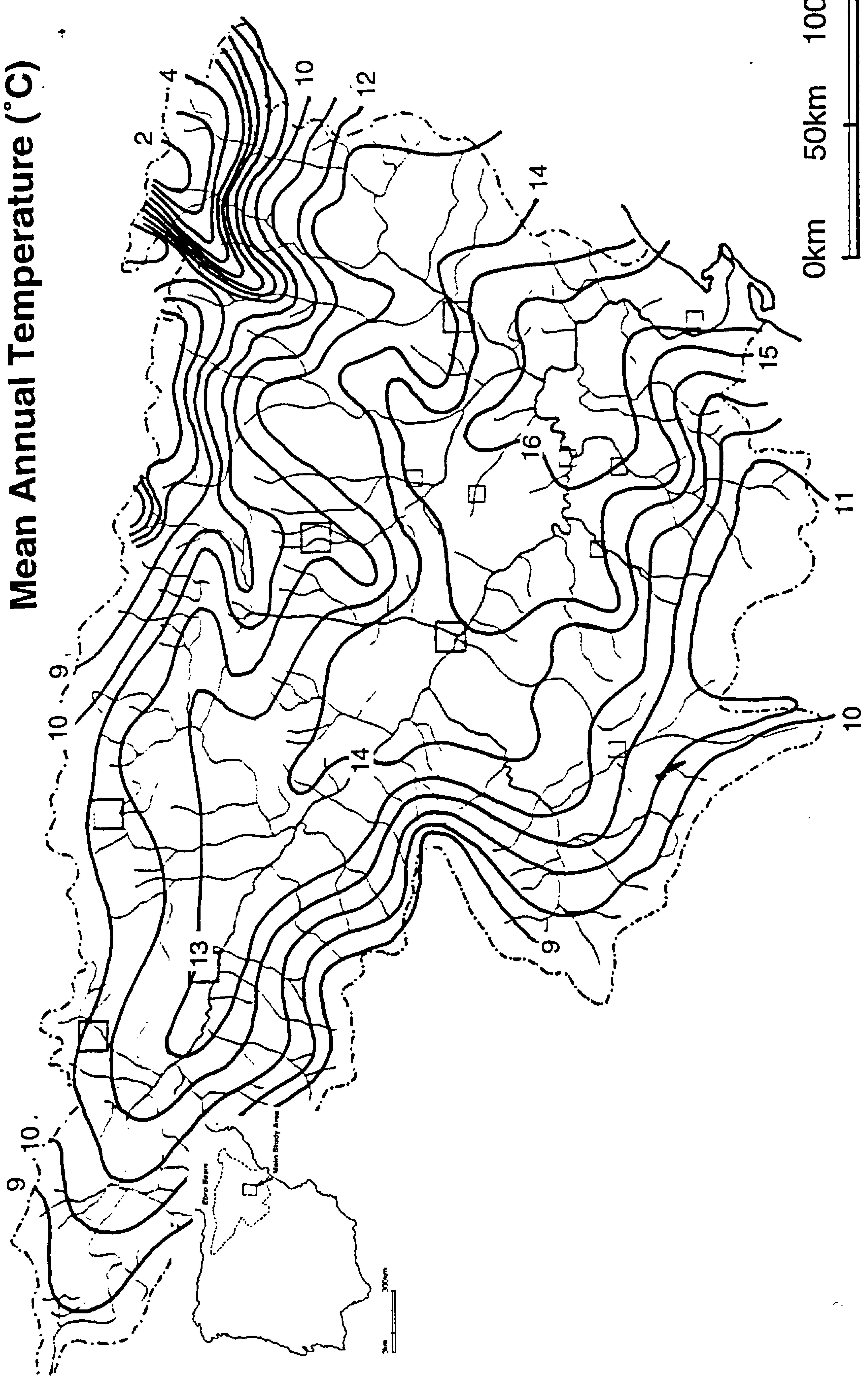


Figure 4.10 Map of mean annual temperature in the Ebro Basin

Despite the large number of endoreic depressions in the Ebro Basin area, only relatively few regularly hold water, and most of these for only a few months of the year. Superficial drainage systems converging on the lakes are limited, and the period of inundation does not usually coincide with the wettest half of the year, implying that groundwater flows maintain water levels into the hydrological deficit period (see Chapter 7). Typical water levels in the seasonal playas do not normally exceed 0.4m, however, water lies over 5.0m deep throughout the year in the Laguna Salada, suggesting a major contribution by groundwater in an area that receives only 300mm/yr rainfall.

Evaporation from the free surface of the lakes is between 1000-1500mm/yr (Sánchez *et al*, 1991), and far in excess of the 300-350mm/yr annual rainfall. The contribution by groundwater, however, is restricted by low hydraulic flow due to the fine grained nature of the Tertiary sediments. High porosity but low permeability mean groundwater flow is slow but constant throughout the year. In winter, evaporation output (<0.5mm/day) from the lake surface is less than the groundwater input, allowing surface water to accumulate along with inputs from direct precipitation and runoff. As summer approaches, evaporation increases (>10-12mm/day) in excess of the groundwater flow, resulting in a fall in water level to just below the sediment surface (Sánchez *et al*, 1991). Although the lake surface appears dry, the sub-surface remains saturated and groundwater flow continues through capillary rise.

Lake systems represent areas of groundwater discharge where the shallow aquifer reaches the surface to evaporate. Even away from the lake depressions, the water table is not far from the surface, lying within 10-11m at the interfluves (García, 1992).

In the Los Monegros region, Samper *et al* (1993) found that groundwater is constrained within horizontally bedded lacustrine limestones, alternating with marl and gypsum layers upto 40m deep. Below this, the aquifer is restricted by heterogeneous detritic clays with some gypsum beds. Flow within the aquifer is heterogeneous across a wide area, although permeability is low, and recharge crudely estimated at 20-45mm/yr.

A similar situation has been found by Sánchez *et al* (1991) in the Alcañiz region, although here, sandstone palaeocanals may represent ribbons of locally enhanced flow. Recharge of groundwaters occurs in the Iberian Mountains to the south, whereupon transmission occurs through low permeable Tertiary sediments to emerge in areas of discharge to the north. Recharge in the Los Monegros area is similarly thought to occur in the Sierra de Alcubierre to the north of the area (Sanchez *et al*, 1989).

4.7 Hydrochemistry

Long flow paths and high residence times through Tertiary evaporites mean groundwaters are generally high in dissolved salts. Further concentration occurs through the action of evaporation in the region of lake bodies, most of which evaporate dry in the summer. Typical groundwater salinities are around 6%*o*TDS, rising to 30%*o*TDS (seawater 35%*o*TDS) near lake bodies, with lake brines ranging from 2%*o*TDS (drinkable by livestock (Balsa *et al.*, 1991)) to over 300%*o*TDS towards the end of the evaporitic cycle (Balsa & Montes, 1991). Salt concentration in lake waters varies considerably between different lakes, different times of the year and between different years.

Lakes with the highest salt concentrations tend to be seasonal, but with sufficient groundwater input to maintain surface water into the late spring/summer evaporation period. Where groundwater flow is insufficient, water levels tend to drop below the lake bottom early on before much evaporative concentration can occur. Lakes and depressions which only flood occasionally have the lowest salinities, since groundwater inputs of salts are limited and can be removed in solution by the free drainage of meteoric waters. Most salts in solution in lake waters come from the re-solution of minerals precipitated the previous year. Much lower contributions are provided by salts dissolved in groundwaters and those picked up from surficial sediments by meteoric waters. For this reason, total concentrations and particularly ionic composition tends to vary little from year to year independent of dilution. Over time however, a general trend occurs towards domination by sodium ions since these are more soluble than gypsum, calcite and especially silicates (Martino, 1988). Dry, ephemeral and permanent lakes are more stable than seasonal and semi-permanent lakes since the latter are more likely to suffer from changes of greater amplitude, particularly during drying episodes when a greater quantity of salts can be lost by deflation (Comín *et al*, 1990).

Dilution of lake waters occurs with the onset of autumn rains, with lakes reaching a maximum depth around early spring. Rainfall may continue into late spring and heavy showers are not unknown in the summer months, however soil moisture deficits, low relief and intense evapotranspiration allow little to reach lake bodies. Runoff typically contributes less than 10% of rainfall to lake waters (Garcia, 1992)

The mineral composition of lake waters is dominated by sodium, chloride and sulphate ions as a result of inflowing waters highly mineralised by Tertiary evaporites particularly rich in gypsum. Most lakes following Eugster & Hardie (1978) IIIb type: $Cl-SO_4-Na-(Mg)$ (Pueyo, 1979). The permanent Laguna Salada has waters richer in sulphate and magnesium ($SO_4-Cl-Mg-Na$ type) (Guerrero *et al*, 1989). Groundwaters are $MgSO_4$ or $CaSO_4$ type (the former is more common near to lake bodies) and are saturated with respect to calcite, and often gypsum (Samper *et al*, 1993).

Mineral deposition is correspondingly dominated by the more insoluble sulphates (mainly gypsum, but also mirabilite, thernadite and bloedite), although chlorides (halite) dominate in the surficial layers of ephemeral lakes. Carbonates (aragonite, dolomite) are only present in minor amounts, with most being represented by detrital calcite (Pueyo, 1979, Pueyo & Inglés, 1987).

4.8 Soils

Soils across the limestone plains of Los Monegros are mainly grey, sub-desert type, becoming dominated by marl and gypsum rendzinas on the slopes (Blanché & Molero, 1986). To the south of the Ebro the humus horizon is poorly developed on limestone regolith, while grey, sub-desert type soils occur on unconsolidated material (ICONA, 1986). In the vicinity of valleys and depressions soil development reflects the diametric distribution of soil moisture availability and soil salinity (Terradas, 1986). The bottom of depressions in particular contain alkaline, saline soils which are seasonally affected by the precipitation of salts (Blanché & Molero, 1986).

4.9 Vegetation

Poor soils, low rainfall and severe annual and diurnal temperature ranges combine to give the Central Ebro Basin one of the poorest vegetation landscapes of the Iberian Peninsular (Ferrar, 1960). Braun-Blanquet (1957) found the flora more comparable with Mauritania than the rest of Spain.. "a little piece of North Africa in Europe". In the phytoclimatic classification of Spain by Allué Andrade (1986), areas of the Central Ebro Basin are identified as 'Subarid Mediterranean', a category that only occurs elsewhere in the arid southeast of Spain (*Figure 4.11* p78).

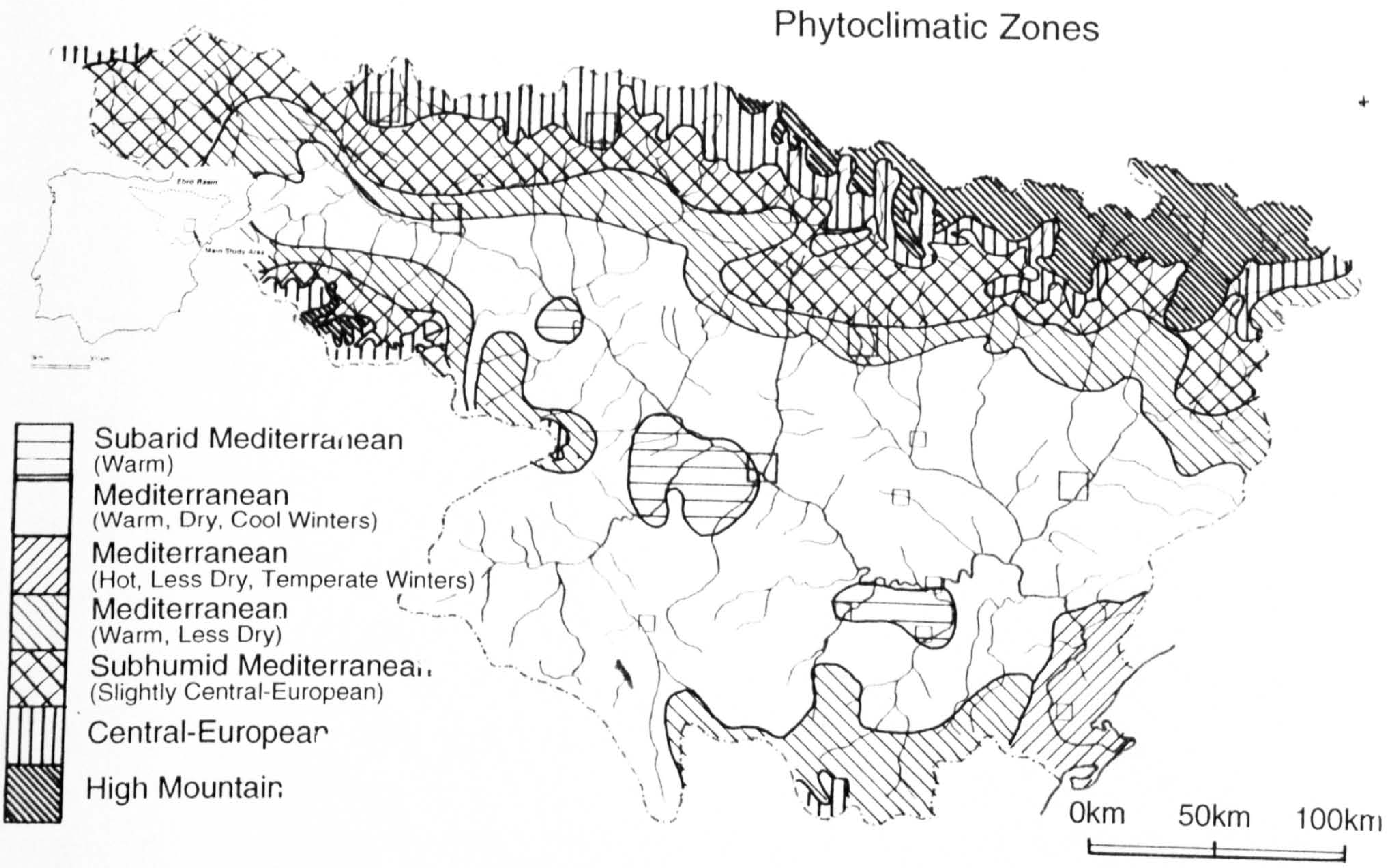
The present landscape is virtually a tree-less steppe currently dedicated to the dry-farming of winter wheat. As with much of the Mediterranean, anthropogenic action has long contributed to the degradation and destruction of the natural vegetation through grazing, ploughing and the collection of firewood.

An almost concentric pattern of vegetation separates the arid central steppe from the wooded foothills of the surrounding mountains (*Figure 4.12* p78). Braun-Blanquet & Bolos (1957) distinguished three altitudinal zones of climax vegetation associations within the central Ebro Basin reflecting this zonation:

1. 350-400m	*Juniperus thurifera* (*Rhamneto-Cocciferetum thuriferetosum*)
2. 400-700m	*Pinus halepensis* & *Quercus coccifera* (*Rhamneto-Cocciferetum caricetosum humilis, pistacietosum* & *cocciferetosum*)
3. 700m+	*Quercus ilex spp. rotundifolia* (*Quercetum rotundifoliae*)

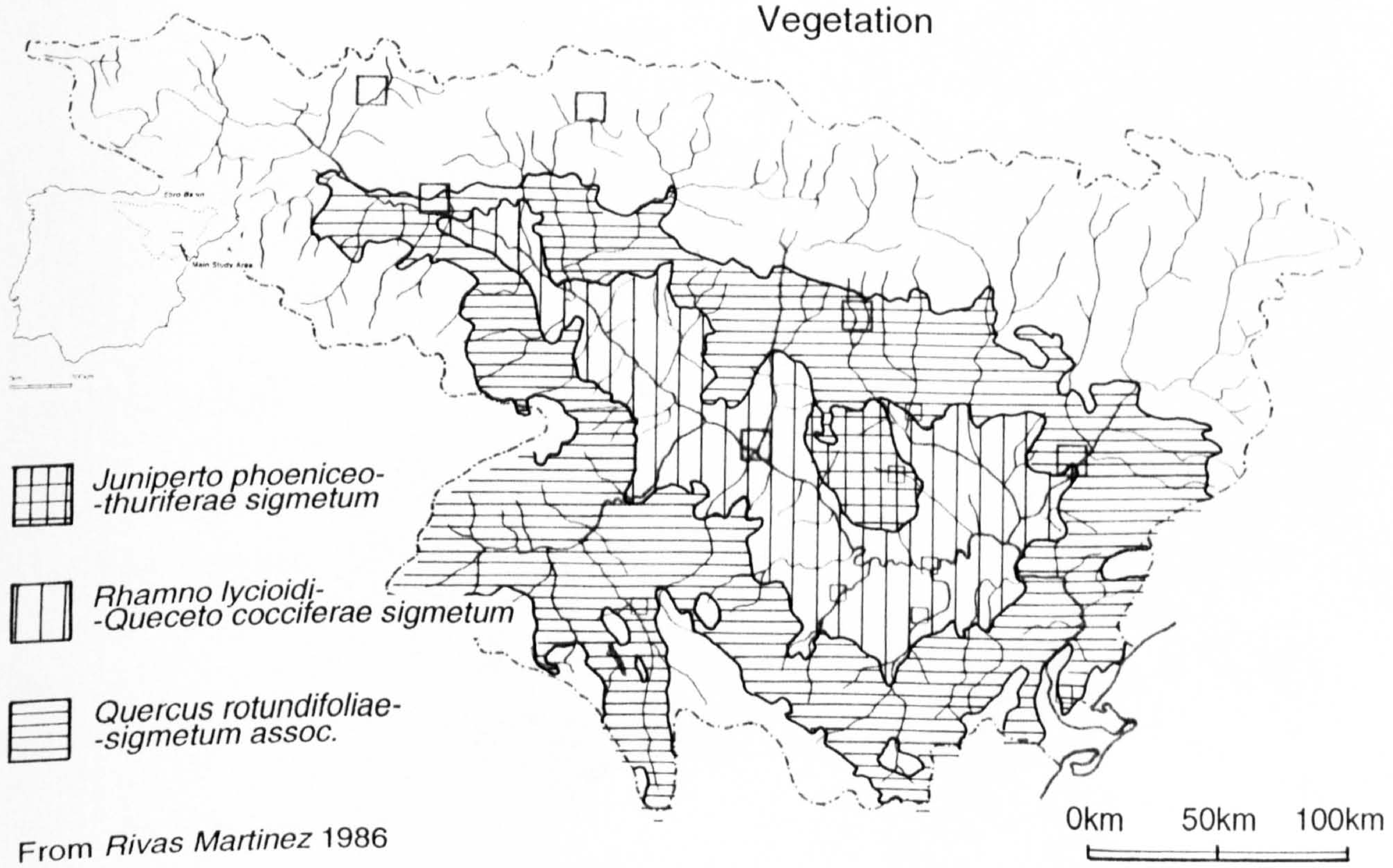
The lowest natural forest climax on the Los Monegros plain is currently represented by isolated trees of *Juniperus thurifera*, thought once to represent a much larger juniper forest from which the area gained its name '*Los Monegros*', derived from '*Monte Negros*' ('Black Hills') (Balsa & Montes, 1991). Vestiges of this former forest still remain around Rotuerta, where *J.thurifera* can still be seen competing successfully with pine upto around 500m near Monegrillo, on the southern slopes of the Sierra de Alcubierre (Ferrar, 1960). The presence of *J.thurifera* is linked to the development of regular thermal inversions in winter which give the central plains a more montane climate than their altitude would suggest. *Juniperus thurifera* also occurs to the south in the Iberian Mountains, but here it is found at much greater altitudes, between 900-1000m (Pérez-Obiol & Roure, 1991)

The majority of the central plains are dominated by grass steppe (*Agropyro-Lygeion*), including *Lygeum spartum* (albardín) and *Stipa*, typical of arid Iberian and North African steppe. On poorer, stony ground or in areas rich in marl or gypsum, other open steppe communities typical of arid Mediterranean areas can be found. These include slopes with thin skeletal soils (*Rosmarino-Ericion*), outcrops of gypsum (*Gypsophillion*), and the saline soils in the bottom of shallow valleys and depressions where halophytes occur (*Suaedetum brevifoliae*).



From *Allué Andrade* 1986

Figure 4.11 **Map of phytoclimatic zones in the Ebro Basin**



From *Rivas Martinez* 1986

Figure 4.12 **Map of vegetation in the Ebro Basin**

Some species, such as *Artemisia herba-alba*, have a much wider distribution and can also be found in the arid and semi-arid areas of eastern Europe and Asia ((Pérez-Obiol & Roure, 1991).

On peripheral higher ground above 500m, and in inversion free areas, the steppe and xerogarrigue is replaced by macchia, characterised by *Pinus halepensis* and *Quercus coccifera* (Terradus, 1986). This open forest community also generally supports a mattoral of bulbous and rhizomatous plants, as well as evergreen shrubs, particularly *Pistacia lentiscus* on the warmer slopes to the south and east (Rivas-Martinez, 1987). This zone finally ends at around 600-700m, with a transition to *Quercus ilex spp. rotundifolia* dominated forest.

Close to water courses and damp ground, deciduous riverine taxa can be found, including *Alnus glutinosa, Corylus avellana, Ulmus glabra* and *Fraxinus angustifolia.* Surrounding fresherwater permanent lakes an emergent aquatic vegetation of *Typha* sp., *Phragmites australis* and *Scirpus* sp occurs. Playa lakes have only limited areas of emergent macrophytes, sustained by groundwater seepage through the summer. Most of the lake margins of these seasonal hypersaline lakes are colonised by halophytes that exhibit a concentric zonation as salinity and inundation frequency declines away from the lake shore (*Figure 4.13* p80)

The more saline and seasonal lakes have a submerged aquatic vegetation of *Ruppia drepanensis, Potamogeton* sp. (*P.pectinatus*) and Characeae (*Lamprothamnium papulosum, Chara vulgaris*) The Laguna Salada is the only deep, permanent, natural inland salt lake in Europe, and is one of the few places away from the coast where *R.maritima var. maritima* can be found.

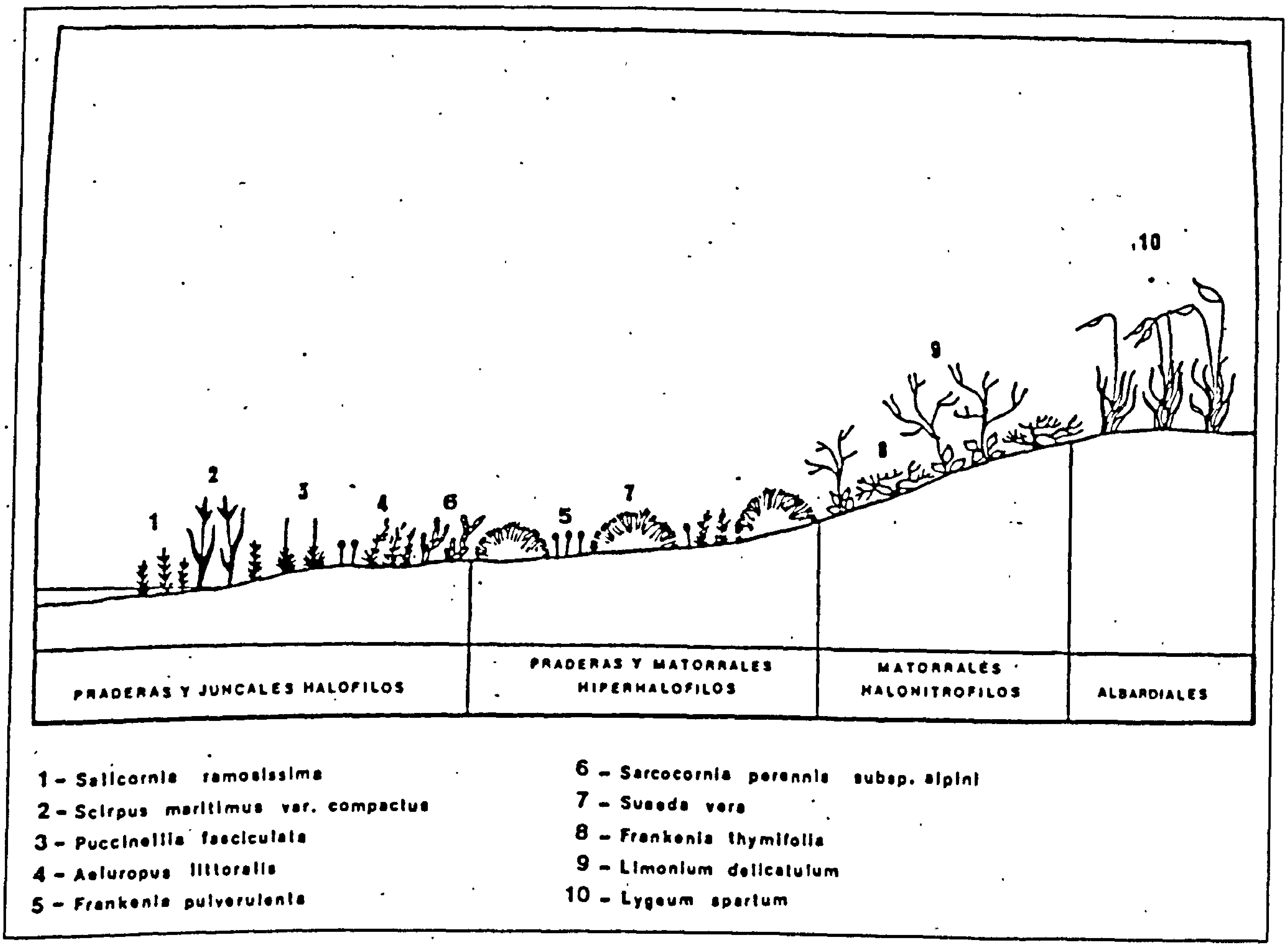


Figure 4.13 **Idealised vegetation sucession on salt lake margins in the Ebro Basin (from Anento Anglés, 1994)**

Chapter 5

Methods

5.1 Field Methods

Samples were collected during 4 fieldwork visits to Spain over 3 years. These took place during July 1990, July & November 1991 and June 1992. Exact dates are described in the relevant chapters.

5.1.1 *Sampling strategy*

Figures 4.3 p64 and *Figure 8.1* p127 provide maps showing the location of all the sites sampled. Sites were selected using 1:50,000 maps, literature references and local knowledge, as well as ease of access. Over 30 lakes were sampled and 17 cores taken (excluding auger cores). Virtually all lakes sampled are included in the surface sample database. Detailed analysis were undertaken on the Livingstone and Cobra cores as well as a short Kayak core from Laguna Gallocanta.

5.1.2 *Sediment cores and sections*

Seven cores were analysed in detail following initial screening and selection. The location, lake type and sampling information for each of these sites is given in *Table 5.1* p82, along with details of the analysis undertaken in *Table 5.2* p83.

Wet lakes were cored using thin (5cm diameter) and fat (10cm diameter) Livingstone type corers from a raft in upto 5m of water. The fat Livingstone was extruded in the field into 1cm slices and bagged. The thin Livingstone cores were extruded and stored whole in drainpipe wrapped in foil and clingfilm. The short Kayak cores were taken from the back of a boat in shallower water and extruded in the field into 1cm slices.

Dry lakes were cored using Hiller and Cobra corers and an auger. Only the Cobra cores were used for the more detailed analysis presented here. The Cobra corer is a 2-Stroke hand-held percussion type corer (COBRA 148: Manufactured by Beremba AB, Box 1286, S-171 25 Solna, Sweden) which drives in a 1m long, 6cm diameter gouge. The hole created is then used for the second drive and so on. The hole is not cased and some problems with contamination can occur at the beginning of each drive through sediment falling down the hole from above. However, this contaminating material can usually be detected and discarded. The problem can be minimised by cleaning the hole out with a larger diameter gouge at the end of each drive. Various size gauges are available although the 6cm diameter gouge seemed to offer the best compromise between sediment quantity and friction. The quantity of sediment extracted was particularly important, not only for macrofossil sampling, but also for the location of suitable material for radiocarbon dating (see section 5.3). Friction

Surface Sample Site Details & Analysis

SiteN°	Site Name	Location	LakeType	Sampling	Lake Area	Water Depth	Core Depth	Altitude	Sampling Date	Pollen	Charcoal	Macros	LOI	Carbonate	Sulphate
1	Laguna Sanñena	Sanñena	1: Permanent fresh lake	Livingston	98.0Ha	2.0m	0.43m	283.0m	19-July-90	Yes(Top)	Yes(Top)	No	Yes(Top)	Yes(Top)	No
2	La Salineta (Core)	Bujaraloz	4: Seasonal playa lake	Livingston	20.0Ha	Wet	1.57m	325.8m	24-July-90	Yes(Top)	Yes(Top)	No	Yes(Top)	Yes(Top)	No
3	La Salineta (Section)	Bujaraloz	4: Relic seasonal playa lake	OpenSection			3.45m	325.8m	24-July-90	Yes	Yes	Yes	Yes	Yes	Yes
	" (Base)	"	"	Hiller			1.20m	"	24-July-90	Yes	Yes	No	Yes	Yes	No
4	Casetas de luis Lagraba	Bujaraloz	Forest	Surface			0.02m	370.0m	24-June-92	Yes	Yes	No	Yes	Yes	No
5	Salina del Camerón	Bujaraloz	4: Seasonal playa lake	Surface	33.4Ha	Wet	0.02m	328.0m	23-June-92	Yes	Yes	Yes	Yes	Yes	Yes
6	Salina del Rebellón (Surface)	Bujaraloz	4: Seasonal playa lake	Surface	13.8Ha	Wet	0.02m	319.0m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
	" (Core)	"	"	Hiller	"		1.90m	"	16-July-91	No	No	No	No	Yes	Yes
7	Salina de Piñol	Bujaraloz	4: Seasonal playa lake	Surface	11.9Ha	Wet	0.02m	337.5m	23-June-92	Yes	Yes	Yes	Yes	Yes	Yes
8	Salina de la Muerte	Bujaraloz	4: Seasonal playa lake	Surface	11.5Ha	Wet	0.02m	334.5m	23-June-92	Yes	Yes	Yes	Yes	Yes	Yes
9	Laguna del Pez (Surface)	Bujaraloz	4: Seasonal playa lake	Surface	7.2Ha	Wet	0.02m	330.0m	23-June-92	Yes	Yes	Yes	Yes	Yes	Yes
	" (Core)	"	"	Hiller	"		2.20m	"	15-July-91	No	No	No	No	Yes	Yes
10	Hoya de los Berzas	Bujaraloz	6: Dry playa lake	Surface	5.2Ha	Dry	0.02m	341.3m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
11	Laguna Guallar	Bujaraloz	4: Seasonal playa lake	Cobra	9.2Ha	Wet	2.00m	336.0m	14-July-91	Yes	Yes	Yes	Yes	Yes	Yes
12	Hoya del Vinagrero II	Bujaraloz	5: Ephemeral playa lake	Surface	3.3Ha	Damp	0.02m	339.4m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
13	Hoya del Vinagrero I	Bujaraloz	5: Ephemeral playa lake	Surface	3.3Ha	Damp	0.02m	337.2m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
14	Hoya de Valdecarreta	Bujaraloz	5: Ephemeral playa lake	Surface	3.3Ha	Damp	0.02m	342.2m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
15	Hoya de Rafelez	Bujaraloz	5: Ephemeral playa lake	Surface	4.3Ha	Damp	0.02m	342.2m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
16	Hoya de los Aljeces	Bujaraloz	5: Ephemeral playa lake	Surface	4.9Ha	Damp	0.02m	338.6m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
17	Laguna de Pito	Bujaraloz	4: Seasonal playa lake	Hiller	56.4Ha	Wet	1.20m	323.4m	15-July-91	Yes(Top)	Yes(Top)	No	Yes(Top)	Yes(Top)	No
18	Hoyo de Botones	Bujaraloz	6: Dry playa lake	Surface	4.4Ha	Dry	0.02m	339.5m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
19	Las Alforjetas	Bujaraloz	6: Dry playa lake	Surface	1.0Ha	Dry	0.02m	352.0m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
20	Clota Yesera I	Bujaraloz	5: Ephemeral playa lake	Surface	2.4Ha	Damp	0.02m	353.5m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
21	Clota Yesera II	Bujaraloz	6: Dry playa lake	Surface	5.4Ha	Dry	0.02m	350.5m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
22	Venta del Carrero (West)	Bujaraloz	6: Dry playa lake	Surface	1.1Ha	Dry	0.02m	362.0m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
23	Venta del Carrero (East)	Bujaraloz	6: Dry playa lake	Surface	1.1Ha	Dry	0.02m	363.0m	25-June-92	Yes	Yes	Yes	Yes	Yes	Yes
24	Hoya del Castillo	Hijar	4: Seasonal playa lake	Cobra	22.0Ha	Wet	5.44m	260.0m	21-July-91	Yes	Yes	Yes	Yes	Yes	Yes
25	Laguna Salada (Salabrosa)	Caspe	1: Permanent fresh lake	Kayak	1.0Ha	0.5m	0.30m	150.0m	17-July-90	Yes	Yes	No	Yes	Yes	No
26	Laguna Salada	Caspe	2: Permanent salt lake	Livingston	23.0Ha	5.0m	2.20m	150.0m	17-July-90	Yes	Yes	Yes	Yes	Yes	Yes
27	Laguna de la Estanca	Caspe	1: Permanent fresh lake	Livingston	16.0Ha	1.2m	1.53m	90.0m	19-July-90	Yes(Top)	Yes(Top)	Yes(Top)	Yes(Top)	Yes	Yes
28	La Estanca	Alcañiz	1: Permanent fresh lake	Livingston	158.0Ha	4.5m	1.93m	337.0m	21-July-90	Yes	Yes	Yes	Yes	Yes	Yes
29	Salada Pequeña	Alcañiz	4: Seasonal playa lake	Cobra	21.0Ha	Wet	4.00m	357.0m	20-July-91	Yes	Yes	Yes	Yes	Yes	Yes
30	Salada Grande	Alcañiz	4: Seasonal playa lake	Surface	120.0Ha	Wet	0.02m	357.0m	16-July-89	Yes	Yes	No	Yes	Yes	No
31	Laguna Gallocanta	Gallocanta	3: Semi-permanent salt lake	Kayak	1330.0Ha	0.5m	0.22m	987.0m	24-July-90	Yes	Yes	Yes	Yes	Yes	Yes
32	Laguna de Alcohozo	La Mancha	3: Semi-permanent salt lake	Surface	71.0Ha	0.5m	0.02m	669.0m	14-July-92	No	No	Yes	Yes	Yes	Yes

Table 5.1 **Surface sample site details and analyses**

Core Site Details

Site N°	Site Name	Location	Latitude	Longitude	Lake Type	Corer	Lake Area	Water Depth	Core Depth	Altitude	Sampling Date
3	La Salineta (Section)	Bujaraloz	41°28'55"	0°09'30"	4: Relic seasonal playa lake	OpenSect/Hiller			4.65m	320m	14-July-91
11	Laguna Guallar	Bujaraloz	41°24'30"	0°13'40"	4: Seasonal playa lake	Cobra	9.2Ha		2.00m	336m	14-July-91
24	Hoya del Castillo	Hijar	41°15'60"	0°30'80"	4: Seasonal playa lake	Cobra	10.0Ha		5.44m	260m	21-July-91
26	Laguna Salada	Caspe	41°14'20"	0°10'50"	2: Permanent salt lake	Livingston	23.0Ha	5.0m	2.20m	150m	17-July-90
28	La Estanca	Alcañiz	41°03'60"	0°12'15"	1: Permanent fresh lake	Livingston	158.0Ha	4.5m	1.93m	342m	21-July-90
29	Salada Pequeña	Alcañiz	41°02'40"	0°13'10"	4: Seasonal playa lake	Cobra	21.0Ha		4.00m	357m	20-July-91
31	Laguna Gallocanta	Gallocanta	40°50'00"	2°11'00"	3: Semi-permanent salt lake	Kayak	1330.0Ha	0.5m	0.22m	987m	24-July-90

Core Analysis

SiteN°	Site Name	Pollen	Charcoal	Macrofossils	Stratigraphy	Geochemistry	L.O.I.	Carbonate	Sulphate	14C-Dates
3	La Salineta (Section)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	1
11	Laguna Guallar	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	1
24	Hoya del Castillo	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	3
26	Laguna Salada	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	3
28	La Estanca	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	2
29	Salada Pequeña	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
31	Laguna Gallocanta	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	0

Table 5.2 **Core site details and analyses**

between the gouge and surrounding sediments can cause problems when levering out the gouge, especially when the playa surface is soft. A platform consisting of a wooden board of approximately 2 square metres with a central hole c.10cm diameter is recommended for most conditions. The gouge was sampled in the field in 2cm slices and bagged.

The exposed cliff section at Laguna Salineta was cleaned using a spade and sampled directly into plastic bags at 10cm intervals.

All samples were sealed for transport back to the UK and stored in a fridge until analysis in the laboratory.

5.1.3 *Surface sediment samples*

Wet lakes were sampled from the top 2cm of Livingstone or Kayak cores or by use of an Eckman grab. Dry lakes were sampled by taking upto 10 subsamples within approximately 4 square metres of the playa surface and mixing them to obtain a homogenised sample (Stevenson, 1981). Only the top 2cm was collected from the surface of dry lakes.

The period of time represented by the sampling depth undoubtedly varies between lakes depending on their sediment accumulation rate. This problem is discussed in more detail in chapter 8.

All samples were sealed in plastic bags for transport back to the UK and stored in a fridge until analysis in the laboratory.

5.2 Laboratory Methods

5.2.1 *Water content and loss on ignition (LOI)*

Sediment ***water content*** was calculated after drying a known weight overnight in an oven at 100°C. ***Loss On Ignition (LOI)*** was determined as a percentage of weight lost after combustion in a furnace at 450°C for a minimum of 6 hours. Both variables are plotted as a percentage of the dry weight of the sample.

5.2.2 *Geochemistry*

Concentrations of total ***potassium, manganese, iron, cadmium, copper, zinc, lead, sodium, magnesium*** and ***calcium*** were measured, after total digestion in nitric and sulphuric acid, in a Phillips (Pye-Unicam) SP9 AAS using an air/acetylene flame. Values are plotted as parts per million. Analysis was undertaken by Mr W Stelling, Geography Dept, Newcastle University

Sulphate was calculated using a barium chloride precipitation technique (Hesse, 1971). Values are plotted as a percentage of the dry weight of the sample. Analysis was undertaken by Mr W Stelling, Geography Dept, Newcastle University.

Carbonate content was calculated from the weight loss between 450°C and 950°C multiplied by 1.36 and expressed as a percentage of the original weight (Bengtsson & Enwell, 1986; Dean, 1974). Values are plotted as a percentage of dry weight of the sample.

Sediment conductivity was only measured for surface samples. This was calculated by mixing 1 part dry sediment to 10 parts of water, agitating, leaving for 12 hours, agitating again and then measuring the conductivity of the water.

5.2.3 *Sediment Composition and Gypsum*

The stratigraphy and sediment composition of the sediment cores and surface samples were recorded in the field and later in the laboratory under a binocular microscope at a magnification of x10-60 following preparation as for macrofossils (see section 5.2.6). A number of variables were examined following preparation in this way and recorded according to the following codes:

Organic Algal Mat or Root Mat:

0. No Sample
1. No mat
2. Algal mat
3. Root mat

Detrital quarz sand:

0. No sample
1. No, not present
2. Yes, present

Clay pelletisation:

0. No sample
1. No, not present
2. Yes, present

Woody plant material:

0. No sample
1. No, not present
2. Yes, present

Estimated (flocculated) clay content:

%. Of total prepared sample

Gypsum crystal size:

0. No sample
1. No crystals
2. Small (size <0.5mm)
3. Mix of small & medium
4. Medium (size 0.5-1.0mm)
5. Mix of medium & large
6. Large (size >1.0mm)
7. Mix of large & small

Gypsum crystal shape:

0. No sample
1. No crystals
2. Irregular/weathered
3. Mix of irregular & lenticular
4. Lenticular
5. Mix of lenticular & prismatic
6. Prismatic
7. Mix of prismatic & massive
8. Massive

Gypsum crystal colour:

0. No sample
1. No crystals
2. Yellow
3. Yellow & translucent
4. Translucent
5. Translucent & transparent
6. Transparent (clear)

5.2.4 *Charcoal*

The Clarke (1982) point count method was used to enumerate charcoal on slides prepared for pollen analysis.

Samples of larger sized charcoal were extracted for AMS Radiocarbon dating. This was undertaken as part of the macrofossil sampling (see section 5.2.6). Identification of the charcoal particles was comparatively easy without further preparation (for eample by using hydrogen peroxide treatment) because of the comparative lack of organics and the white background of fine gypsum crystals. Care had to be taken however since some confusion was possible with the matt black particles of broken *Ruppia* seeds.

5.2.5 Pollen Analysis

Preparation of samples for Pollen analysis

Pollen samples were prepared using a standard acetolysis method following hydroflouric acid digestion (Moore & Webb, 1978). However, due to the low pollen concentration and high clay/mineral content of the sediments it was found necessary to pre-treat the sample before digestion to reduce the quantity of minerogenic material. Failure to remove this material caused the slide to quickly turn opaque due to the precipitation of dissolved minerals as the slide dried out. Further problems also occurred with the large clay fraction which caused a reduction in clarity on the slide, making grains appear 'hazy' and causing difficulties in determining fine detail.

A filter method was chosen rather than centrifuging since this reduced the risk of pellet loss during decanting. The removal of the clay matrix appeared to make the sample less willing to remain in the test-tube during decanting, even after centrifuging at relatively high revolutions (4500rpm). Filtering also allowed a continuous hot water/acid wash to be performed which removed some of the carbonates, sodium chlorides and to some degree, the sulphates. If this was not performed then slides would often turn opaque soon after preparation as these minerals recrystalized. All these problems were compounded by the relatively low pollen concentration of the sediments which meant typical dry weights of 0.8-1.2g being analysed. A 5 micron nylon filter was used to retain the pollen substrate. Visual comparison of slides made up without pre-treatment showed no apparent loss of material outside this size range. Inspection of the filter under a microscope after washing revealed no residue retained on its surface.

Preparation Method

1. Approximately 0.8 to 1.2g dry weight of sediment was removed from the required level and weighed accurately into a beaker. Three *Lycopodium* tablets were added and 10ml of 10% hydrochloric acid. The beaker was then placed on a hot plate and heated.

2. After cooling, the samples were then filtered through a 110 micron sieve into the top of the filtering apparatus. A mechanical suction pump was used to draw the filtrate through the finer 5 micron nylon filter into a flask. Typical filtering times were around 20 minutes for 200ml of warm water. The substrate was then washed off the nylon filter and into a beaker using a jet of distiled water. The nylon filter was then discarded. The excess water in the beaker was boiled off and the sample poured into a plastic centrifuge tube. The washings were made up with distiled water and then centrifuged for 5 minutes at 4000rpm.

3. The liquid was decanted and the pellet transferred into PTFE beakers. Each beaker was topped up with 40% HF and placed on a hot plate. The liquid was boiled for 5 hours and then washed back into centrifuge tubes.

4. After centrifuging for 5 minutes at 4000rpm, the liquid was decanted. The pellet was resuspended in 10% HCl to dissolve any residual silico-flourides, and the tubes were then centrifuged and decanted as before.

5. The pellet was resuspended in glacial acetic acid to dehydrate the sample prior to acetolysis. The sample was then centrifuged and decanted as before.

6. Acetolysis of the resuspended pellet was performed by adding 8ml of acetolysis mixture (9 parts acetic anhydride : 1 part conc. sulphuric acid) to the tubes, then centrifuging and decanting as before.

7. The pellet was resuspended in glacial acetic acid, centrifuged and decanted.

8. A few drops of 10% KOH were added to neutralise the acid together with a few drops of safranin stain. The pellet was then resuspended in distiled water, centrifuged and decanted.

9. The pellet was resuspended in 1ml of glycerol jelly and mixed thoroughly. Microscope slides were prepared from this mixture.

Pollen identification and counting

Pollen was identified and counted using an Olympus CH2 microscope at x400 magnification (upto x1000 for closer identification, using immersion oil). Both phase contrast and natural light were used for illumination where appropriate. At least 200 tree pollen or 500 total pollen were counted for each sample.

Published keys and type material were used for identification. Published keys included: Punt *et al* (1976); Moore & Webb (1978); Punt & Clarke (1980); Stevenson (1981); Valdés, Díez, & Fernández (1987); Moore, Webb & Collinson (1991); Reille (1992). Constant reference was also made to the extensive Mediterranean type slide collection of Dr A C Stevenson (over 2500+ species).

Presentation of Results

Diagrams were prepared using *Tilia 1.07* and *Tilia Graph 1.16* computer packages (Grimm, 1991: @Illinois State Museum, USA). Percentage values of trees, shrubs, herbs & ferns were calculated as a percentage of the total terrestrial pollen component excluding the Chenopodiaceae. Aquatics were calculated as a percentage of the total pollen (terrestrial pollen component plus aquatics) but excluding the Chenopodiaceae. Chenopodiaceae were calculated as a percentage of total pollen, including aquatics and Chenopodiaceae. The exclusion of the Chenopodiaceae from the total pollen sum was found necessary because of its dominance of the local pollen rain, particularly when it was found growing over the dry lake surface.

A *Lycopodium* spike was introduced in order to calculate absolute pollen concentrations. Full taxon absolute pollen concentration diagrams are not included, although total pollen concentration is shown for reference next to each pollen percentage diagram.

5.2.6 *Macrofossil Analysis*

Preparation of samples for macrofossil analysis

Due to the high alkalinity of the samples, sodium pyrophosphate (calgon) proved ineffective at disaggregating the samples, as did the use of an ultrasonic bath. It was therefore necessary to use a dilute acid. 5%HCl acid was effective in some circumstances but required prolonged soaking of the sample and repeated 'topping up'. Using 10%HCl, however, it was possible to quickly dissaggregate even the most stubborn of carbonate clays, but with a corresponding loss of macrofossil carbonate structures such as Ostracods and Molluscs. Preliminary analysis using 5%HCl proved only a limited presence of carbonate based macrofossils and in only the most recent sediments. It was therefore decided to concentrate on other macrofossils and process a lot more sediment in the time available using 10%HCl.

All samples were filtered at 180 microns following disaggregation as above. Preliminary analysis of the filtrate using this size of mesh size did not reveal any macrofossils which may have been lost otherwise.

Preparation Method

1. Approximately 30g to 50g dry weight of sediment was removed from the required level and weighed accurately into a beaker. 200ml of 10%HCl was then carefully added and the mixture left to soak overnight.

2. After gentle stirring, the sample was filtered using a 180 micron mesh and the filtrate washed into a petri dish using distiled water.

Macrofossil identification and counting

Macrofossils were identified and counted under water in a petri dish at x10-60 magnification using an Olympus VM-ILA-2 binocular microscope with KL 1500 fibre optic light source. Data are presented as counts per 100g dry weight of sediment. Stratigraphy and macroscopic charcoal was also examined in this way.

Provisional identification of macrofossils was undertaken with the kind assistance of Dr Hilary Birks (Bergen University, Norway) and Dr Peter Murphy (University of East Anglia). Seed keys and references were used for further identification; Martin & Barkley (1961); Katz *et al*, (1965); Montgomery (1977); Cirujano (1990) etc (see also Chapter 2 for details on specific species), together with reference to type material at the

Natural History Museum, London. Plant material gathered during fieldwork was also used to establish a type material collection. This was identified with the kind assistance of the Botany Department, Autonoma University, Madrid.

Presentation of Results

Results were prepared as for pollen (see section 5.2.5) and geochemistry using *Tilia* and *Tilia Graph 1.16* computer packages. Macrofossil concentrations were calculated and presented as numbers per 100g dry weight of sample.

5.3 Radiocarbon Dating

Considerable problems had to be overcome in extracting material for radiocarbon dating. Low organic content and calcareous geology dictated the use of allochthonously derived terrestrial material for AMS dating. Large sections of the sediment cores were prepared for macrofossil analysis and examined for either charcoal or the seeds and stem parts of terrestrial plants (Chenopodiaceae & Caryophylaceae). Very little suitable material could be found within the sediments and for future studies in these environments it is strongly recommended that the maximum amount of sediment possible is extracted, using multiple coring if necessary. The selection of levels for dating down the core was controlled entirely by where it was possible to date rather than where one would like to date.

Other studies have commonly used bulk carbonate dates and subtracted the 'hardwater' error from the deviation shown in the surficial sediments or other points of known age. The extrapolation of this error down the core however is particularly susceptible to changes in inputs of allochthonously derived carbonate material. Most of the carbonate found in playa lakes in the Ebro Basin is detrital in origin (see chapter 4, section 4.7). The extraction of clearly distinguishable authoctonous carbonate material, such as molluscs shells and ostracod valves, is not possible because they are poorly preserved. The combined use of charcoal/terrestrial seeds and bulk carbonate dating may make it possible to investigate the variation in the error of the carbonate fraction and therefore to obtain approximate dates from bulk carbonate where charcoal/seeds are not present (eg. Radle *et al.*, 1989). However, it was not possible to employ this approach in this study due to the limited allocation of funding for dating.

Fifteen samples of charcoal, terrestrial plant parts or seeds were successfully AMS radiocarbon dated. Details of each date, together with their calibration to calender years, are presented in *Figure 5.1* p91. The time/depth relationship for all radiocarbon dated cores is presented in *Figure 5.2* p91, with further details discussed within each core description section (Chapter 9). Funding was provided by NERC (Allocation N°464/0891) and preparation undertaken by NERC Radiocarbon Laboratory, East Kilbride for counting at, Arizona, USA.

AMS Radiocarbon Dates

Site	Level	Material	Date	Calibrated	C13	Reference
La Salineta (section)	10-11& 20-21cm	Chenopodiaceae seeds	127 98% Modern			AA9917
La Estanca	162-165cm	Chenopodiaceae seeds	430±50 BP	cal AD 1441	-24.2	AA9919
	182-185cm	Chenopodiaceae seeds	470±50 BP	cal AD 1432	-25.0 Estimated	AA9920
Salada Pequena	32-34 & 44-48cm	Charcoal	1340±50 BP	cal AD 665	-25 0 Estimated	AA9921
	102-106cm	Charcoal	1225±50 BP	cal AD 786	-25 0 Estimated	AA9922
	164-166cm	Chenopodiaceae plant remains	2325±50 BP	cal BC 398	-24 8	AA9923
	186-188cm	Charcoal	2230±50 BP	cal BC 277	-24.9	AA9924
	236-238cm	Charcoal	2675±60 BP	cal BC 828		
Laguna Salada	50-51cm	Chenopodiaceae plant remains plus Caryophyllaceae seeds	315±60 BP	cal AD 1573	-22.5	AA9926
	73-75cm	Chenopodiaceae plant remains plus Caryophyllaceae seeds	420±50 BP	cal AD 1443	-25 0 Estimated	AA9927
	191-194cm	Charcoal	5725±60 BP	cal BC 4628	-25 0 Estimated	AA9929
Laguna Guallar	60-62cm	Charcoal	7485±80 BP	cal BC 6311	-21.1	AA9930
Hoya del Castillo	174-176cm	Charcoal	5275±70 BP	cal BC 4144		
	278-282cm	Charcoal	7325±65 BP	cal BC 6129	-22 5	AA9931
	410-412cm	Charcoal	8855±80 BP			

Note: Radiocarbon calibration using University of Washington Radiocarbon Calibration Program 1987 Rev.2 0

Table 5.3

Table 5.3 **Core AMS radiocarbon dates**

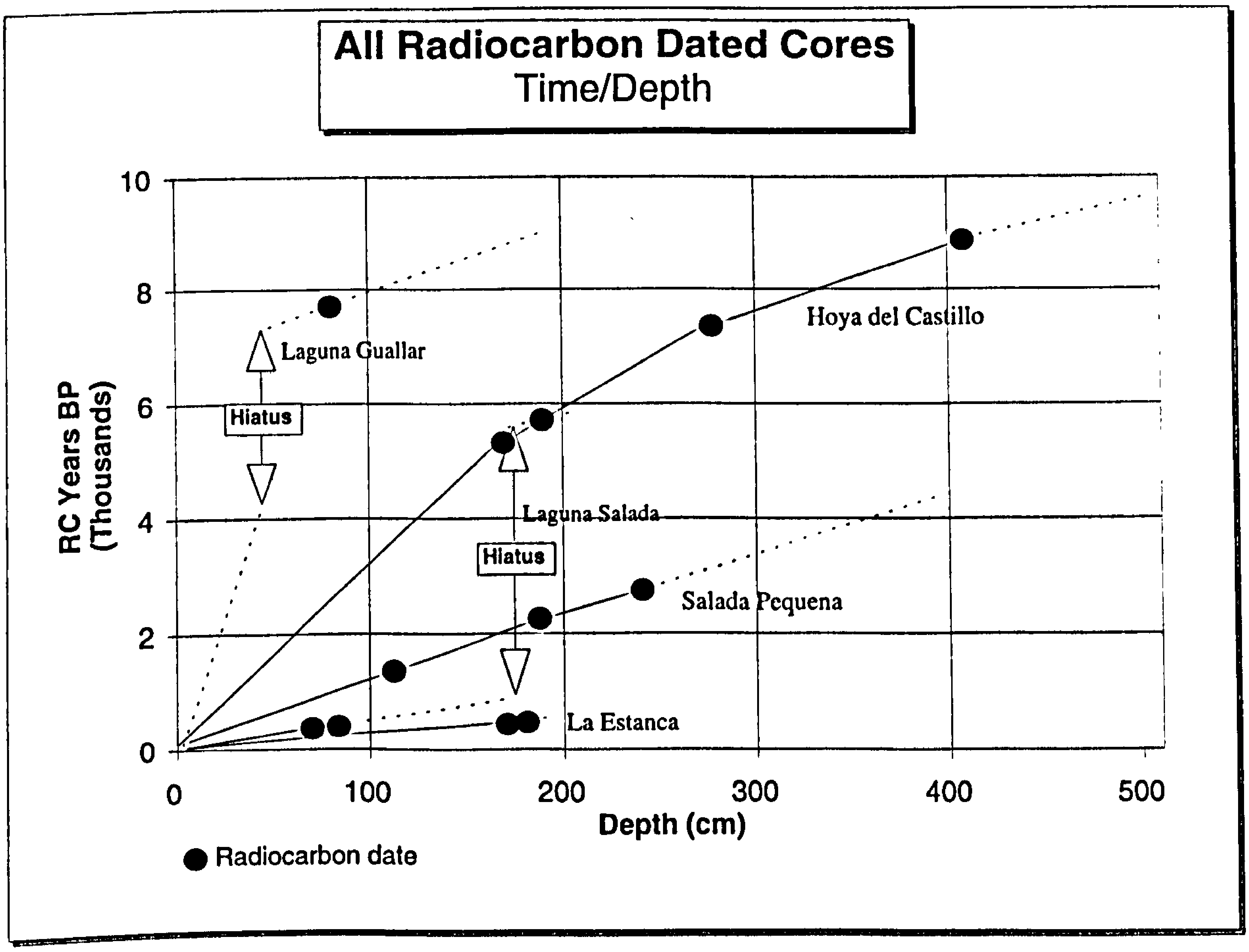


Figure 5.1 **Time/depth curves for all radiocarbon dated cores studied**

5.3.1 *Sediment accumulation rates and time-depth curves*

The steady accumulation of undisturbed unoxidised sediment is obviously a prime criterion in palaeolimnological studies and one of major concern in shallow playa lakes subject to mixing by wave action and surface organisms, and that regularly dry out. The existence of a hard surficial salt crust or algal mat however frequently restricts the amount of disturbance under all but the most arid conditions. This is especially true for many Spanish playa lakes where groundwater flows are still maintained during desiccation due to evaporitic pumping, leaving the surface appearing dry but maintaining high moisture levels in the sub-surface sediment. The small size and shallow basin slope of many of the lakes also restricts the erosive and reworking capacity of runoff waters in the summer, whilst restricting the potential fetch for wave development in the winter. Observed deflation and that implied by shoreline accumulation zones tends to be of catchment sediment, washed out over the hard surface crust by runoff from summer storms while the integrity of the underlying sediment is maintained. Although hiatuses in the sediment record do occur, heterogeneity and stratigraphic integrity are generally better preserved than appears widely thought for this type of lake system.

Maximum sediment depths were obtained from the smaller and less obvious lake basins. Large lakes such as Laguna Grande (120Ha), Laguna de la Playa (193Ha) and Laguna Gallocanta (1330Ha) were found to have very slow rates of sediment accumulation (<0.33mm/yr) and to have the shallowest depth of sediment. The Laguna de la Playa has a slightly longer sequence than the neighbouring smaller Laguna Guallar (9Ha), but the 1.4m core extracted is 60cm shorter than the core from the Laguna Guallar. A core of 2.0m extending back to the late glacial has recently been obtained from Laguna Gallocanta (1330Ha) by Prof. F.Comín and colleagues at Barcelona University (pers.comm.). This compares with a core of 5.0m covering the Holocene from the much smaller Hoya del Castillo (10Ha) included in this study. The idea that the longest sediment sequences are found in the largest basins is clearly misplaced. Small, steep sided basins offer the best protection against deflation and the greatest amount of focussing of the sediment influx.

Time depth relationships for all cores that have been radiocarbon dated are presented in *figure 5.1* (Laguna Guallar, Hoya del Castillo, Laguna Salada, Salada Pequeña, La Estanca). Both the Laguna Guallar and Laguna Salada have suspected hiatuses during the mid Holocene period.

The olive rise provides dating control on a short (20cm) core taken from Laguna Gallocanta and reveals a very slow sediment accumulation rate of *ca.*0.33mm/yr. A radiocarbon date obtained from the uppermost sediments (10-20cm depth) of the La Salineta section contained too much modern material. Three samples were also taken for thermoluminesence (TL) dating although the results are not available yet. Time/depth relationships for each site are discussed in more detail in Chapter 9.

Chapter 6

Surface sample transect across a small playa lake

6.1 Abstract

Surface samples taken across a small playa lake during summer desiccation were analysed for pollen, charcoal, macrofossils, geochemistry and sediment composition in order to determine the lateral variation across the lake sediment surface. Distribution was found to be influenced not only by hydroseral succession but also by time of year. Sediment and macro/micro fossil focussing is strongest in summer when the lake is dry and weakest in spring when the lake is fully flooded.

6.2 Introduction

Palaeoenvironmental reconstruction based on a single vertical core may not necessarily accurately reflect basin wide changes. Few studies have been undertaken to evaluate the degree of horizontal or lateral variation in palaeoenvironmental parameters across shallow playa lake basins. It is important to assess any variation in these parameters since changes may occur within the lake basin itself in relation to the coring site independent of time and the prevailing palaeoenvironment. Surface samples were taken across a playa lake (Salada Pequeña) in order to evaluate these taphonomic problems, as well as provide possible environmental analogues between offshore and near shore facies with respect to inundation regime, inwash and hydroseral succession.

6.3 Study Site

The Salada Pequeña is a small 21 Ha seasonal playa lake, approximately circular in shape, located 5km west of the town of Alcañiz and 2km south-west of the La Estanca reservoir. Full details of this site are provided in Chapter 9, section 9.5.

6.4 Methods

Sampling was undertaken in June 1992 at the start of the summer when the lake was desiccated. Seven samples were taken at 40m intervals from the shore of the lake to the lowest point of the basin. The distribution of the main vegetation growing in the lake and on the immediate shore area was also noted and recorded.

At each sampling point upto 10 subsamples were taken of the top 2cm of the lake sediment surface within an area of approximately $2m^2$ (Stevenson, 1981). Each sample collected was analysed for pollen, geochemistry (loss on ignition, carbonate, sulphate), charcoal, macrofossils and sediment composition. The results are presented at the end of the Chapter as follows:

Figure 6.1 location of transect and stratigraphy p99
Figure 6.2 terrestrial pollen & charcoal p100
Figure 6.3 macrofossils, aquatic pollen & geochemistry p101
Figure 6.4 absolute pollen concentration of *Olea* and *Pinus* p102

6.5 Discussion

Pollen

The area surrounding the lake is virtually treeless and largely dedicated to the dry farming of cereals. Arboreal pollen probably reflects mainly the regional pollen rain component, in turn favouring the more prolific and easily distributed pollen producers.

Olea and *Pinus* pollen dominate the arboreal pollen component, however it is clear that their distribution across the lake surface is not uniform (*Figure 6.2 p100*). *Olea* pollen occurs in greater percentages (and quantities) towards the centre of the lake, while *Pinus* pollen occurs in higher percentages (and quantities) towards the lake shore (*Figure 6.4*). Two main reasons may be forwarded to explain this pheneomena:

1) The first relates to the differential flotational properties of the two types of pollen grain. Pollen falling onto the lake in spring when surface water still remains on the lake is generally blown towards the leeward shore by the strong winds that often occur at this time of year. *Pinus* pollen in particular has great flotational capabilities by virtue of its air retaining sacks or bladders. *Olea* pollen in contrast has a small compact grain morphology, making it unlikely to float for any great distance. As these pollen grains fall upon the lake waters therefore, *Olea* will tend to sink relatively quickly to remain in much the same position, while in contrast, *Pinus* pollen will remain free floating, allowing it to be blown by the wind towards the lake shore where it is deposited in greater numbers.

2) The second reason may be related to the time of year at which *Pinus* and *Olea* flower. The dominant pine in the area, *Pinus halepensis*, generally flowers earlier in the spring than olive, which can flower as late as June (Mateo, 1987). By the time olive flowers in the late spring, water in the lake is confined only to the central part of the basin and any pollen falling on the surrounding basin, and not already incorporated into the forming salt crust, is liable to be washed into this central area by occasional surface run-off. A centripetal concentration of *Olea* pollen therefore occurs in contrast to pine pollen which falls on the lake in early early spring during high water, whereupon it is blown shorewards to accumulate in a centrifugal pattern.

The pollen of aquatic plants such as *Ruppia* and *Potamogeton* have a delicate reticulate patterning that enables them to float by retaining air bubbles in much the same way as the bladders of *Pinus* pollen. The distribution of the pollen of these taxa however does not follow the same pattern as *Pinus*, indeed they tend to show the opposite distribution, with a greater percentage towards the centre of the lake. This pattern is perhaps unusual given that the accumulation of *Ruppia drepanensis* pollen along the windward shores of playa lakes during spring flowering in the region is a common occurrence (Peuyo, 1979).

It would appear that local factors concerning the distribution of the pollen bearing plants within the lake itself is more important. The centre of the basin is likely to retain water the longest and provide the greatest depth of water for aquatic plant development. Dried remains of unidentified aquatic plants were found during sampling lying within the Chenopodiaceae fringe, towards the centre of the lake. Pollen produced from these plants may travel only a short distance before becoming incorporated within the sediment, perhaps because of limited dispersal due to their dense number. Alternatively, underwater flowering may be more common than previously thought, a process more common to *Ruppia maritima var. maritima*, but not unknown in *Ruppia drepanensis* (Cirujano *et al*, 1988).

Charcoal

The distribution of microscopic charcoal across the lake closely parallels that of *Olea*, with a marked increase shown towards the central area. The coincidental decrease in *Pinus* at the same point could easily be viewed as a fire event if the transition had instead appeared vertically in a sediment core. The reason for this concentration of charcoal particles may relate to the timing of fire events within the year, in a way similar to the differential deposition of late flowering olive pollen. Most burning occurs during the summer drought when the lake is low or completely dry. At this time of year the material falling on the surface of the lake is more likely to become concentrated at the lowest point of the basin, carried by accumulating runoff waters during rare summer storms or the first of the winter rains.

Macrofossils

Ruppia seeds are relatively heavy, do not float, have an asymmetrical shape and often have their penduncle still attached. This makes them difficult to disperse not only by wind and wave action, but also by runoff over the dry lake bed during occasional summer storms. The even distribution of *Ruppia* seeds across the lake surface reflects this resistance to dispersal.

The concentration of undifferentiated *Ruppia* seed parts in the centre of the lake however is probably due to two main processes. The first reflects the ease of dispersal of these lighter seed parts, comparable with the light Caryophyllaceae seeds also found concentrated in this part of the lake. Since wind and wave action would probably encourage a shoreward drift in such a shallow lake, the centripetal distribution is probably attributable to runoff carrying the lighter seeds and seed debris into the lowest part of the basin. The second process affecting the distribution of *Ruppia* seed debris can be attributed to seed breakage. Brock (1980) found that *Ruppia* seed breakage was encouraged by repeated wetting and drying of the seed coat. Seeds in the basin centre are likely to undergo the most frequent wetting and drying, since it is here that even the most ephemeral waters gather first before evaporating. Observation of salt crystals within broken *Ruppia* seeds would also suggest another, perhaps related process, whereby crystal growth within a damaged seed could cause sufficient pressure to break open the seed coat.

No completely intact *Ruppia* seeds were found in samples taken from the centre of the lake. This may be the result of successful germination, seed breakage processes or the excess concentration of lighter seed parts. The slight drop in *Ruppia* pollen and increase in *Potamogeton* pollen and *Chara* oospores may however suggest that a lack of *Ruppia* plants in the lake centre may be responsible for the lack of intact *Ruppia* seeds. The lake centre is the most saline part of the lake due to the concentration of evaporites at the lowest point of the basin. It was noticeable during sampling that there were few plant remains visible on the salt crust that was forming towards the lake centre as the final waters evaporated. Charophytes such as *Lamprothamnium papulosum* may be favoured towards the centre in such circumstances due to their ability to tolerate higher salinities than *Ruppia* (chapter 2). Alternatively, plant growth in this area may be restricted to periods of deep water and maximum dilution, in turn favouring *Potamogeton* and Charophytes better adapted to these conditions.

Uncalcified Charophyte oospores are lighter and more mobile than *Ruppia* seeds. Their relatively even distribution across the lake probably reflects both this greater mobility and greater adaptability of Charophytes in tolerating the widest variety of environmental conditions within a shallow, saline, playa lake. The slight shoreward distribution is probably a result of wind action causing an accumulation of mobile oospores, although the shallow water depth, wave action and turbulence may provide a competitive advantage favouring smaller Charophytes over *Ruppia.*

Terrestrial annuals of the Chenopodiaceae, such as *Salicornia herbacaea* and *Suaeda fruticosa*, invade the surface of the playa as water levels retreat at the end of spring. The seeds of these plants appear to closely reflect the distribution of the plants themselves, their limited mobility probably a strategy against being washed into the wetter and more saline lake centre. This is in contrast to the dispersal strategy of the Caryophyllaceae (mostly *Spergularia*) which often occur as perennials higher up the lake shore. The seeds of these plants can afford to be smaller, lighter and much more mobile since their perennial habit does not require such a high investment in successful germination and survival. A large number of these seeds therefore end up displaced from their favoured habitat, concentrated at the lake centre by runoff waters.

Relatively few faunal remains were found within the lake, while no remains at all were found at the lake centre or near the shore. This might indicate that re-deposition has been limited and that remains generally occupy the same location as living specimens. *Chironomus* Chironomids are phytophagous and the distribution of head capsule remains appears closely linked to that of the remains of aquatic plants and organic matter within the lake. The ephippia of *Moina mongolonica* probably reflects a similar distribution of algae and shelter in the lake, including the shore areas where nutrients are released into the lake from the breakdown of summer annuals such as the Chenopodiaceae during winter flooding.

Geochemistry

The Salada Pequeña displays the classic playa lake concentric pattern of evaporite deposition from the least soluble carbonates at the shore, to sulphates, then finally the most soluble sodium chlorides at the centre. Halite was not measured as part of the geochemical analysis, however halite crystals were observed during sampling as part of the white salt crust forming around the last remaining waters to be evaporated.

Much of the sulphate occurs as crystals of gypsum ($CaSO_4$), formed from the evaporation of the sulphate-rich groundwater. Precipitation of gypsum crystals can occur through two main mechanisms, the first in free water as saturation is reached when lake waters evaporate in late spring, the second by capillary rise within the subsurface during the summer drought. Crystals formed in free water have a prismatic shape, and dominate the sediments towards the centre of the lake. Gypsum crystals formed interstitially within the subsurface have a lenticular shape and tend to dominate away from the lake centre. Further towards the lake shore the phreatic water surface lies too deep for capillary rise in the summer. Here, gypsum is of detrital origin and restricted to small irregular crystal forms. Gypsum crystals that have formed away from the lake centre also appear to become yellower in colour, losing their clear transparency or white translucence. This could reflect increasing concentrations of tannic acids released into the sediment by decomposing terrestrial vegetation (Cody & Cody, 1988).

While sediments from the lake centre are composed mainly of evaporites, increasing amounts of detrital quartz and silicates can be found towards the shore. These minerals have been eroded from the lake catchment, possibly from the enclosing sand/mudstone palaeocanal network. The non-calcareous clays present in the lake sediments probably have a similar origin, declining with distance from the lake shore. Since the sampling method involved the sieving out of the clay size fraction, the retention of these clays reflects both their incorporation in the algal/organic mat that covers the bottom of the lake, and the effect of clay pelletisation at the lake margins.

The high carbonate content of shoreline sediments could reflect a number of origins. The groundwaters are normally saturated with respect to carbonate (Sanchez *et al*, 1991), so precipitation is only likely to occur after dilution of lake waters by meteoric waters during periods of high water. Precipitation is likely to occur throughout the lake, but only on the higher shore areas is the sediment likely to escape dilution by additional evaporites as these also precipitate as lake levels fall further. Alternatively, precipitation can occur simply by the entry of dilute, but carbonate rich meteoric runoff waters, into the saturated lake brine. Since the lake waters can hold no further carbonate, precipitation will be spontaneous upon water entering the lake at the shore.

Meteoric waters contribute as little as 10% of lake waters (Samper *et al.*, 1994) and dilution during the winter seldom reaches undersaturation with respect to carbonate. Pueyo (1979) found little carbonate precipitation occurring in lake waters, explaining that most of the carbonate minerals found were detrital in origin.

Surface samples taken from locations around the lake catchment show that the carbonate content of basin surficial sediments remain similarly high, while sulphate levels are proportionaly less. It could be suggested therefore that these sediments, transported by runoff, represent the main carbonate source for the lakes marginal sediments.

Heightened loss on ignition (LOI) values towards the centre of the lake are probably linked to both wetter reducing conditions favouring preservation and increasing lake productivity and macrophyte growth. The central area is dominated by evaporite sedimentation which probably acts to dilute LOI values at this location, particularly at the very centre of the lake where LOI values are seen to fall.

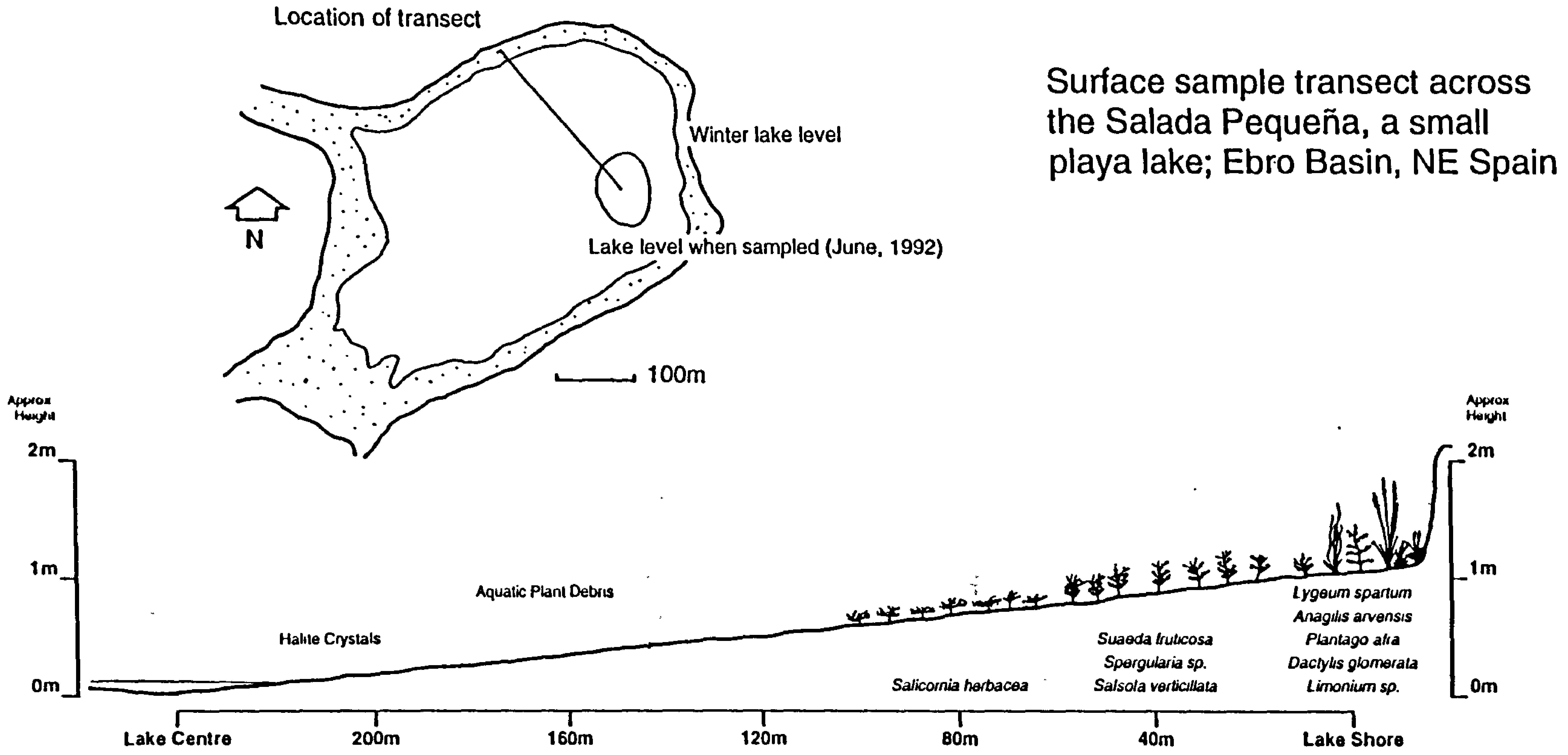
6.6 Conclusions

Although most palaeoecological parameters show a relatively even distribution across the lake basin, some important variations can be noted. Centripetal focussing occurs of late flowering *Olea* pollen, charcoal, and the lighter Caryophyllaceae seeds and broken *Ruppia* seeds. This is related to their transport to the lowest point of the basin by surface run-off during the summer desiccation. In contrast, a centrifugal shoreward distribution is shown by early flowering *Pinus* pollen, which is blown by the wind as it floats on the lake during high water in early spring. A shoreward distribution is also shown by Chenopodiaceae seeds which do not appear to travel far from their parent plants that colonise the lake margins during the summer draw-down. Limited dispersal is also shown by *Ruppia* seeds and lake fauna which are both closely associated with the aquatic macrophyte zone.

The evidence of these differences in distribution suggest that although shallow water depths and turbulence associated with playa lakes undoubtedly help to reduce the degree of sediment focussing during the winter lake-full stage, reworking by surface run-off during the summer desiccation appears to be limited. A thick algal mat combined with salt crust helps to protect the playa surface from erosion during periods of low water, and forms an effective barrier to any further material falling onto the lake surface once the surface crust has formed in late spring. It is this later material arriving on the lake sediment surface in summer that is liable to re-working and washing into the central basin.

Geochemical parameters vary across the playa surface in line with their solubility and precipitation series, ranging from carbonates at the shore, to sulphates, and eventually the most soluble sodium-chlorides in the central area of the basin. A change in the crystal structure of gypsum similarly occurs from lenticular to prismatic, associated with a change from subsurface precipitation due to capillary rise around the lake shore, to precipitation in free-water in the deeper areas of the lake. Near-shore facies can be further differentiated by detrital quartz from shoreline erosion and yellow-discoloured gypsum from humic acids associated with soil formation.

Figure 6.1 Salada Pequeña (transect): location of transect and stratigraphy



Surface sample transect across the Salada Pequeña, a small playa lake; Ebro Basin, NE Spain

	Lake Centre	200m	160m	120m	80m	40m	Lake Shore	
Sediment Structure								
Organic Mat	2	2	2	2	2	3	3	Non(1) Algal(2) Root(3)
Detrital Quartz	1	1	1	1	1	2	2	No(1) Yes(2)
Clay Pelletisation	1	1	1	1	1	1	2	No(1) Yes(2)
Woody Plant Material	1	1	1	1	1	2	2	No(1) Yes(2)
Flocculated Clay Content	10%	20%	40%	50%	50%	45%	60%	Estimated%
Gypsum								
Crystal Size	2	2	2	3	3	2	2	Non(1) S(2) M(4) L(6)
Crystal Shape	5	4	4	4	4	4	2	Non(1) I(2) L(4) P(6) M(8)
Crystal Colour	5	5	3	2	2	2	2	Non(1) Y(2) T(4) C(6)

Figure 6.1 Salada Pequeña (transect): Location of transect and stratigraphy

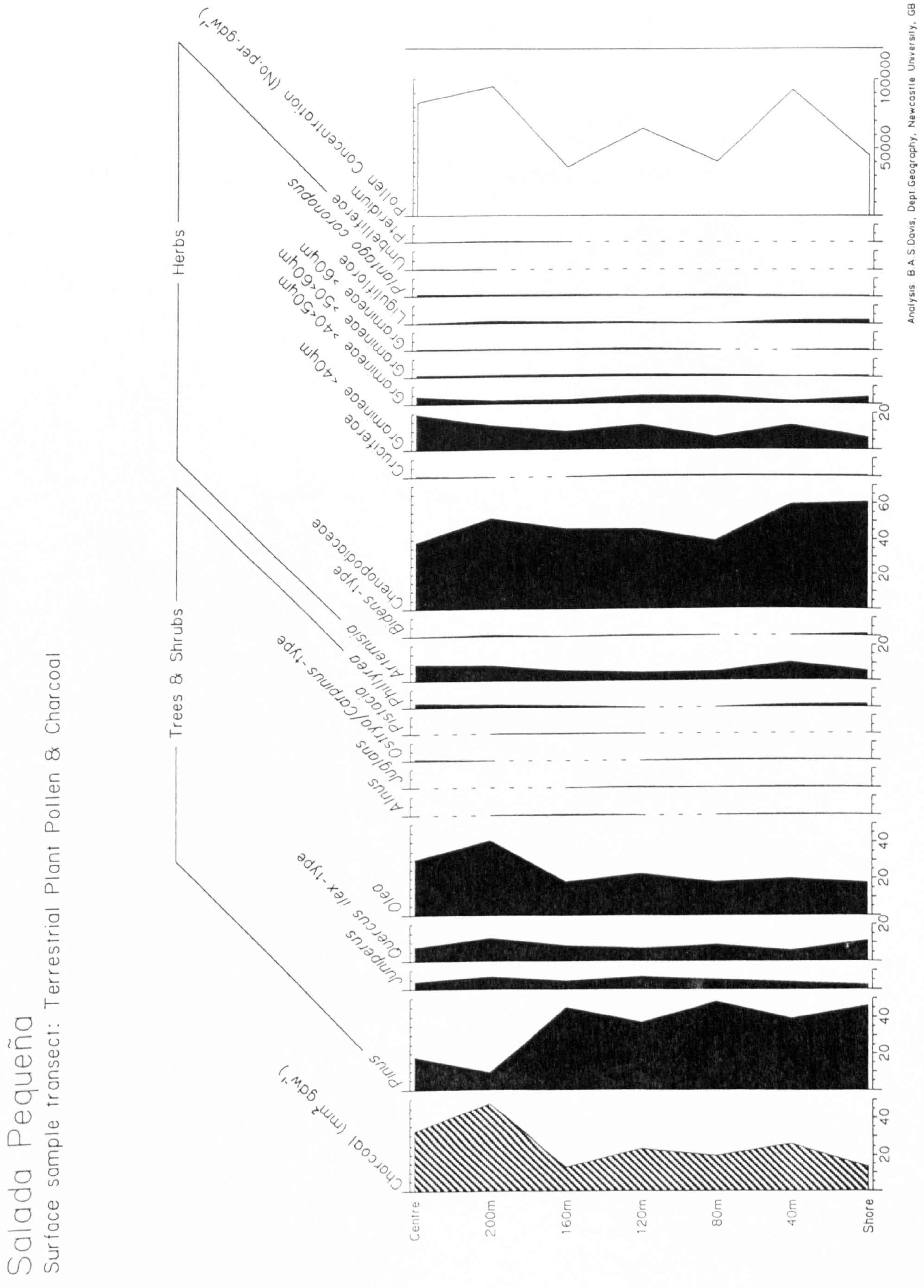


Figure 6.2 **Salada Pequeña (transect): terrestrial pollen & charcoal**

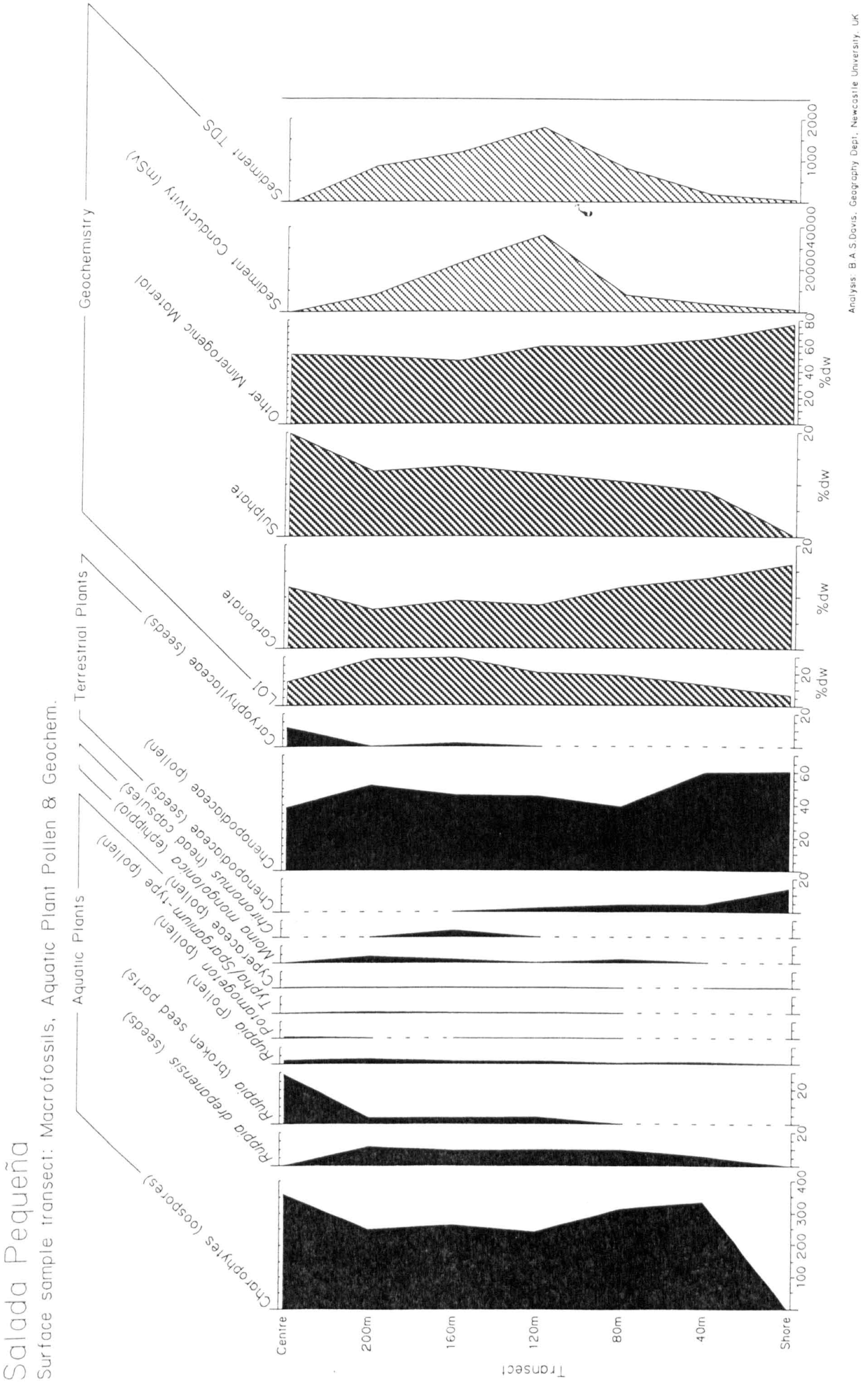


Figure 6.3 **Salada Pequeña (transect): macrofossils, aquatic pollen & geochemistry**

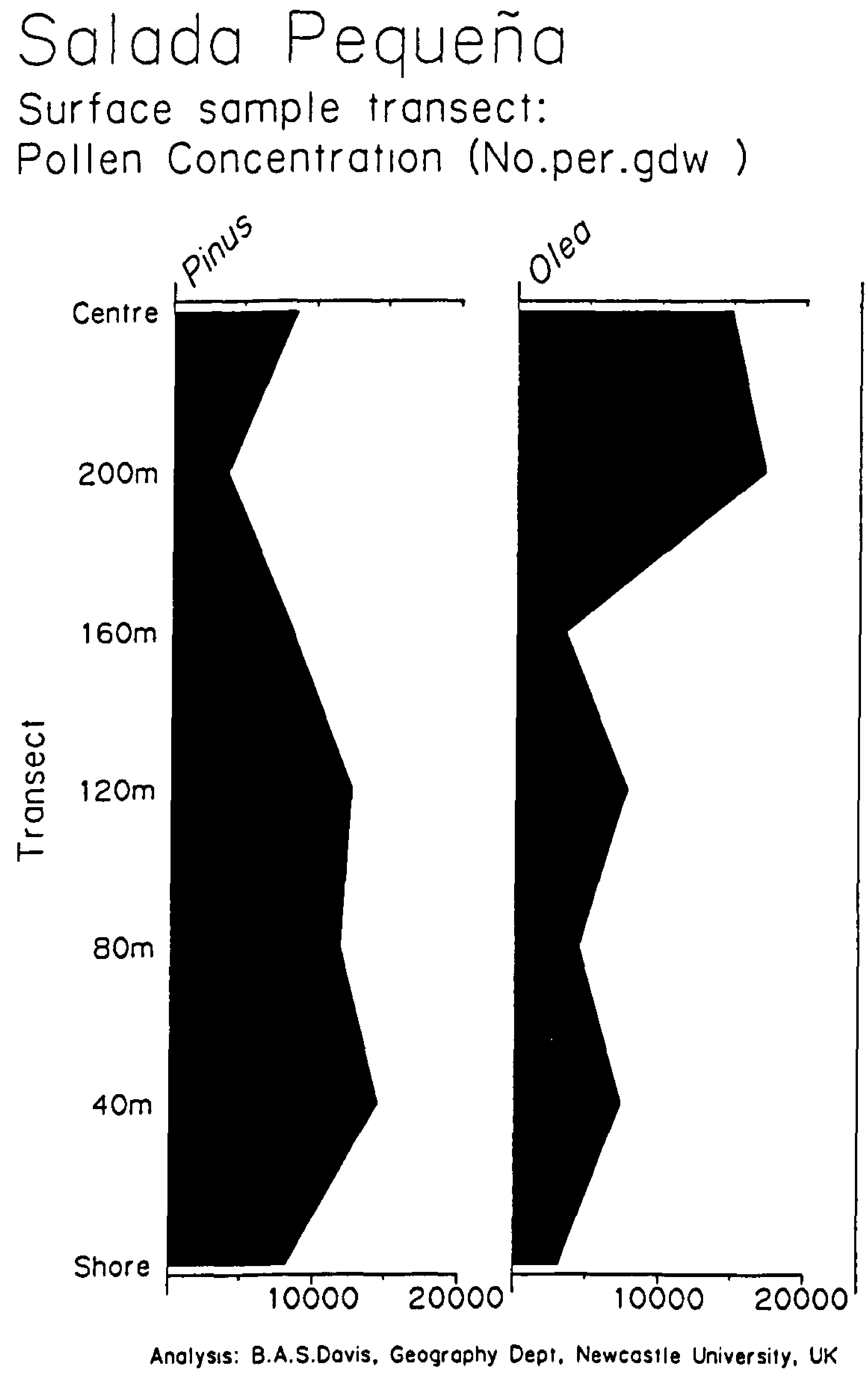


Figure 6.4 **Salada Pequeña (transect): *Pinus* and *Olea* pollen concentration**

Chapter 7

An 8 stage semi-quantitative palaeohydrological model for Spanish endoreic lakes based on surface samples

7.1 Abstract

Surface samples taken from 28 inland lakes from throughout Spain were analysed for pollen, geochemistry and sediment composition. Lakes sampled ranged from permanent freshwater to ephemeral hypersaline waters. Each lake was found to contain a distinctive suite of indicators which could be used to interpret the palaeohydrological record. A model is presented of eight lake types associated with eight distinctive hydrological regimes, together with a simple water balance model for investigating lake palaeohydrology.

7.2 Introduction

The use of surface sample data sets from modern lake environments to characterise and interpret the palaeohydrological record has been widely applied in work on diatom and ostracod assemblages (Fritz *et al*, 1991; De Deckker & Forester, 1988; De Deckker, 1988b). Few studies have however sought to apply the same principles to other palaeoenvironmental indicators, including pollen, macrofossils, geochemistry and sediment structure. The use of these indicators has widely shown to provide a useful basis for characterisation of the palaeohydrological environment (Birks, 1973; Kershaw, 1979; Bowler & Teller, 1986; De Deckker, 1988a; Teller & Last, 1990). This study combines both approaches in examining the same environmental indicators in samples of surface sediment from lakes in Spain with distinctly different hydrological regimes. The resultant dataset provides an empirical basis for palaeohydrological interpretation through the use of modern analogue lake environments.

The lakes sampled ranged from the almost completely dry to the permanently flooded, and from the almost fresh to the hypersaline. In all, 27 lakes were sampled in the Ebro Basin, together with Laguna Alcohozo in La Mancha. Samples from a further 13 lakes from Southern Spain are currently awaiting full analysis, which will eventually increase the number and variety of modern analogue lake environments.

Natural permanent/semi-permanent mineralised or saline lakes are at present under-represented in the current data set. A number of additional lakes of this type have been sampled, although there is a general problem here given the scarcity of such lakes in inland Spain.

7.3 Methods

Lakes sampled ranged from those that held water all year to those that flooded every 6 years or less. Most were seasonal saline playa lakes, although a number of freshwater/mineralised reservoirs were included, along with a permanent salt lake and two semi-permanent salt lakes.

Samples were collected from the deepest point of all the lakes. Sampling details are given in Chapter 5, section 5.1.3. Analysis was undertaken on each sample for pollen, macrofossils, geochemistry (LOI, sulphate & carbonate) and sediment composition (see Chapter 5).

Permanent lakes were distinguished as those that always contain water all year around. These were divided between those containing fresh or mineralised water and those containing saline water. The former group of lakes were mainly old endoreic lakes that had been artificially filled with water to create reservoirs or hunting reserves. No natural lakes of this type were included in the data-set since no lakes of this type occur in the Ebro Basin. Examples in southern Spain have now been sampled and will be included when analysis is complete. Unfortunately , there is only one example of a natural, permanent, inland salt lake within Spain, the Laguna Salada. Analysis was therefore confined only to this one example.

Semi-permanent salt lakes are similarly limited in their occurrence within Spain, with only one natural example sampled from the Ebro Basin. This was supplemented by an artificial lake in Central Spain whose water level is maintained by inputs of waste irrigation water. Both lakes regularly dry out every few years, but although shallow, usually manage to maintain water levels throughout the summer months.

Seasonal salt lakes dry out every summer and are the most common form of inland salt lake in Spain. Periods of inundation can range between different lakes and different years, from almost 12 months including most of the summer, to only a few months in winter. Periods of inundation less than this result in the permanent colonisation of the lake floor by halophytic terrestrial vegetation. A continuum probably exists between lakes that flood almost for an entire year, to those that flood only in exceptionally wet years. In the Los Monegros area of the Ebro Basin, over 100 small endoreic lakes or basins occur at different altitudes over a relatively level groundwater surface in an area of only 100km^2. Seasonal and inter-seasonal changes in the groundwater level floods different lakes for different time periods, while all are exposed to approximately the same climatic regime. Sampling was concentrated on lakes in this area and was undertaken over three days at the beginning of the summer desiccation in late June. Lakes still containing surficial water at this time were classified as seasonal, those whose sediment surface was still wet were classified as ephemeral, while those that were waterless at the time of sampling were considered dry. This classification was confirmed for both this area and others within the Ebro Basin with reference to maps, literature and local knowledge.

Examination of surficial sediments requires a degree of caution, particularly when interpreting the occurrence of elements that may undergo diagenetic processes before entering the sedimentary record. In particular, sodium-chlorides are highly soluble, and while forming an important component of playa surface sediments, do not appear to be preserved at depth. Hence, in the geochemical analysis, the '*other minerogenic material*' category reflects an unknown sodium-chloride component at the surface, but mainly clastics at depth. Further problems may be encountered due to differing rates of sediment deposition within different lake environments, particularly when comparing the concentration of macrofossils. Pollen concentrations are therefore given for reference since the pollen rain may be considered to be a temporal constant in such circumstances. Problems may still occur with sediment focussing, as well as increased pollen concentrations in ephemeral and dry lakes due to locally occurring Chenopodiaceae and other terrestrial vegetation growing at the sampling site itself.

7.4 Results

The results of the surface sample analysis are presented in *figure 7.1.A* p106 (macrofossils & aquatic plant pollen) and *figure 7.1.B* p107 (geochemistry, sediment structure and gypsum). Insufficient sediment was available for macrofossil, sediment structure or gypsum analysis from the Salada Grande (site 30), while no pollen analysis has yet been performed at Laguna Alcahozo (site 32). Terrestrial plant pollen and charcoal are dealt with in chapter 8. Lakes are presented according to the permanency and salinity of the lake environments involved. Surface samples are presented from six out of the eight main lake types recognised, although ordering within these groups is necessarily arbitrary given the lack of detailed hydrological information. Some overlap may occur, particularly between the seasonal, ephemeral and dry lakes, where a continuum is likely to apply. Only provisional analysis has been undertaken on samples from shallow, permanent, **lake categories 7 and 5**, which **are not included** in *figure 7.1 A & B* p106-107.

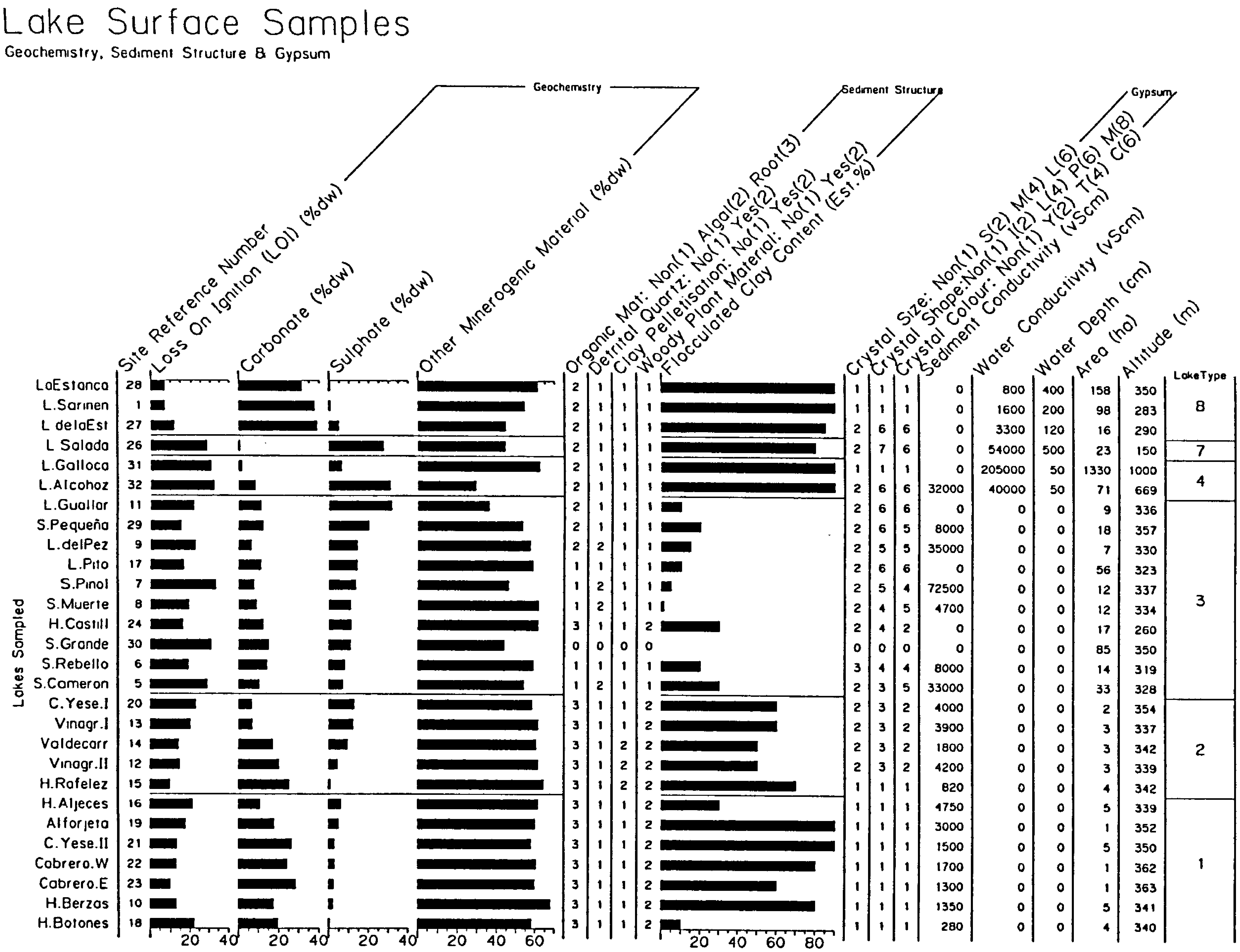
7.5 Discussion

Eight lake types were identified, along with a distinctive set of palaeoenvironmental indicators, that allows the reconstruction of lake type from the analysis of sediment cores. Permanent lakes were divided into deep (>3.0m), freshwater (type 8) and saline (type 7) lakes, and shallow (1.5-3.0m), freshwater (type 6) and saline (type 5) lakes. Lakes with shallower water depths were less permanent and hypersaline, categorised as semi-permanent (type 4), and seasonal (type 3). As lake level (groundwater level) becomes lower and flooding occurs only in particularly wet years, lake waters became less saline and ephemeral (type 2), and eventually dry (type 1). All 8 lake types are illustrated in *figure 7.2* p108, while *table 7.1* p114 provides a seasonal summary of the main environmental conditions of each lake types

8. *Lake Type: Permanent, Stratified (Depth >3.0m)*
Lake Water: Fresh/Mineralised (Salinity <0.5->5mS)

All the lakes of this nature in the Ebro Basin are artificial reservoirs or hunting reserves, filled by diverted river waters in the winter and emptied for irrigation purposes in the summer. The through flow of water prevents the accumulation of salts and allows the growth of less halophytic aquatic plants. With water levels generally maintained at a high but fluctuating level, emergents are confined to areas of the shore where their roots can still reach the water table during periods of low water. Inorganic turbidity combined with

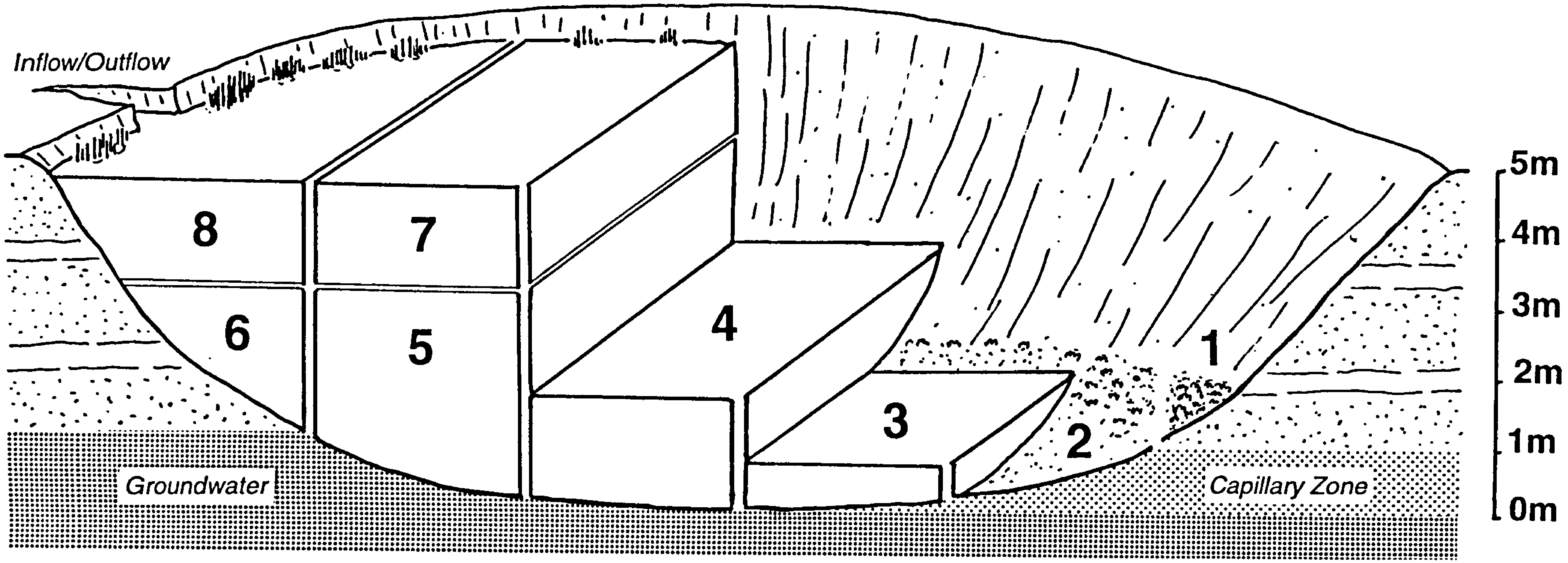
Figure 7.1A **Lake surface samples: macrofossils and aquatic plant pollen**



Analysis: B.A.S.Davis, Geography Dept, Newcastle University, UK

Figure 7.1B **Lake surface samples: geochemistry, sediment structure and gypsum**

An 8 stage palaeohydrological model for Spanish salt lakes



1 Dry	(depth <-1.0m)	*fresh/mineralised*
2 Ephemeral	(depth 0.0--1.0m)	*mineralised/saline*
3 Seasonal	(depth 0.5-0.0m)	*hypersaline*
4 Semi-Permanent	(depth 1.5-0.5m)	*hypersaline*
5 Permanent (unstratified)	(depth 3.0-1.5m)	*saline*
6 Permanent (unstratified)	(depth 3.0-1.5m)	*fresh/mineralised*
7 Permanent (stratified)	(depth >3.0m)	*saline*
8 Permanent (stratified)	(depth >3.0m)	*fresh*

Figure 7.2 **An 8 stage palaeohydrological model for Spanish salt lakes: a diagram illustrating the main lake stages**

thermal stratification linked with anoxia or sulphide build up at depth similarly restricts submerged aquatics to the shallow margins above the thermocline. Overall productivity is further reduced by the low nutrient content of the inflow waters.

Potential fossil remains are restricted due to the distance of plants from the sampling site at the centre of the lake, as well as the overall lack of plant growth in general. Sediment focussing is limited by the flat basin shape of these lakes. Evidence of aquatic plants is mainly provided by the pollen of *Potamogeton, Typha* and Cyperaceae, which although also present in the more saline lakes, here occur in greater quantities. Pollen of plants more clearly associated with freshwaters are also found, including *Nymphaea* and *Myriophyllum spicatum* (see chapter 2). *Ruppia* pollen may also be present in small quantities as a result of *Ruppia* growth when water salinity is elevated due to the stagnation of waters during dry years. Halophytic terrestrial plants such as Chenopodiaceae do not tend to invade the exposed lake margins during the summer draw-down due to the low salinity of the lake mud. Observations would appear to indicate that growth of terrestrial plants is limited and mainly confined to the Gramineae.

Sediment deposition consists mainly of carbonate rich silts and clays. Carbonate content exceeds 30%, close to classification as a marl lake (35-65%), while sulphates only occur in very small amounts. Precipitation of carbonate occurs in the summer as dissolved CO_2 is reduced by elevated water temperatures and photosynthesis. Charophyte growth may also be important cause of carbonate precipitation (chapter 2). Winter deposition is dominated by silts and clays carried by inflow waters, reworking of material at lake margins, and inputs from runoff. The result is the formation of seasonal laminae or rhythmite sequences within the sedimentary record which appears to remain preserved even in water depths as little as 2.0m in the Laguna Sariñena (site 1) and the Laguna de la Estanca (site 27). The preservation of such laminations is not uncommon in lakes with low organic content and a high proportion of clastics or precipitates (Anderson & Dean, 1988)

Virtually no gypsum crystals are present in the sediments, with the filtrate greater than 200µm composed mainly of algal organics and flocculated non-calcareous clays (around 90%). Where gypsum crystals do occur, they are of the small, clear or transparent, prismatic type, formed in free water. The very low loss on ignition values (<12%) is consistent with the low organic productivity often associated with marl lakes and the low nutrient content of the diverted inflow waters.

7. Lake Type: Permanent, Stratified (Depth >3.0m)
Lake Water: Saline (Salinity 40-50mS)

The Laguna Salada in the Ebro Basin is the only truly permanent natural hypersaline lake in Spain. Characterisation of this lake type is therefore restricted to this example alone. Inflow is from groundwaters which maintain the lake level at upto 5.0m and buffer it to within 0.6m of this figure throughout the year (Guerro *et al*, 1989). Evaporation is intense in the summer and represents the only outflow. Water salinities are therefore high, but relatively stable and dominated by sulphates which probably precipitate in summer under evaporitic concentration. Crystals were also found however, within the cyanobacterial algal mat that covers the bottom of the lake below the anoxic chemocline. These interstitial forms had a massive morphology and probably comprise magnesium sulphates such as thernadite rather than gypsum (calcium sulphate), since calcium levels in the lake waters are very low. Sulphate reduction by bacteria does not appear to limit the amount of sulphate within the sediments which composes almost 35% dry weight, comparable with hypersaline playa lakes such as Laguna Guallar (site 11) and the Salada Pequeña (site 29). In contrast, carbonate levels are almost negligible at below 1% dry weight.

The occurrence of fossil aquatic plant indicators in the surface sample is restricted to Charophyte oospores and Cyperaceae pollen. Although *Ruppia maritima var. maritima* is known to occur in the lake (Balsa *et al*, 1991), its perennial habit favours vegetative reproduction, limiting the production and distribution of pollen and seeds. The high salinity of the lake waters generally precludes all other aquatic macrophytes, confining them to isolated areas of the lake margins near freshwater inflows. The salt tolerant annual Charophyte, *Lamprothamnium papulosum*, produces abundant oospores, however it remains restricted, along with *R.maritima var maritima*, to the shallower areas above the chemocline (3.0m), below which lies a thick cyanobacterial algal mat. The high sulphide and anoxic conditions below the chemocline also preclude aquatic fauna and preserves the accumulation of organic matter, resulting in elevated loss on ignition values. Laminations are preserved within the sediments from the annual accumulation of precipitated sulphates, organic matter, and non-calcareous silts and clays. Flocculated non-calcareous clays mixed with organics compose over 80% of the sediment remaining after treatment with 10%HCl and filtering.

6. Lake Type: Permanent, Unstratified (Depth 1.5-3.0m)
Lake Water: Fresh/Mineralised (Salinity <0.5->5mS)

Shallower lakes (<3.0m deep) do not stratify and the bottom waters remain well oxygenated. Macrophytes are no longer confined to the lake margins and can colonise the entire lake leaving seeds and vegetative remains. Emergent macrophytes (*Typha* and *Phragmites*) are particularly prevalent in low salinity lakes, often colonising the entire lake bottom if conditions are shallow enough (<*ca.*1.5m). Physical and chemical characteristics are similar to deeper lakes (type 8), although with lower levels of carbonate levels and sulphate levels.

Apart from the marginal areas of deeper lakes, there are few lakes of this type that could be sampled in the Ebro Basin. Samples taken from lakes in the south of Spain have only undergone provisional analysis and are not included in the surface sample data set.

5. Lake Type: Permanent, Unstratified (Depth 1.5-3.0m)
Lake Water: Saline (Salinity 40-50mS)

Shallower saline lakes contain similar macrophytes to lake type 7, but these are not restricted by stratification and can colonise the entire lake as with lake type 6. *R.maritima var maritima* is able to occupy the central parts of the lake, leaving its seeds, although emergent vegetation is restricted to the margins due to the high salinity. Physical and chemical characteristics are similar to lake type 7.

4. *Lake Type: Semi-Permanent (Depth 0.5-2.0m)*
Lake Water: Saline-Hypersaline (Salinity <20->300mS)

Two examples of this lake type were sampled, the Laguna Gallocanta (site 31), a natural shallow (<2.0m) hypersaline lake that dries out approximately every 20 years (Comin *et al.*, 1983), and Laguna Alcohozo (site 32) which is maintained artificially by waste irrigation water. Laguna Gallocanta lies at the terminus of a large endoreic basin, the run-off from which constitutes a major part of the annual inflow to the lake. This is in contrast to other lakes in the Ebro Basin which have only small catchments and rely primarily on groundwater flows. A consequence of this is that a large amount of lake sediment is composed of non-evaporitic, clastic material, mainly non-calcareous silts and clays eroded from the basin. This factor, together with the high organic content and dominance of sodium and chloride ions within the lake waters, appears to limit the proportion of carbonate and sulphate minerals contained within the sediment.

Laguna Alcohozo may be more typical in that it occupies a small catchment rich in gypsum, fed by only minor inputs from run-off. The level of the lake is artificially maintained by waste groundwater extracted for irrigation purposes. This sulphate-rich groundwater is concentrated further by evaporation in the shallow (<1.0m) waters of the lake throughout the summer, forming clear or transparent prismatic gypsum crystals and other sulphate mineral deposits that result in very high sediment sulphate levels (over 30% dry weight). Carbonate levels are low in comparison, although high organic productivity and reducing conditions result in elevated LOI values.

Semi-permanent lakes tend to be shallow, and exposure to strong winds ensures circulation of the water and an absence of stratification. Submerged macrophytes with high salt tolerances such as the Charophyte, *Lamprothamnium papulosum*, are able to colonise large areas of the lake bed including the lake centre where the surface samples were taken. Oospore concentrations are therefore very high, along with algal feeders such as the Cladocera *Daphnia* and *Moina*. *Ruppia*, in contrast, is confined to the less saline margins, represented only by the long distance transport of its pollen. Emergent vegetation is extremely limited around the margins of the lakes, as well as being some distance from the sampling site in the case of Laguna Gallocanta (site 31). The invasion of lake muds by terrestrial halophytes such as members of the Chenopodiaceae during periods of low water would appear to be restricted by the development of a thick salt crust at the margins of the lake, with consequently little pollen of this family recorded.

3. *Lake Type: Seasonal (Depth 0.0-1.0m)*
Lake Water: Hypersaline (Salinity <5->300mS)

Many of the lakes within the Ebro Basin are seasonal, drying and refilling each year. Depressed evaporation in the winter allows groundwater inflow to exceed water outflow, which, together with direct contributions from rainfall onto the lake and as run-off from the lake catchment, combine to raise water levels to around 1.0m. Evaporation during the long, dry summer however exceeds the rate at which the groundwater flow can replace the water being lost, resulting in lake desiccation and the precipitation of salts.

Although the lake surface may appear dry in summer, the sulphate-rich groundwater still remains sufficiently close to the lake surface to allow capillary rise, resulting in the interstitial precipitation of gypsum just below the sediment surface. These distinctive lenticular shaped gypsum crystals contrast with the prismatic types formed from gypsum precipitation in free water. This difference in crystal morphology gives a clear means of differentiation between lakes which permanently hold water and deposit only prismatic gypsum crystals, and those lakes that periodically dry out and deposit a greater or lesser proportion of lenticular gypsum crystals.

Loss on ignition figures are slightly lower than for more permanent saline lakes, perhaps indicative of lower organic production or greater oxidation. In contrast, carbonate levels are higher, reflecting a proportionally greater contribution from catchment erosion.

During periods of high water and low salinity, the halophytic annual macrophyte, *Ruppia drepanensis* grows throughout the shallow lake bottom, where its seeds and pollen are deposited in large quantities. This may not occur every year for every lake however, requiring an extended period of both flooding and low salinity (together with low turbidity) for the plant to complete its 3 month reproductive cycle (see chapter 2). This combination of circumstances can be quite complex given that lakes which flood less often tend to be less saline and so require less dilution, but which also flood for a shorter period of time.

In contrast to semi-permanent salt lakes, Charophyte oospores occur only infrequently within the sediment of seasonal salt lakes, being replaced instead by the seeds and pollen of the annual angiosperm, *Ruppia drepanensis*. The Charophytes have a broader salinity tolerance and shorter reproductive cycle than *Ruppia*, and it is not altogether clear why they should be out-competed by *Ruppia* in such an ephemeral and highly saline environment. A variety of factors may be important, including the greater resistance of *Ruppia* seeds to prolonged desiccation, the greater ability of *Ruppia* to cope with high turbidity and perhaps the consistently lower salinities experienced by seasonal salt lakes at peak water levels. Seasonal salt lakes tend to have a lower build-up of dissolved salts within lake waters through time due to repeated desiccation reducing the throughput of salt-rich waters and causing salt loss through deflation and downward flushing during the summer, as well as re-dissolution lag during refilling.

In particularly wet years, salinity may fall sufficiently low to allow *Potamogeton* growth, while freshwater seepage at the lake margins may sustain small beds of salt tolerant emergents such as *Typha* and *Scirpus*. The limited occurrence of these, and other freshwater plants, is reflected in the lower pollen values than those of permanent fresher water environments.

A large community of annual halophytes may colonise the exposed mud flats surrounding the lake during the summer draw-down, although longer inundation periods and the development of salt crust limits their presence in the inner areas of the lake. Chenopodiaceae pollen is therefore kept low (<40%), although the lighter seeds of Caryophyllaceae may be washed into the centre of the lake (see chapter 6).

2. *Lake Type: Ephemeral (Depth 0.0-0.5m)*
Lake Water: Mineralised (Salinity >0.5mS)

Lakes which do not fill every year hold less saline water when they do flood because of the lower level of surficial evaporite minerals available for redissolution. Fewer fill-dry cycles, little capillary rise, downward flushing by meteoric water drainage and dilution by erosional inwash all contribute to lower levels of mineral salts in the surficial sediments. This factor, combined with the low frequency and short duration of flooding, allows halophytic terrestrial vegetation to colonise the entire lake bed surface. In particular, Chenopodiaceae seeds can be found in virtually all surface samples and values for Chenopodiaceae pollen generally exceed 50% of total pollen. The proximity and density of plants, together with depleted rates of deposition of evaporites, also helps raise pollen concentrations. Caryophyllaceae seeds are not recorded since their dispersal from the lake margins is restricted by the thick growth of Chenopodiaceae.

Sulphate levels are reduced, but lenticular gypsum crystals formed by capillary rise still occur in small numbers, taking on a yellower colour due to the presence of humic acids. Capillary rise also produces pelletisation of clays, an increasing proportion of which are calcareous, responsible in part for raising carbonate levels. However, the drier, oxidising environment, causes a drop in loss on ignition (LOI) values.

Although the occurrence of *Ruppia* seeds and pollen declines, quick growing Charophytes may still flourish in the absence of competition from *Ruppia*, taking advantage of the reduced turbidity caused by the substrate stabilising terrestrial vegetation cover. This cover however can quickly start to decay under prolonged flooding, releasing nutrients to the water and encouraging algal growth on which Chironomids and Cladocera can feed.

1. *Lake Type: Dry (Depth 0.0-<0.2m)*
Lake Water: Fresh/Mineralised (Salinity <0.5mS)

This lake type very rarely floods, and then only temporarily after heavy rain rather than due to a steady rise in groundwater. The sediments more closely resemble a soil, with free drainage from the basin leaching the more soluble minerals, including sulphates, but leaving the less soluble carbonates. No lenticular gypsum crystals or clay pelletisation occur in the sediments since groundwater is sufficiently depressed to prevent capillary rise. Aquatic plant growth is virtually unknown and the surface sediments do not contain their seeds and pollen. Terrestrial plants show further diversification, with perennials and less halophytic species occurring across the lake surface. Seeds of the Caryophyllaceae can now be found since plants of this family are able to colonise the central area of the lake. The Chenopodiaceae become less dominant and the concentration of their seeds and pollen start to fall.

Table 7.1 An 8 stage palaeohydrological model for Spanish salt lakes: A seasonal summary of the main environmental conditions influencing each lake type

8. *Lake Type:* ***Permanent, Stratified (Depth >3.0m)***
Lake Water: ***Fresh/Mineralised (Salinity <0.5->5mS)***
6. *Lake Type:* ***Permanent, Unstratified (Depth 1.5-3.0m)***
Lake Water: ***Fresh/Mineralised (Salinity <0.5->5mS)***

Winter: Inflowing streams and runoff from winter rains cause the lake basin to fill and overflow. Inflow waters are low in nutrients and dissolved sulphates, but rich in dissolved carbonates and suspended silts and clays which settle out in the centre of the lake.
Summer: Basin overflow is maintained by the continued influx of stream waters or groundwater. CO_2 depletion occurs through photosynthesis and high water temperature (plus growth of Charophytes), causing the precipitation of carbonates. In deep lakes (lake type 8), thermal stratification restricts submerged macrophytes to shallow waters (lake type 6) while emergents occur around the lake margins. Freshwater species also tolerant of mineralised waters, such as *Potamogeton, Chara vulgaris* and *Typha* tend to dominate.

7. *Lake Type:* ***Permanent, Stratified (Depth 3.0->5.0m)***
Lake Water: ***Saline (Salinity 40-50mS)***
5. *Lake Type:* ***Permanent, Unstratified (Depth 1.5-3.0m)***
Lake Water: ***Saline (Salinity 40-50mS)***

Winter: Runoff and groundwater inflows are insufficient to cause basin overflow. High water levels however reduce precipitation of dissolved salts and sedimentation is dominated by the settling out of suspended silts and clays.
Summer: Increased evaporation causes a fall in lake level and the precipitation of sulphates. The lake level is maintained by high inflows of groundwaters rich in dissolved salts. In deep waters (lake type 7), thermal or chemical stratification causes anoxia and sulphide build-up in the lower layers. This restricts salt tolerant benthic organisms and macrophytes such as *Ruppia maritima var maritima* and *Lamprothamnium papulosum* to shallow lakes (lake type 5) and the margins of deep lakes.

4. *Lake Type:* ***Semi-Permanent (Depth 0.5-2.0m)***
Lake Water: ***Saline-Hypersaline (Salinity <20->300mS)***

Winter: Water levels increase with winter rains and depressed evaporation, however they remain shallow enough (<2.0m) to prevent stratification. Submerged macrophyte growth is therefore possible throughout the entire lake.
Summer: Increased evaporation and decreased runoff cause a fall in lake level, but desiccation occurs only in very dry years. Water salinity rises to high levels, causing precipitation of prismatic gypsum. Macrophyte growth is restricted to species tolerant of hypersalinities, particularly the Charophyte, *Lamprothamnium papulosum*. High primary productivity and seasonal decline in macrophyte beds provides food for Cladocera and Chironomids.

3. *Lake Type:* ***Seasonal (Depth 0.0-1.0m)***
Lake Water: ***Hypersaline (Salinity <5->300mS)***

Winter: Runoff and groundwater inflow exceed the depressed rate of evaporation. The lake begins to fill and surface minerals redissolve. Quick growing salt tolerant aquatic annuals such as *Ruppia drepanensis* colonise the lake. Eventual death of these plants releases nutrients into the water causing seasonal algal blooms. Resuspension of silts and clays through turbulence, as well as algal blooms, may cause high turbidity, restricting the growth of smaller macrophytes such as *Lamprothamnium papulosum*.
Summer: Evaporation exceeds groundwater flow. Water levels start to fall causing precipitation of dissolved minerals; first of prismatic gypsum, then halite. Draw down exposes dry lake margins which are then colonised by annual terrestrial halophytes (Chenopodiaceae), away from central salt crust. Low salinity groundwater seeps at the lake margins support scattered *Typha* and *Scirpus*. Evaporitic pumping of sulphate-rich groundwater causes subsurface precipitation of lenticular gypsum.

2. *Lake Type:* ***Ephemeral (Depth 0.0-0.5m)***
Lake Water: ***Mineralised (Salinity >0.5mS)***

Winter: Lake flooding is reduced to periods of no more than a few weeks in very wet years. Few surface minerals are available to redissolve so lake waters are less saline. Deep water dilution is therefore not necessary allowing immediate colonisation by *Ruppia drepanensis* and Charophytes when conditions permit. Initial turbidity is low since the substrate is stabilised by existing terrestrial vegetation. Eventual decay of this vegetation however increases turbidity and provides food and shelter for Cladocera and Chironomids.
Summer: The groundwater drops below the sediment surface before evaporitic concentration can occur. Few minerals are therefore precipitated. The lake sediments are mainly dominated by carbonates eroded from the basin. Annual halophytes (mainly members of the Chenopodiaceae) colonise the entire lake bed surface. Groundwaters remain close enough to the surface (<1.0m) to allow capillary rise, resulting in clay pelletisation.

1. *Lake Type:* ***Dry (Depth 0.0-<0.2m)***
Lake Water: ***Fresh/Mineralised (Salinity <0.5mS)***

Winter: The lake basin is filled only for very short periods following heavy rainfall. No aquatic plants occur since flooding is too short and infrequent to sustain a seed bank and allow time for growth. Rotting terrestrial vegetation may occasionally sustain populations of more mobile and ephemeral Cladocera and Chironomids.
Summer: The downward drainage of winter rains readily flush any surface salts into the groundwater. The low surface salinity and reduced frequency of flooding encourages greater terrestrial plant diversity and the growth of halophytic perennials at the centre of the basin.

7.6 Conclusions

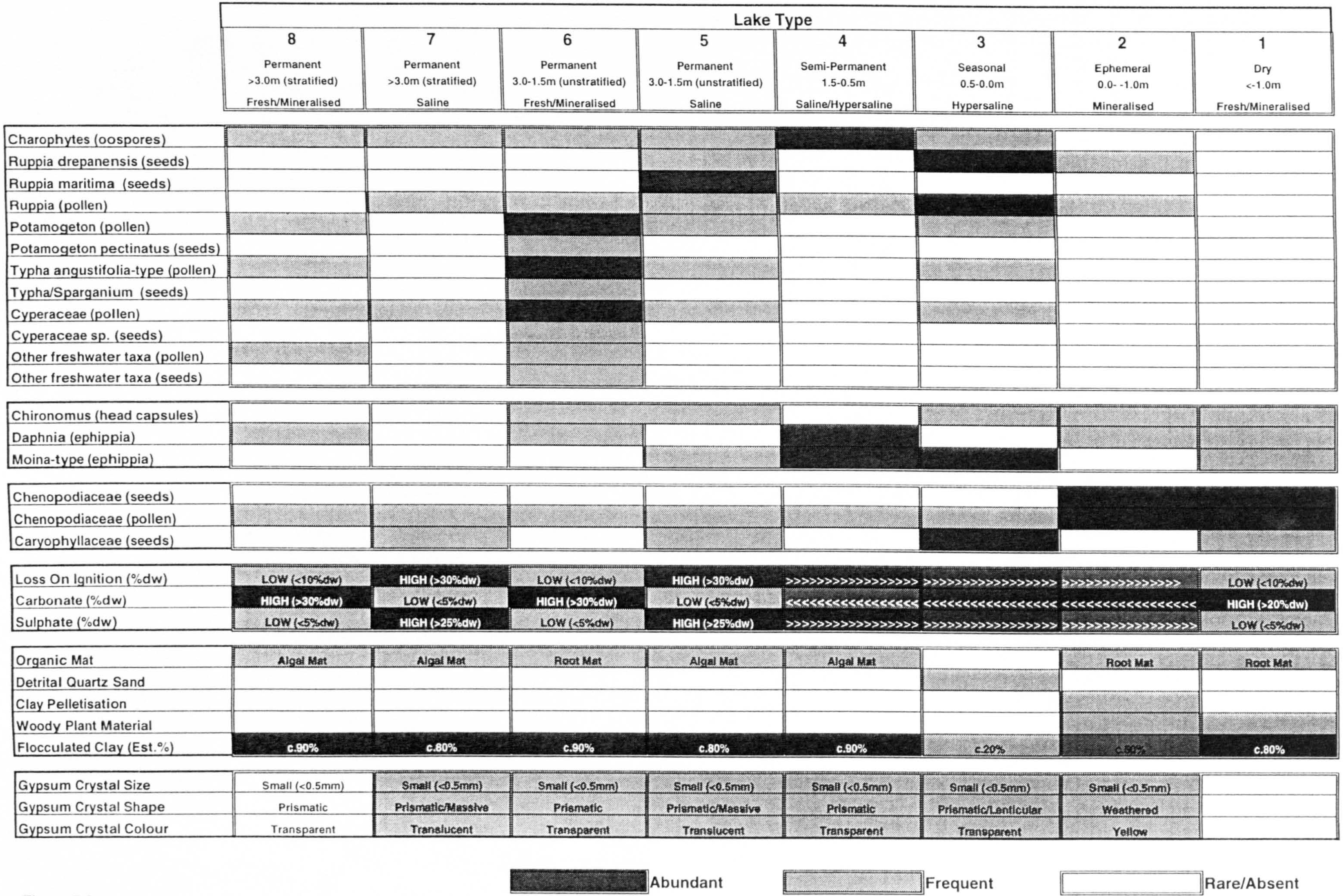
A summary of the main palaeoenvironmental indicators distinctive of each of the eight hydrological regimes is provided in *figure 7.3* p117. Examination of these indicators within a sediment core taken from a lake allows the reconstruction of its palaeohydrology. This includes a semi-quantitative measure of water depth.

Periods of abundant freshwater taxa and high carbonate levels are distinctive of lake overflow, with fresh, permanent, and often deep water. Intermittent overflow, or temporary high levels in closed-basin lakes are likely to result in the occurrence of species such as *Ruppia* and *Potamogeton pectinatus*, which have a broad salinity tolerance. Where lakes have no outflow, the concentration of dissolved ions within lake waters occurs through evaporation, raising the salinity of the lake water accordingly and increasing the amount of precipitated minerals such as sulphates within the lake sediments. With the exception of Laguna Gallocanta (site 31), lake water inputs from precipitation and run-off are minor since lake catchments are generally small, precipitation is low and evaporation high. Groundwater flows therefore provide the main defence against intense summer evaporation of lake waters. In permanent salt lakes, high groundwater flows in summer regulate lake level and water salinity, maintaining stable, deep water, saline conditions throughout the year. Deep water results in stratification and anoxia or sulphide build-up in the lower layers. This limits the occurrence of salt tolerant macrophytes to the lake margins, along with their seeds and pollen.

Shallower lakes (<2.0m deep) tend to be semi-permanent, being more vulnerable to any inter-annual variability in runoff and groundwater recharge. Shallow water depths result in variations in lake level producing proportionally greater changes in water salinity than in deeper permanent lakes. In addition, free evaporation from a water surface all-year round, accompanied by shallow water depths, can lead to a greater tendency towards hypersaline conditions. This environment favours Charophytes such as *Lamprothamnium papulosum* with a high salinity tolerance, and which are able to grow unhindered throughout the shallow lake.

Declining groundwater inputs finally result in a period of lake desiccation during the summer half of the year as lake levels drop below the sediment surface. Lakes become seasonal, filling during the winter (<1.0m deep) and drying out during the summer. Water salinities vary considerably with water depth throughout the year, although a greater frequency of low salinity conditions appears to occur than in semi-permanent lakes during steady state conditions. *Ruppia drepanensis* seeds and pollen dominate, together with *Typha angustifolia*-type and Cyperaceae pollen from small beds of emergents fed by freshwater seeps along the lake margins. Evaporite sedimentation dominates, with sediments low in organic content and high in sulphates. Evaporation of surface water in spring causes the precipitation of prismatic gypsum. Lake groundwaters however often remain close to the surface in summer, allowing evaporation to continue through capillary rise and salts to accumulate in sub-surface sediments to form lenticular gypsum.

As the period of flooding and sediment surface salinity declines, so the lake bed surface becomes increasingly colonised by annual terrestrial halophytes (Chenopodiaceae). In seasonal lakes that are flooded for more than 7 months of the year, these plants tend to be confined to exposed mud-flats at the lake margins. Dryer lake basins can become completely covered by these plants, eventually being replaced by perennials and



An 8 Stage Palaeohydrological Model for Spanish Endoreic Lakes

	Lake Type							
	8 Permanent >3.0m (stratified) Fresh/Mineralised	7 Permanent >3.0m (stratified) Saline	6 Permanent 3.0-1.5m (unstratified) Fresh/Mineralised	5 Permanent 3.0-1.5m (unstratified) Saline	4 Semi-Permanent 1.5-0.5m Saline/Hypersaline	3 Seasonal 0.5-0.0m Hypersaline	2 Ephemeral 0.0- -1.0m Mineralised	1 Dry <-1.0m Fresh/Mineralised
Charophytes (oospores)	▨	▨	▨	▨	■	▨	□	□
Ruppia drepanensis (seeds)	□	□	□	▨	□	■	▨	□
Ruppia maritima (seeds)	□	□	□	■	□	□	□	□
Ruppia (pollen)	□	▨	▨	▨	▨	■	▨	□
Potamogeton (pollen)	▨	□	■	▨	□	▨	□	□
Potamogeton pectinatus (seeds)	□	□	▨	□	□	□	□	□
Typha angustifolia-type (pollen)	▨	□	■	▨	□	▨	□	□
Typha/Sparganium (seeds)	□	□	▨	□	□	□	□	□
Cyperaceae (pollen)	▨	▨	■	▨	□	▨	□	□
Cyperaceae sp. (seeds)	□	□	▨	□	□	□	□	□
Other freshwater taxa (pollen)	▨	□	▨	□	□	□	□	□
Other freshwater taxa (seeds)	□	□	▨	□	□	□	□	□
Chironomus (head capsules)	□	□	▨	▨	□	▨	▨	▨
Daphnia (ephippia)	▨	□	▨	□	■	□	▨	▨
Moina-type (ephippia)	□	□	□	▨	■	■	□	▨
Chenopodiaceae (seeds)	□	□	□	□	□	□	■	■
Chenopodiaceae (pollen)	▨	▨	▨	▨	▨	▨	■	■
Caryophyllaceae (seeds)	□	▨	□	▨	□	■	□	▨
Loss On Ignition (%dw)	▨ LOW (<10%dw)	■ HIGH (>30%dw)	▨ LOW (<10%dw)	■ HIGH (>30%dw)	■ >>>>>>>>>>>>>>>>>>	■ >>>>>>>>>>>>>>>>>>	■ >>>>>>>>>>>>>>>>	▨ LOW (<10%dw)
Carbonate (%dw)	■ HIGH (>30%dw)	▨ LOW (<5%dw)	■ HIGH (>30%dw)	▨ LOW (<5%dw)	■ <<<<<<<<<<<<<<<<<	■ <<<<<<<<<<<<<<<<<	■ <<<<<<<<<<<<<<<<<	■ HIGH (>20%dw)
Sulphate (%dw)	▨ LOW (<5%dw)	■ HIGH (>25%dw)	▨ LOW (<5%dw)	■ HIGH (>25%dw)	■ >>>>>>>>>>>>>>>>>>	■ >>>>>>>>>>>>>>>>>>	■ >>>>>>>>>>>>>>>>>>	▨ LOW (<5%dw)
Organic Mat	▨ Algal Mat	▨ Algal Mat	▨ Root Mat	▨ Algal Mat	▨ Algal Mat	□	▨ Root Mat	▨ Root Mat
Detrital Quartz Sand	□	□	□	□	□	▨	□	□
Clay Pelletisation	□	□	□	□	□	□	▨	□
Woody Plant Material	□	□	□	□	□	□	▨	▨
Flocculated Clay (Est.%)	■ c.90%	■ c.80%	■ c.90%	■ c.80%	■ c.90%	▨ c.20%	■ c.50%	■ c.80%
Gypsum Crystal Size	□ Small (<0.5mm)	▨ Small (<0.5mm)	▨ Small (<0.5mm)	▨ Small (<0.5mm)	▨ Small (<0.5mm)	▨ Small (<0.5mm)	▨ Small (<0.5mm)	□
Gypsum Crystal Shape	□ Prismatic	▨ Prismatic/Massive	▨ Prismatic	▨ Prismatic/Massive	▨ Prismatic	▨ Prismatic/Lenticular	▨ Weathered	□
Gypsum Crystal Colour	□ Transparent	▨ Translucent	▨ Transparent	▨ Translucent	▨ Transparent	▨ Transparent	▨ Yellow	□

■ Abundant ▨ Frequent □ Rare/Absent

Figure 7.3

Figure 7.3 **An 8 stage palaeohydrological model for Spanish endoreic lakes: a diagram of palaeoenvironmental indicators for lake stage classification** less halophytic species as flooding frequency declines still further. Groundwaters below these basins remain too low to allow capillary rise in the summer or to impede drainage in the winter, with flooding generally confined to periods of intense storm runoff.

Eight distinctive lake types can be therefore be identified within the data set, ranging from the permanently wet to the almost permanently dry. Each lake type and accompanying hydrological regime has its own distinctive set of palaeoenvironmental indicators which allow interpretation of the palaeohydrological record. By reference to the pollen, macrofossils, geochemistry and sediment structure preserved within the lake sediments it is therefore possible to reconstruct past lake levels and hydrological regimes by comparing the modern and fossil assemblages to find the most suitable analogous environment.

7.7 Lake Hydrology and Palaeohydrology

The classification of lake types according to palaeoenvironmental indicators employed in this study allows the semi-quantitative reconstruction of lake depth. A simple hydrological model can then be used to explore the possible palaeohydrologial conditions that gave rise to these changes in lake level. This section develops a simple hydrological model for the type of groundwater fed lakes that occur in the Ebro Basin.

Annual rainfall is greatly exceeded by annual evaporation in all areas throughout Spain where endoreic lake systems occur. In the Ebro Basin, the hydrological deficit typically exceeds 800mm per year, with annual evaporation in excess of 1200mm and annual rainfall less than 400mm. Lake levels are therefore mainly maintained by inputs of runoff and groundwater, with direct precipitation onto the lake forming only a minor component.

Most lakes have only small catchments with poorly developed surficial drainage systems. Full saturation of catchment soils occurs for only a few months in the winter when potential evapotranspiration is at its lowest. High soil porosity and low relief ensures rapid downward drainage of surficial water, restricting runoff to less than 10% of annual rainfall (Samper *et al.*, 1993), but allowing sufficient percolating water to recharge the underlying aquifer.

Lakes typically occupy the lowest parts of the surface topography, close to the phreatic water surface. Discharge of aquifer groundwaters into the lakes help maintain water levels into the hydrological deficit period, and in the case of permanent lakes, throughout the entire year.

Simple water balance calculations used in lake level studies based on surface hydrology (Bowler, 1981; Street-Perrott & Harrison, 1985; Bowler, 1986; Almendinger, 1993) cannot be applied to these types of lake systems since runoff inputs are negligible and annual evapotranspiration exceeds annual precipitation. More complex models specific to groundwater fed closed-basin lakes have been developed (Almendinger, 1990), however these require detailed information on groundwater flows and assume high aquifer permeability.

In the Los Monegros area of the Ebro Basin, net precipitation inputs calculated on a monthly basis (*Figure 7.4* p119) show an annual hydrological surplus of 19.3mm during December and January. In order to maintain lake levels outside this period and to greater depths, groundwater flow must make up for any evaporational loss. Since the hydrological surplus is all that is available to the groundwater aquifer, then

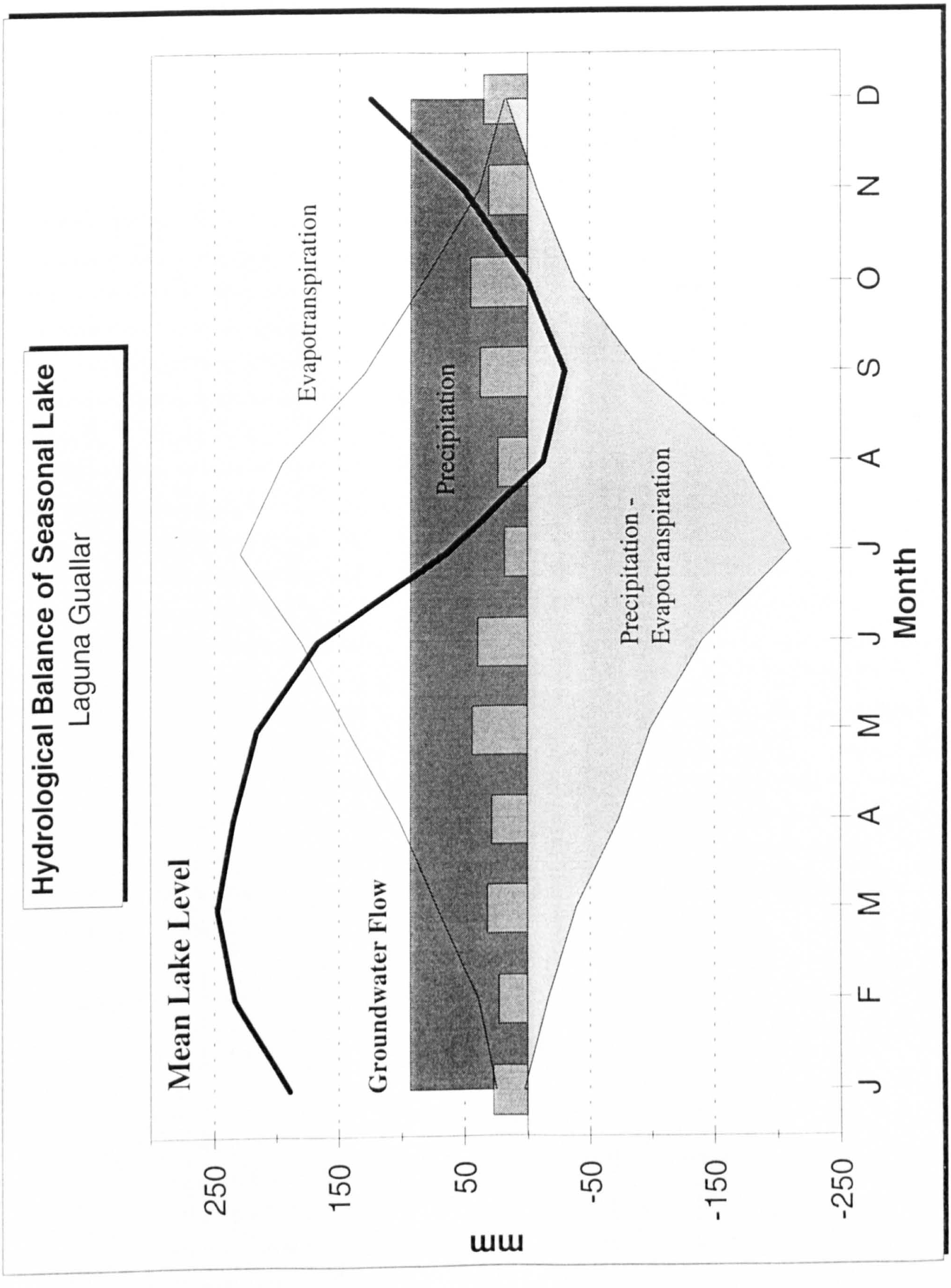


Figure 7.4 Hydrological balance of a seasonal lake: the Laguna Guallar

'concentration' of this available water must occur into the lake body. This can be viewed in a similar way to the concentration of runoff waters from a surrounding catchment. The area of this groundwater 'catchment' therefore represents the amplifier effect necessary to gather sufficient water to raise lake water levels to their observable level (*Figure 7.5* p121). The amplifier value is empirically derived, unlike that of runoff, which is calculated from the surface area of the catchment. Because of this, the groundwater 'catchment' amplifier value inherently includes any amount of leakage from the aquifer, which is assumed to remain constant over time.

Calculation of this amplifier value can be determined by assuming equilibrium conditions in the annual lake water balance, whereby precipitation and groundwater inputs to the lake exactly equal evaporation and groundwater outputs in any one particular year. Groundwater outputs are assumed to be exactly equal to groundwater inputs minus loss through evapotranspiration. In reality, fluctuations in precipitation from year to year cause variations in lake depth and flooding period, although the damping effect caused by slow hydraulic flows within the aquifer reduce this to a minimum in the short term. The response time of the groundwater to changes in the hydrological balance varies according to the conductivity of the aquifer. For the purposes of calculating K (the groundwater amplifier value) in the hydrological model, groundwater discharge is assumed to remain constant throughout the year, with winter recharge re-distributed completely by the time the following period of winter recharge occurs. Variations in annual precipitation and evapotranspiration are however likely to produce years of hydrological surplus and deficit which will be carried through into the following year. These long term changes affect the periodicity of lake level change which may produce years when water lies all year around in a 'seasonal' lake, or cause a 'permanent' lake to dry out completely. It is the frequency of these events that is important since the sampling process inherently reflects change over a timescale of a number of years depending on the depth of sediment and its accumulation rate. The heterogeneity of the sediment record and the rapidity and scale (±3.0m) of lake level changes over a sampling interval of between 20-30 years suggests that lake systems are responsive to changes in the hydrological balance over a similar timescale.

Within the hydrological model, the annual loss of water from the lake by evaporation is assumed to be exactly compensated for by water flowing into the lake from the groundwater 'catchment', plus any precipitation falling onto the lake surface. This represents equilibrium conditions within the annual hydrological budget. The remaining depth of water in the lake represents the inflow and outflow of groundwater in equilibrium with the phreatic water surface.

This is given by the equation

$$L = Gi + P = Go + E$$

Where L = mean lake level
Gi = groundwater input
P = precipitation
Go = groundwater output
E = evaporation

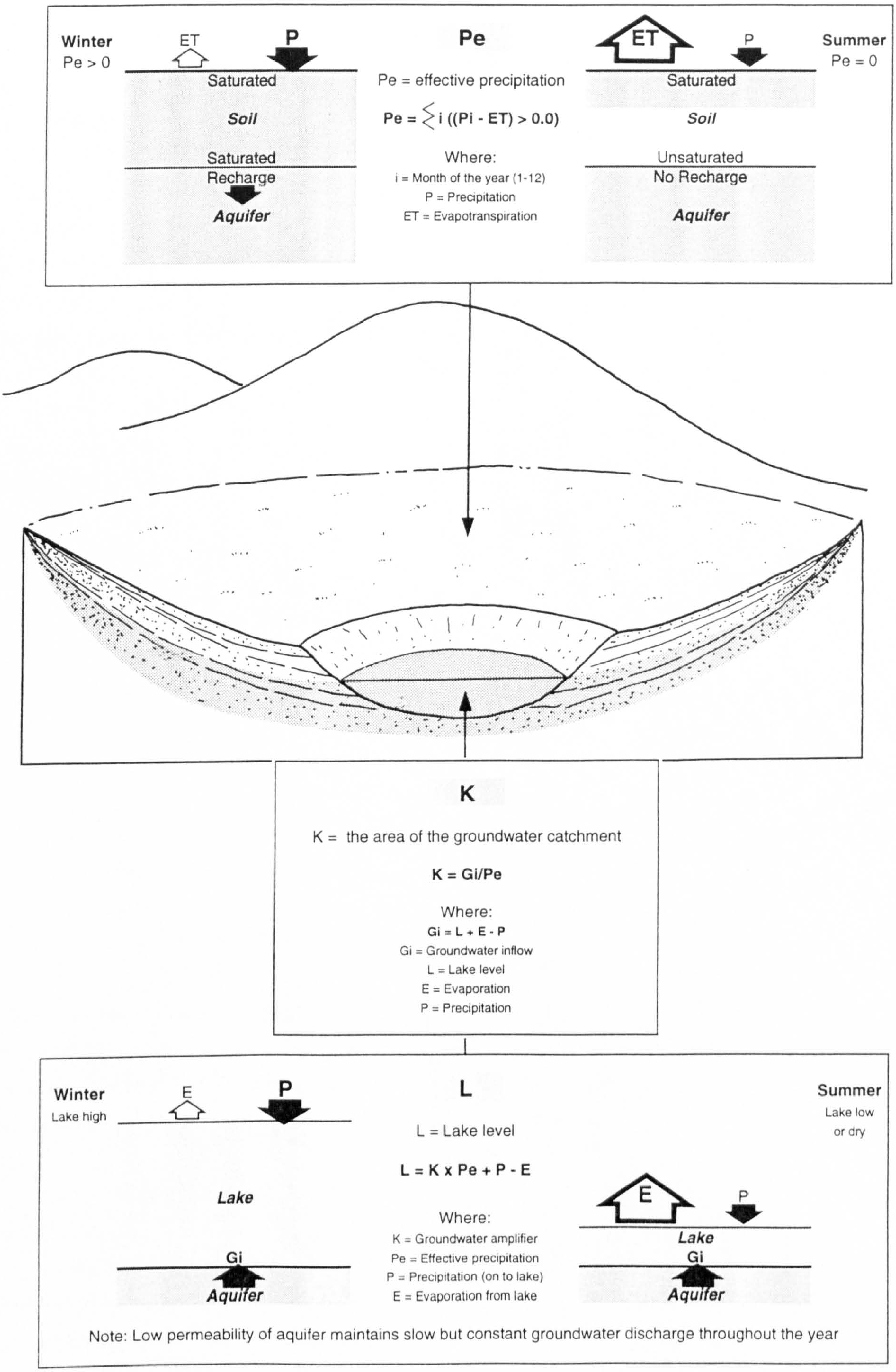


Figure 7.5 **A simple hydrological model for groundwater fed lakes**

The groundwater contribution is then given by

$$Gi = L + E - P$$

$$Go = L + P - E$$

The groundwater amplifier constant K can then be calculated as

$$K = Gi / Pe$$

Where Pe = effective precipitation

Given by

$$Pe = \Sigma i\,((Pi - ETi) > 0.0\text{mm})$$

Where i = month of the year

ET = evapotranspiration

Once K has been established for a particular lake system, the effects on lake level of changes in **P**, **Pe**, **E** and **ET** can be studied since

$$L = K * Pe + P - E$$

Calculations based on mean annual values can however be misleading when categorising lake types by their annual and inter-annual variation in lake level. Thus a seasonal lake (type 3) may have a mean lake level close to, or below 0m, but an annual winter maximum of over 0.5m. The annual variation in lake level can be calculated by applying the above equation on a month by month basis.

$$Li = ((K * Pe) / 12) + Pi - Ei + L(i-1)$$

The low permeability of aquifers in many endoreic areas of Spain reduces seasonal variations in groundwater flows, which tend to remain constant throughout the year. Groundwater inputs to the lake are therefore equal for each month. This assumption may not be valid in all areas, particularly where the aquifer geology is of well jointed limestone, however this is generally not the case in the Ebro Basin.

Lake levels are dynamic, reflecting the water balance of previous months as well as inputs and outputs of the current month. The net accumulation of water during the winter months helps maintain water levels well into the hydrological deficit period in early summer. Annual variations in water balance are also set within inter-annual variations that are not included in the simple equilibrium model so far discussed. The annual water balance is liable to vary from one year to the next along with precipitation evaporation and evapotranspiration. Semi-permanent lakes reflect this inter-annual variation, with water levels periodically dropping to below the sediment surface during particularly dry years. Similarly, ephemeral lakes may flood to shallow depths during wet years, but remain dry in most other years.

The amplitude of the seasonal variation in lake level determines the minimum and maximum depth of water within a lake body within any particular year. These minimum and maximum values represent the boundary conditions between different lake types shown in the palaeolimnological record. The periodicity of inter-annual fluctuations is also likely to be important within the timescale of the sampling interval used in palaeolimnological analysis. A 2cm slice of sediment core may represent a 50 year record of lake level fluctuations. Care must be taken in interpreting the palaeolimnological parameters used to reconstruct these changes since they may reflect the extremes of lake level more closely than the mean. However, this variation is inherently incorporated in the classification system since sampling of lakes within the data set was by the same method, and probably reflects a similar scale of lake level variation within a similar sampling timescale.

Within this dynamic pattern of annual and inter-annual lake level change, a number of threshold conditions can be established that give rise to distinctive palaeolimnological indicators. These are summarised in *figure 7.3* p117.

Application

The Laguna Guallar is a seasonal playa lake in the Los Monegros area of the Central Ebro Basin. The lake is dry for around 4 months per year during the summer, while filling to over 0.3m deep during the winter. Assuming a mean annual water depth of 0.0m, calculation of the groundwater amplifier constant is as follows

$$K = (L + E - P) / Pe$$

$$K = (0.0\text{mm} + 1509.4\text{mm} - 388.3\text{mm}) / 19.3\text{mm}$$

$$K = 58.1$$

The monthly variation in water depth can then be calculated using monthly precipitation and evapotranspiration data in the formula

$$L_i = ((K * Pe) / 12) + P_i - E_i + L(i-1)$$

Li is set at zero at the beginning of the hydrological year in October. The result is shown in *figure 7.4.* Lake levels peak in March at 25cm, and are at their lowest in September at -3cm. Lake levels fall to below the sediment surface between July and October. This would appear close to the observed behaviour of this lake, although the effects of water temperature, salinity and subsurface lowering on evapotranspiration rates are likely to cause some deviation. The calculated depth is a mean figure for the entire lake, consequently, although the basin shape is shallow, some areas at the centre are likely to be deeper than this figure and some areas at the margins will be shallower.

Using this simple lake level model, the approximate mean annual lake level required for each lake type can be predicted for the Laguna Guallar given the present annual variation in lake level. The appropriate values of Pe required to create this condition are also presented.

Table 7.2 Calculated Pe under different lake conditions at the Laguna Guallar:

Lake Type	*Mean Depth*	Pe	*% of current* Pe *(19.3mm)*
1. Dry	-1.0m	<-3.0mm	
2. Ephemeral	-0.5m	-3.0-8.1mm	-15.5-41.9%
3. Seasonal	0.0m	8.1-19.3mm	41.9-100%
4. Semi-Permanent	1.0m	19.3-41.6mm	100-215.5%
5. Permanent (unstratified)	1.0-3.0m	41.6-86.2mm	215.5-446.6%
7. Permanent (stratified)	3.0-16.0m	86.2-376.1mm	446.6-2307.3%
8. Permanent with outflow	16.0m	>376.1mm	>2307.3%

The Laguna Salada is a permanent salt lake 20km distant from the Laguna Guallar, and occupying a lower position in the regional aquifer. Much greater groundwater flows maintain lake levels at around 4.0m throughout the year. Calculation of the K value is as follows

$$K = (4000.0\text{mm} + 1509.4\text{mm} - 388.3\text{mm}) / 19.3\text{mm}$$

$$K = 265.4$$

The Laguna Salada (K = 265.4) has a much larger amplifier value than the Laguna Guallar (K = 58.1), suggesting that it is much more sensitive to changes in effective precipitation and aquifer recharge. This can be shown by calculating the lake level that would occur in the two lakes given a 1mm change in effective precipitation.

$$L = K \times Pe + P - E$$

Laguna Guallar: **$L = 58.1 * 19.3 \pm 1\text{mm} + 388.3\text{mm} - 1509.4\text{mm}$**

$L = 0.0\text{mm} \pm 58.3\text{mm}$

Laguna Salada: **$L = 265.4 * 19.3 \pm 1\text{mm} + 388.3\text{mm} - 1509.4\text{mm}$**

$L = 4000.0\text{mm} \pm 266.5\text{mm}$

Lakes that are sensitive to changes in effective precipitation have large K values (**K x Pe >> P**), while lakes more sensitive to precipitation have low K values (**K x Pe > = or < P**). Effective precipitation occurs when evapotranspiration is at its lowest during the winter months. Changes in the amount of precipitation during this period is therefore particularly important to the hydrology of lakes that have large K values.

The application of this simple water balance model allows the investigation of changes in precipitation, effective precipitation, evaporation and evapotranspiration on lake water depth in predominantly groundwater fed areas. Runoff is assumed to be negligible, although this could be calculated separately and the total deducted from effective precipitation available for groundwater flow. The combination of this model with the 8 stage palaeohydrological model previously discussed allows both the semi-quantitative reconstruction of historical changes in lake level, together with a quantitative means of exploring changes in the main factors influencing lake hydrology. The value of K, incorporating both the area of the groundwater catchment and any leakage that may occur, is assumed to remain constant over time once calculated against the present hydrological condition of the lake basin

Chapter 8

Pollen surface samples & vegetation-climate groups

8.1 Abstract

Surface samples from 29 lakes throughout the Ebro Basin were analysed for pollen and charcoal. Comparison of the pollen record with the contemporary vegetation is used to allow a better understanding of the way the palaeo record represents a real landscape. The arboreal component is particularly over-represented, with values of over 50% TTP occurring in treeless areas.

The pollen vegetation record is divided into 6 main climatic groups according to current bio-geographical information: Sub-Mediterranean, Oro/Supra-Mediterranean, Mediterranean, Pinus, Steppe & Artemisia. Each grouping is then compared at 6 sites across a climatic gradient to investigate their sensitivity and response to 3 main climatic variables: Precipitation, P\PET and m (mean minimum temperature of the coldest month).

8.2 Pollen Surface Samples

8.2.1 *Introduction*

The use of surface samples allows comparison of the preserved pollen record with the contemporary vegetation of the area. This is particularly important since it allows a better understanding of the way the palaeorecord represents a real landscape. The overall pattern of vegetation revealed by pollen analysis closely resembles the current vegetation landscape of the area. However, in interpreting this record, the nature of the depositional environment needs to be considered. Large lakes reflect the regional pollen rain component more than small lakes which tend to be dominated by local vegetation (Jacobsen & Bradshaw, 1981). To this can be added problems of differential deposition associated with seasonal playa lakes (Chapter 6). Furthermore, the driest ephemeral lakes are likely to be almost completely dominated by local vegetation since they more resemble the depositional environment of a soil rather than a lake. It is beyond the scope of this work to begin to quantify these differences, however, the number of lakes of differing size and inundation regime within such a small area such as Los Monegros could provide the means to do so.

8.2.2 *Methods & Results*

Pollen and charcoal analysis were undertaken on surface samples taken from 29 lakes within the Ebro Basin (*Figure 4.3* p64 & *Figure 8.1* p127). Lakes ranged from permanent to ephemeral, and in size, from

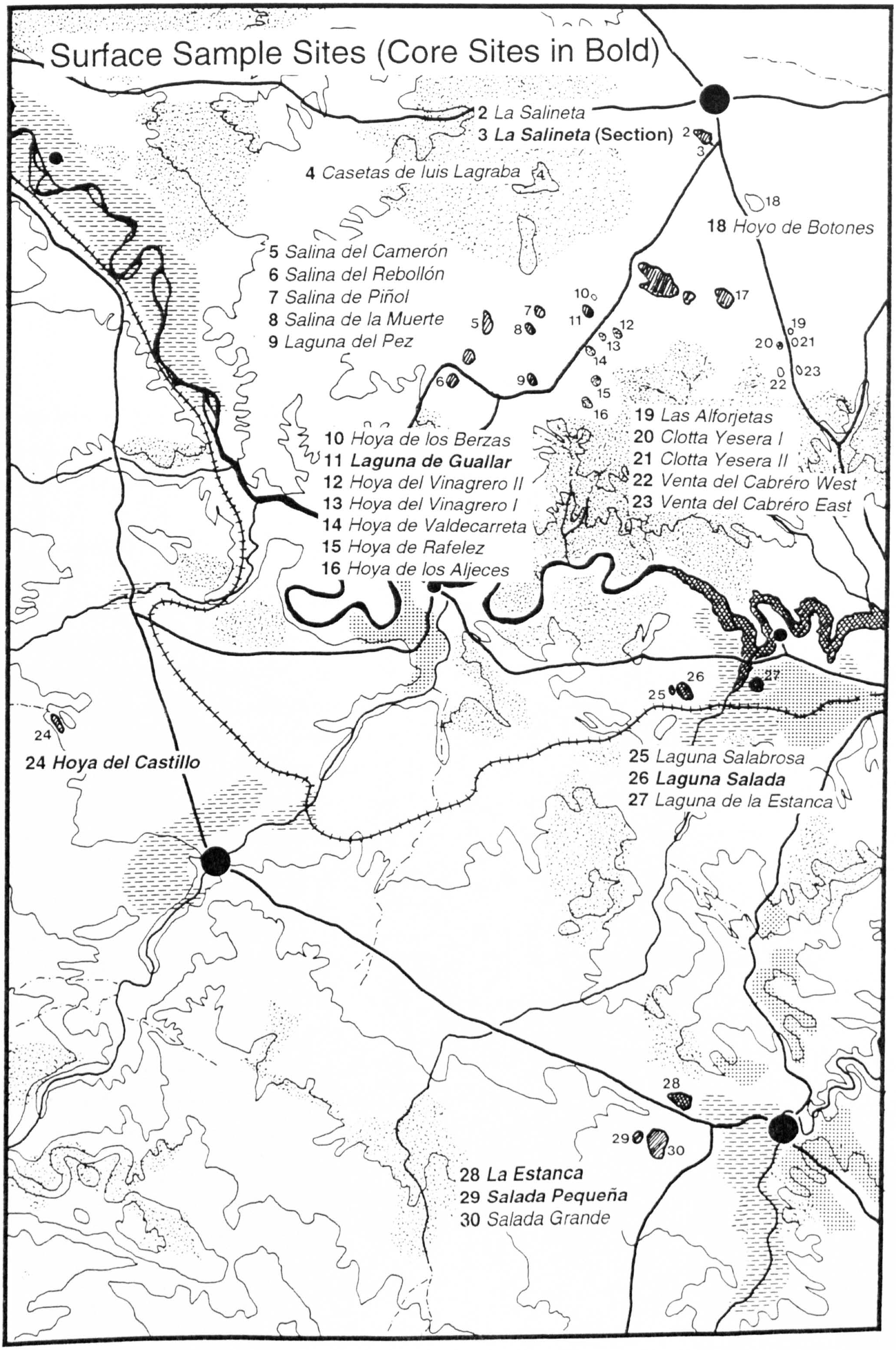


Figure 8.1 **Location map of surface sample sites in the main study area**

1330Ha to 1Ha. A surface sample was also analysed from the wooded hills 5km north-west of the main endoreic lake area of Los Monegros (Casetas de Luis Lagraba, Site Ref.No 4). Lake samples were collected from the deepest part of each lake. Sampling details are given in chapter 5, section 5.1.3. Results are as follows:

Figure 8.2A	terrestrial plant pollen and charcoal p129
Figure 8.2B	lake type (level) and vegetation summary p130

8.2.3 *Discussion*

8.2.3.1 *Arboreal Pollen*

The arboreal component is dominated by *Pinus*, *Quercus ilex*-type and *Olea* pollen, corresponding to a landscape of mainly *Pinus halepensis* and *Quercus coccifera* scrub, together with plantations of cultivated *Olea europaea*. This is accompanied by typical Mediterranean xerophytic matorral shrubs, such as *Phillyrea*, *Juniperus*, *Ephedra* and *Pistacia*.

Forest Cover

In the Los Monegros area (sites 2 & 5-23) the arboreal component comprises over 50% of the total terrestrial pollen sum (excluding Chenopodiaceae), despite the largely treeless nature of the landscape. This higher than expected representation due to long distance transport suggests that high arboreal pollen values may still occur in the semi-arid Mediterranean, even when the landscape has been completely cleared of trees. In contrast, total arboreal pollen values rise to 90% at site 4, located in the forested hills 8km to the north-west. A difference of 40% in the total arboreal component separates full forest cover from completely treeless steppe. This can be attributed to a number of factors including the low pollen productivity of typical steppe plants, the high pollen productivity of local *Pinus* woodland, and the proximity of this woodland to the steppe area.

Olive Cultivation

Olive cultivation is widespread in the Ebro Basin, particularly on the drier and warmer southern slopes, near Caspe and Alcañiz, and near the town of Bujaraloz. Here, *Olea* pollen values rise above 10%, reaching over 60% at site 30 (the Salada Grande), some 2km from the extensive olive groves that surround Alcañiz. Background levels within the regional pollen rain are sustained at between 5-10% even at sites within the treeless Los Monegros area. This would appear to agree with Bottema (1974), Van Zeist *et al* (1975) and Mateus (1992) who suggest that *Olea* pollen is well dispersed. Values above 5% may therefore indicate extensive olive cultivation within a large regional area. Much higher values of 20% (5km distant) and 60% (2km distant) can be found closer to the main olive growing areas, suggesting agreement with Stevenson (1981) that olive is a prolific producer of pollen, but a poor disperser. Caution has to be extended to these conclusions

Figure 8.2A **Lake surface samples: terrestrial plant pollen and charcoal**

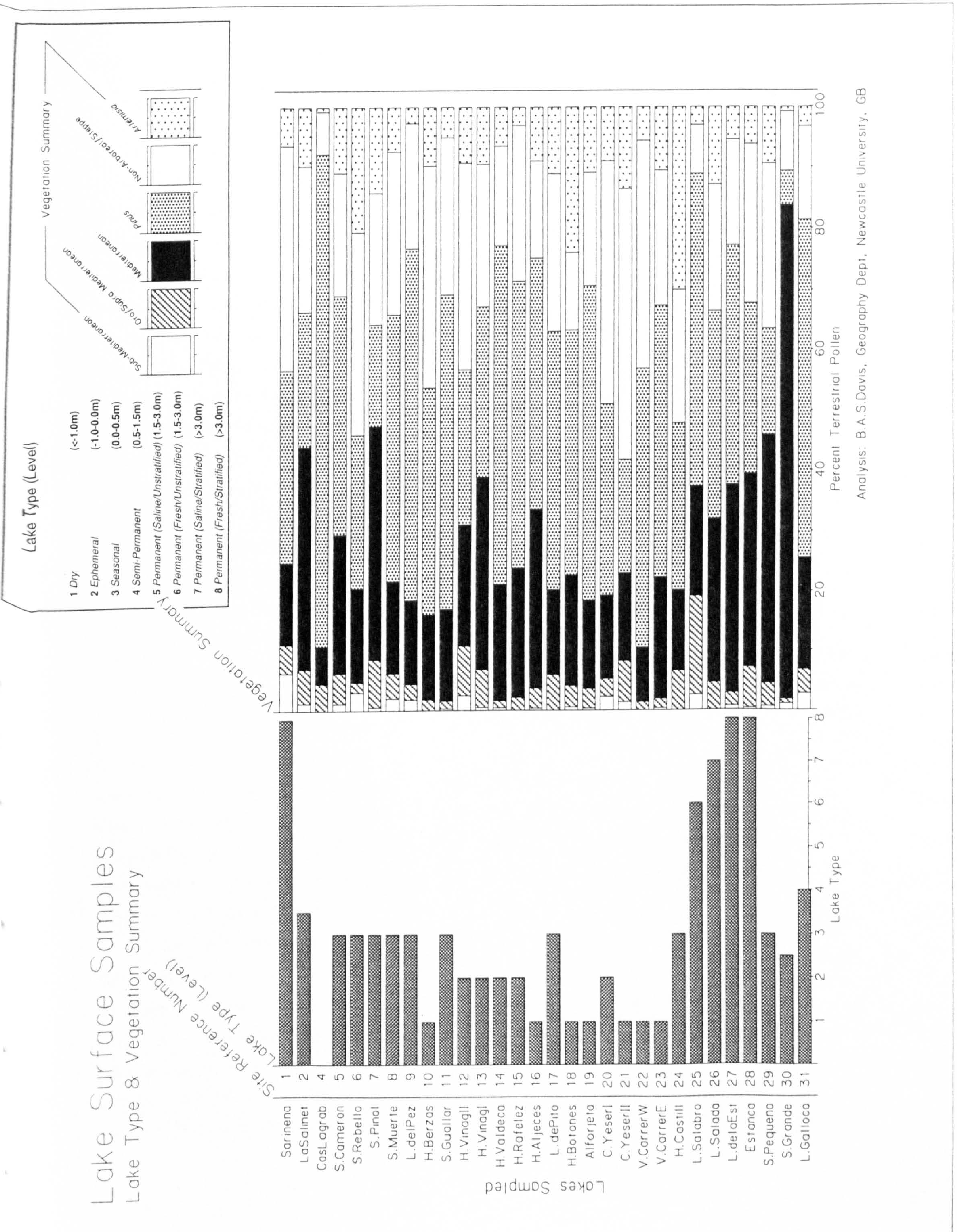


Figure 8.2B **Lake surface samples: lake type (level) and vegetation summary**

however given the taphonomic problems that appear to be associated with olive pollen deposition in playa lakes (chapter 6) where over-representation of *Olea* may occur.

8.2.3.2 *Non-Arboreal Pollen*

Although dominated by arboreal pollen, most of the vegetated landscape of the Ebro Basin is in fact non-arboreal steppe. The over-representation of arboreal taxa can be attributed not only to long distance transport from wooded areas, but also the poor pollen production and dispersal capabilities of many arid land herbaceous plants. This also partly explains the low taxonomic diversity of the pollen record, along with the low pollen concentrations and poor preservation often associated with playa lake deposits.

High *Artemisia* pollen values reflect the extreme continental climate of the basin, particularly at sites in the central Los Monegros area. *Artemisia herba-alba* steppe is accompanied by areas of grass (*Stipa*) steppe, with high Gramineae values (20-30%) occurring at almost all sites. The widespread occurrence of larger Gramineae grains (>50µm) reflects both the widespread cultivation of winter wheat, and the naturally occurring *Lygeum spartum* grass.

Disturbance as a result of anthropogenic action can also be seen in the extensive occurrence of many ruderals such as *Anthemis*-type, *Bidens*-type, *Liguliflorae*, *Plantago* and *Rumex*. Most of these taxa can also be expected for an naturally disturbed arid landscape, particularly *Plantago*, which is often associated along with the Chenopodiaceae in arid environments.

Chenopodiaceae and Artemisia

The ratio of Chenopodiaceae to *Artemisia* pollen (C/A or A/C) has been used as an aridity indicator by Barnosky (1988) in Montana, El-Moslimany (1990) in the Middle East and by Van Campo & Gasse (1993) on the Tibetan Plateau. These have been based on the principle that *Artemisia* tends to be characteristic of semi-arid steppe, and is replaced by Chenopodiaceae as conditions become drier until Chenopodiaceae dominates under arid desert conditions. While *Artemisia* is likely to originate from steppe vegetation alone, halophil ous Chenopodiaceae also actively colonise the margins of saline lakes in arid areas. Increasing amounts of Chenopodiaceae pollen may therefore reflect either the regional replacement of steppe by desert or the local exposure of mudflats with low lake levels.

Chenopodiaceae dominates the non-arboreal pollen component at many of the lakes sampled in the Ebro Basin. The origins of this Chenopodiaceae pollen is probably largely attributable to the seasonal development of marginal halophytic vegetation during summer draw-down rather than the aridity of the environment. A close relationship exists between the permanence and salinity of lake waters and the quantity of Chenopodiaceae pollen found (Chapter 7). The Ebro Basin has a continental semi-arid Mediterranean climate, characterised by *Artemisia* and grass (*Stipa* and *Lygeum spartum*) steppe, with few areas of truly desert conditions that would encourage dominance by Chenopodiaceae. Soil conditions are highly saline in parts, with surface exposures of gypsum, however, even here, halophilic Chenopodiaceae are in competition from other perennial halophytes.

Artemisia and Chenopodiaceae are both openland taxa that require unforested open areas in order to flourish. Ratios of the two taxa are less applicable therefore where arboreal vegetation is present in large amounts (El-Moslimany, 1990). The Ebro Basin has a particularly steep precipitation gradient, declining over 300mm in less than 30km from the surrounding mountains to the central plains. Vegetation also declines from forest to steppe over the same distance. The proximity of the forest however allows a large amount of arboreal pollen to occur even at unforested sites. This means that in areas that are virtually treeless, arboreal pollen constitutes over 50% of total terrestrial pollen. Interpretation of any ratio should not therefore necessarily be constrained by such a high proportion of arboreal pollen since this may not reflect direct habitat competition.

No attempt was made to apply Chenopodiaceae-*Artemisia* ratios to the palaeo record as an aridity indicator. The Chenopodiaceae were separated from the terrestrial plant sum since all evidence suggested that the vast majority of pollen present represented marginal lake vegetation. The use of Chenopodiaceae pollen as a lake level indicator must also be approached with caution however. Values over 50% total pollen undoubtedly appear to represent complete colonisation of the lake basin and sample site. Lower values may represent increased inundation or alternatively, increased competition from other less salt tolerant terrestrial plants as a result of increased basin dryness. Plant colonisation can also be inhibited in shallow hypersaline lakes during desiccation by the formation of a thick salt crust, while intense evaporation of water logged areas at the margins of freshwater lakes may produce saline soils that favour Chenopodiaceae growth.

8.2.3.3 *Charcoal*

Charcoal counts show large variations, although these partly reflect differences in deposition rates suggested by the close correlation between high pollen and charcoal concentrations. Higher charcoal concentrations can be found in the central Los Monegros area where conditions are more arid and field burning and scrub clearance are still regularly practised.

8.3 Vegetation-Climate Groups

8.3.1 *Introduction*

An approximate semi-quantitative measure of palaeo-climate can be established from the known distribution and environmental tolerance of indicator plant species. More accurate quantitative measures have been applied in continental scale analysis (*cf.* Huntley & Prentice, 1988; Webb *et al.*, 1993) using transfer functions based on pollen surface samples and climatic data. The use of multi-proxy studies, using lake level as well as pollen data, have also been employed may help to constrain such models (Guiot *et al.*, 1993). These large scale studies are beyond the scope of this work, however it is nevertheless interesting to investigate any climate relationships with the data available, particularly since little work has addressed the Mediterranean vegetation and climate in detail.

A particular problem with using pollen data in palaeo-climatic modelling is the low taxonomic resolution available for relating environmental variables to known species tolerances. This is particularly so in the Mediterranean, where the dominant forest canopy is often composed of species of *Quercus* and *Pinus* whose pollen is poorly differentiated. Only broad climatic inferences can therefore be made at a family level without the benefit of species differentiation and niche occupancy. Some pollen types can be attributed to broad climatic types, such as 'typical' Mediterranean species such as *Olea, Phillyrea, Pistacia* and *Quercus ilex. Pinus* however is found in a variety of climatically distinct areas. In many continental scale pollen-based climate reconstructions (cf. Huntley & Prentice, 1988), *Pinus* is often associated with sub-arctic boreal forest and consequently likely to produce poor reconstructions at Mediterranean latitudes at such a large scale of analysis. The conclusions of Huntley & Prentice (1988) that temperatures were depressed in the south and east of Spain during the European altithermal 6.0Kyr BP may be related to this confusion. Charcoal evidence from this area at this time (Vernet & Thiebault, 1987) indicates that the dominant pine was *Pinus halepensis*, commonly associated with lowland southern Mediterranean pine forests and sensitive to frost (Le Houérou, 1981). In similar studies in the USA (cf. Webb *et al*, 1993), pine is differentiated between southern and northern areas to more accurately reflect these differences. A further problem in the Mediterranean region however is the importance of altitude, with the montane Mediterranean pine forests (cf. *P.nigra, P.sylvestris*) being less sensitive to frost but more sensitive to drought than their lowland equivalents.

8.3.2 *Vegetation-Climate Modelling*

8.3.2.1 *Introduction*

Six broad vegetation-climate groups were constructed from the known environmental tolerances and contemporary distribution of the major species that form the main pollen types in the Ebro Basin. This is a relatively crude method of climate reconstruction, however it is intended more as a qualitative guide than a quantitative measure of climate. All pollen types were allocated into one of six groups that were then used to construct a vegetation summary of the fossil record.

The utility of each grouping as a climate indicator is compared at 6 surface sample sites across a climatic gradient in the Ebro Basin. This is used to investigate each groups sensitivity and response to 3 main climatic variables: Precipitation (P), P\PET and **m** (mean minimum temperature of the coldest month).

8.3.2.2 *The Model*

Information on the plant-environment relations and distribution of the main pollen types were derived from Rivas-Martinez (1987), Mateo (1987) and Le Houérou (1992). Six groups were constructed in all:

1. Sub-Mediterranean
2. Oro/Supra-Mediterranean
3. Mediterranean
4. *Pinus*
5. Arid Steppe/Openland
6. *Artemisia*

1. Sub-Mediterranean

Rainfall is relatively high, from 600 to 1400mm, and the winters cool or cold. Mean annual temperatures are in the range 8 to 12°C, and the mean minimum temperature in the coldest month is between -3 to 1°C. Summer drought is less pronounced than in the other categories.

The natural vegetation is composed mainly of deciduous forest, although conifers increase with declining winter temperatures at higher altitudes. This category also includes riverine taxa, including *Alnus glutinosa, Corylus avellana, Ulmus glabra* and *Fraxinus angustifolia.*
Pollen taxa: *Betula, Carpinus*-type, *Corylus, Fagus, Juglans, Ulmus, Alnus.*

2. Oro/Supra-Mediterranean

Winters are cold with the mean minimum for the coldest month between -4 to -1°C. Mean annual temperatures are in the range 8 to 13°C. Rainfall can vary from 200 to 800mm per year. Rainfall is strongly seasonal, with a prolonged summer drought.

Vegetation includes *Juniperus thurifera* and xerophytic shrubs such as *Ephedra.*
Pollen taxa: *Juniperus, Ephedra fragilis*-type, *Ephedra distachya*-type.

3. Mediterranean

Climate and vegetation types overlap between Supra and Meso-Mediterranean categories. Rainfall is at the higher end of both categories, between 300 to 1400mm. Slightly warmer winters, and/or wetter early season conditions allow the growth of evergreen oaks and sclerophyllous shrubs adapted to prolonged summer drought, including *Q.coccifera, Quercus ilex* , *Q.suber, Pistacia lentiscus* and *Olea europaea.*
Pollen taxa: *Quercus ilex*-type, *Quercus suber*-type, *Mentha-type,* Ericaceae, *Halimium, Helianthemum, Olea, Phillyrea, Pistacia, Vitis*

4. Pinus

Pinus is represented by two distinctly different groups, divided between the thermo-mediterranean lowland forests of *Pinus halepensis,* and the upland montane-mediterranean hydrophilous forests dominated by

P.nigra and *P.sylvestris*. It is not possible to differentiate the two directly from the pollen record, although the presence of other species may help.

Pinus halepensis is the dominant pine in the Central Ebro Basin and is characteristic of warmer meso-mediterranean conditions, with the mean minimum for the coldest month between -1 to 4°C and mean annual temperatures from 13 to 17°C. *Juniperus phoenicea* is co-dominant in the arid zone (200-400mm), while *Quercus ilex* takes on this role in the semi-arid zone (400-600mm) (Le Houérou, 1981).
Pollen taxa: *Pinus*

5. Steppe/Openland

Declining arboreal taxa are associated with declining available soil moisture, reduced number of growing days and extreme variation in temperature. Diurnal and seasonal temperatures show large variations often associated with a continental climate. Rainfall is low or very low (<400mm) with prolonged drought. Steppe or grassland replace scrub and forest, although this is complicated by anthropogenic clearance for cultivation.
Pollen taxa: All herbaceous species except the Chenopodiaceae and *Artemisia.*

6. Artemisia

Artemisia steppe (*A.herba-alba*) forms a large part of the Central Ebro Basin, and equally, a large proportion of the pollen rain. It is particularly well adapted to a continental climate with warm summers, drought (150-250mm), and xeric soil conditions. In the Ebro Basin it is also often associated with anthropogenically degraded nitrophilous matorral (Mateo, 1987).
Pollen taxa: *Artemisia*

8.3.3 *Model Testing*

The sensitivity of the vegetation-climate climate groups were tested using 6 sites chosen for their proximity to meteorological stations and the permanency of their waters (*Table 8.1* p136). The latter factor would appear to be important given some of the potential taphonomic problems encountered in playa lakes (Chapter 6).

Table 8.1 Surface sample site, meteorological station and meteorological data

Lake Site	Met.St.	P	T	m	PET	P/PET
31 Gallocanta	Daroca	436	12.18	-1.3	1009	0.72
1 Sariñena	Sarinena	405	14.48	0.9	805	0.50
2 La Salineta	Bujaraloz	391	14.40	2.6	1254	0.31
28 La Estanca	Alcaniz	378	14.10	1.2	768	0.49
26 Laguna Salada	Chiprana	332	14.20	1.3	1191	0.28
24 Hoya del Castillo	Hijar	319	14.50	1.1	750	0.41

A number of climatic variables were plotted against the percentage total terrestrial pollen assemblage of the 6 vegetation-climate groups (*Figures 8.3* p137, *8.4* p137, *8.5* p139 *& 8.6* p143). All sites have a meso-mediterranean climate and are relatively similar in their climatic regime. This results in little differentiation of mean temperature (T) which provides a poor discriminatory function (*Figure 8.3* p137). Greater variation is provided by precipitation (P), m and P\PET (Penman), although many sites have the same rank for all three functions.

Precipitation (P)

Precipitation values at the sites studied range from 436 to 319mm per year, transgressing the semi-arid:arid boundary at around 400mm.

Declining precipitation is accompanied by a decline in forest cover and increase in openland **steppe** (*Figure 8.4* p137). A large part of this increase is attributable to *Artemisia* (*Figure 8.4.1* p138), which particularly favours arid conditions. ***Pinus*** shows a double peak at both ends of the precipitation gradient, reflecting the distribution of sub-humid, montane pine forest and arid, lowland Mediterranean pine forest. The **Mediterranean** vegetation (including *Quercus ilex*-type) increases in the semi-arid zone between 330 and 380mm, mainly as a result of *Olea* from olive plantations (*Figure 8.4.2* p138). **Supra-mediterranean** vegetation (mainly *Juniperus* & *Ephedra*) occurs at a more consistent level at all 6 sites, although increasing slightly with increasing aridity. **Sub-mediterranean** vegetation (deciduous forest) constitutes the lowest contribution to the pollen rain, and demonstrates a marked decline around the semi-arid:arid boundary at 400mm.

P/PET

P/PET values range from 0.28 to 0.72 and cross the arid (<0.43), semi-arid (0.43-0.60) and sub-humid (>0.60) bioclimatic boundaries (Le Houérou, 1992).

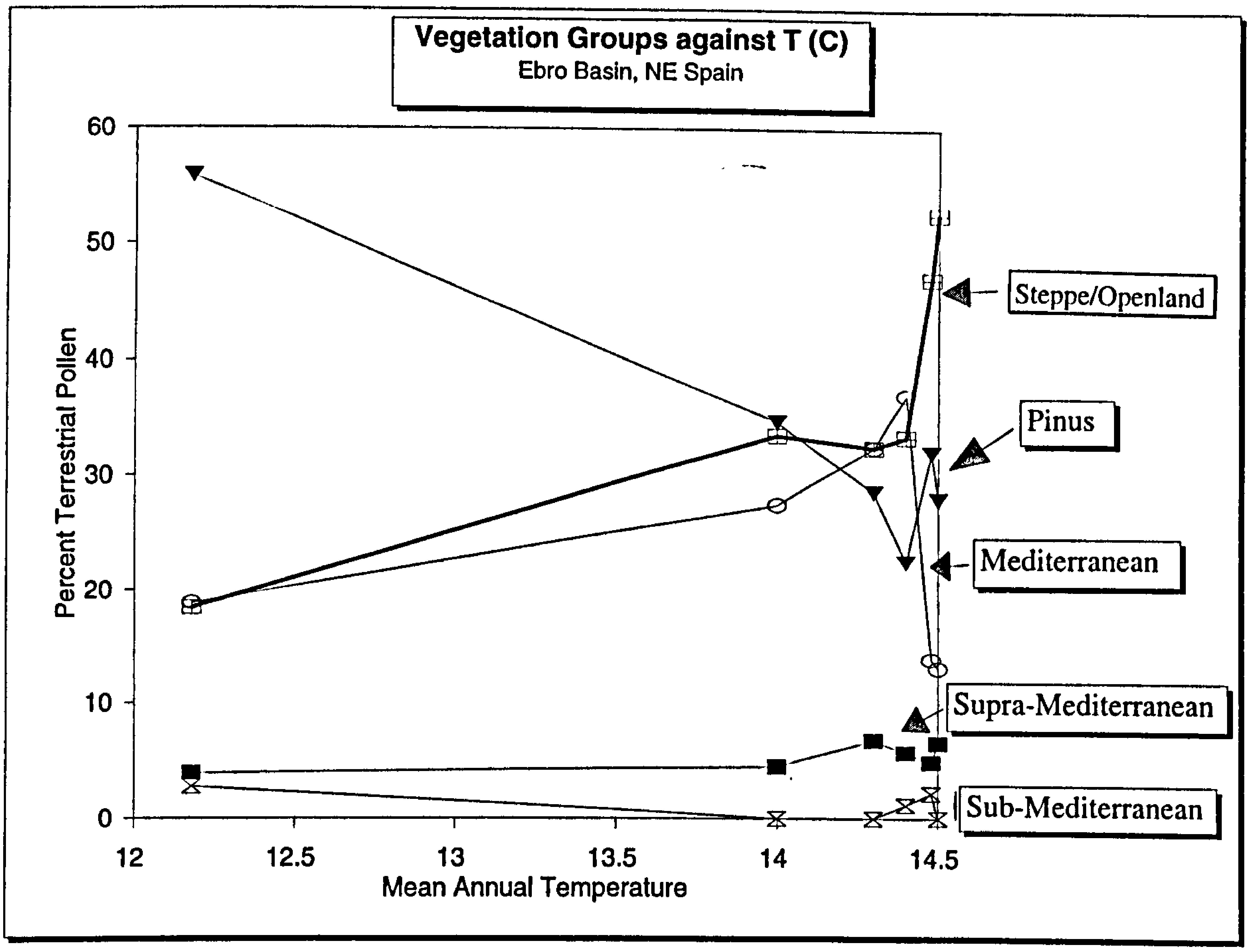


Figure 8.3 **Pollen vegetation-summary groups plotted against mean annual temperature (T) at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin**

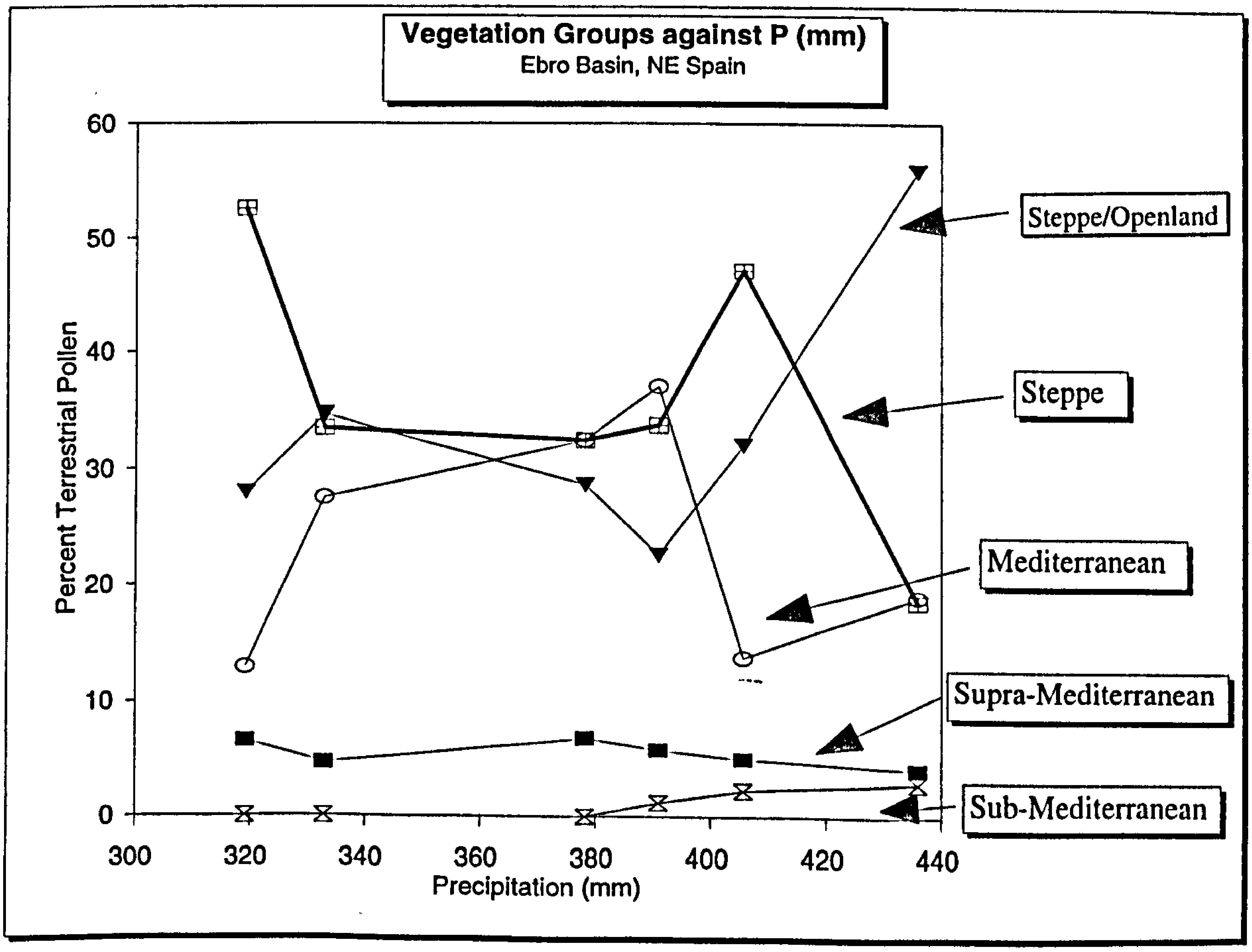


Figure 8.4 **Pollen vegetation-summary groups plotted against mean annual precipitation (P) at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin**

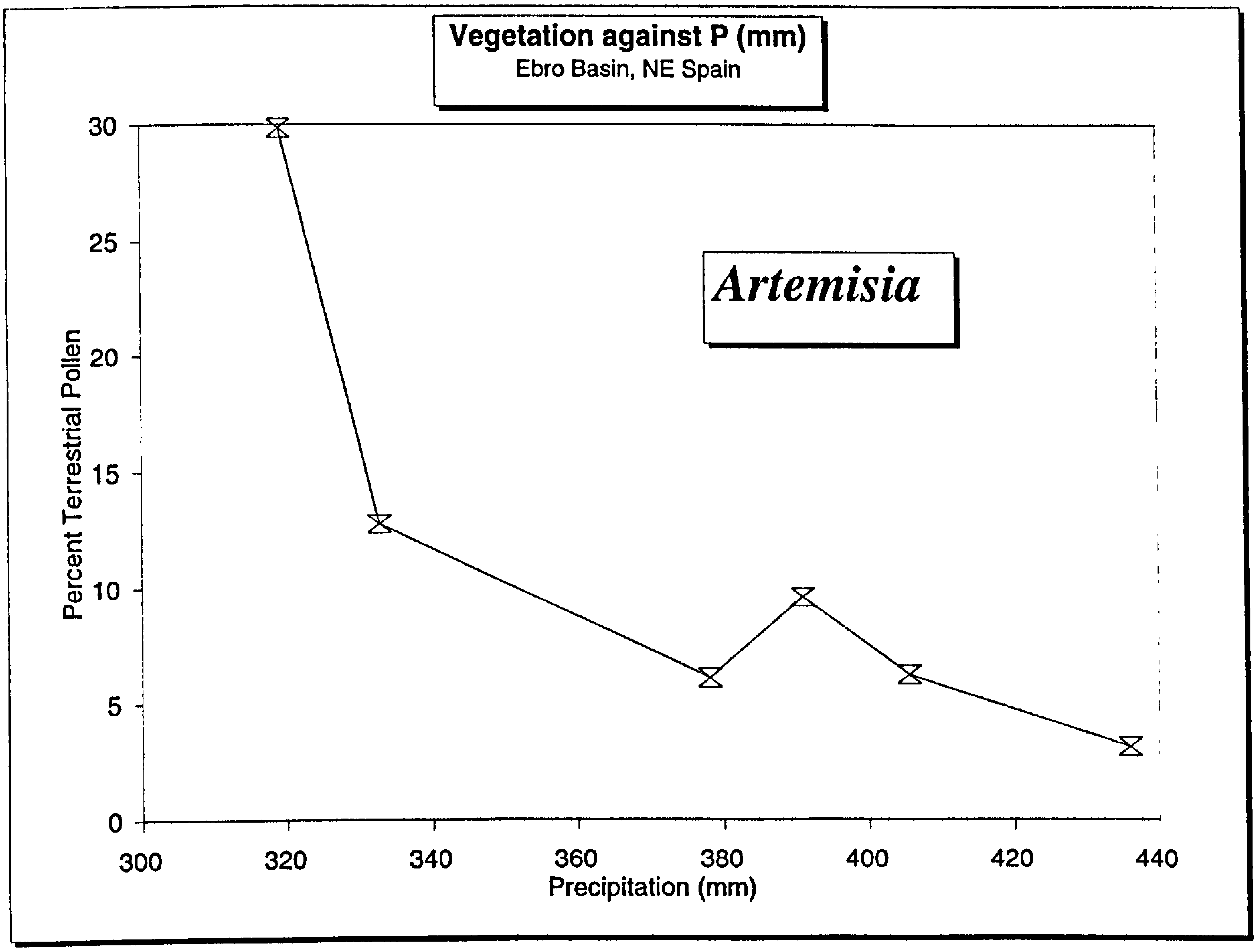


Figure 8.4.1 *Artemisia* pollen plotted against P at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin

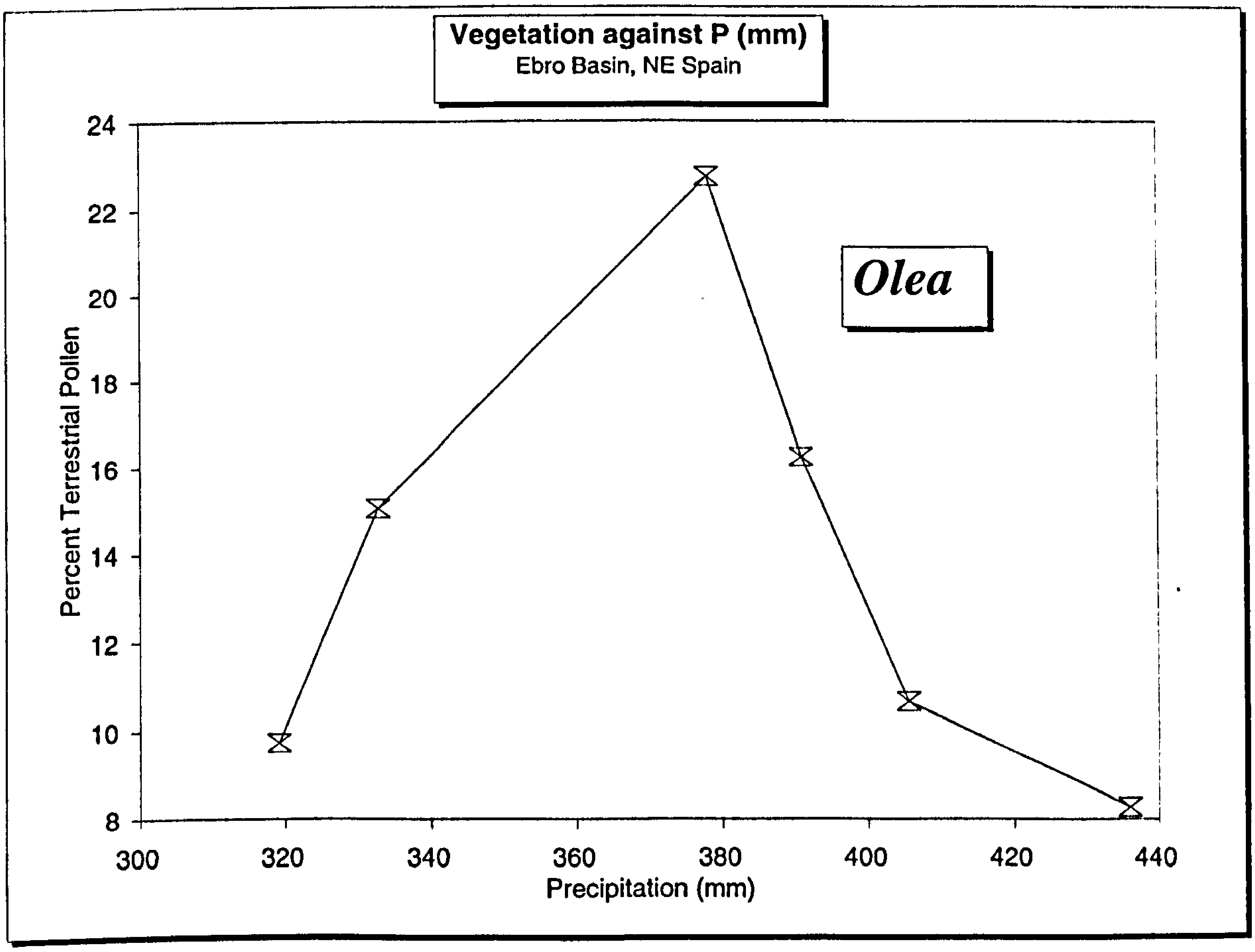


Figure 8.4.2 *Olea* pollen plotted against P at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin

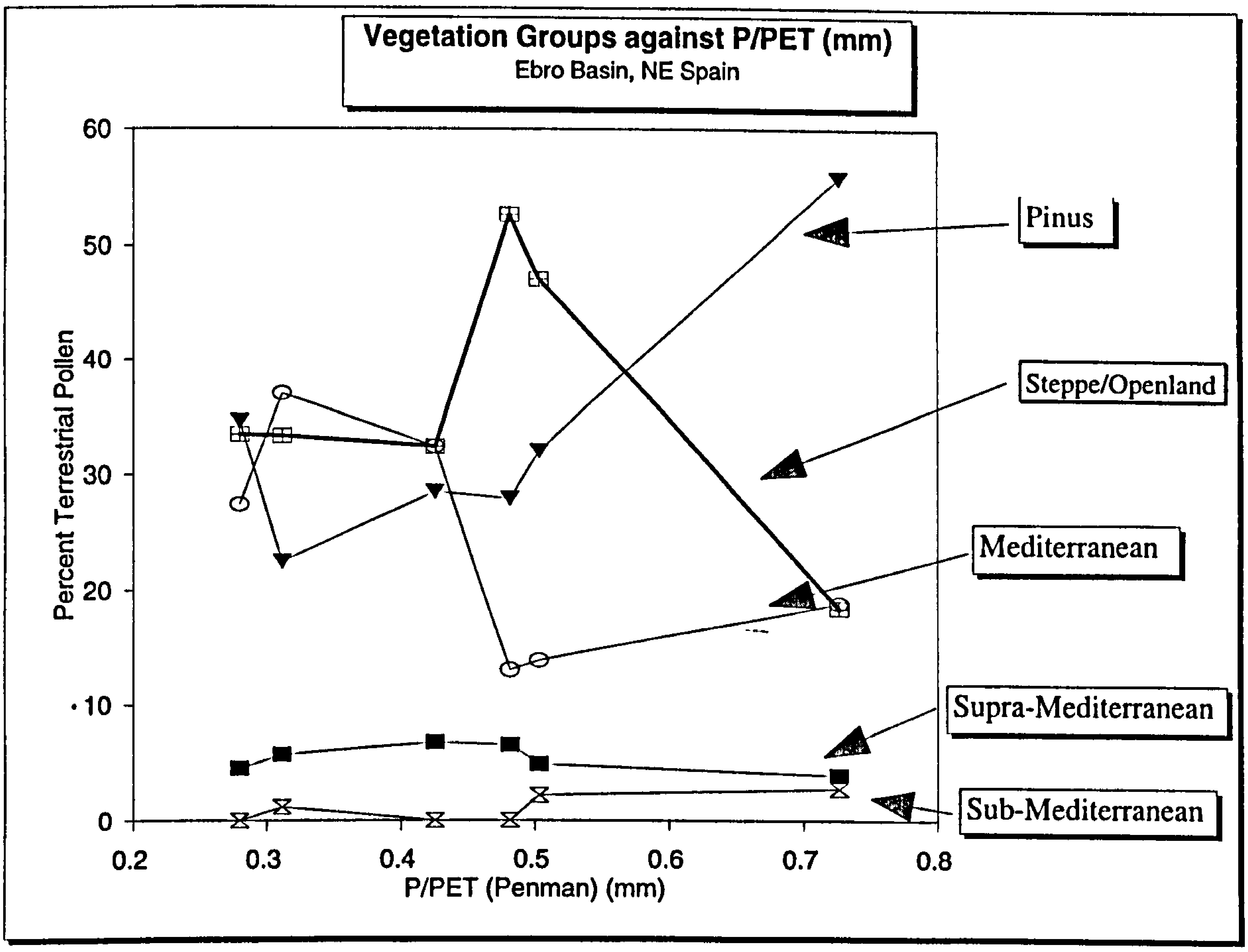


Figure 8.5 **Pollen vegetation-summary groups plotted against drought stress (P/PET) at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin.**

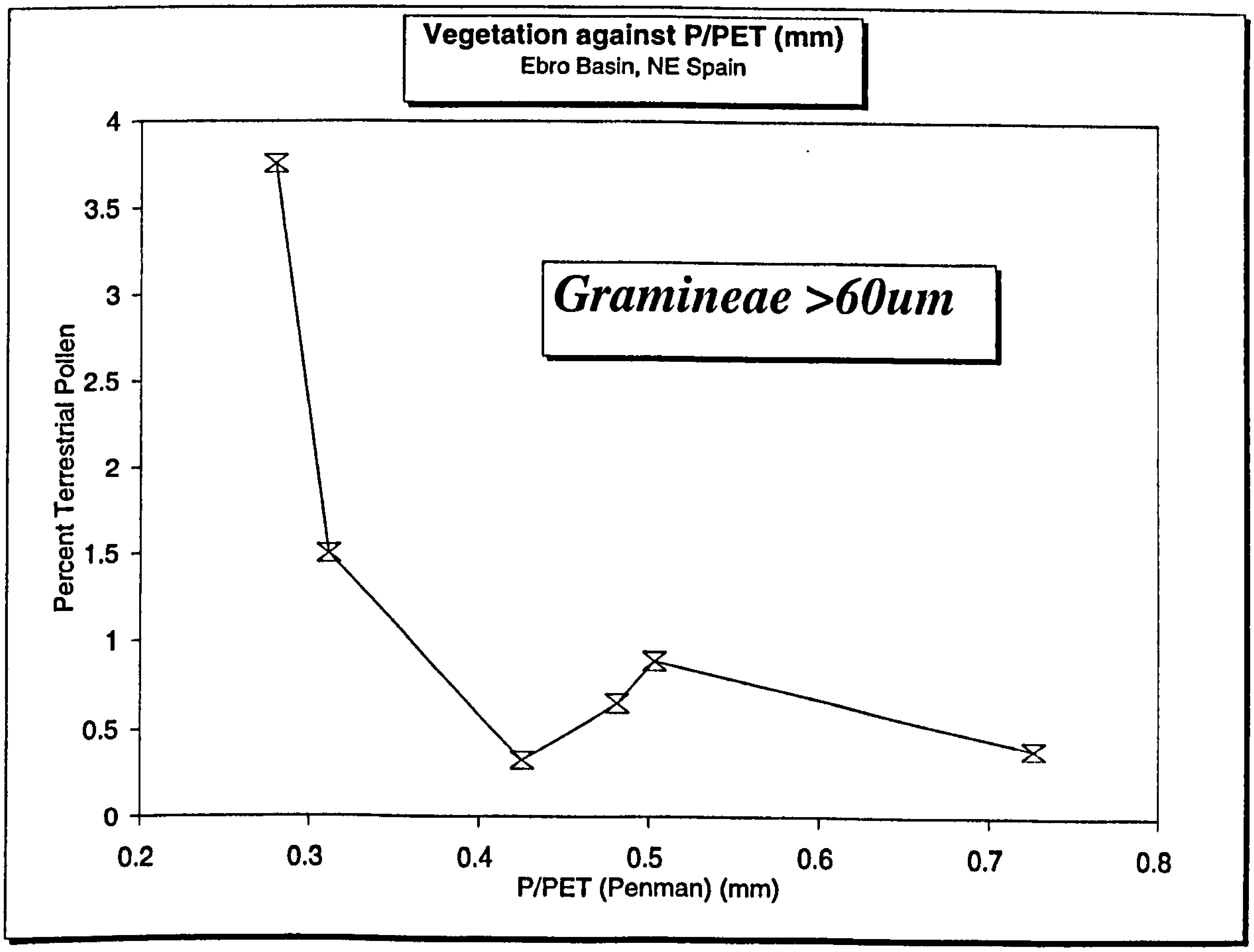


Figure 8.5.1 **Gramineae>60µm pollen plotted against P/PET at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin**

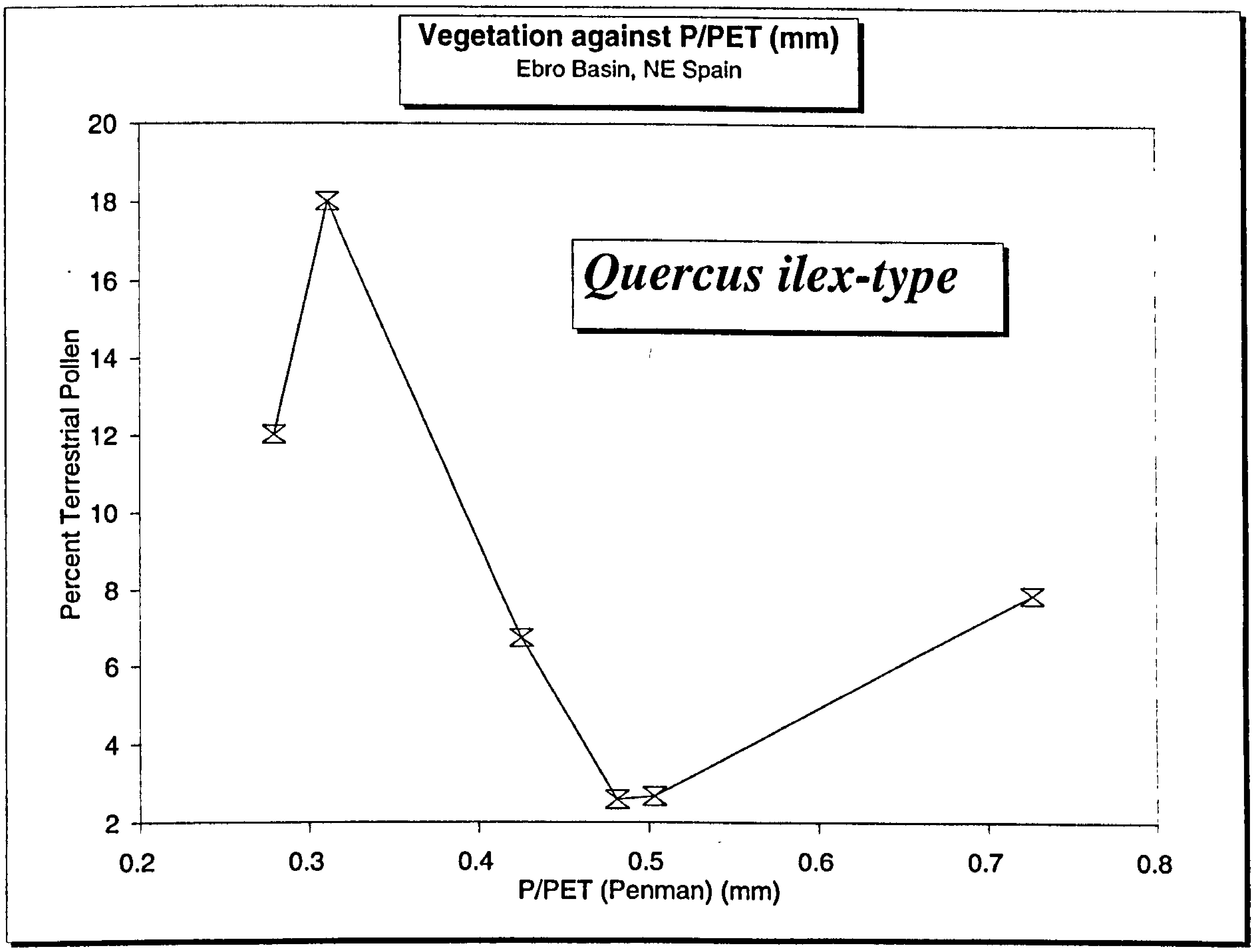


Figure 8.5.2 Quercus ilex-type pollen plotted against P/PET at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin

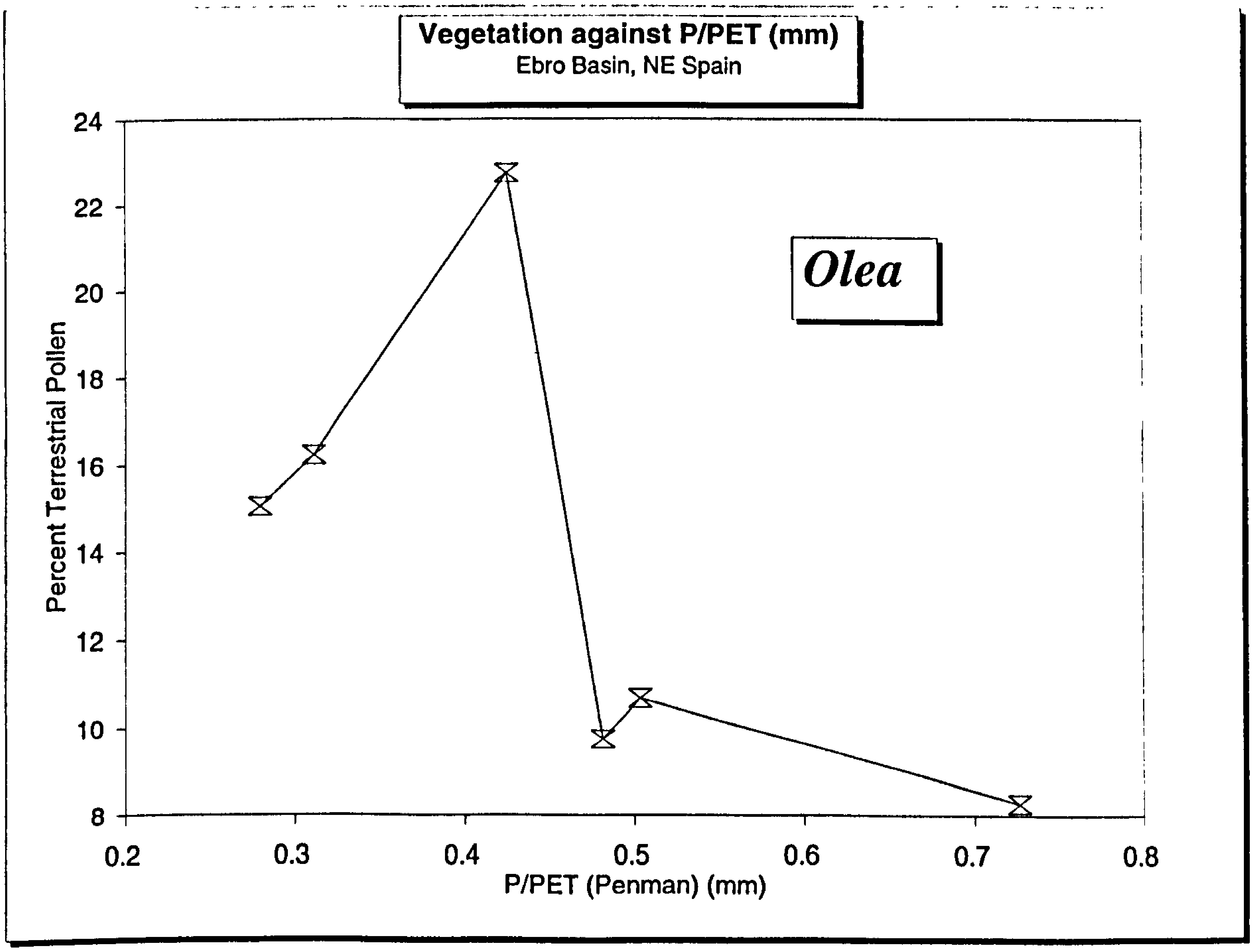


Figure 8.5.3 Olea pollen plotted against P/PET at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin

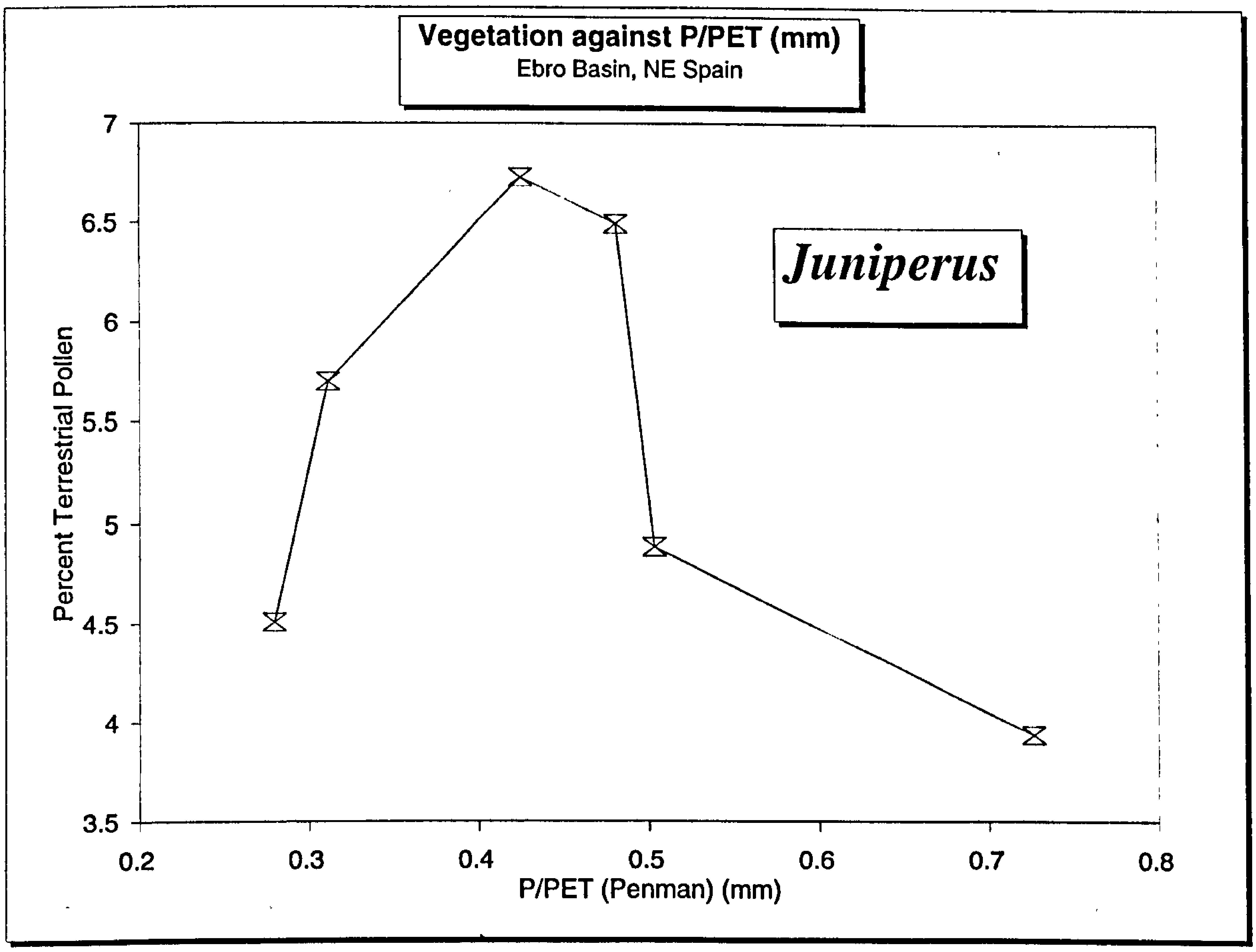


Figure 8.5.4 ***Juniperus*** **pollen plotted against P/PET at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin**

Declining ratios (increasing drought stress) are accompanied by a general reduction in woodland and increase in **steppe** (*Figure 8.5* p139). Cereal and *Lygeum spartum* size Gramineae (>60μm) increase below the arid (<0.43) boundary. ***Pinus*** and the **Mediterranean** taxa group show a similar relationship to precipitation, with pine increasing at the sub-humid and arid ends of the gradient, while Mediterranean taxa peak in the middle semi-arid zone. Within the Mediterranean group, *Quercus ilex*-type (*Q.coccifera*?) (*Figure 8.5.2* p140) peaks at a slightly lower ratio than *Olea* (*Figure 8.5.3* p140). The **supra-mediterranean** vegetation, consisting mainly of *Juniperus* (*Figure 8.5.4* p141), increases with declining ratios (<0.5), while the **sub-mediterranean** group displays the opposite trend.

m *(Mean minimum temperature of the coldest month)*

The mean minimum temperature of the coldest month provides a guide to winter cold stress and ranges from -1.3 to 2.6°C at the sites studied.

The vegetation response to **m** is almost the same as P/PET, with decreasing temperatures equivalent to increasing P/PET ratios (*Figure 8.6* p143).

Pinus decreases with declining values of **m**, while the opposite is true of the **Mediterranean** group and to some extent, **steppe**. Within the Mediterranean group, *Olea* (*Figure 8.6.1* p143) is more thermophilious than *Quercus ilex*-type (*Figure 8.6.2* p144). **Supra-mediterranean** vegetation also increases slightly with warmer winter temperatures, although **sub-mediterranean** taxa decline below 1.0°C. The distribution of *Juniperus* (*Figure 8.6.3* p144) probably reflects aridity rather than warm winter temperatures.

8.3.4 *Discussion*

The role of anthropogenic impact in dictating vegetation development is clearly important in assessing the relative role of climate, since the two are clearly inter-related within the current landscape. Clearance of the land for pasture and winter wheat, together with the development of irrigated *huertas* and terraced olive groves provide ample evidence of anthropogenic alteration of the natural vegetation. This problem may be compounded by the use of study sites that are located close to urban areas due to the need for proximity of meteorological stations.

Evidence of some climatic link is however strongly suggested by changes in the vegetation-climate groups along the climate gradient. The broad nature of the vegetation-climate groups provides some room for anthropogenic alteration without necessarily affecting the group proportions. Hence *Quercus coccifera* (*Quercus ilex*-type pollen) scrub can become degraded into *Rosmarinus officianalis* (*Mentha*-type pollen) maquis, or replaced by olive plantations, while remaining within the **Mediterranean** group.

The balance between steppe or openland vegetation and the other arboreal groups will however inevitably be affected by forest clearance activities. It is noticeable that anomalously high steppe values occur at sites (Laguna Sariñena and La Estanca) with intensive irrigated cultivation occurring close by. Generally,

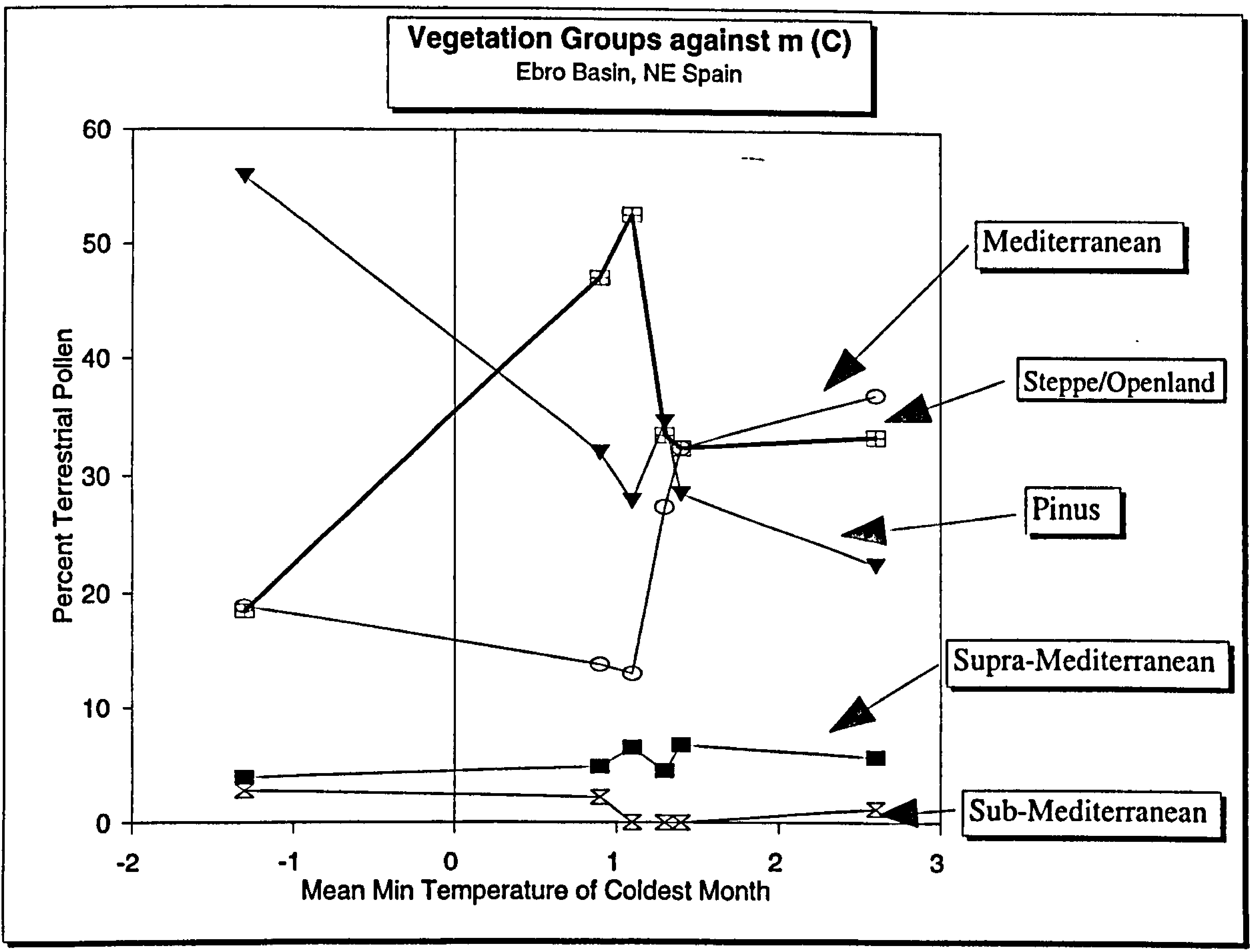


Figure 8.6 **Pollen vegetation-summary groups plotted against temperature of the coldest month (m) at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin**

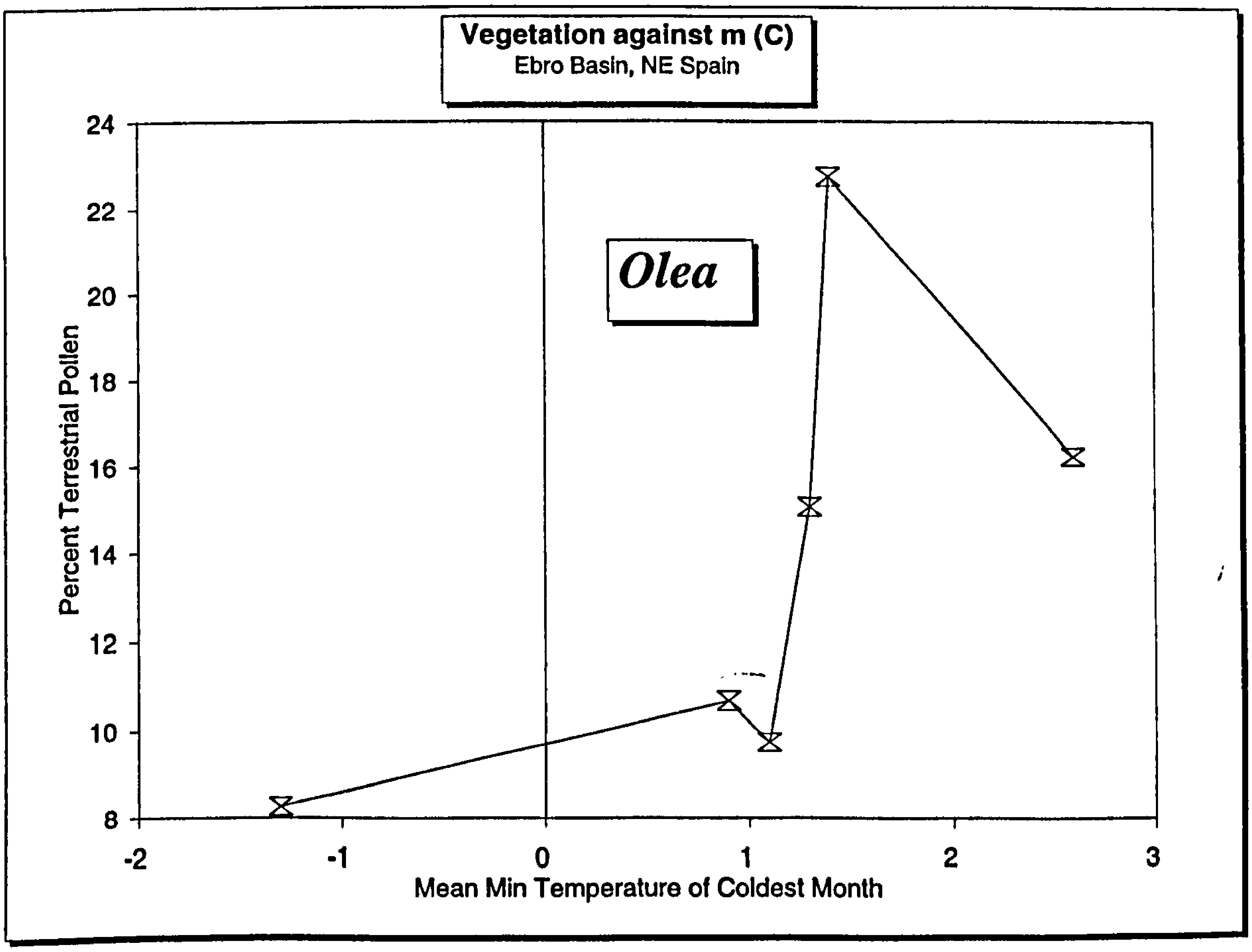


Figure 8.6.1 Olea **pollen plotted against m at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin**

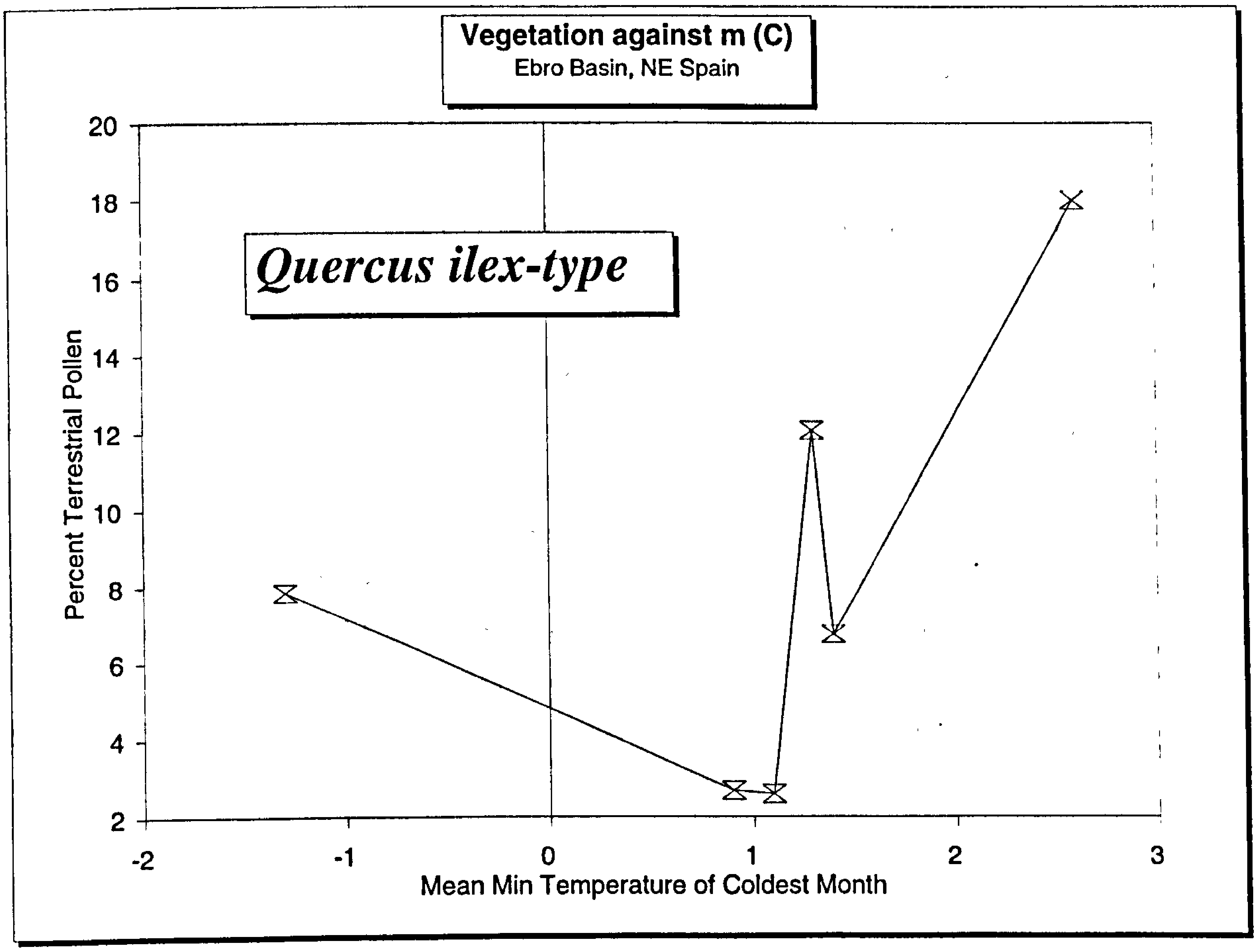


Figure 8.6.2 Quercus ilex-type **pollen plotted against m at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin**

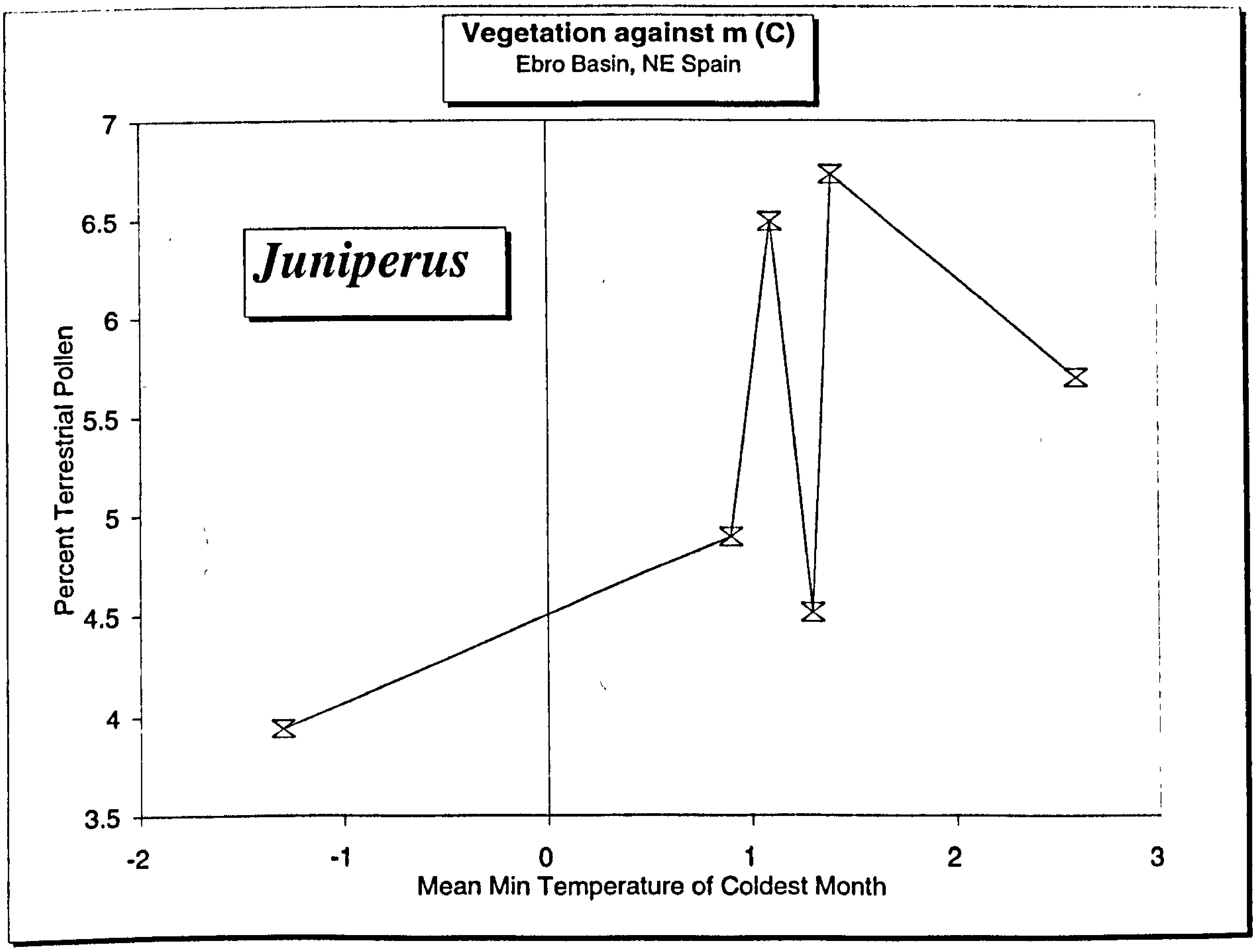


Figure 8.6.3 Juniperus **pollen plotted against m at 6 lake sites along a sub-humid/semi-arid climate gradient in the Ebro Basin**

openland **steppe** increases with aridity while woodland declines. ***Artemisia*** dominates at the most arid end of precipitation gradient, reflecting its tolerance of extreme xeric conditions.

Pinus has a clear bi-modal response to **P** and **P/PET** that confirms the relative importance of pine at opposite ends of the precipitation gradient. Differentiation between these two groups may be possible by the presence (montane forest) or absence (lowland forest) of **sub-mediterranean** taxa that are not associated with arid conditions.

Comparison between the theoretical climate response of the vegetation-climate groups (section 8.3.2.2) and the actual applied results (section 8.3.2.3) reveal some important differences. The **Mediterranean** group appears to be influenced more by **P\PET** and especially **m** rather than by precipitation. This may reflect the broad precipitation tolerance of the group, allowing other factors to become more dominant. The preference for warmer winters suggests that *Quercus coccifera* is the main driving species for this group rather than *Quercus ilex* (Le Houérou, 1992). Similarly, the **supra-mediterranean** group dominated by *Juniperus* shows a preference for warmer winter conditions than would not suggest the main juniper was *J.thurifera*. This is partly related to the dominance of *J.oxycedrus* and *J.phoenicea* within a matorral environment, but mainly the importance of aridity rather than temperature in determining the prevalence of juniper.

8.3.5 *Conclusions*

The simple analysis of a small number of climatic variables at only 6 sampling sites within the Ebro Basin can only support provisional assessment of climate-vegetation relationships. In particular, the inter-linkages between certain climate parameters (*eg*. **m** and P/PET), and anthropogenic activity (*eg*. deforestation and cereal cultivation) are difficult to separate with such a small data-set. It is clear however that climate plays an important role in determining the distribution of vegetation and represents a valid basis for interpretation. The climate response of the six vegetation-climate groups can therefore be summarised as:

1. Sub-mediterranean
Climate: Cool winters (m<1.0°C); Moderate rainfall (>400mm per year); High P/PET (>0.5)

2. Supra-mediterranean
Note: Poor indicator since apparently wide tolerance of current climate conditions (m=1.3-2.6°C; P=436-319mm; P/PET=0.72-0.28).
Climate: Low rainfall (<400mm); Low P/PET (<0.5)

3. Mediterranean
Climate: Warm winters (m>1.0°C); Low rainfall (<400mm per year); Low P/PET (<0.4)

4. Pinus

Climate: Montane pine forest (*P.nigra, P.sylvestris*)occurs under similar conditions to the **sub-mediterranean** group. Lowland pine forest (*P.halepensis*) occurs in the absence (or very low values) of **sub-mediterranean** taxa: Climate: Cold winters (m<1.0°C?); Low rainfall (<340mm per year); Low P/PET (<0.4)

5. Steppe/Openland

Climate: Cool winters (m=0.0-1.0°C); Low rainfall (<400mm); Low P\PET (>0.5)

6. Artemisia

Climate: Low rainfall (<340mm)

Chapter 9

Core Sites & Core Descriptions

9.1 Introduction

Palaeoenvironmental reconstruction is based on the analysis of seven cores from seven separate lake sites within the Ebro Basin. Site details and core descriptions are given for the following lakes in the appropriate sections:

Three seasonal playa lakes:	Laguna Guallar	(section 9.2)	p158
	Hoya del Castillo	(section 9.3)	p171
	Salada Pequeña	(section 9.5)	p193
One relic seasonal playa lake:	La Salineta (Section)	(section 9.4)	p185
One permanent salt lake:	Laguna Salada	(section 9.6)	p209
One semi-permanent salt lake:	Laguna Gallocanta	(section 9.7)	p223
One reservoir (flooded playa):	La Estanca	(section 9.8)	p234

A summary of the palaeoenvironmental record for the past 10Kyrs from all of the cores (except La Salineta), including lake type (level) and summary vegetation data, is provided in *figure 9.1.1* p149. Location maps for all the coring sites are given in *figures 9.1.2-7* p150-155. Core correlation, dating and zoning is shown in *figure 9.1.8* p156. Zoning was undertaken manually according to changes in both lake and terrestrial environments. It is intended only as a guide to description and correlation.

Appendix 1 provides information on diagram units and a quick reference guide to some of the main palaeoenvironmental indicators. A quick guide to interpretation of these indicators is given in Appendix 2. All dates given in the text and illustrated on diagrams are in radiocarbon years BP unless otherwise stated. A calibration guide for converting to calendar years is provided in Appendix 3.

Summary details of core analysis for each of the sites is provided in *table 5.2* p83. All cores were analysed for pollen, charcoal, macrofossils, and geochemistry (LOI and carbonates). Most cores were analysed for sulphates and sediment structure (including gypsum crystal morphology). The Laguna Salada, Salada Pequeña and La Salineta were also investigated for cations and trace metals.

A summary vegetation record is provided from pollen data according to the six phytoclimatic groupings discussed in Chapter 8, section 8.3. Lake type (level) was also reconstructed manually using the eight stage palaeohydrological model described in Chapter 7. Palaeoenvironment information from each sample level was compared with the model and a lake type allocated. Where a combination of lake types was suggested, or where a lake type was clearly transitional, intermediate lake types were also recorded. For instance, if a lake type fell between seasonal (type 3) and ephemeral (type 2), it was given the value 2.5. The classification of lake types is discussed more fully within each core description.

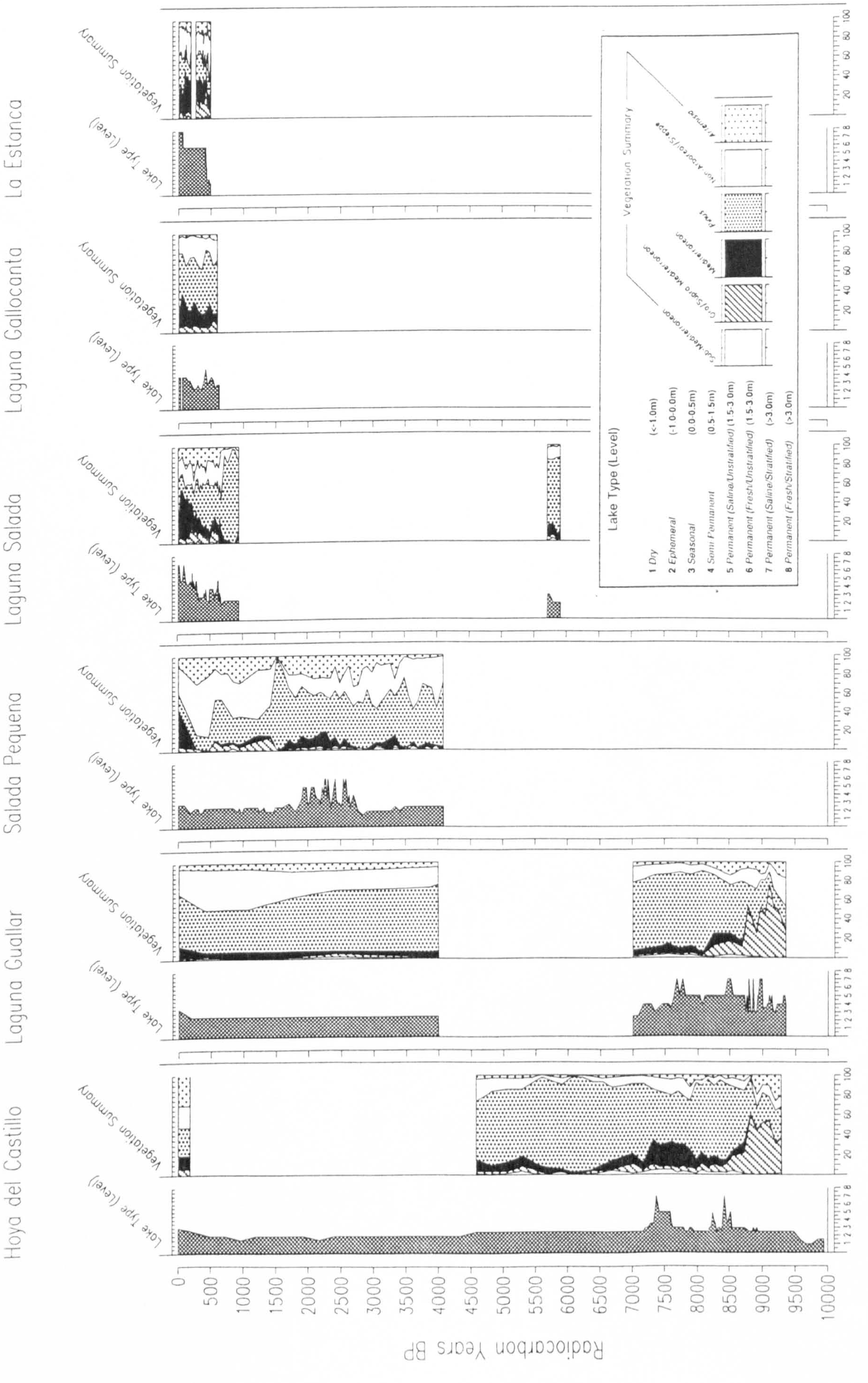


Figure 9.1.1 **All radiocarbon dated sites: lake type (level) and vegetation summary against time (RC years BP)**

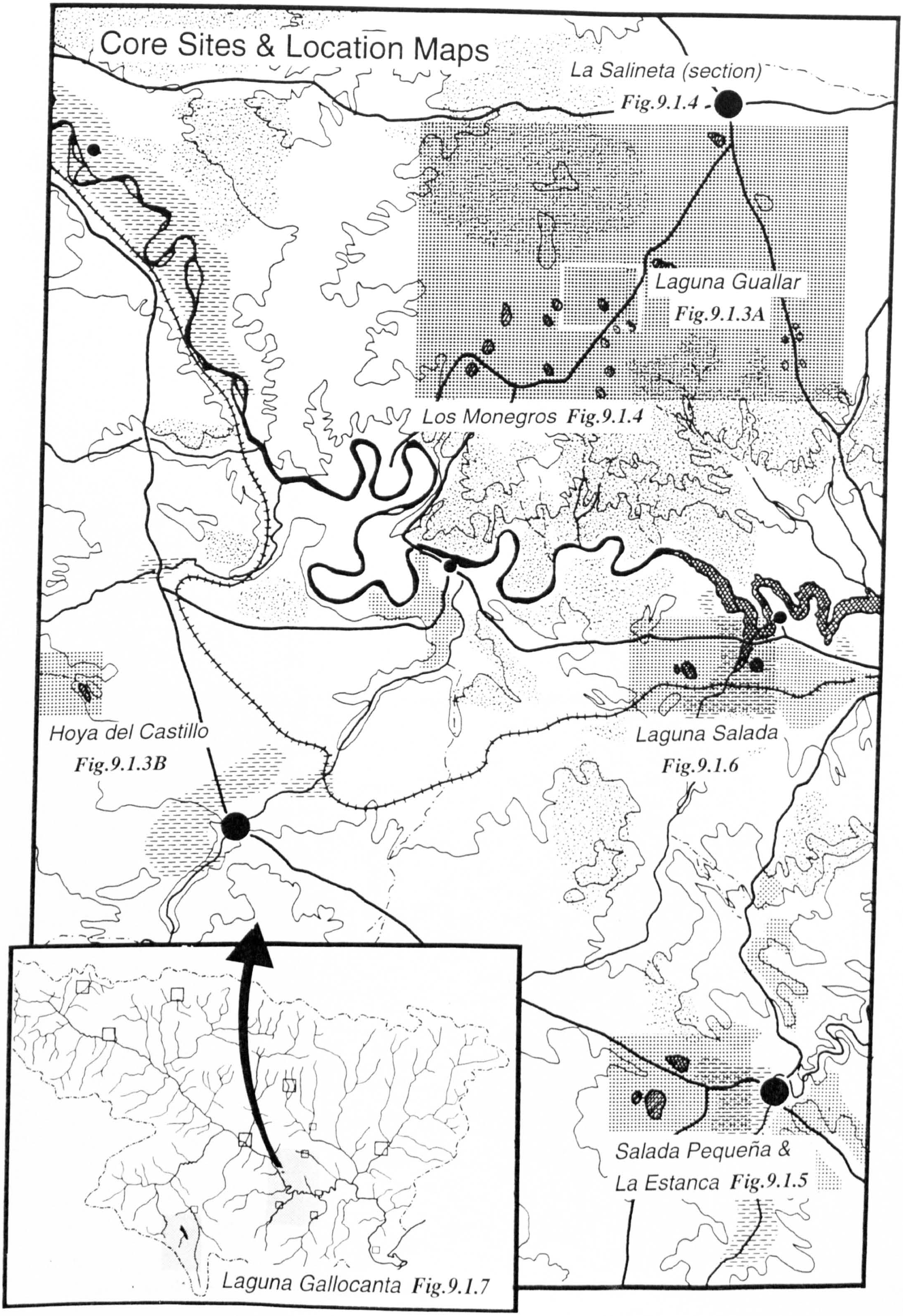


Figure 9.1.2 **Location map of core sites and detailed site location maps**

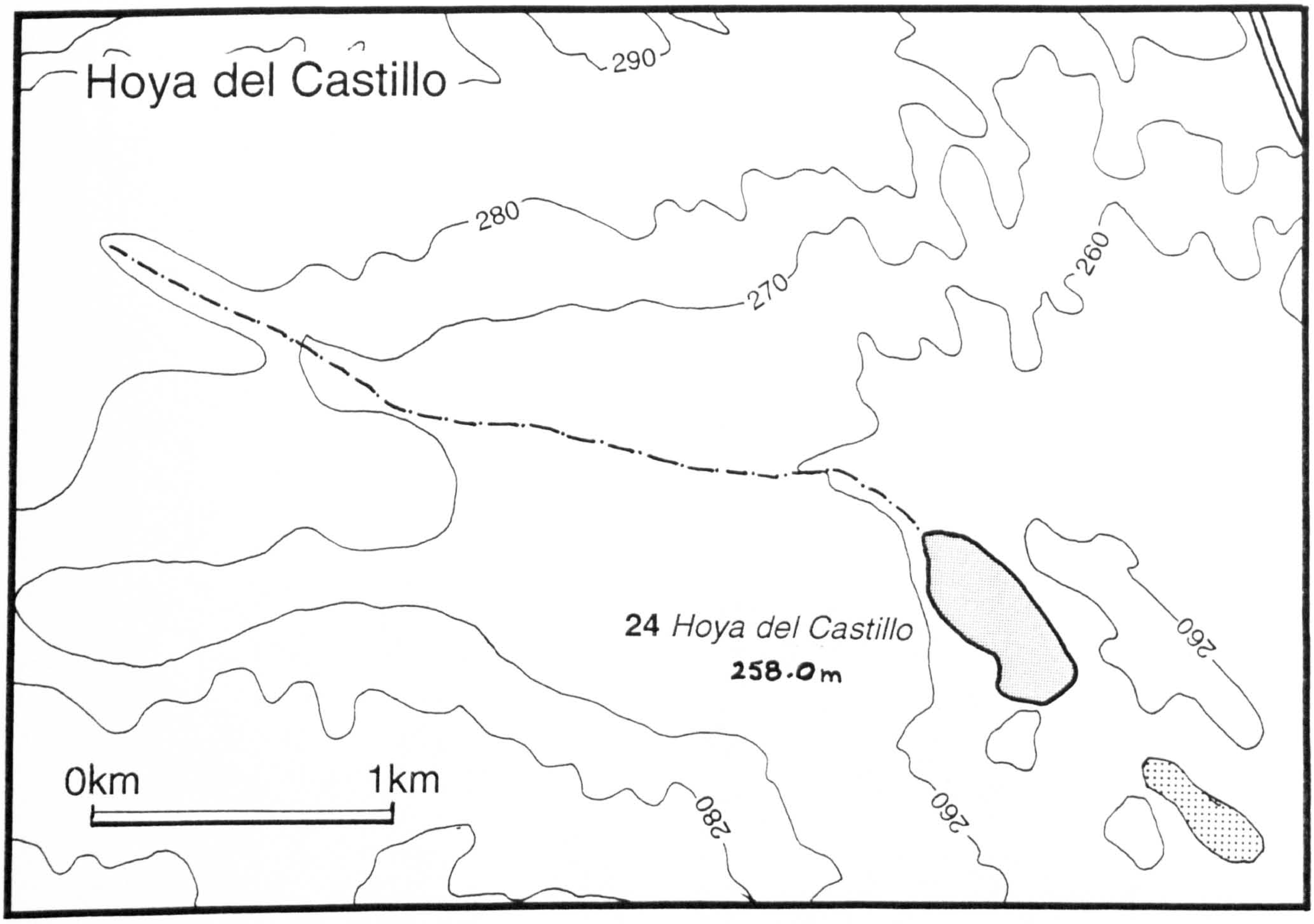


Figure 9.1.3B Hoya del Castillo: location map

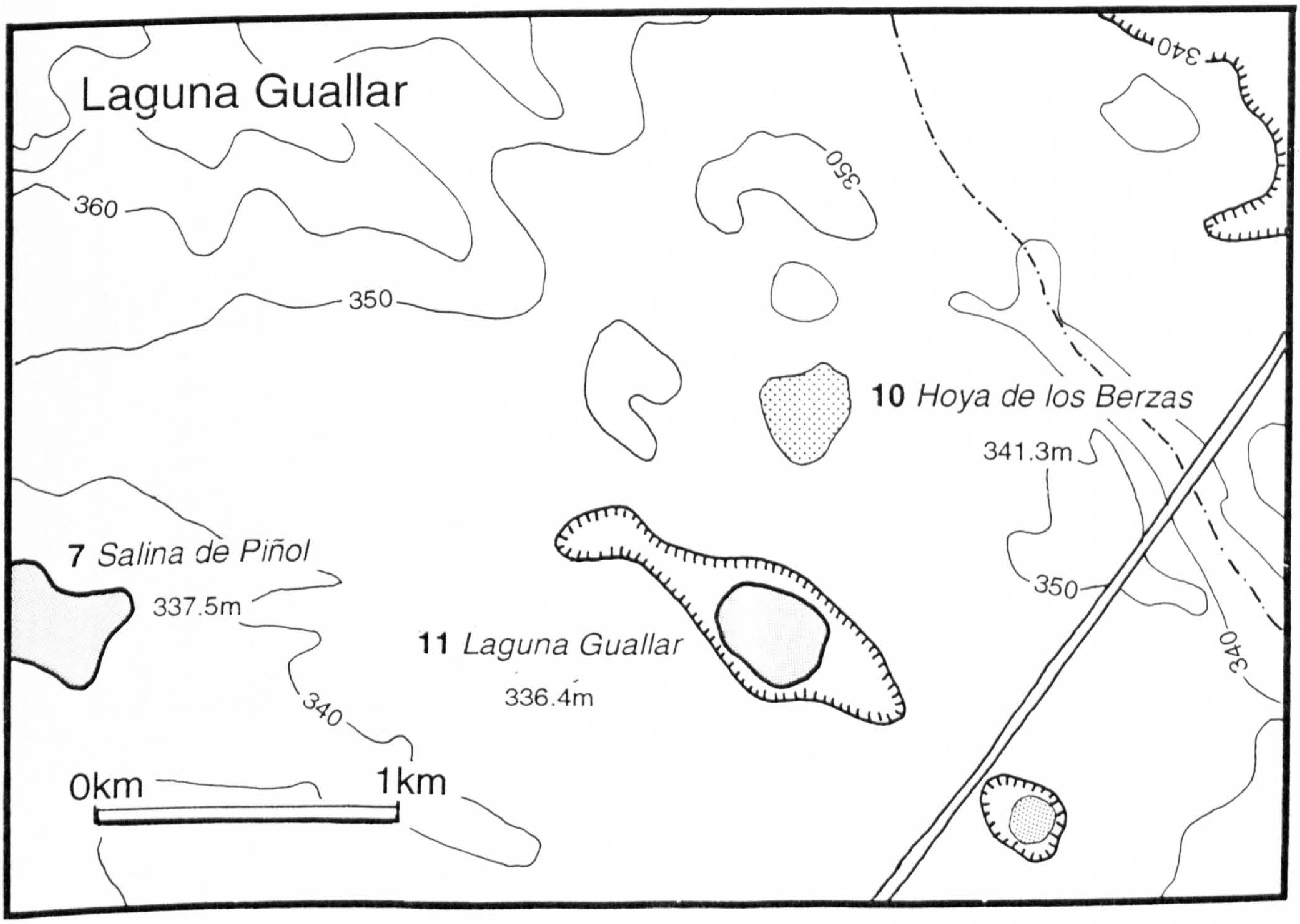


Figure 9.1.3A Laguna Guallar: location map

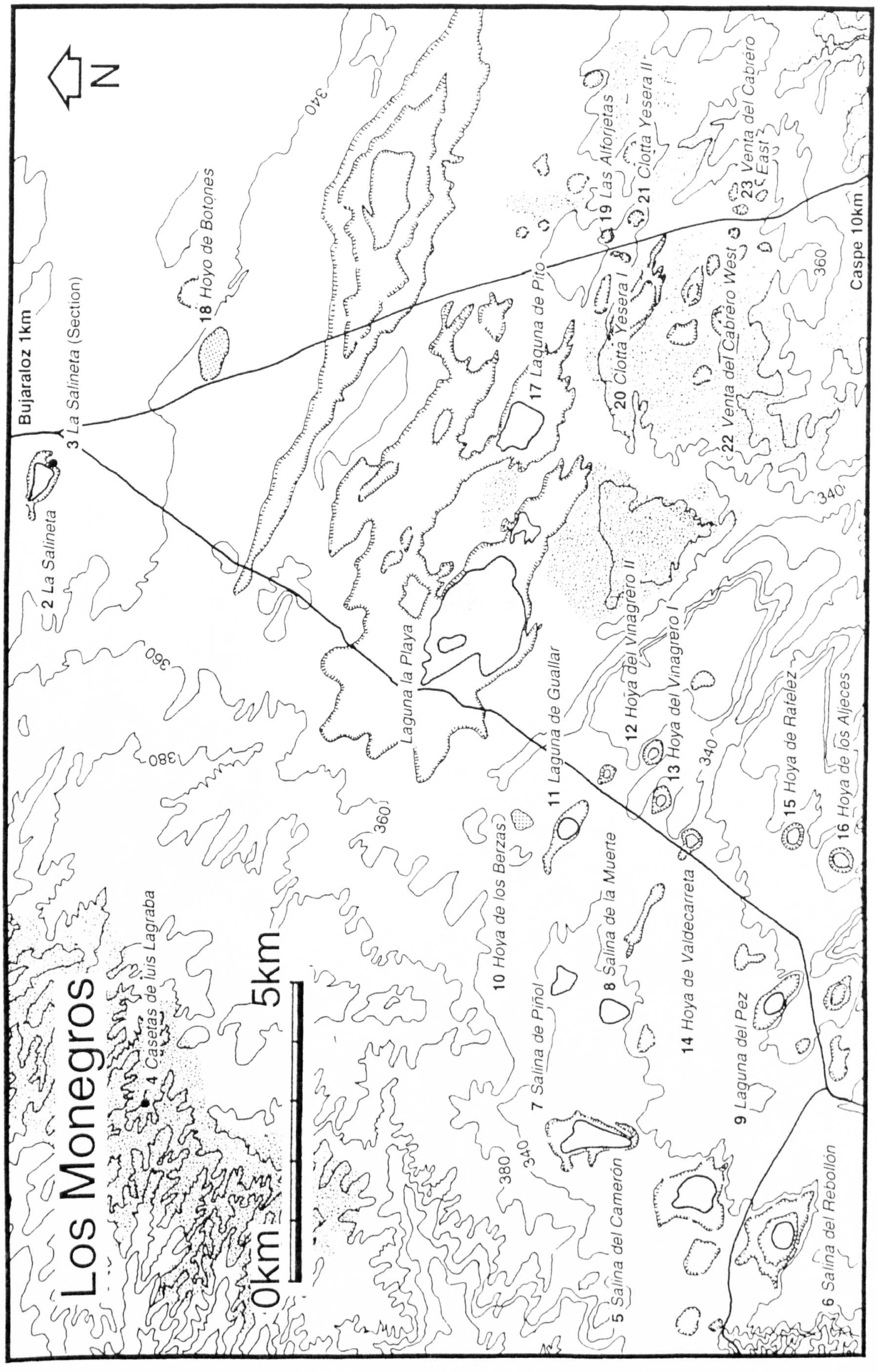


Figure 9.1.4 **La Salineta: location map**

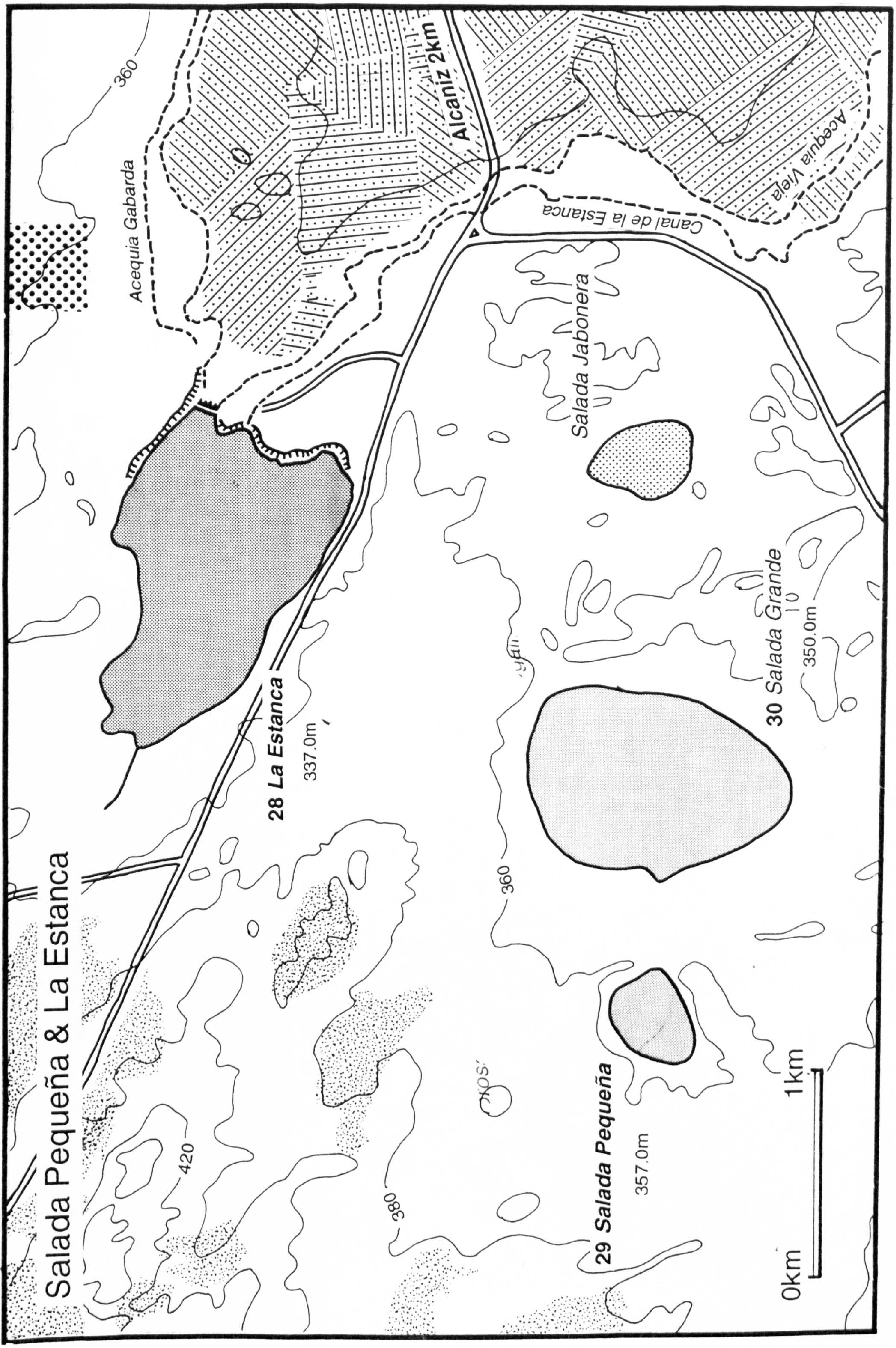


Figure 9.1.5 **Salada Pequeña and La Estanca: location map**

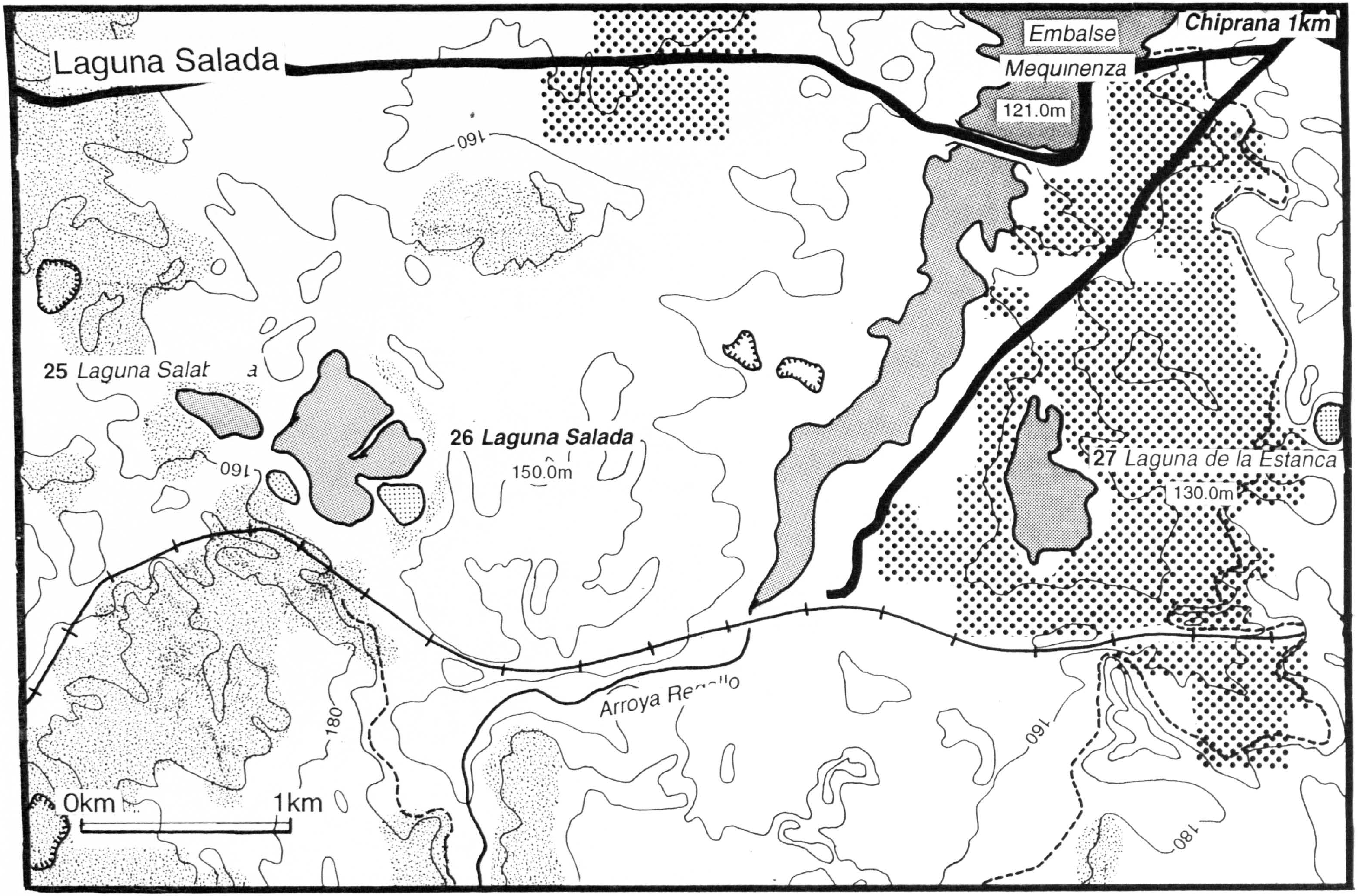


Figure 9.1.6 **Laguna Salada: location map**

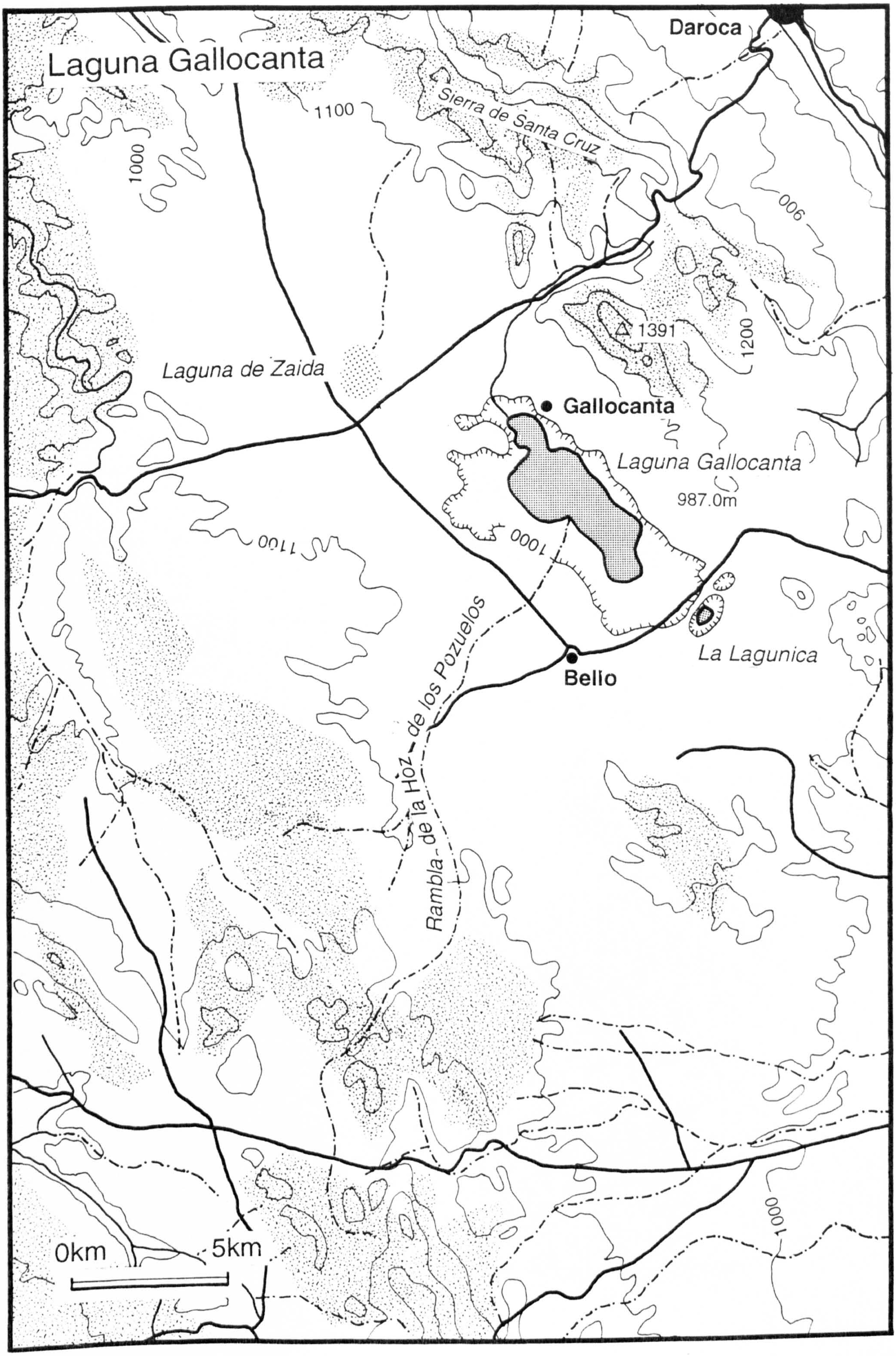


Figure 9.1.7 Laguna Gallocanta: location map

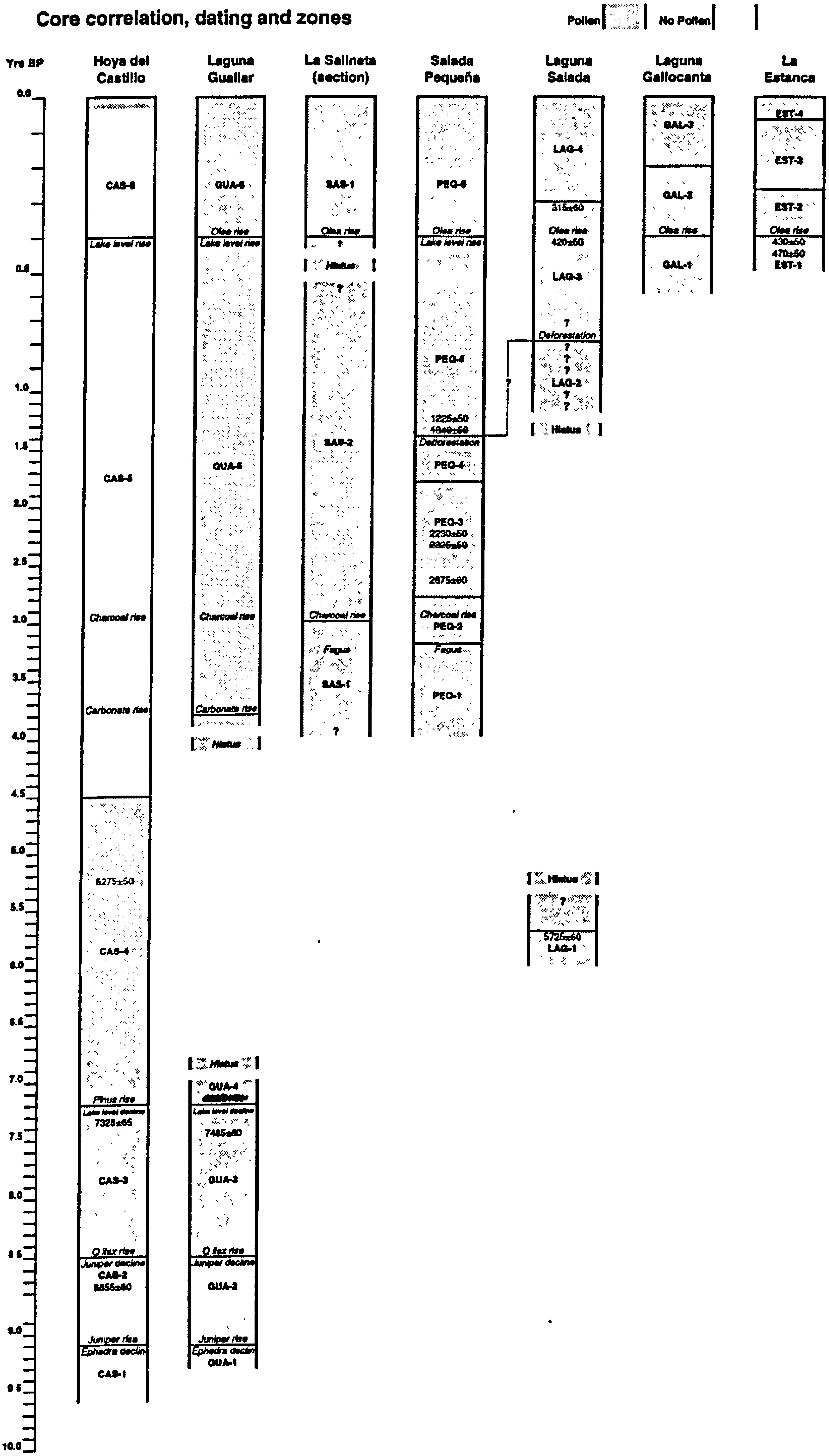


Figure 9.1.8 Core correlation, dating and zones

Table 9.1 Water chemistry data for lakes in the Ebro Basin

Site	Site Ref.	Date	Conductivity vScm	Units	Ca	Mg	Na	K	CO3	SO4	Cl	Author/s
Laguna Gallocanta	31	July, 1990	205000	mg/l	58.36	7075	4820	415		5.836	23113	
Salada Grande	30	?1984		mg/1	80	2040				20.18	18.72	
Salada Pequena	29	?1984		mg/l	90	312.2				3.68	1.98	Alonso & Comelles, 1985
La Estanca	28	July. 1989	1400	mg/l	17.6	31.5	114	3		0.255	22.69	
	28	July, 1990	800	mg/l	17.97	31.8	7.56	8		0.268	22.69	
	28			mg/l	180	24				3.8	0.054	Alonso & Comelles, 1985
La Estanca Chiprana	27	July, 1990	3200	mg/l	60.36	239.4	142	11.8		2.309	153.14	
Laguna Salada	26	July, 1989	71000	mg/l	52.34	10275	4045	193		6.244	10139	
	26	July, 1990	54000	mg/l	56.14	40500	3759	147		5.742	7941	
Laguna Salabrosa	25	July, 1990	3400	mg/l						1.939	96.42	
Laguna Guallar	11	?1988 max		meq	7.5	1729.1	3426	274.7	11.6	88.5	6361.6	
	11	?1988 min		meq	49.9	218	502.5	41.8	3.4	69	569.4	Sanchez et al, 1989
Laguna Sarinena	1	July, 1990	1800	mg/l	6.03	26.6	289	20		0.305	263.75	
	1	July, 1990	1500	mg/l	6.72	32.1	283	6.53		0.276	269.42	

Table 9.1 Water chemistry data for lakes in the Central Ebro Basin

9.2 Laguna Guallar

9.2.1 *Site Description*

The Laguna Guallar (Lat.41°24'30" Long.0°13'40") is a small (9.2ha) seasonal, hypersaline, playa lake at an altitude of 336.4m. It is located 10km southwest of the town of Bujaraloz, and 2.5km southwest of the Laguna de la Playa, the largest playa lake in the Ebro Basin (192.6Ha). The Laguna Guallar itself is surrounded to the north and south by cliffs of weathered clays, limestones and evaporites extending upto 10m or more to the Los Monegros plain (*Figure 9.1.3A* p151). At the western end of the lake is a broad dry gully which has been used as a dump for stones and rubble ploughed-up from the shallow calcrete layer that underlies large areas of the surrounding fields. To the east is a wide dry platform, slightly raised above the level of the lake, and forming what is thought to be the deposition zone for deflated material from the lake (Pueyo, 1979). The origin of the depression is thought to be as a result of solution and subsidence (Sanchez *et al.*, 1991: see *Figure 4.7* p68), although its alignment from northwest to southeast is probably as a result of deflation caused by the strong prevailing northwesterly winds (Pueyo, 1979).

The lake is seasonal, holding water for upto 8 months during the winter half of the year while drying out completely in the summer. Water depths rarely exceed 40cm across the flat basin floor. The lake water is hypersaline, although salinity varies widely throughout the filling and drying cycle. Sanchez *et al.* (1989) provide data on the water chemistry in *table 9.1* p157.

Surface efflorescences of the more soluble salts (mostly halite NaCl) occur during the summer, while mineral sedimentation consists mainly of insoluble salts. Lenticular gypsum ($CaSO_4$) forms by evaporitic pumping during the summer, set within a matrix of detrital material and a small amount of embedded carbonates ($CaCO_3$), including calcite, dolomite and magnesite (Pueyo, 1979).

The surrounding landscape consists of a gently rolling treeless steppe, dedicated to the dry farming of winter cereals. Halophytes occupy most of the bottom of the depression, with annual species of Chenopodiaceae such as *Salicornia ramosissima*, colonising right upto the lake margins.

9.2.2 *Analysis & Methods*

Coring was performed using a handheld 'Cobra' percussion corer in the centre of the lake while it was dry in July 1991. 2.0m of sediment was extracted in 2x1m drives, each drive being sampled in the field in 2cm slices. The final drive ended in almost solid gypsum, however due to the problems of jacking up this last drive on the soft lake surface, it was decided not to attempt another drive. Unlike the other lakes cored, it is not clear whether this gypsum layer represents bedrock or not. The technical problems of using this equipment on a soft sediment surfaces have now been overcome, and it would probably be possible to extract a deeper core, given a second attempt. It is perhaps worth noting that a 1.6m core extracted using a Hiller corer from the neighbouring lake of Laguna de la Playa covered almost exactly the same sequence as the 2.0m core retrieved from Laguna Guallar using the Cobra. It has become clear on using the two types of corer together on numerous occasions that the limits of one usually reflect the limits of the other. The Hiller corer used at Laguna de la Playa failed to penetrate the same gypsum band despite some hefty loading on top (mentioning no names!). The 2.0m extracted from Laguna Guallar may therefore represent the actual limit of Cobra coring technology after all.

The core was subsampled in the laboratory at 4cm intervals for analysis of geochemistry (loss on ignition; carbonate; sulphate), macrofossils and sediment composition. Pollen and microscopic charcoal were analysed at 8cm intervals.

9.2.4 *Dating control*

An AMS radiocarbon date of 7485±80 BP was obtained from a large piece of charcoal at 60-62cm. Stratigraphic correlation using pollen with the better dated Hoya del Castillo core (*Figure 9.1.8* p156) provides a dating control for the rise and fall of juniper. A hiatus in the sediment record occurred at around 40cm for an undetermined period. The increase in carbonate, and later, charcoal, is similar to the Hoya del Castillo core, where a tentative date of around 4.0Kyr BP may be extrapolated. This would imply a very slow accumulation rate at the Laguna Guallar of 0.1mm/yr upto the present day. Although this may seem unlikely, this is supported by the onset of the olive rise (0.4K yr BP) in only the very uppermost sediments (2-8cm). The time/depth relationship is presented in *figure 9.2.1.*

9.2.5 *Results*

The results are presented as follows:

Zone GUA-1 (194(Base)-175cm)

Lake Environment: Semi-Permanent/Permanent (unstratified) Saline Lake (lake types 4-5)

Macrofossils: Charophytes
Pollen: Ruppia, Cyperaceae
Geochemistry: High sulphate, low Carbonate
Gypsum: Prismatic

Charophyte oospores (*Lamprothamnium papulosum*) occur in very high concentrations (1000-7000 per 100g dw), distinctive of a shallow, semi-permanent, hypersaline lake (lake type 4). This is supported by the occurrence of prismatic gypsum and high sulphate levels, although seeds of the perennial *Ruppia maritima var maritima* also show that the lake became deeper, less saline, and more permanent at times (lake type 5).

Terrestrial Environment: *Ephedra distachya*-type, *Artemisia* Steppe

Pollen: *Ephedra distachya*-type, *Juniperus*, *Artemisia*, *Gramineae*,
Charcoal: Low
Geochemistry: Low carbonate

Ephedra distachya-type pollen (*E.distachya*, *E.major*) is particularly well represented in this zone compared to the rest of the Holocene, with values of over 6%TTP. Values of *Juniperus* are also high (20-45%), and rise throughout the zone as *Pinus* declines to below 20%TTP. *Olea* also declines and disappears after being present in the earliest levels of the zone.

The large non-arboreal component (30-45%TTP) is comparable with the present largely treeless landscape established following anthropogenic deforestation in the late Holocene. *Artemisia*, however, forms a more important part (*ca.*15%TTP) of this open steppe than in the late Holocene (*ca.*10%TTP) at this site. Large Gramineae pollen (>50µm) are likely to indicate natural grass steppe such as *Lygeum spartum* rather than cereals due to the calculated age of the sediments (see *figure 9.1.8*) and low levels of anthropogenic indicators (*eg.* charcoal and ruderals).

Low carbonate levels (<7% dw) and lack of detrital quartz suggests low levels of catchment erosion, although the presence of some Compositae may indicate disturbance within the mainly open landscape.

<u>Zone GUA-2</u> (175-118cm)

Lake Environment: Oscillating: Permanent Saline-Seasonal Playa Lake (lake type 7-3)

Macrofossils: *Ruppia maritima* var *maritima*/*Ruppia drepanensis*
Pollen: *Ruppia*, Cyperaceae
Geochemistry: High sulphate, low carbonate
Gypsum: Prismatic/lenticular

The lake deepens in this next zone, but with a higher amplitude and frequency of lake level change. Periods of deep, stratified, lake levels (lake type 7) are indicated by prismatic gypsum without evidence of local macrophyte growth (*eg.* seeds). The alternative explanation of restricted macrophyte growth through low lake levels and seasonal desiccation can be discounted since this would cause evaporitic pumping and sub-surface lenticular gypsum growth. Lower, but nevertheless permanent lake levels, without stratification (lake type 5) are shown by seeds of *Ruppia maritima* var *maritima*. Much lower lake levels than the previous zone are also shown by the appearance of lenticular gypsum and seeds of *Ruppia drepanensis*, associated with seasonal lake conditions with periodic desiccation (lake type 3). The oscillations in lake level become more frequent towards the end of the zone.

Terrestrial Environment: Juniper Woodland & *Artemisia* Steppe

Pollen: Juniperus
Charcoal: Low
Geochemistry: High carbonate

Juniperus increases to levels of over 75%TTP, forming an extensive juniper forest at the expense of openland taxa and particularly *Ephedra distachya*-type. The arboreal component remains high at around 75%TTP throughout the zone, but *Pinus* gradually replaces *Juniperus* towards the end of the zone as it declines to below 40%TTP. The rise of *Pinus* is also accompanied by the appearance of deciduous tree taxa at around 150cm.

The steppe remains dominated by *Artemisia* despite the overall decline in the percentage of non-arboreal taxa, indicating that extreme continental conditions persisted into this next zone. A general reduction in aridity is shown, however, by a reduction in Chenopodiaceae and *Plantago*, and increase in *Lygeum spartum*-size Gramineae pollen (>50μm), indicative of Esparto steppe.

Carbonate levels rise to over 10% in the zone, suggesting either increased catchment erosion compared to the earlier zone, or confirming periods of low lake level with seasonal desiccation.

Zone GUA-3 (118-50cm)

Lake Environment: Fluctuating Permanent Saline Lake (lake type 5-7)

Macrofossils: Ruppia maritima, Ruppia drepanensis
Pollen: Cyperaceae, *Ruppia, Potamogeton*
Geochemistry: High/very high sulphate, low carbonate
Gypsum: Lenticular/prismatic

Abundant *Ruppia maritima* seeds (10-70 per 100g dw) with lenticular gypsum and seeds of *Ruppia drepanensis* (5-35 per 100g dw) indicate mainly deep, permanent lake conditions alternating rapidly with desiccation and strong evaporitic pumping. This is particularly so for the middle part of the zone where high evaporation and groundwater flow are suggested by very high sulphate levels (45% dw). This level of sulphate is almost twice that recorded at any lake within the surface sample data set (chapter 7). The correspondingly low values of carbonate (<5% dw) draws comparison with the Laguna Salada (lake type 7), a deep, permanent saline lake, although even here, sulphate composes only 28% dw of the surface sediment. The extremely high sulphate values at the Laguna Guallar within the middle part of the zone probably reflects a high frequency of fill-dry cycles producing repeated precipitation of sulphate minerals. The resulting macrophyte deaths during falling lake levels may have provided food for Cladocera which occur in the upper levels of the zone.

High levels of *Lamprothamnium papulosum* oospores (>7000 per 100g dw) mark a sharp drop in lake level at the end of the zone and restoration of semi-permanent lake conditions similar to zone GUA-1. These in turn decline further as lenticular gypsum replaces prismatic gypsum and the lake dries out almost completely.

Terrestrial Environment: *Pinus* & *Quercus ilex*-type Woodland, Grass Steppe

Pollen: *Pinus*, *Quercus ilex*-type, deciduous trees, Gramineae
Charcoal: Low
Geochemistry: Low Carbonate

Juniperus declines sharply at the onset of zone GUA-3 as *Pinus* continues to increase and *Quercus ilex*-type rises to over 10%TTP. The overall arboreal component also rises throughout the zone, upto 90%TTP, with *Pinus* making the largest contribution (*ca.*70%). *Olea* also reappears after disappearing in zone GUA-1. The peak in *Pinus* at 88cm coincides with the drop in lake level and dramatic rise in sulphate levels.

The advance of woodland in the zone sees the decline of *Artemisia* steppe and its replacement by grassland. Large Gramineae pollen occur as in earlier levels, presumably reflecting natural Esparto (*Lygeum spartum*) grassland.

Charcoal peaks sharply towards the end of the zone, where a large piece was AMS radiocarbon dated to 7485±80BP. This can be correlated to a similar peak in charcoal and radiocarbon date at the Hoya del Castillo, in zone CAS-3. The vegetation response to this fire event is not as clear as at the Hoya del Castillo, although *Quercus* does peak at this point.

Low carbonate (<5%) and Compositae reflect continued catchment stability.

Zone GUA-4 (50-40cm)

Lake Environment: Ephemeral/Seasonal Playa Lake (lake type 2.5: intermediate)

Macrofossils: None
Pollen: Ruppia, low Chenopodiaceae
Geochemistry: High sulphate, low carbonate
Gypsum: Lenticular

Macrofossil remains disappear as water levels in the lake continue to decline. Desiccation of the basin at this point may have caused an hiatus in the sediment record between this zone and the previous zone (GUA-4:GUA-3) or the following zone (GUA-4:GUA-5). Prismatic gypsum and high sulphate:low carbonate indicates seasonal desiccation (lake type 3) but not for prolonged periods. Drying out of the basin may have produced oxidising conditions, resulting in low pollen concentrations and cessation of the pollen record in the zone.

Terrestrial Environment: *Pinus* Woodland & Grass Steppe?

Pollen: None

No samples taken from the zone contained sufficient pollen for counting despite analysis of upto 2g of sediment. Values indicated on the pollen diagram are extrapolated from samples taken on either side of the zone.

Zone GUA-5 (40-8cm)

Lake Environment: Ephemeral/Seasonal Playa Lake (lake type 2.5: intermediate)

Macrofossils: None
Pollen: Ruppia
Geochemistry: High Carbonate, high Sulphate
Gypsum: Lenticular

Lenticular gypsum indicates continued seasonal desiccation of the lake, as in the previous zone. Low Chenopodiaceae values (<10%) show that they remained marginal, and that the lake did not dry out for long enough during the summer months to allow colonisation of the lake bed surface (lake type 2). The lack of *Ruppia* pollen (<3%), however, does not fit with a clear lake type 3 classification, and suggests an intermediate lake type 2.5.

Terrestrial Environment: (*Pinus* Woodland), Cereal Cultivation and Grass Steppe

Pollen: *Pinus*, Gramineae, *Artemisia*, *Plantago*
Charcoal: High
Geochemistry: High carbonate
Stratigraphy: Detrital quartz

Declining arboreal pollen throughout the zone occurs principally through the loss of *Pinus*. Arboreal pollen at 16 and 24cm reaches values some 15% lower than in the present treeless landscape (67%TTP), and must indicate even greater levels of clearance in the late Holocene. This is similar to the situation shown at the Salada Pequeña core in zone PEQ-5, dated at some time later than 1225±50BP. In contrast however to zone PEQ-5 at the Salada Pequeña, *Juniperus* shows no sign of recovery throughout the zone, despite its dominance earlier in the core.

Woodland clearance sees the expansion Gramineae, and particularly large (>50μm) Gramineae pollen grain sizes. Unlike zone GUA-1, *Artemisia* does not form a proportionately large part of the non-arboreal pollen component, but does approach 10%TTP. The increase of large Gramineae may indicate the expansion of cereal cultivation since values approach their present-day levels where cereal farming is the dominant landuse.

Anthropogenic disturbance is also indicated by high levels of charcoal and rising levels of *Plantago*. A dramatic increase in carbonate levels to over 10% that marks the onset of the zone is comparable with zone CAS-5 in the Hoya del Castillo core. The carbonate rise in zone CAS-5 is also followed by a similar increase in charcoal to levels not seen since the early Holocene. The occurrence of detrital carbonate and quartz suggests intense catchment erosion that is not indicated in earlier zones.

Zone GUA-6 (8-0cm)

Lake Environment: Seasonal Playa Lake (lake type 3)

Macrofossils: Ruppia drepanensis
Pollen: Ruppia
Geochemistry: High carbonate, high sulphate
Gypsum: Lenticular/prismatic

Ruppia drepanensis seeds and prismatic gypsum suggest the lake has become wetter within this latest zone. The lake remains seasonal, however, with some lenticular gypsum indicating summer desiccation and evaporitic pumping.

Terrestrial Environment: (*Pinus* Woodland), Cereal Cultivation and Grass Steppe

Pollen: *Olea,Pinus*, Gramineae, *Plantago, Artemisia, Plantago*, Chenopodiaceae
Charcoal: High
Geochemistry: High Carbonate

The surrounding environment remains much the same as in the previous zone, with an increase in *Olea* reflecting the late medieval expansion of Olive cultivation in the area. Catchment erosion does not decline and high levels of *Plantago* and Chenopodiaceae may suggest declining soil fertility and/or erosion. The rise in Chenopodiaceae in this, and in the previous zone, does not coincide with a fall in lake level, but rather a rise to levels comparable with those earlier in the record where Chenopodiaceae values were much lower. It seems likely therefore that Chenopodiaceae values in this case reflect rising soil salinity rather marginal vegetation in response to variations in lake level. The coincidental increase in carbonate and Chenopodiaceae at the onset of zone GUA-5 may have been caused by formation of the calcrete layer that is currently being ploughed-up from surrounding fields. Indeed the removal of this calcrete layer with the recent introduction of deep mechanical ploughing may have helped restore groundwater recharge and caused the recent rise in lake levels. This is discussed in more detail in Chapter 10.

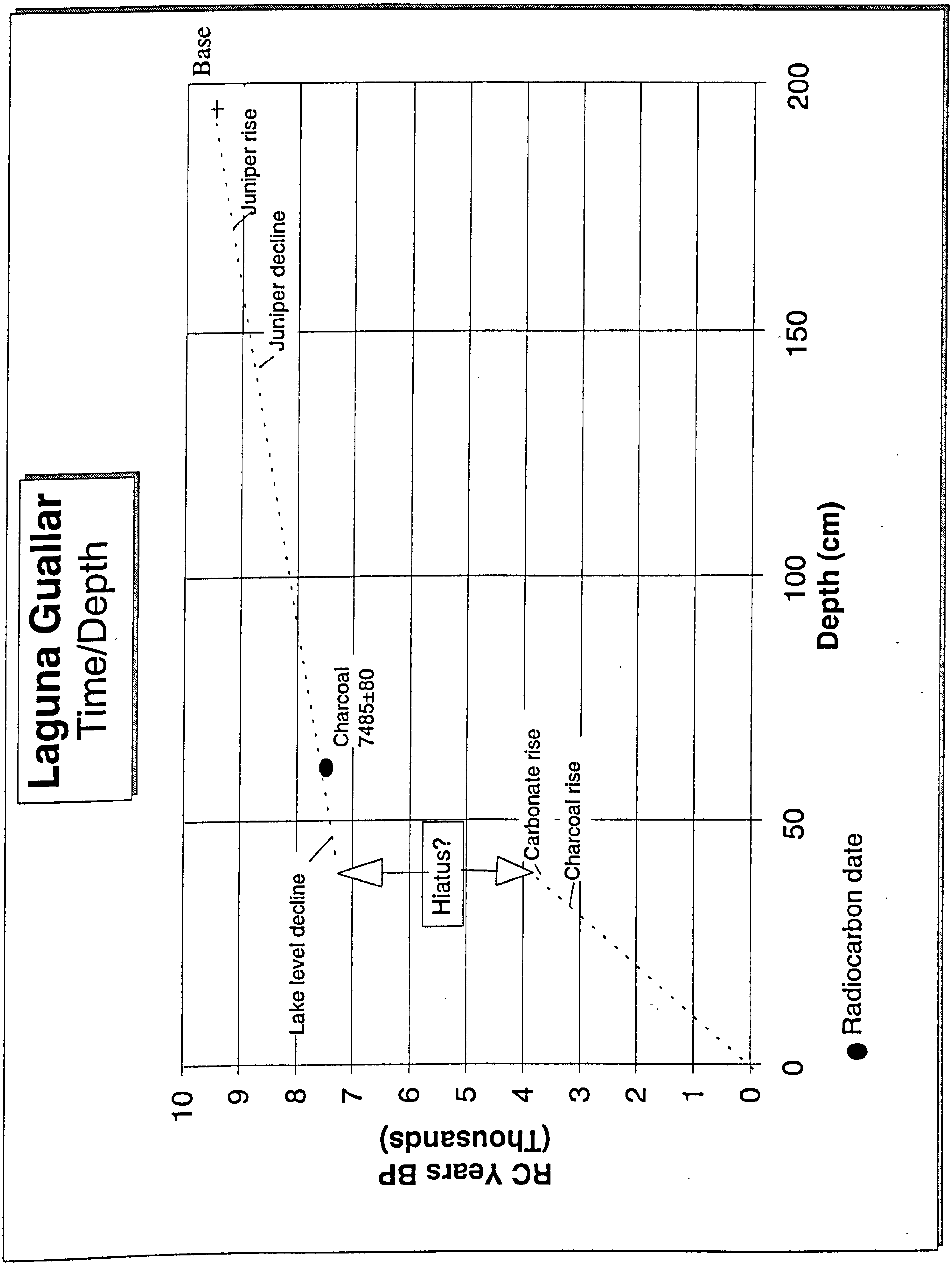


Figure 9.2.1 **Laguna Guallar: radiocarbon time/depth curve**

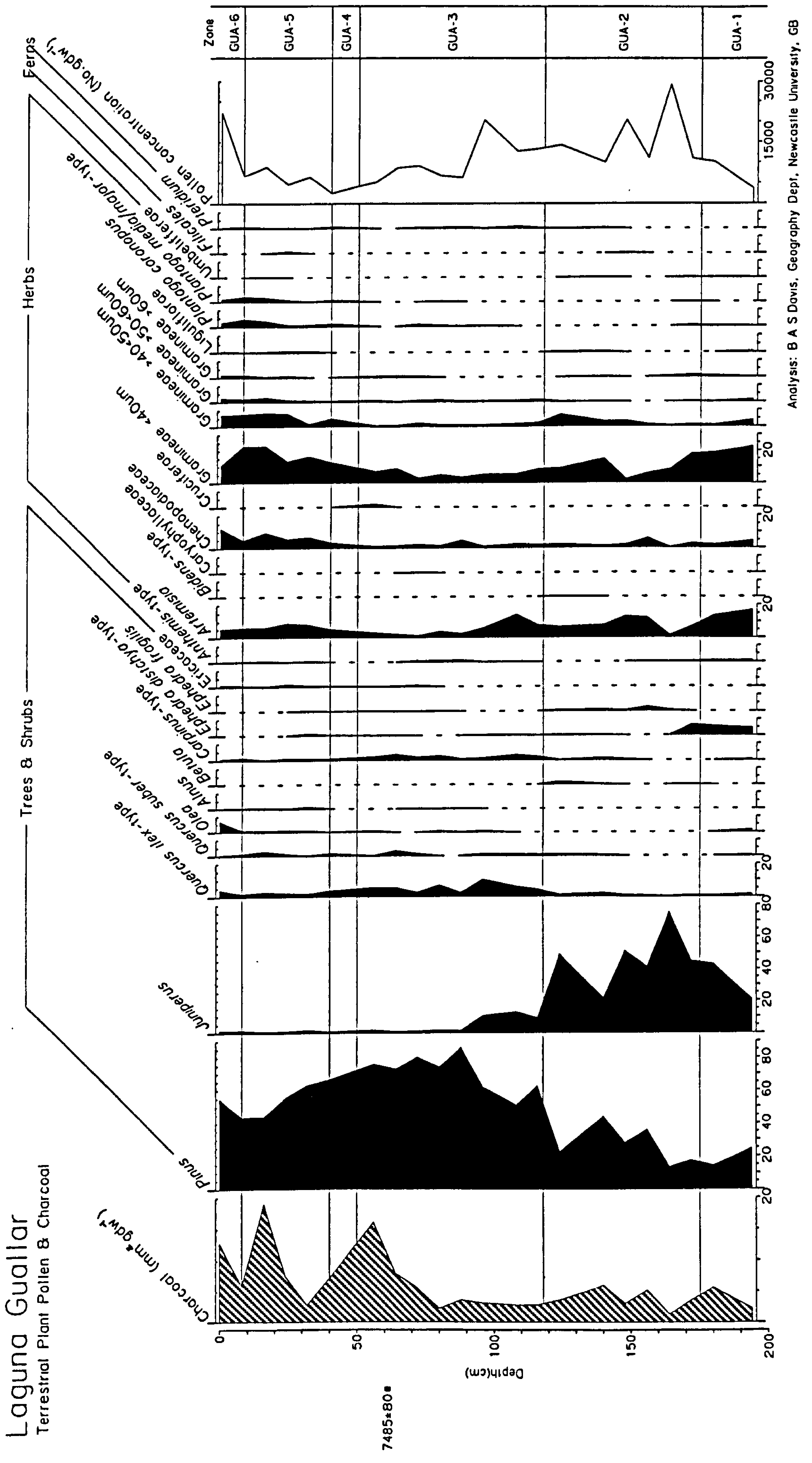


Figure 9.2.2 **Laguna Guallar: terrestrial plant pollen and charcoal**

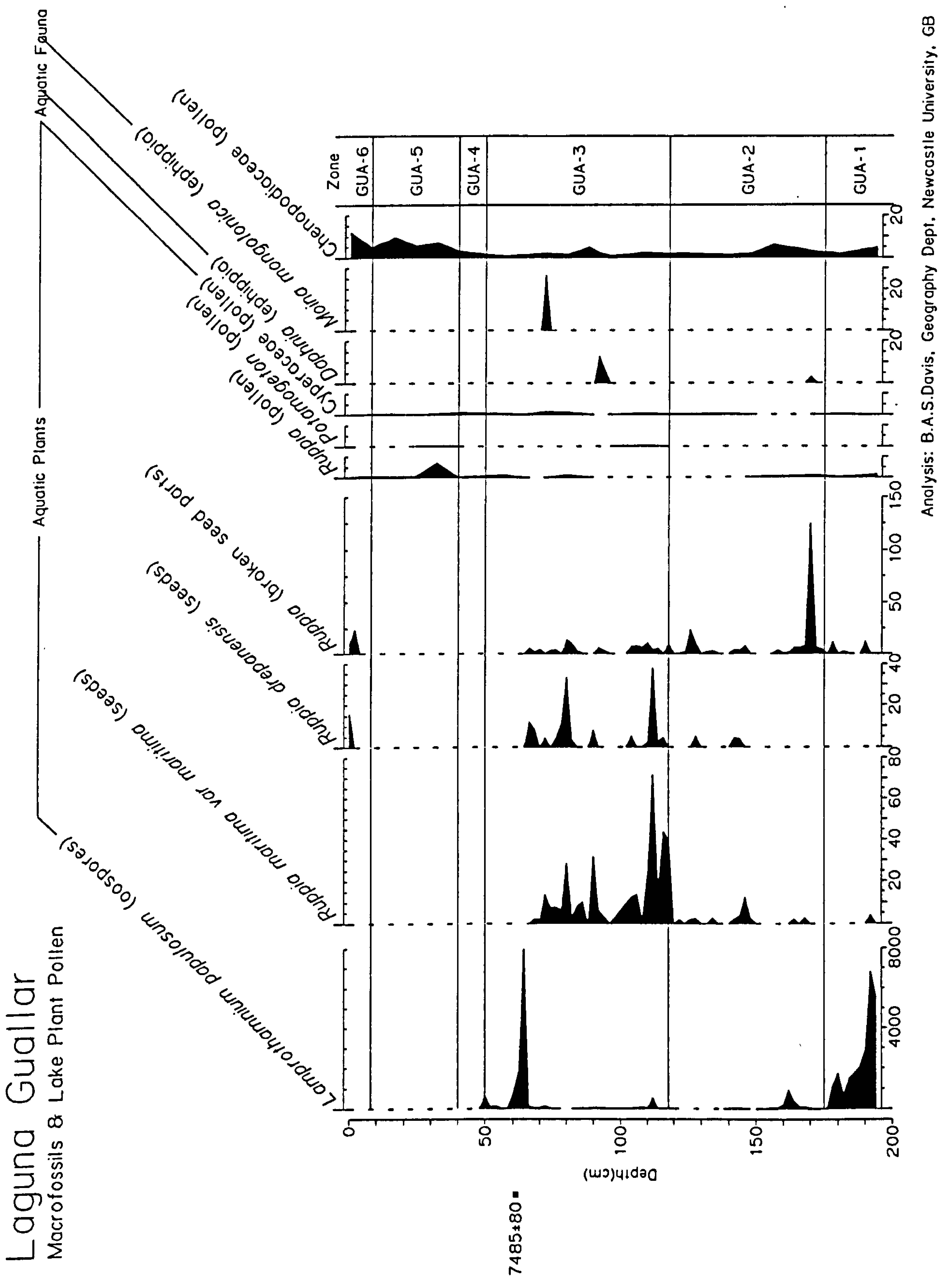


Figure 9.2.3 **Laguna Guallar: macrofossils and aquatic plant pollen**

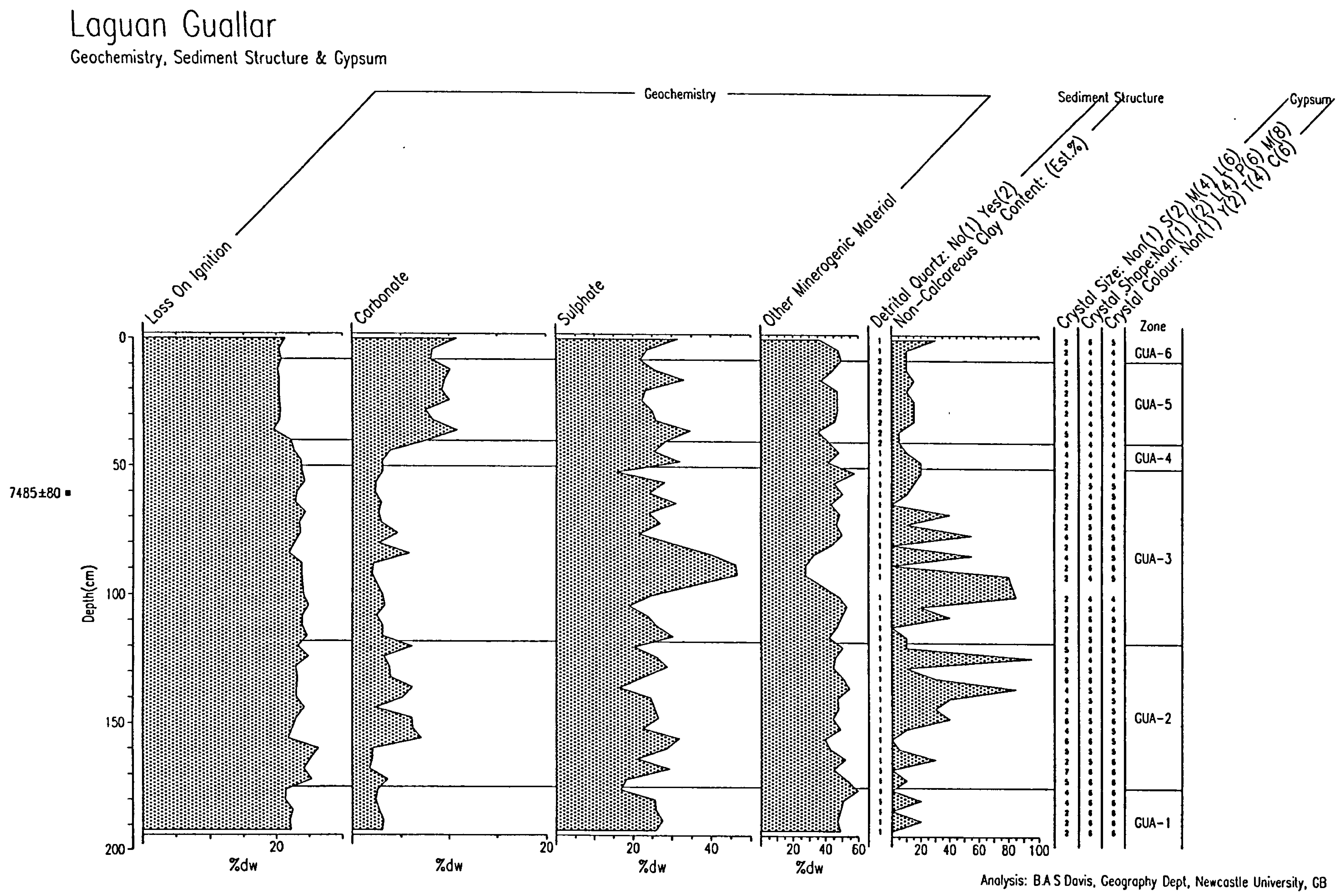


Figure 9.2.4 **Laguna Guallar: geochemistry, sediment composition and gypsum**

Figure 9.2.5 **Laguna Guallar: lake type (level) and vegetation summary**

9.3 Hoya del Castillo

9.3.1 *Site Description*

The Hoya del Castillo (Lat.41°28'55" Long.0°09'30") is a small seasonal playa lake (17.0Ha) lying 8km northwest of the town of Hijar at an altitude of 260m, around 100m lower than the playa lakes of Alcañiz and Bujaraloz. The lake lies in a shallow depression set amongst low hills and surrounded by fields of dry farmed winter cereals (*Figure 9.1.3B* p151). A small ephemeral stream enters from the west, while low cliffs surround the remainder of the basin. Halophytes grow around the lake shore, and annual species of Chenopodiaceae covered much of the dried lake surface when the lake was visited in July 1991. Salt crust formation was localised and poorly developed. The water table was found to be at a lower depth than other lakes cored, suggesting most precipitated salts were being flushed out of the surface layers and back into the groundwater. The surface appeared cracked and very dry, comparable with lakes in the Bujaraloz area that only flood for a few months of the year.

9.3.2 *Analysis & Methods*

The lake was dry when visited, allowing coring in the centre of the lake using a 'Cobra' percussion corer. 5.04m of sediment was extracted in 6*1m drives, each drive being logged and sampled in the field in 2cm slices.

The core was subsampled in the laboratory at 8cm intervals for analysis of pollen, geochemistry (loss on ignition; carbonate; sulphate), charcoal, macrofossils and sediment composition. In addition, macrofossil and sediment composition analysis was also performed on each 2cm slice continuously throughout the main macrofossil zone between 150cm and 450cm.

Pollen concentrations were too low for counting below 448cm to the base of the core, and above 152cm to the core surface. A surface sample from the top of the core provided sufficient pollen to be included in the surface sample data set (Chapter 8).

9.3.3 *Dating control*

Three samples of charcoal provided AMS radiocarbon dates at 174-176cm (5275±50), 278-282cm (7325±65 BP) and 410-412cm (8855±80). The time-depth relationship is presented in *figure 9.3.1* and shows that sediment accumulation may have been continuous throughout the Holocene, although at a lower rate in the late Holocene when the lake was drier .

9.3.4 *Results*

The results are presented as follows:

Pollen data from the current lake surface (0-2cm) is presented in *figure 8.2.A* p129 (Terrestrial Plant Pollen and Charcoal) and *figure 7.1A* p106 (Aquatic Plant Pollen).

Zone CAS-1 (504cm(Base)-440cm)

Lake Environment: Dry/Ephemeral Playa Lake (lake type 1-2)

Macrofossils: None
Pollen: (450-440cm only) *Ruppia*
Geochemistry: High carbonate, low sulphate
Sediment structure: Clay pelletisation
Gypsum: Rosettes, Lenticular

Low lake levels in this earliest zone provide poor conditions for pollen and macrofossil preservation until after 450cm. Clay pellets occur along with gypsum rosettes in the lower levels of the zone, reflecting podsolic conditions and capillary rise associated with dry and ephemeral lakes (lake type 1-2). As the groundwater rises through the zone, lenticular gypsum crystals start to form and sulphate levels increase as evaporitic pumping becomes stronger.

Terrestrial Environment: *Ephedra distachya*-type & *Juniperus* Woodland, *Artemisia* Steppe

Pollen: (450-440cm only) *Ephedra distachya*-type, *Juniperus*, *Artemisia*, Gramineae
Charcoal: (450-440cm only) Low
Stratigraphy: Detrital weathered clays, detrital quartz
Geochemistry: High Carbonate

The pollen record for the zone does not start until after 450cm. Before this period, high carbonate levels, detrital quartz, and oxidised, weathered clays suggest arid conditions with intense catchment erosion. Low levels of organic content may also indicate a poorly vegetated landscape.

The onset of the pollen record after 450cm shows a vegetation almost identical to that at the Laguna Guallar in zone GUA-1. *Ephedra distachya*-type (7%TTP), *Juniperus* (25%TTP) and *Pinus* (30%TTP) all occur at similar levels to those shown in GUA-1, although with around 15% more *Pinus*, and correspondingly less *Juniperus*. *Olea* is also present in low quantities.

Levels of arboreal pollen at the Hoya del Castillo are *ca.*10%TTP greater than the Laguna Guallar, indicting greater woodland cover. The non-arboreal component also shows that *Artemisia* (*ca.*25%TTP) was more prevalent than at the Laguna Guallar (only 15%TTP), while grassland cover was much more diminished (12%TTP, as against 20%TTP in zone GUA-1). The greater levels of *Artemisia* at the Hoya del Castillo represents a difference that persists to the present day, where values of Artemisia exceed 30%TTP at the Hoya del Castillo, but reach only 6%TTP at the Laguna Guallar.

Zone CAS-2 (440-400cm)

Lake Environment: Ephemeral/Seasonal Playa Lake (lake type 2-3)

Macrofossils: None
Pollen: Ruppia
Geochemistry: Low carbonate, high sulphate, high LOI
Stratigraphy: Thinly laminated lacustrine clays
Gypsum: Prismatic

Lake levels increase in this second zone, with a change from sub-surface lenticular gypsum to prismatic gypsum precipitated in free water. Sulphate levels (3-15%dw) remain much lower than at the Laguna Guallar (>20%dw), reflecting differences in groundwater and lake levels between the two lake systems that have persisted to the present day. Lake levels at the Laguna Guallar during this period (zone GUA-2) alternate between permanent and seasonal lake conditions. In contrast, *Ruppia* pollen and the lack of macrofossil remains indicate shorter winter flooding at the Hoya del Castillo, while higher Chenopodiaceae values (*ca.*20%TP versus <8%TP) suggest longer summer desiccation.

Terrestrial Environment: Juniper Woodland & *Artemisia* Steppe

Pollen: Juniperus, Ephedra distachya-type, *Artemisia*

Charcoal: Low

The terrestrial landscape again closely resembles that at the Laguna Guallar at this time (zone GUA-2), with the disappearance of *Ephedra distachya*-type and rise in *Juniperus* to levels over 50%TTP. *Juniperus* dominates the zone, but again, as in the previous zone, with around 10% more *Pinus* and 10% less *Juniperus* than at the Laguna Guallar. The peak in *Juniperus* at around 410cm corresponds with an AMS radiocarbon date of 8855±80BP on a piece of charcoal at the same level.

Higher levels of woodland cover also remain at the Hoya del Castillo, with arboreal pollen percentages rising to over 95%TTP, accompanied by a corresponding decline in openland taxa.

The high levels of vegetation cover may have stabilised catchment erosion since carbonate values drop markedly to around 8%dw.

Zone CAS-3 (400-266cm)

Lake Environment: Permanent Saline-Seasonal Playa Lake (lake type 7-3)

Macrofossils: Ruppia maritima var *maritima*
Pollen: Ruppia, Potamogeton, Cyperaceae
Geochemistry: Low & high sulphate, low carbonate
Stratigraphy: Finely laminated lacustrine clays
Gypsum: Prismatic

The presence of seeds of the perennial *Ruppia maritima* var *maritima* indicate periods of high lake levels (1.5-3.0m) during the zone, with permanent, but unstratified, water (lake type 5). Lower lake levels and more temporary, seasonal, lake conditions (lake type 3) are also suggested by seeds of the annual, *Ruppia drepanensis*. Very high lake levels (>3.0m), sufficient to cause stratification (lake type 7), are indicated by an absence of macrofossil remains, while sulphate levels remain high and prismatic gypsum does not suggest desiccation. Sulphate levels peak during high water stages, reflecting an increase in groundwater contribution to the lake during these periods, but they remain at relatively low levels (<20%dw) compared to the deeper and more saline Laguna Guallar (>40%dw). The lower salinity of the lake water at the Hoya del Castillo suggested by lower sulphate levels is confirmed by the presence of low salinity tolerant Cladocera, including *Daphnia* and *Moina*-type (but not the halophytic *M.mongolonica*), as well as *Typha angustifolia*-type pollen from emergent macrophytes. High lake levels and low salinity lake waters can best be explained by high contributions of meteoric waters to this lake in comparison with others such as the Laguna Guallar which have a poorly developed surficial drainage network and much higher levels of groundwater.

As with the Laguna Guallar (GUA-3), lake levels at the Hoya del Castillo during this zone reach their highest within the Holocene. The similarity between the two lake systems may also be seen in the occurrence of two periods of particular high lake level, separated in the middle of the zone by a period of much lower lake level. At the Hoya del Castillo, this arid period is marked by a drop in sulphate levels (<5%dw), while at the Laguna Guallar, evaporation of the much more saline lake waters results in a sharp peak in sulphate (>40%dw).

Terrestrial Environment: Pine/Evergreen Oak Woodland & Grass Steppe

Pollen: Pinus, Quercus ilex-type, deciduous trees, Gramineae
Charcoal: High
Geochemistry: Low carbonate

The decline of *Juniperus* and rise of *Pinus* and *Quercus ilex*-type at the onset of zone CAS-3 is identical to zone GUA-3 at the Laguna Guallar. Values of *Pinus* (*ca.*70%TTP) and *Quercus ilex*-type (*ca.*10%TTP) are similar to levels of the same dominant arboreal taxa in zone GUA-3 at the Laguna Guallar. The similarity extends to the reappearance of *Olea* and increase in deciduous taxa.

Overall levels of arboreal pollen rise to over 90%TTP except between 340-260cm, where a peak in charcoal coincides with an increase of upto 20%TTP in the non-arboreal component. The opening up of the woodland cover sees a clear increase in *Quercus ilex*-type (upto 20%TTP) and Gramineae at the loss of *Pinus*. Higher levels of large Gramineae pollen (>40μm) also occur during this period, although it is not possible to distinguish cultivated cereals from natural Esparto grassland which both have large pollen grain sizes.

An AMS radiocarbon date of 7325±65BP was provided by charcoal towards the end of the peak in microscopic charcoal at around 280cm. Comparison with a slightly earlier date at the onset of a similar peak in charcoal at the Laguna Guallar successfully brackets the most intensive part of this period of anthropogenic disturbance at between 7485±80BP-7325±65BP.

Zone CAS-4 (274-150cm)

Lake Environment: Ephemeral/Seasonal Playa Lake (lake type 2-3)

Macrofossils: None
Pollen: Ruppia
Geochemistry: Low sulphate, low carbonate
Stratigraphy: Weathered clays

Gypsum: Yellow, lenticular

Lake levels fall rapidly prior to the onset of zone CAS-4, as macrofossils disappear and gypsum crystals change from prismatic to lenticular. The drop in lake level corresponds to the end of zone GUA-3 at the Laguna Guallar, where a similar drop in lake level causes a hiatus in the record.

Sediment accumulation continues at the Hoya del Castillo, however, with low *Ruppia* pollen values and lack of macrofossils suggesting ephemeral lake conditions (lake type 2), although Chenopodiaceae does not rise to sufficiently high levels (>40%TP: see Chapter 7) to support this. Low pollen concentration values also support the idea of greater basin aridity and oxidising conditions, which may also explain the lack of macrofossil evidence. The lake was therefore probably intermediate between seasonal (lake type 3) and ephemeral (lake type 2), with only a short summer desiccation preventing terrestrial plants from invading the basin floor, but with sufficient terrestrial material close by to release humic acids and cause a yellowing of gypsum crystals.

Terrestrial Environment: Pine Woodland

Pollen: Pinus
Charcoal: Low
Stratigraphy: Weathered clays

Pinus values reach over 80% TTP at around 225cm, and suggest development of an extensive, monospecific pine woodland. This later declines to below 60% TTP as *Quercus ilex*-type, Gramineae, Chenopodiaceae and *Plantago* expand again as lake levels ultimately drop again at the end of the zone. The rise of *Pinus* does not correspond with high lake levels or high levels of deciduous taxa that may indicate development of a sub-humid montane forest (see Chapter 8, section 8.3.2.4). Instead, high aridity is indicated, suggestive of a lowland Mediterranean pine forest of *Pinus halepensis*. The development of this pine forest is similar to that shown in zone PEQ-4 at the Salada Pequeña, which also corresponds with a drop in lake level and charcoal values (see section 9.5). However, unlike the Salada Pequeña, the later decline of pine at the Hoya del Castillo does not correspond with an increase in charcoal. If anthropogenic action was responsible for the decline in *Pinus* and increase in *Quercus ilex*-type and grass steppe, then this was not achieved through the firing of the vegetation cover.

An AMS radiocarbon date obtained from a piece of charcoal at 174-176cm provides a date for the decline of pine of before 5275±50BP.

Zone CAS-5 (150-8cm)

Lake Environment: Ephemeral Playa Lake (lake type 2)

Macrofossils: Caryophyllaceae
Pollen: None
Geochemistry: Low Sulphate, high Carbonate
Stratigraphy: Weathered clays
Gypsum: Yellow, lenticular

A further drop in lake level at the onset of zone CAS-5 results in the oxidation of pollen which becomes too sparse to count. Sulphate levels also fall-off due to the fall in groundwater and lack of evaporitic pumping and salt deposition, which also reduces the flocculation of non-calcareous clay. Some Caryophyllaceae seeds were also found, along with remnants of root mat. The occurrence of lenticular gypsum confirms that the lake was ephemeral (lake type 2) for the majority of the zone, although an absence of gypsum crystals at at least two levels (40cm & 72cm) indicates almost dry lake (lake type 1) conditions.

Terrestrial Environment: High Erosion

Pollen: None
Geochemistry: High carbonate
Stratigraphy: Weathered clays

Carbonate values increase to around 13%dw after 130cm, indicating higher levels of catchment erosion of detrital carbonate clays. This corresponds closely with similar high carbonate values in zone CAS-1 in the early Holocene, and zone GUA-5 at a similar time period in the late Holocene.

Charcoal values (*Figure 9.3.6*) remain low during the onset of the carbonate rise, but increase later at around 90cm. This sequence of carbonate rise followed by charcoal rise is the same as in zone GUA-5 at the Laguna Guallar and may indicate that the onset of erosion was not initiated by agricultural intensification. The absolute levels of charcoal concentration are also considerably less (*ca.*25mm^{2}gdw) than the earlier clearance period at the end of zone CAS-3 (*ca.*>80mm^{2}gdw), despite indications that the sediment accumulation rate was slower at this time (*Figure 9.3.1*). This may relate to increased oxidation of the charcoal record in zone CAS-5, but probably reflects a much greater woodland cover available for combustion in zone CAS-3.

Zone CAS-6 (8-0cm)

Lake Environment: Seasonal Playa Lake (lake type 3)

Macrofossils: Charophytes, *Ruppia drepanensis*
Pollen: Ruppia, Potamogeton, Cyperaceae
Geochemistry: High sulphate, high Carbonate
Stratigraphy: Weathered clays
Gypsum: Lenticular/prismatic

Lake levels rise again in the final zone, with the return of prismatic gypsum, high sulphate levels, and aquatic macrofossils in the uppermost layers. The predominance of Charophytes over *Ruppia drepanensis* may suggest a shorter flooding period or less saline waters than in other playa lakes such as the Laguna Guallar which also shows an increase in lake level at the top of the core (GUA-6). The lake can be classified as seasonal at this point (lake type 3), although high Chenopodiaceae pollen values (>35%TP) (*Figure 7.1A*), and the presence of large numbers of Caryophyllaceae seeds, indicates prolonged summer desiccation.

Non-Lake Environment: Cereal Cultivation & *Artemisia* Steppe

Pollen: Pinus, Olea, Artemisia, Graminae
Charcoal: High
Geochemistry: High Carbonate

Due to the poor preservation of pollen, palynological evidence within this zone is confined to the analysis of a single surface sample (*Figure 8.1*). The current treeless landscape maintains an arboreal pollen component of over 50%TTP due to long distance transport. This represents a decline of 25%TTP since the last recorded pollen at 150cm. Over the same time period, *Olea* increases significantly from 2% to 8% TTP, along with *Artemisia*, which increases from 5% to almost 30% TTP.

Carbonate values remain high, and the sediments are dominated by weathered clays, indicating continued catchment erosion.

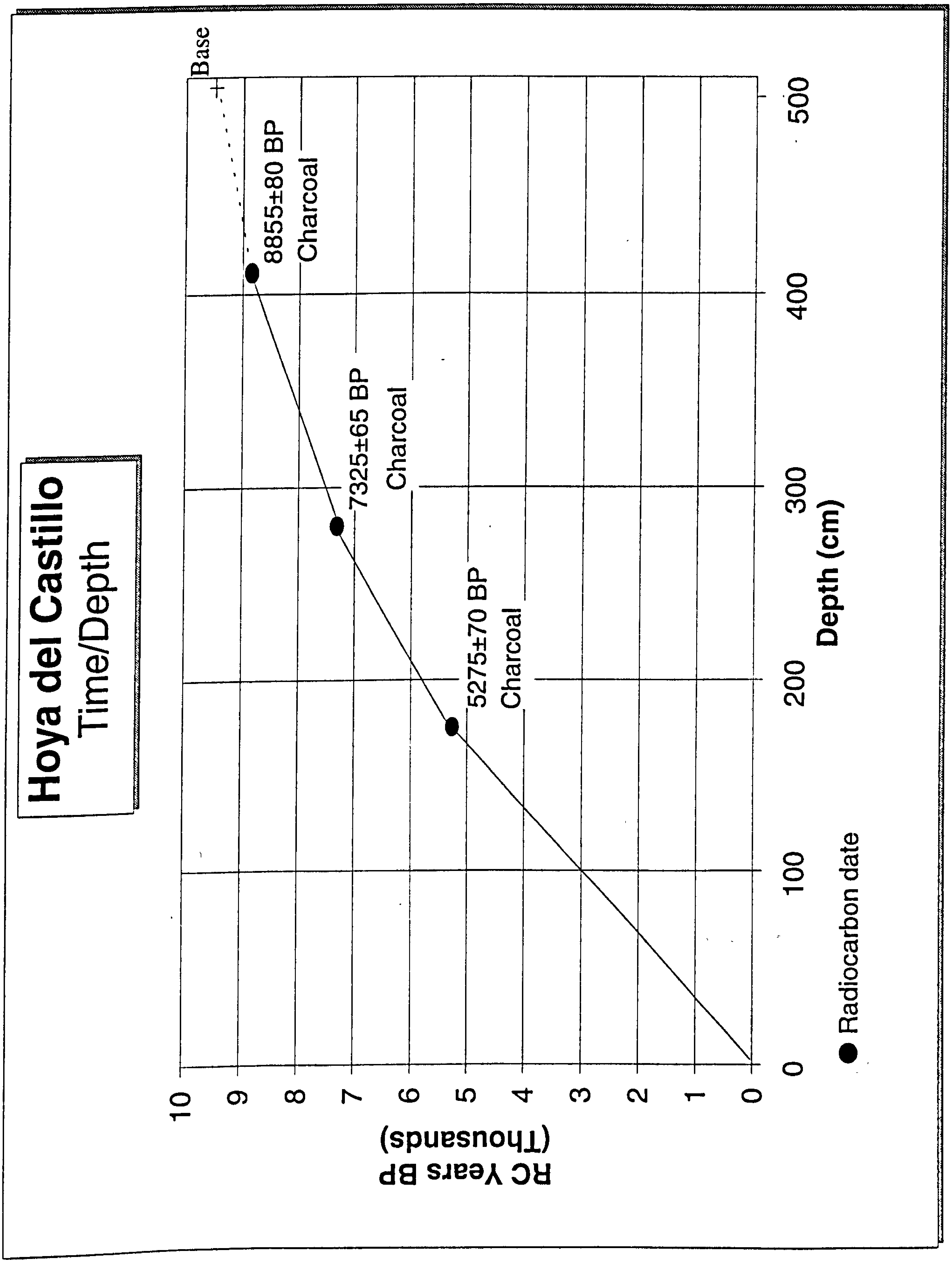


Figure 9.3.1 **Hoya del Castillo: radiocarbon time/depth curve**

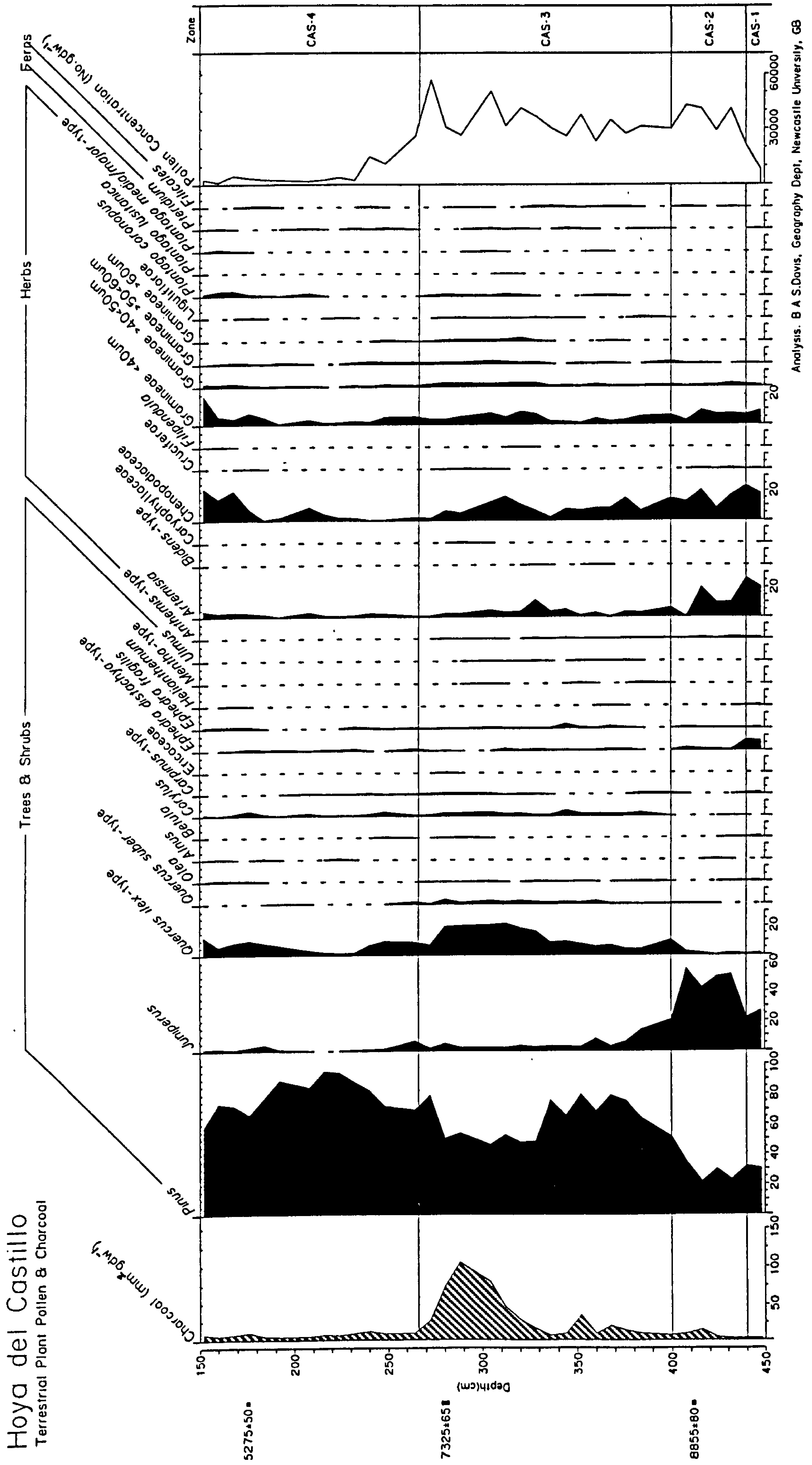
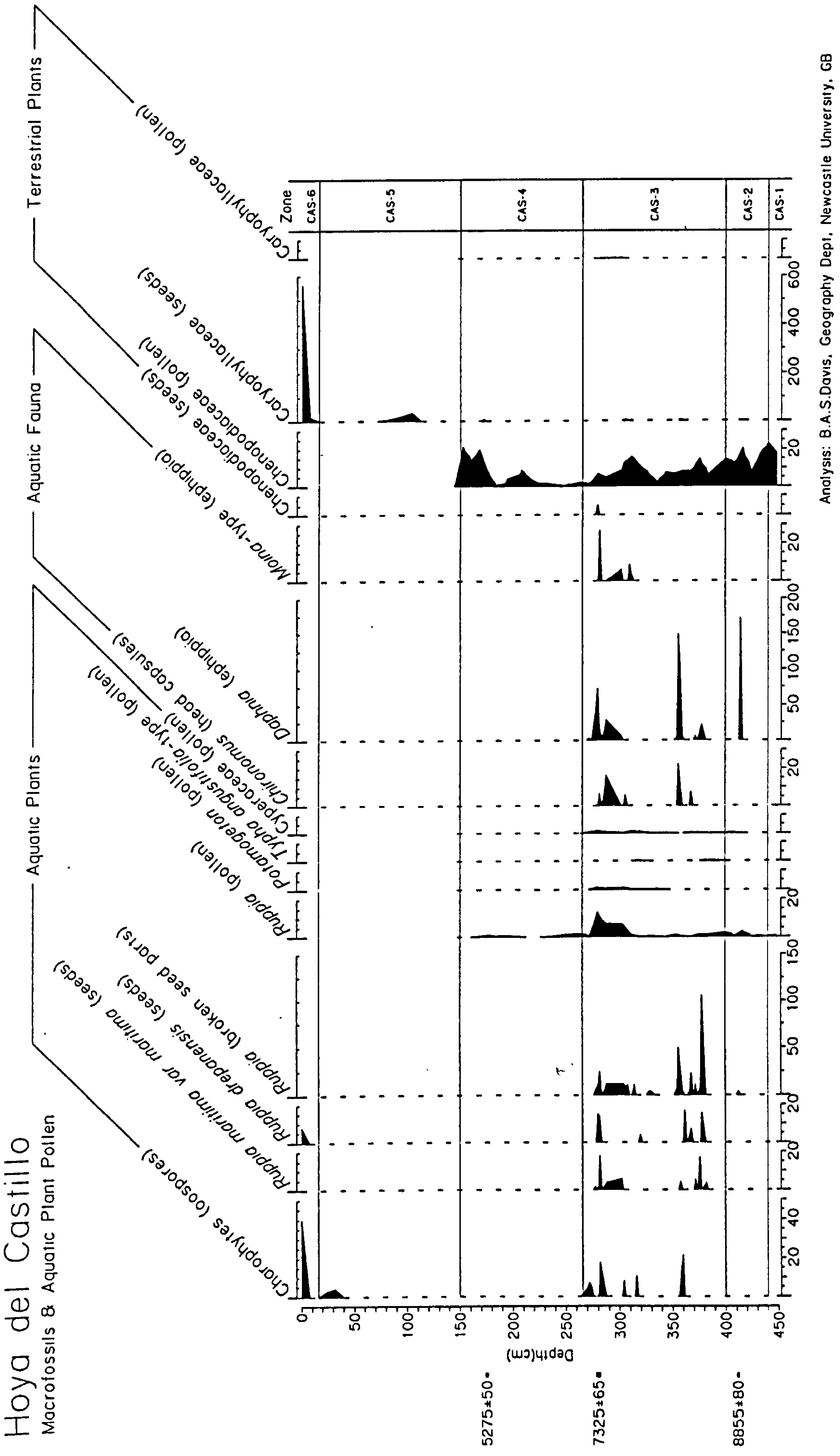


Figure 9.3.2 **Hoya del Castillo: terrestrial plant pollen and charcoal**



Analysis: B.A.S.Davis, Geography Dept, Newcastle University, GB

Figure 9.3.3 **Hoya del Castillo: macrofossils and aquatic plant pollen**

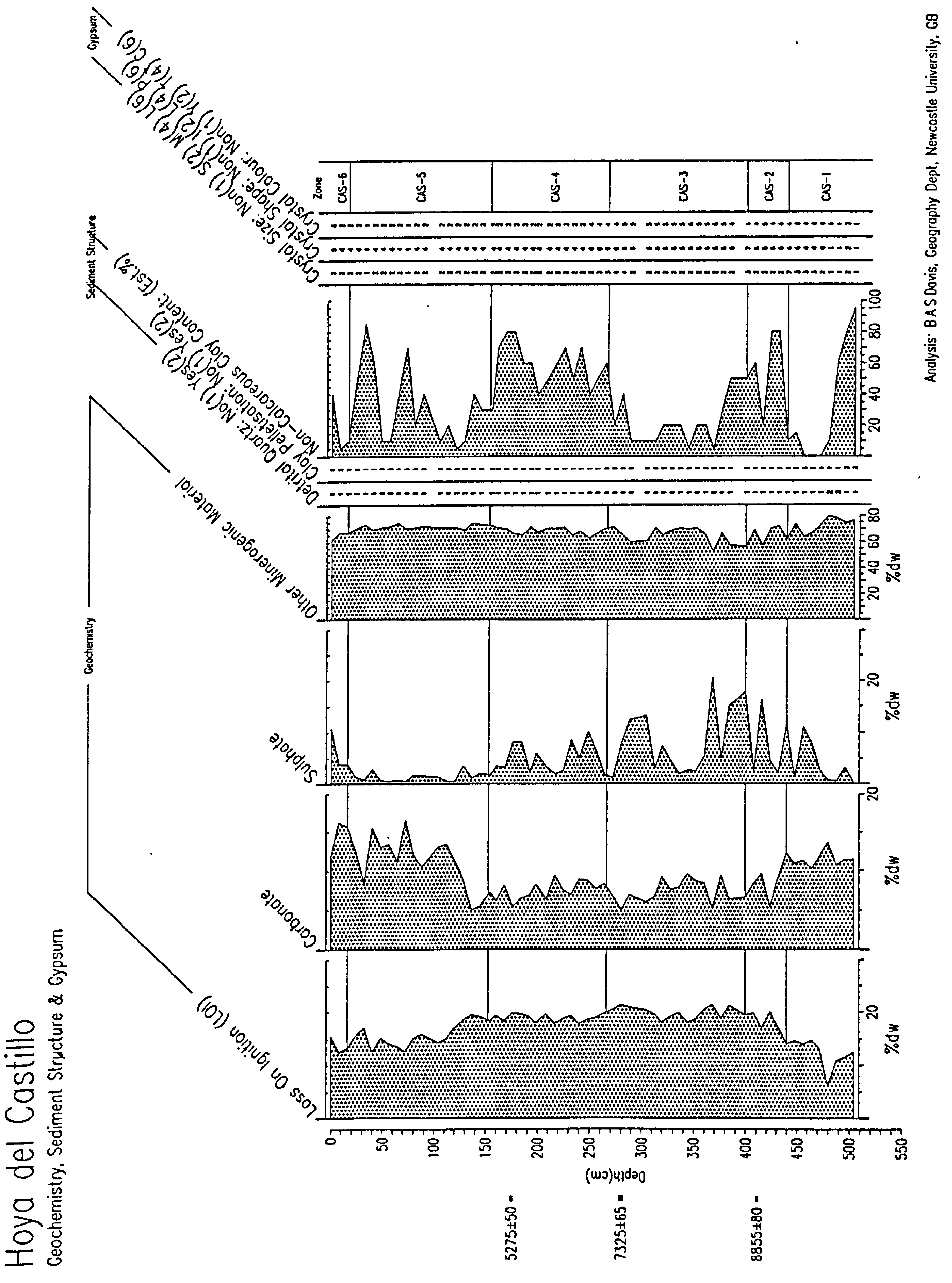


Figure 9.3.4 **Hoya del Castillo: geochemistry, sediment composition and gypsum**

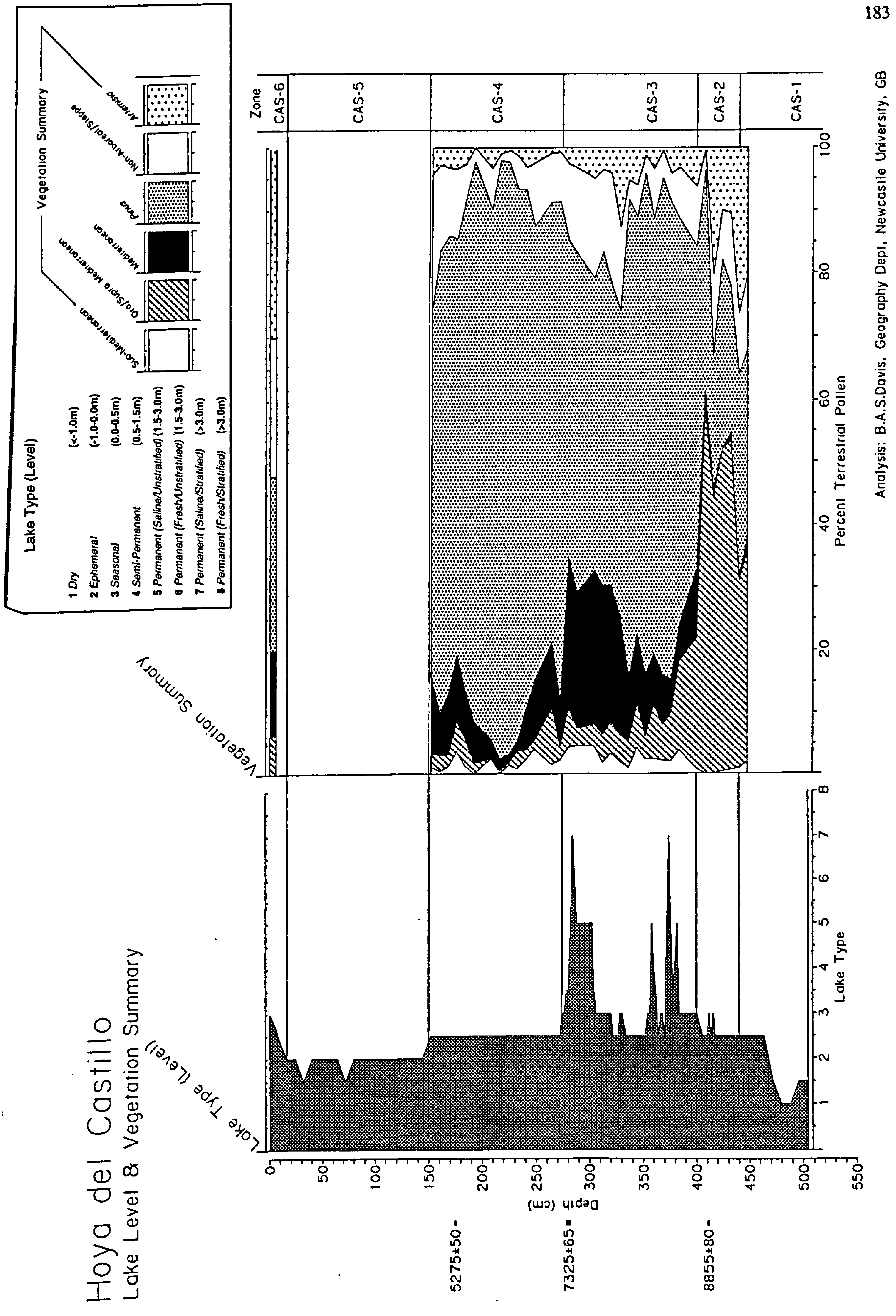


Figure 9.3.5 **Hoya del Castillo: lake type (level) and vegetation summary**

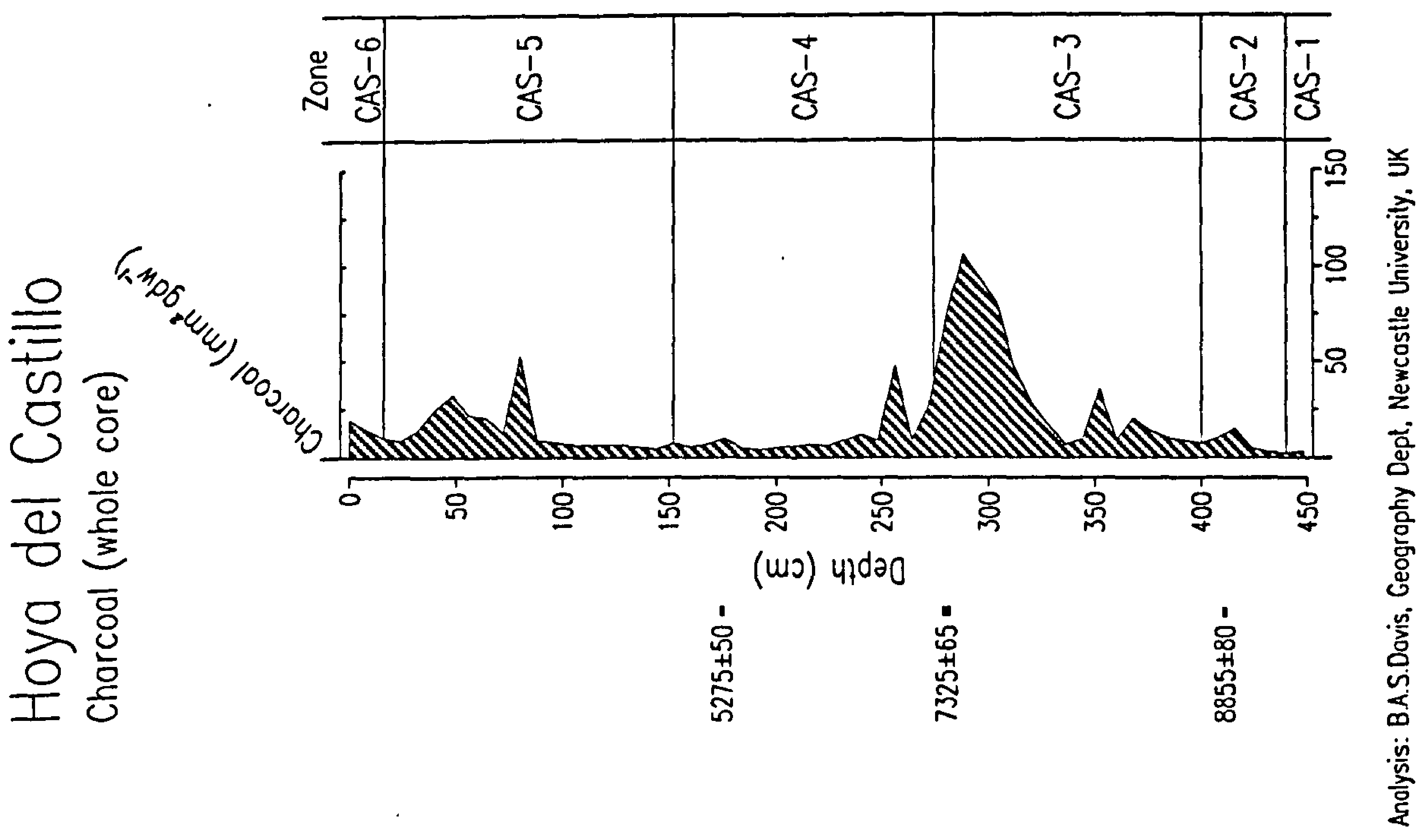


Figure 9.3.6 **Hoya del Castillo: charcoal for the whole core**

9.4 La Salineta (Section)

9.4.1 *Site Description*

La Salineta lies to the north of the main Los Monegros endoreic system, at an altitude of 325.8m, just 1.5km south of the town of Bujaraloz (*Figure 9.4* p152). The present lake of 20.0Ha is inset within a much larger palaeolake some 3-4m above the present lake level. The deposits of the palaeolake have been eroded to form cliffs surrounding the present lake. These cliffs are particularly well developed at the windward southeastern end of the basin, where exposure to wave action is at its greatest.

The present inset lake is a seasonal playa that appears to hold water for longer and deeper than most. A thick 4" halite salt crust covers the surface during the summer, remaining soft and 'wet', even when all other lakes in the area are baked dry. This extensive precipitation of mineral salts has been commercially exploited in the past, and the ruins of a small salt works exists at the eastern end of the basin. Dantin (1942) quotes Donayre as observing salt production at La Salineta around 1862 at 4600 tonnes/yr, a figure which is considerably more than the 1400 tonnes/yr he observed being extracted at the much larger works at Laguna de la Playa.

The predominance of sodium-chloride precipitation is reflected in high values for these elements in the water chemistry. Data on water chemistry is provided in *table 9.1* p157.

The palaeolake sediment surface sits almost level with the rolling plains of the steppe and is visible over the ploughed ground as an area of pale grey lacustrine clays. For a short section to the east, a small 1.0m cliff marks the boundary of the old lake with the desert soils of the steppe.

Natural vegetation is severely restricted by the dominance of dry winter wheat farming in the surroundings of the lake. Halophytes surround the shore of the lake and an algal mat covers the lake bottom, becoming visible when the salt crust re-dissolves with the autumn rains. Martino (1988) observed that no aquatic plant life appeared to be present in the lake.

9.4.2 *Analysis & Methods*

Samples were taken from a 3.5m cliff of exposed palaeolake sediments at the eastern end of the present lake in July 1991, and again in November of the same year. After cleaning the cliff face with a spade, sediment was carefully extracted by hand in 1cm slices every 10cm from top to bottom (0-360cm). The base of the cliff forms the shore of the present lake, below which it was found necessary to use a Hiller corer. A further 105cm was sampled below the base of the cliff using the Hiller, a total record of 4.65m. A subsequent visit in June 1992 provided the opportunity to use a Cobra corer to extend the record at the cliff base, achieving an extra 3.8m of recovery and providing a lot more sediment. The total depth of 8.45m is by far the longest sediment record from any of the lakes so far investigated in the area. Unfortunately this core has yet to be studied in detail.

Analysis was performed on all samples at the 10cm sampling interval from the open section(0-360cm), however due to the lack of sediment, only pollen analysis was undertaken on the Hiller core (360-465cm).

Palaeoenvironmental analysis performed on sediment from this site included pollen, geochemistry (loss on ignition; carbonate; lead; zinc; cadmium; copper; manganese; iron; calcium; sodium; potassium and magnesium), charcoal, and macrofossils. The sediment composition is not displayed since this was uniform throughout, consisting of pale grey lacustrine clays containing small, translucent, lenticular gypsum crystals.

9.4.3 *Dating control*

Chenopodiaceae seeds were extracted at 10-11cm & 20-21cm for AMS radiocarbon dating. The sample was too recent for accurate dating, returning a result of 127.98% modern. Samples were also taken from lower down the sequence for TL dating but no results are yet available.

Without absolute dating control, the age of the sequence is difficult to establish on the pollen evidence alone. The nature of the site suggests that it is of some age, although the presence of *Fagus* at 350cm may indicate that it covers the late Holocene. *Fagus* does not appear until 3.0Kyr BP at the Salada Pequeña, and is not found at any of the early Holocene sites in the Ebro Basin. The earliest *Fagus* appears on the Spanish side of the Pyrenees is around 5.0Kyr BP (Montserrat, 1992). The later increase in charcoal is also distinctive of the late Holocene.

The lake basin has a very shallow gradient and is unlikely to have built up sediment very quickly. This would suggest that the drop in groundwater that caused the formation of the inset lake must have occurred very rapidly indeed, within the last thousand years perhaps. This may have been a result of doline collapse, since deflation is unlikely to have removed such a huge quantity of sediment so quickly. The alternative assessment, and one which seems to fit better with the location of the lake in the surrounding topography, is that it dates from the last interglacial.

9.4.4 Results

The results are presented as follows:

Figure 9.4.1: Terrestrial Plant Pollen & Charcoal
Figure 9.4.2: Macrofossils, Aquatic Plant Pollen & Geochemistry
Figure 9.4.3: Lake Type (Level) & Vegetation Summary

Zone SAS-1 (465(Base)-250cm)

Lake Environment: Seasonal Playa Lake (lake type 3)

Macrofossils: None
Pollen: Ruppia, Potamogeton, Typha

Gypsum: Lenticular

Lenticular gypsum and *Ruppia* pollen occurs throughout the zone, suggesting seasonal playa lake conditions (lake type 3). Chenopodiaceae values remain low throughout the zone (<20%TP: Total Pollen) and do not suggest long periods of summer desiccation.

Terrestrial Environment: *Pinus* & *Quercus ilex*-type Woodland, Grass Steppe

Pollen: *Pinus*, *Quercus ilex*-type, Gramineae (>50μm)
Charcoal: Low
Geochemistry: Low carbonate & trace metals

Pinus values fluctuate at around 55%TTP (Total Terrestrial Pollen), with a significant proportion of *Quercus ilex*-type (*ca.*8%TTP) and *Juniperus* (5%TTP) also present. Total arboreal pollen remains at around 70%TTP throughout the zone. This figure is close to the current contribution of 65%TTP arboreal pollen at the Laguna Guallar and La Salineta inset lake (*Figure 8.2B*), and probably represents a landscape similar to today's treeless steppe. Both large (>50μm) and small (<50μm) Gramineae pollen occur consistently at all levels and suggest either cereals or natural Esparto steppe. *Artemisia* is also present at values around 10%TTP, close to those of the present day.

Carbonate values (*ca.*12%dw) and trace metal values are lower than in the more recent (upper) levels in the section, although this may be a function of sediment accumulation rate, since pollen concentrations are also lower. Low values of Compositae, charcoal, and relatively high woodland cover may support the geochemical evidence for relatively low rates of catchment disturbance and erosion in this zone.

Zone SAS-2 (250-25cm)

Lake Environment: Seasonal/Ephemeral Playa Lake (lake type 3-2)

Macrofossils: Non
Pollen: Chenopodiaceae
Geochemistry: High carbonate & trace metals
Gypsum: Lenticular

Periods of lower lake level in zone SAS-2 are marked by peaks in the Chenopodiaceae pollen curve, which reach values of over 40%TP at around 220cm and 65cm. This may suggest periods of ephemeral lake conditions (lake type 2), but this is not clearly supported by macrofossil evidence of Chenopodiaceae seeds (see chapter 7). Aquatic plant pollen also increases in the zone, including low salinity tolerant emergent macrophytes such as *Typha*. The apparently contradictory increases in Chenopodiaceae and aquatic plants may indicate declining salinity of the lake waters due to lower contributions from groundwater. Lenticular gypsum continues to show seasonal desiccation, but the lower salinity of the lake waters may have permitted increased aquatic plant growth despite a shorter flooding period.

Terrestrial Environment: *Pinus* & *Juniperus* Woodland, Grass Steppe

Pollen: *Pinus, Juniperus,* Gramineae (>50µm)
Charcoal: High
Geochemistry: High carbonate & trace metals

Woodland cover declines within the zone following a sharp peak in charcoal at around 175cm. The arboreal component is reduced by up to 30% to *ca.*60% TTP, slightly lower than the current contribution of 65%TTP (taken from a surface sample analysed from the inset lake). *Juniperus* values increase to over 10%TTP and deciduous tree pollen declines from a steady 6%TTP in the previous zone, to less than 3%TTP.

The non-arboreal component continues to be dominated by grasses, with a slight increase in the larger Gramineae pollen sizes (cereals or Esparto grasses), particularly towards the end of the zone. As at the nearby Laguna Guallar site (10km distant), woodland clearance (zone GUA-5) does not seem to favour *Artemisia* at the La Salineta.

Disturbance indicators, such as Compositae, do however increase, along with carbonate values. Carbonate levels (15-20%dw) are relatively high in zone SAS-2 compared to comparable sites and may indicate increased catchment erosion. Concentrations of anions and trace metals also increase above 210cm, although this may be due to a reduction in sediment accumulation rate suggested by a concurrent increase in pollen concentration.

Zone SAS-3 (25-5cm)

Lake Environment: Dry/Ephemeral Playa Lake (lake type 1-2)

Macrofossils: Chenopodiaceae
Pollen: Chenopodiaceae
Geochemistry: High Ca:Mg ratio, high trace metals, low sodium
Gypsum: Lenticular

An increase in Chenopodiaceae pollen to over 50% TP and the appearance of Chenopodiaceae seeds indicates the development of an almost dry, ephemeral lake (type 2). The uppermost sediments (0-10cm) include the roots of terrestrial vegetation growing on top of the section. The lake ceased to form at this point and became dry (type 1).

Unlike all the other cores examined, levels of sodium decline in the uppermost sediments as a result of leaching by the downward percolation of meteoric waters. Pedogenesis has now replaced lake development within the zone, while deflation or doline collapse has started to form the new inset lake basin.

Terrestrial Environment: (Pinus Woodland), Cereal Cultivation & Grass Steppe

Pollen: Pinus, Olea, Gramineae (>50µm)
Charcoal: High
Geochemistry: High carbonate

The vegetation landscape remains much the same as in the previous zone, except for the disappearance of *Juniperus*, and the appearance of *Olea*, reflecting the late Medieval expansion of olive cultivation in the area. Interpretation is difficult due to suspected pedogenic processes causing disturbance of the sedimentary record. This may have allowed the downward penetration of contemporary pollen into the lower layers of the zone. This is supported by radiocarbon dating of Chenopodiaceae seeds from 10cm and 20cm, which were found to be too modern (*ca.*<200yrs BP) to secure a date using this technique.

The dating of the onset of pedogenesis and the drop in groundwater (*ca.*3.5m) associated with formation of the inset lake is complicated by possible erosion of the uppermost sediment layers. The top of the section may not necessarily represent the complete sediment record for this site. Pollen evidence from zone SAS-3 indicates that lake levels did not drop until very recently (*ca.*0.4Kyr BP), however, contamination of these uppermost layers by pedogenic processes seems almost certain. The termination of sediment accumulation at this site must therefore remain uncertain. The existence of *Fagus* pollen at 370cm and anthropogenic disturbance in zone SAS-2 supports the possibility that formation of the inset lake occurred relatively recently in the latter stages of the late Holocene.

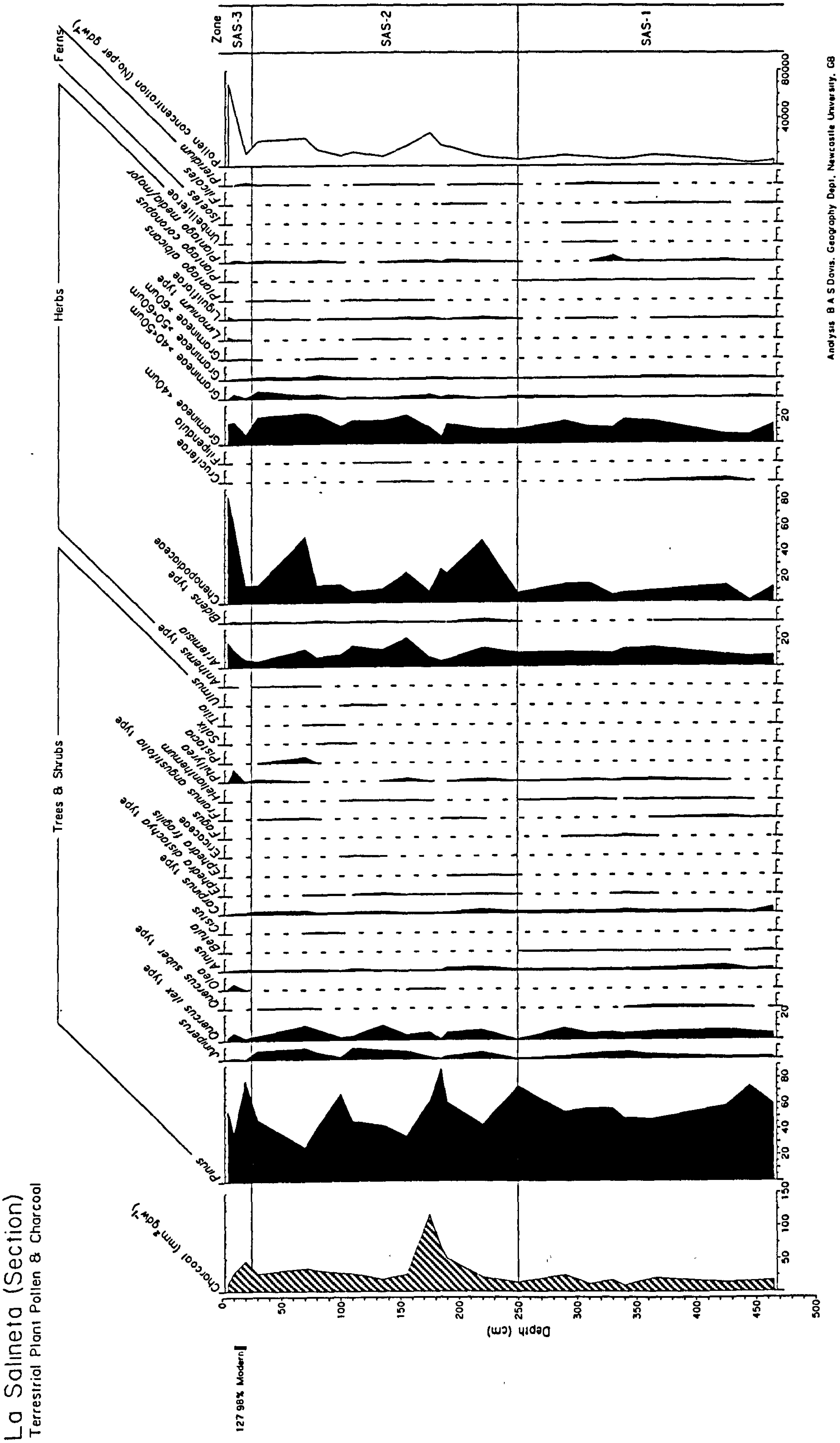


Figure 9.4.1 **La Salineta (section): terrestrial plant pollen and charcoal**

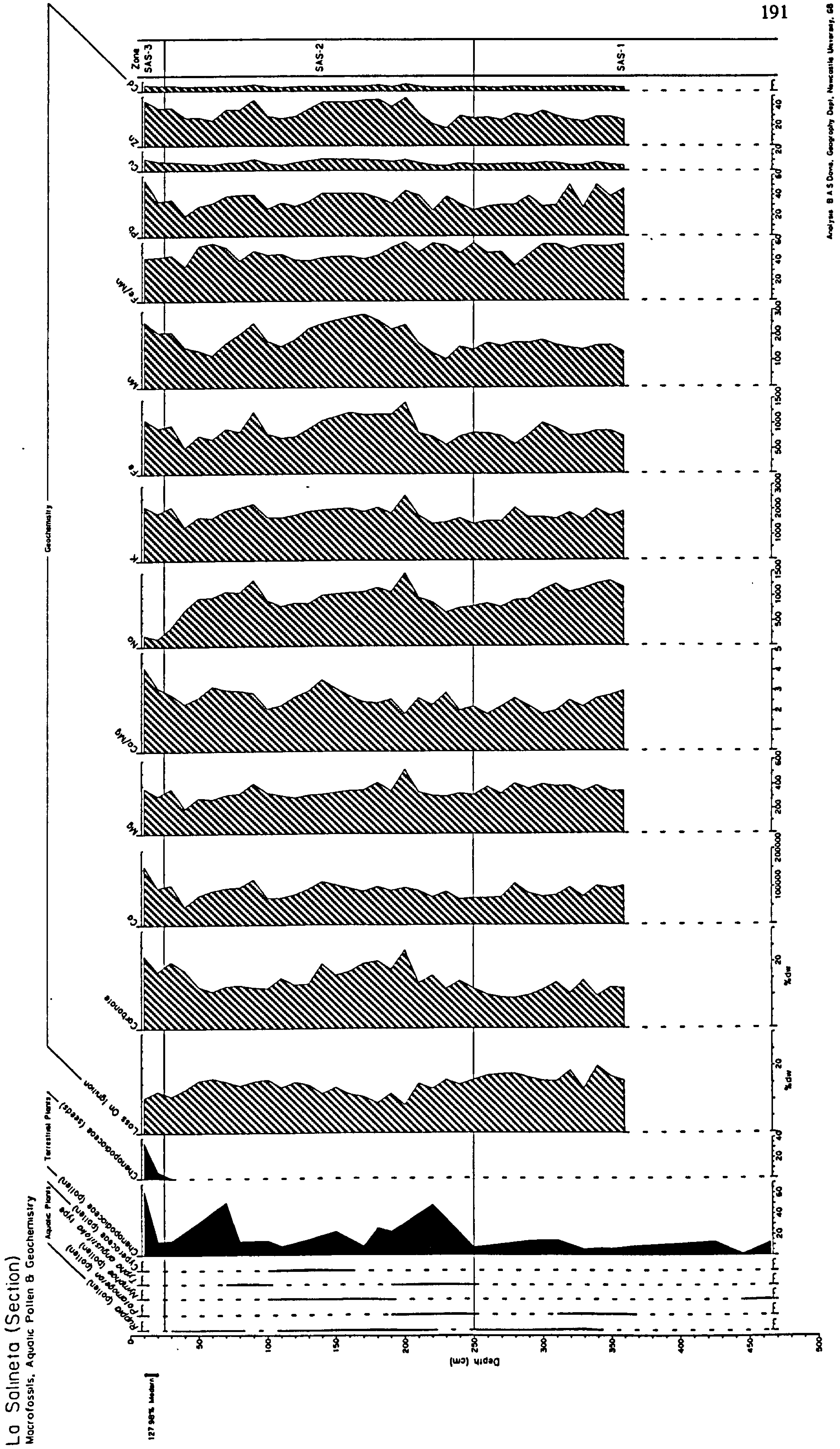


Figure 9.4.3 **La Salineta (section): macrofossils, aquatic plant pollen and geochemistry**

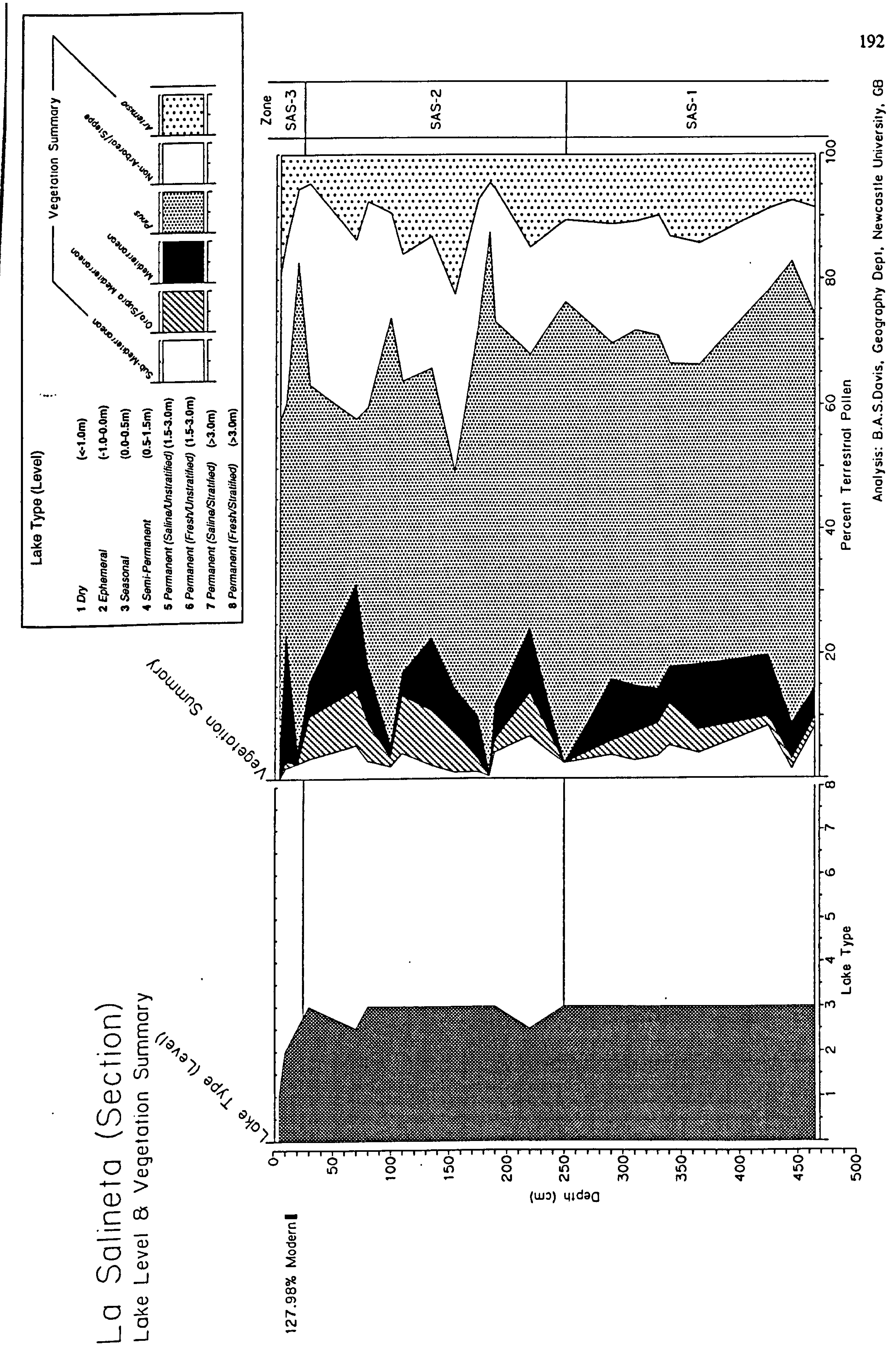


Figure 9.4.4 **La Salineta (section): lake type (level) and vegetation summary**

9.5 Salada Pequeña

9.5.1 *Site Description*

The Salada Pequeña (Lat.41°02'40" Long.0°13'10") is a small (21.0Ha), seasonal playa lake located 5km west of the town of Alcañiz and 2km south-west of La Estanca reservoir (*Figure 9.5* p153). It forms one of a number of seasonal playa lakes in the area, including the much larger (85.0Ha) Salada Grande, located 500m east of the Salada Pequeña. The Salada Pequeña lies 7m above the Salada Grande and 20m above La Estanca at an altitude of 350m above sea level.

The Salada Pequeña is bordered on the east side by a prominent Tertiary sandstone palaeocanal, against which lies the lowest and wettest part of the lake basin. Opposite this area, the basin grades more gently to where a small alluvial fan extends from a dry gully. An upper terrace, around 1.5m above the present lake shore, surrounds both the Salada Pequeña and the Salada Grande, marking a once higher lake level. Current lake levels do not generally exceed 80cm in the deepest part of the lake, with lower levels more common throughout the 7-8 months of the year when surficial water is present. In summer, a hard efflorescent salt crust forms as the lake dries up, protecting the sediment from deflation and keeping the subsurface sediments damp. Lake waters are generally hypersaline and dominated by sodium-chlorides and sulphates. The dominant minerogenic sedimentary process appears to be sub-surface growth of lenticular gypsum within the capillary zone.

The surrounding gentle slopes are dedicated to the dry farming of cereals with very little natural vegetation. Shore vegetation follows the standard succession (Bourrut, 1991; Chapter 4) with the lake surface colonised primarily by annual Chenopodiaceae around the margins which extend further into the centre during dry years. The following plants were found along the shoreline area; *Anagallis arvensis, Lygeum spartum, Plantago afra, Chenopodiaceae spp., Salsola verticillata, Dactylis glomerata.* The damper and less saline dry gully/alluvial fan contained the following species; *Juncus spp., Lygeum spartum,* and *cf.Puccinella.* The uncultivated slopes and low hill tops were largely denuded of soil with low plant densities of mainly *Artemisia herba-alba* and Gramineae including *Stipa.*

9.5.2 *Analysis & Methods*

The lake was dry when coring was undertaken in July 1991. A manually operated percussion 'Cobra' corer was used to extract 4.0m of sediment from the lake centre. Each of the four 1.0m drives were logged and sampled in the field at 2cm intervals.

Surface samples were also taken along a line into the lakes hydrological centre (lowest point) in order to evaluate the surface distribution of the various palaeoenvironmental indicators used in the core analysis (Chapter 6).

The core was subsampled at 8cm intervals for analysis of pollen, geochemistry (loss on ignition; carbonate; sulphate; lead; zinc; cadmium; copper; manganese; iron; calcium; sodium potassium and magnesium), charcoal, macrofossils and sediment composition. In addition, macrofossil and sediment composition analysis was also performed on each 2cm slice continuously between 20cm and 350cm

9.5.3 *Dating Control*

Material for AMS radiocarbon dating was extracted at all levels where it was available. Unfortunately 2 samples were lost in processing at the radiocarbon laboratory. Four dates where obtained from charcoal (32-34cm & 44-48cm, 340±50BP; 102-106cm, 1225±50BP; 186-188cm, 2230±50BP and 236-238cm, 2675±60BP) and one from Chenopodiaceae plant remains (164-166cm 2325±50BP).

The time/depth relationship is shown in *figure 9.5.1*. Two dates are shown as reversals, and there is good reason to suspect that these samples were contaminated with 'old carbon'. The sample of charcoal collected between 32-48cm was composed of a large number of very small fragments that were not easily cleaned. Similarly, the Chenopodiaceae plant remains at 164-166cm were also difficult to clean compared to the other samples which were large single pieces of charcoal. Treatment by the radiocarbon laboratory appears to have been minimal and carbonaceous clay covering the samples could easily have contaminated the result, producing an unusually old date. Contamination may also have occurred through confusion between the small samples of charcoal gathered between 32-48cm and small fragments of *Ruppia* seed. Large particles can be easily distinguished under a binocular microscope, but the presence of *Ruppia* pollen at the same level may indicate that particles of broken seeds were also present and mistaken for charcoal. Both charcoal and *Ruppia* seeds appear matt-black but can easily be distinguished by their shape and cell structure, so long as the particle is of sufficient size for this to be seen under the microscope. Examination at higher magnifications may clearly be important if a sample is too small to be positively identified immediately.

The time/depth curve is plotted without reference to these two anomalous dates and shows a good linear relationship. The 'charcoal' dated between 32-48cm shows a deviation of 900 years from the line, while the Chenopodiaceae plant remains at 164-166cm show a smaller deviation of around 400 years. For the purposes of core analysis and description, both there dates have been ignored.

9.5.4 *Results*

The results are presented as follows:

Zone PEQ-1 (400-304cm)

Lake Environment: Seasonal or Ephemeral Playa Lake (lake type 3-2)

Macrofossils: Charophytes
Pollen: Ruppia, Potamogeton, Cyperaceae
Geochemistry: Low sulphate
Stratigraphy: Non-calcareous (pelletized) clay. Grey clays changing upwards into light blue clays then dark blue clays.
Gypsum: Yellow, lenticular

Lenticular gypsum and *Ruppia* pollen indicate development of a seasonal playa lake (type 3), although a lack of macrofossil evidence and low pollen concentration suggest oxidising conditions more associated with a drier, ephemeral lake (lake type 2). This is also partly supported by high Chenopodiaceae pollen values (up to 40%TP), but not by Chenopodiaceae seeds, which do not occur. Humic acids from this well developed terrestrial plant community may have caused the yellowing of gypsum crystals (see Chapters 6 and 7). The lake during zone PEQ-1 was therefore transitional between ephemeral and seasonal lake types (type 2.5).

The zone is particularly unusual in having low levels of sulphate (*ca.*5%dw) while supporting a well developed aquatic community of *Ruppia, Potamogeton* and Cyperaceae. This combination is similar to that of the Salada Rebollon (Site Ref.No.6) which was studied as part of the modern surface sample data set (*Figure 7.1A & B*). The Salada Rebollon has a well developed surficial catchment (*Figure 9.1.4*) but lies close to the edge of the Los Monegros plain, where groundwater levels are lower (García, 1992). The lake is seasonal (lake type 3) but unlike many other lakes in the area, it has a well developed drainage basin that provides inflows of low salinity meteoric water from runoff.

The Salada Pequeña is currently a seasonal playa lake (type 3) (zone PEQ-6) with high levels of sulphate (*ca.*20%dw), and low levels of pollen from low salinity tolerant macrophytes such as *Potamogeton* and *Cyperaceae*. The lake is clearly different from that which existed in zone PEQ-1, although both were seasonal in nature. The lake today is supported by high inflows of high salinity groundwater which help raise sulphate levels in the sediments and the salinity of the lake water. Meteoric inflows from run-off are restricted by the low gradient of the basin catchment and its small overall size. The latter is three times less than that of the Salada Rebellon, which also has a much steeper and more defined surficial catchment.

The hydrological environment of the Salada Pequeña during zone PEQ-1 was therefore supported by greater levels of run-off water and lower levels of groundwater input. Since catchment size or angle are unlikely to have varied over this time period, this was probably related to changes in the distribution of precipitation such that run-off was increased (high storm frequency?), while groundwater recharge was reduced (low winter rainfall?).

Terrestrial Environment: Pine Woodland & Grass Steppe

Pollen: Pinus, Compositae, Gramineae
Charcoal: Low
Geochemistry: High potassium

The terrestrial pollen indicates an open, degraded, *Pinus* forest community with grass steppe. Total arboreal pollen values are only slightly higher than in the present-day treeless landscape (60%TTP: Total Terrestrial Pollen) at around 55% TTP, although with wide variations (±>10TTP). Overall arboreal pollen values are similar to those at the Hoya del Castillo in the final stages of zone CAS-4, which covers a similar time period (see *figure 9.1.8*), although *Juniperus* and *Quercus ilex*-type (<4%TTP) are less well represented at the Salada Pequeña.

The non-arboreal component in zone PEQ-1 is distinguished, by both high amounts of Compositae, including *Bidens*-type & Liguliflorae, and low amounts of *Artemisia*. The lack of *Artemisia* (<5%TTP) is directly comparable with the Hoya del Castillo (zone CAS-4), and contrasts with the high levels of *Artemisia* in the following zones higher up the core.

Possible anthropogenic indicators are poorly represented, with only one grain of *Olea* pollen in the upper levels of the zone, and low levels (<3%TTP) of cereal/Esparto size Gramineae pollen (>40μm) in the smaller size range (40-50μm). Charcoal levels occur at their lowest levels within the core record, and although influenced by sediment accumulation rate, do not appear to indicate intensive firing of the vegetation.

Potassium levels peak within the zone, possibly linked to the inwash of Illite-rich clays (Bengtsson & Enell, 1986). Catchment erosion is also suggested by high trace metal and carbonate values, while flocculated non-calcareous clays suggest capillary rise. Stevenson *et al.* (1992) and Macklin *et al.* (1994) report elevated magnetic susceptibility values and low frequency dependent values at this level, indicative of subsoil and bedrock erosion. The evidence for intense catchment disturbance is further supported by high percentages of Compositae pollen.

Zone PEQ-2 (304-240cm)

Lake Environment: Ephemeral Playa Lake (lake type 2)

Macrofossils: Charophytes
Pollen: Chenopodiaceae
Geochemistry: Low sulphate
Stratigraphy: Weathered lenticular gypsum with some prismatic crystals. Pelletized non-calcareous clay. Dark blue clay.
Gypsum: Yellow, lenticular

The lake becomes drier and more ephemeral in zone PEQ-2, with values of Chenopodiaceae pollen exceeding 45%TP, indicative of dry conditions permitting colonisation of the entire lake basin floor (type 2). Evidence of aquatic vegetation virtually disappears, except for very low *Ruppia* pollen values (<1%TP) and Charophyte oospores (<20 per 100g dw). Low sulphate levels indicate continued low inputs of groundwater, which may have dropped further to below the capillary zone (lake type 1), preventing the flocculation of non-calcareous clay. Short periods of standing water also may be indicated by occasional prismatic gypsum.

Terrestrial Environment: *Pinus* & *Quercus ilex*-type with *Artemisia* Steppe

Pollen: Pinus, Quercus, Artemisia, Compositae
Charcoal: High
Geochemistry: High potassium

Quercus sp. peak at the start of the zone, rising to over 10%TTP, but disappear later as *Pinus* dominates again. Total arboreal pollen values remain similar to the previous zone (*ca.*55%TTP), while the non-arboreal component sees a sharp increase in *Artemisia* from less than 5%TTP to over 20%TTP. Rising charcoal values may indicate greater anthropogenic disturbance, although *Olea* and large cereal/Esparto Gramineae (>40μm) pollen disappear.

Catchment erosion continues from the previous zone, with high levels of Compositae and peaks in potassium and trace metals. Stevenson *et al.* (1992) and Macklin *et al.* (1994) also note continued high magnetic susceptibility values during this period.

Zone PEQ-3 (240-155cm)

Lake Environment: Fluctuating Permanent (Unstratified) Mineralised/Saline Lake (lake types 6, 5 & 3)

Macrofossils: Ruppia maritima var maritima, Potamogeton pectinatus

Pollen: Ruppia, Potamogeton,

Geochemistry: High sulphate

Stratigraphy: Dark blue lacustrine clays with laminations

Gypsum: Prismatic

Rising lake levels at the start of zone PEQ-3 are marked by high levels of Charophytes (up to 700 per 100g dw), indicative of a shallow, semi-permanent lake (lake type 4). Deeper, less saline conditions then evolve with the appearance of seeds of *Potamogeton pectinatus* (lake type 6). The continued presence of lenticular gypsum in this early part of the zone, as well as seeds of *Ruppia drepanensis*, suggests wide fluctuations in lake level, with high water alternating with periods of desiccation (lake type 3). High sulphate levels indicate that high lake levels were now being sustained by an increased contribution from groundwater. Peaks in sulphate early on in the zone may have been the result of frequent fill-dry cycles causing the continued precipitation of mineral salts. Rapid changes in lake level would also have caused the periodic death of macrophytes, sustaining large communities of Cladocera, along with benthic invertebrates such as *Chironomus* larvae.

The peak in *P.pectinatus* seeds at 292cm may also indicate a peak in (low salinity) lake levels (lake type 6). This coincides with the disappearance of *Ruppia* seeds, decline in sulphate (<10%dw), and a peak in carbonate to over 20%dw. Formation of an organic algal mat is suggested by a peak in the flocculated clay content, while waterlogging of catchment soils may have led to a peak in the Fe/Mn ratio (Engstrom & Wright, 1984).

Potamogeton pectinatus is later replaced by *Ruppia maritima var maritima* (lake type 5) in the upper part of the zone as continued evaporitic concentration and mineral salt build-up increases the salinity of the lake water. This is shown by decline in the Ca:Mg ratio, reflecting a change from low magnesium calcite (low salinity) to high magnesium calcite (high salinity) deposition. A similar change in ratio can be seen in the more recent sediments of the Laguna Salada (LAG-4, section 9.5.3) where a similar increase and stabilisation in lake level occurred. Fluctuations in lake level also become less frequent at the Salada Pequeña at this stage as prismatic gypsum replaces lenticular gypsum. A radiocarbon date provided by a piece of charcoal indicates that the lake change from a mineralised lake, to a saline lake, at around 2230±50BP.

Declining lake levels towards the end of the zone are marked by the replacement of *Ruppia maritima var maritima* by the annual, *Ruppia drepanensis*, more typical of seasonal playa lakes (lake type 3). *Ruppia* pollen values also rise suggesting greater sexual reproduction and environmental stress (Chapter 2).

Terrestrial Environment: Quercus ilex-type & Pinus Woodland with *Artemisia* & Grass Steppe

Pollen: *Quercus ilex*-type, *Pinus*, *Artemisia*, Gramineae (>40µm), (*Olea*, *Juglans*)
Charcoal: High
Geochemistry: Low potassium and trace metals

The zone is characterised by a large increase in *Quercus ilex*-type pollen, which rises to over 10%TTP. Deciduous taxa ('sub-mediterranean') also become more established, although *Pinus* continues to form the major part of the arboreal component.

A single grain of *Juglans* pollen is recorded for the first time in the Ebro Basin at the onset of the zone, dated to 2675±60. Other possible anthropogenic indicators also appear within the zone including *Olea* and large Gramineae (>40µm) indicative of cereals or Esparto steppe.

High levels of anthropogenic activity is also suggested by peaks in the charcoal curve. Catchment disturbance however appears to have been stabilised, with low potassium and trace metal values. Compositae are also replaced by *Artemisia*, which rises to over 20%TTP.

Zone PEQ-4 (155-120cm)

Lake Environment: Seasonal/Ephemeral Playa Lake (lake type 3-2)

Macrofossils: *Ruppia drepanensis*
Pollen: Chenopodiaceae, *Ruppia*
Geochemistry: High sulphate
Stratigraphy: Blue/grey clays changing to red clays
Gypsum: Lenticular

Lake levels fall rapidly at the end of zone PEQ-3, and the onset of zone PEQ-4. Lenticular gypsum and *Ruppia* seeds (*R.drepanensis*) and pollen indicate the restoration of seasonal lake conditions (lake type 3). High sulphate levels (*ca.*15%dw) however indicate that the lakes hydrology now differs fundamentally from earlier seasonal lake conditions experienced in zone PEQ-1, when sulphate levels were much lower (*ca.*5%dw). Groundwater flows now sustain a much more saline lake, with lower levels of pollen from low salinity tolerant plants such as *Potamogeton* and Cyperaceae.

Terrestrial Environment: *Pinus* Woodland

Pollen: *Pinus*

Charcoal: Low

Geochemistry: Low potassium and other trace metals

Values of Pinus rise rapidly to over 85%TTP, indicating the establishment of a monospecific woodland similar to that found at the Hoya del Castillo in the mid-Holocene (CAS-4). The similar disappearance of deciduous taxa and fall in lake levels indicates that the woodland was probably an arid lowland Mediterranean *Pinus halepensis* forest.

Low charcoal values and the virtual disappearance of cultivation indicators, such as *Olea* and large Gramineae (>40μm), suggests a marked decline in agricultural production. Potassium and other trace metals remain low as erosion is checked by re-vegetation..

Zone PEQ-5 (120-16cm)

Lake Environment: Ephemeral/Seasonal Playa Lake (lake type 2-3)

Macrofossils: Charophytes

Pollen: Ruppia, Chenopodiaceae

Geochemistry: High sulphate

Stratigraphy: Red clays. Pelletized non-calcareous clay

Gypsum: Lenticular

Seasonal playa lake conditions (lake type 3) continue into zone PEQ-5, with *Ruppia* pollen and lenticular gypsum. High Chenopodiaceae values (30-40%TP) and yellow gypsum crystals (see zone PEQ-1) indicate a well developed terrestrial vegetation close to ephemeral lake conditions, resulting in a transitional classification (lake type 2.5). Peaks in the Chenopodiaceae curve (>40%TP) coincide with definite periods of ephemeral lake conditions (lake type 2).

Sulphate levels remain high (>10%dw), indicating sustained inputs of groundwater. This is also supported by high levels of non-calcareous (flocculated or pelletized) clays which suggest capillary rise and saline lake sediments. The greater salinity of the sediments is reflected in higher levels of flocculated clays than in earlier zones (PEQ-1, PEQ-2), when lake salinity was lower.

A drop in sulphate occurs at the end of the zone, similar to levels shown early on in the core (*ca.*5%dw) in zones PEQ-1, and PEQ-2. This coincides with the disappearance of *Ruppia* pollen and a major peak in Chenopodiaceae (>80%TP). This can be interpreted as a fall in groundwater levels and therefore lake level.

Terrestrial Environment: *Juniperus & Pinus* Woodland with *Artemisia* & Grass Steppe

Pollen: Juniperus, Pinus, Artemisia, Gramineae (<50μm)

Charcoal: High

Geochemistry: High potassium and trace metals

The onset of the zone is marked by a sharp decline in *Pinus* to levels (*ca.*20%TTP) markedly lower than those in zones PEQ-1-2-3 (*ca.*50%), prior to reafforestation, but similar to todays (PEQ-6). This reflects a decline in arboreal pollen from *ca.*55%TTP to *ca.*30%TTP and a marked increase in charcoal from the earlier zone (PEQ-4). Charcoal at 102-106cm, just after deforestation, was radiocarbon dated at 1225±50.

Unlike earlier deforestation episodes of lower intensity (PEQ-1-2-3; CAS-3 and end of zone CAS-4), *Juniperus* increases within the zone to higher levels (>10%TTP), than *Quercus ilex*-type.

Artemisia values do not increase to levels significantly greater than their pre-afforestation level (*ca.*20%), despite the large increase in openland. Gramineae however increase to over 40%TTP, with a large amount of smaller pollen size grasses (<50μm) similar to zone PEQ-1. Large (40-50μm) and very large (>50μm) Gramineae indicative of cereals or Esparto steppe, does not increase significantly until later in the zone, after 42cm, following a second episode of clearance and decline in *Juniperus.*

High values of Compositae (particularly Liguliflorae) suggest catchment disturbance, while increasing erosion is indicated by high potassium and trace metal values. Stevenson *et al.* (1992) and Macklin *et al.* (1994) note high magnetic susceptibility and frequency dependant values during this period, indicative of the loss of recently developed top soil.

Zone PEQ-6 (16-0cm)

Lake Environment: Seasonal Playa Lake (lake type 3)

Macrofossils: Charophytes, *Ruppia drepanensis*

Pollen: Ruppia, Potamogeton

Geochemistry: High sulphate

Stratigraphy: Red clays

Gypsum: Prismatic

Rising lake levels see the return of prismatic gypsum and aquatic macrofossils and the decline of Chenopodiaceae (<40%TP). *Ruppia drepanensis* seeds and relatively low levels of Charophyte oospores (*ca.*260 per 100g dw) suggest seasonal, high salinity, hypersaline playa conditions (lake type 3). Concentrations of sulphate increase from the previous zone reflecting higher inputs of groundwater.

Higher lake levels are found in the most recent sediments of all of the sediment cores investigated in the Ebro Basin.

Terrestrial Environment: *Olive* Plantations with *Artemisia* & Grass Steppe

Pollen: *Olea*
Charcoal: Low
Geochemistry: High sodium

The final zone is marked by a dramatic rise in *Olea* pollen (>30%TTP) with the onset of Late Medieval olive cultivation. Quercus ilex-type also recovers to levels (*ca.*7%TTP) not seen since zone PEQ-3.

Stability appears to return to the catchment, with the disappearance of Compositae and an increase in large Gramineae (>40μm) indicative of cereals or Esparto steppe. *Artemisia* also declines to close to their pre-charcoal rise (PEQ-1) level (*ca.*10%).

High sodium values from surficial sodium chloride salt deposits effectively dilute the geochemical (cation & trace metal) record making down-core comparison difficult.

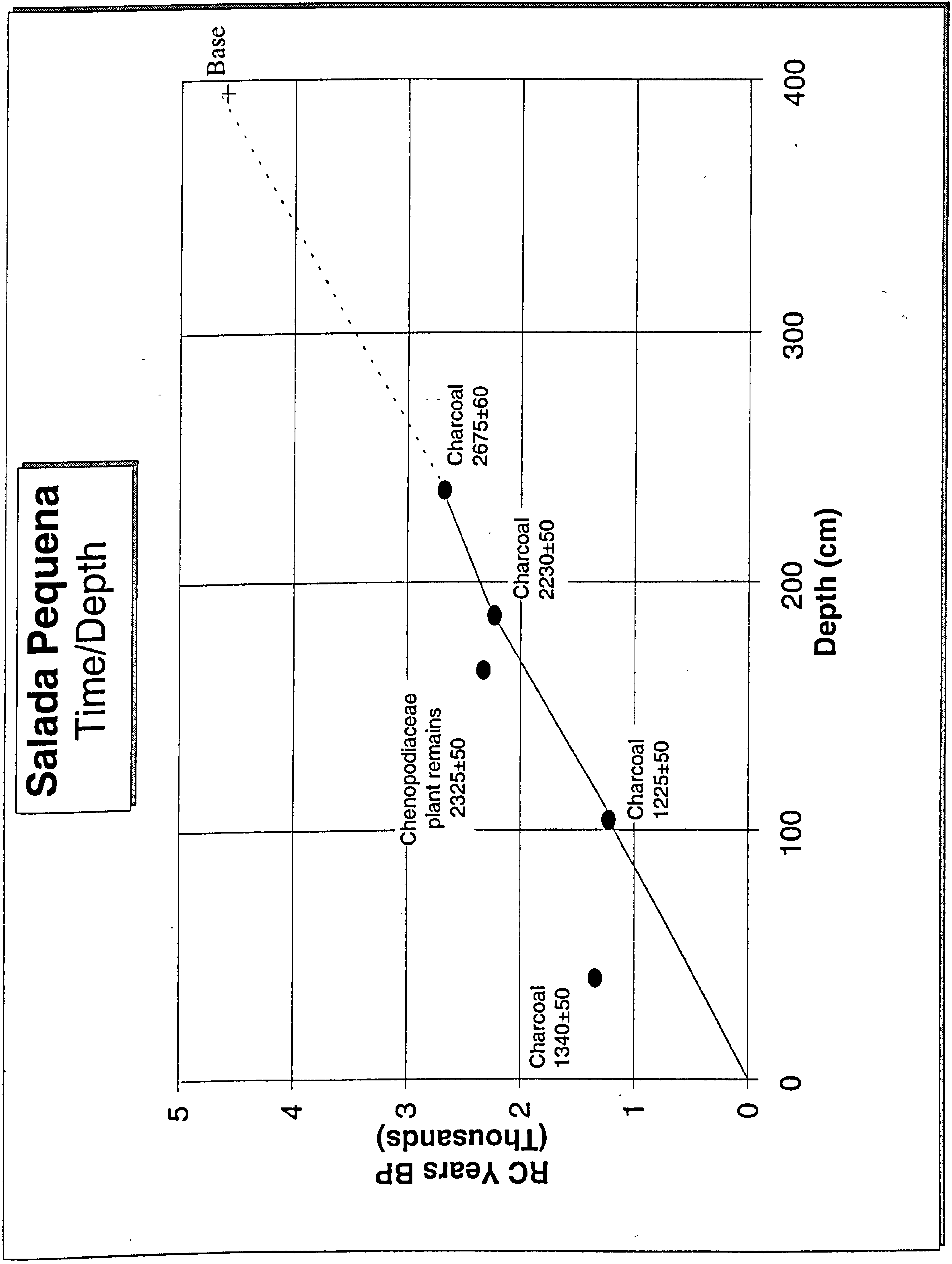


Figure 9.5.1 **Salada Pequeña: radiocarbon time/depth curve**

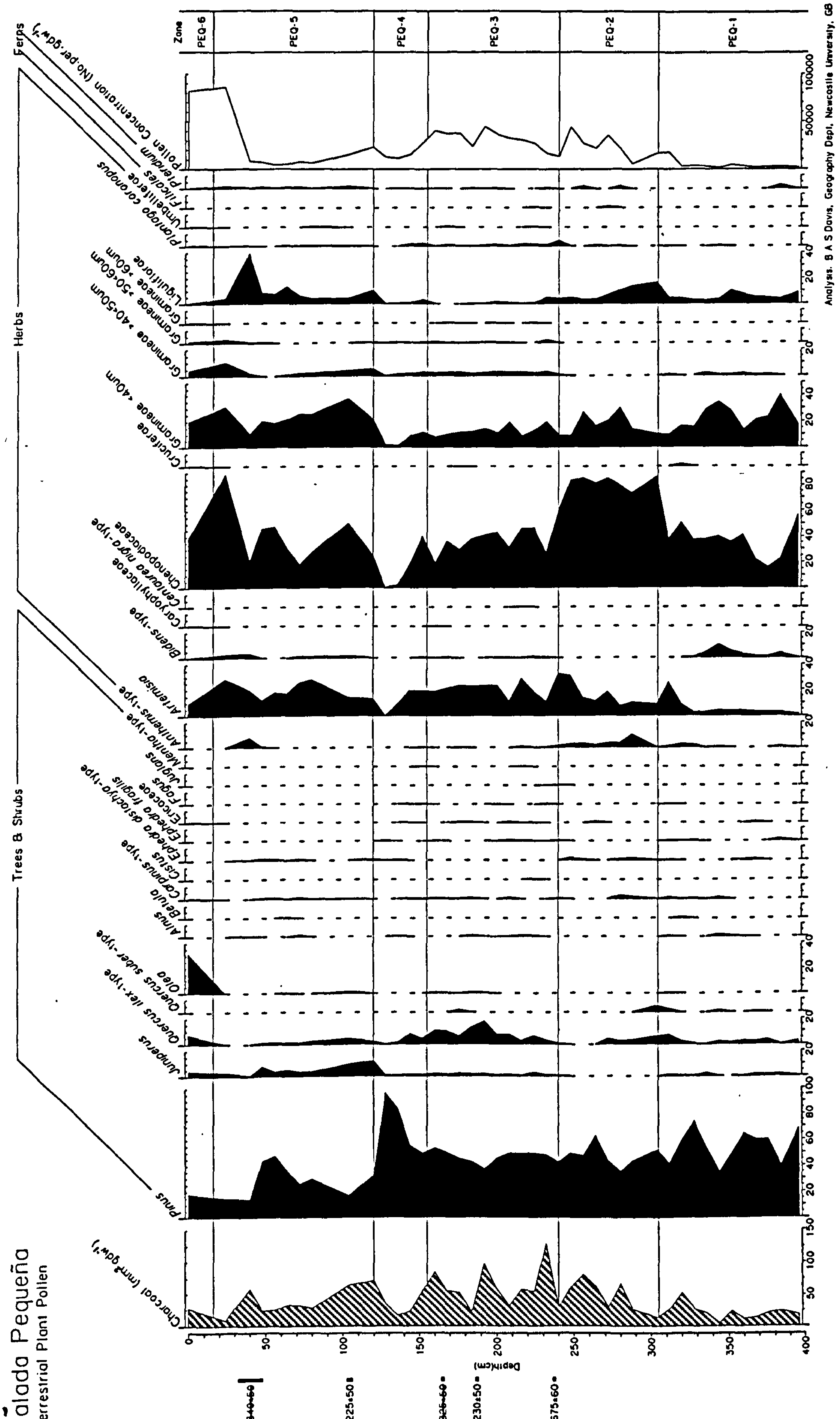
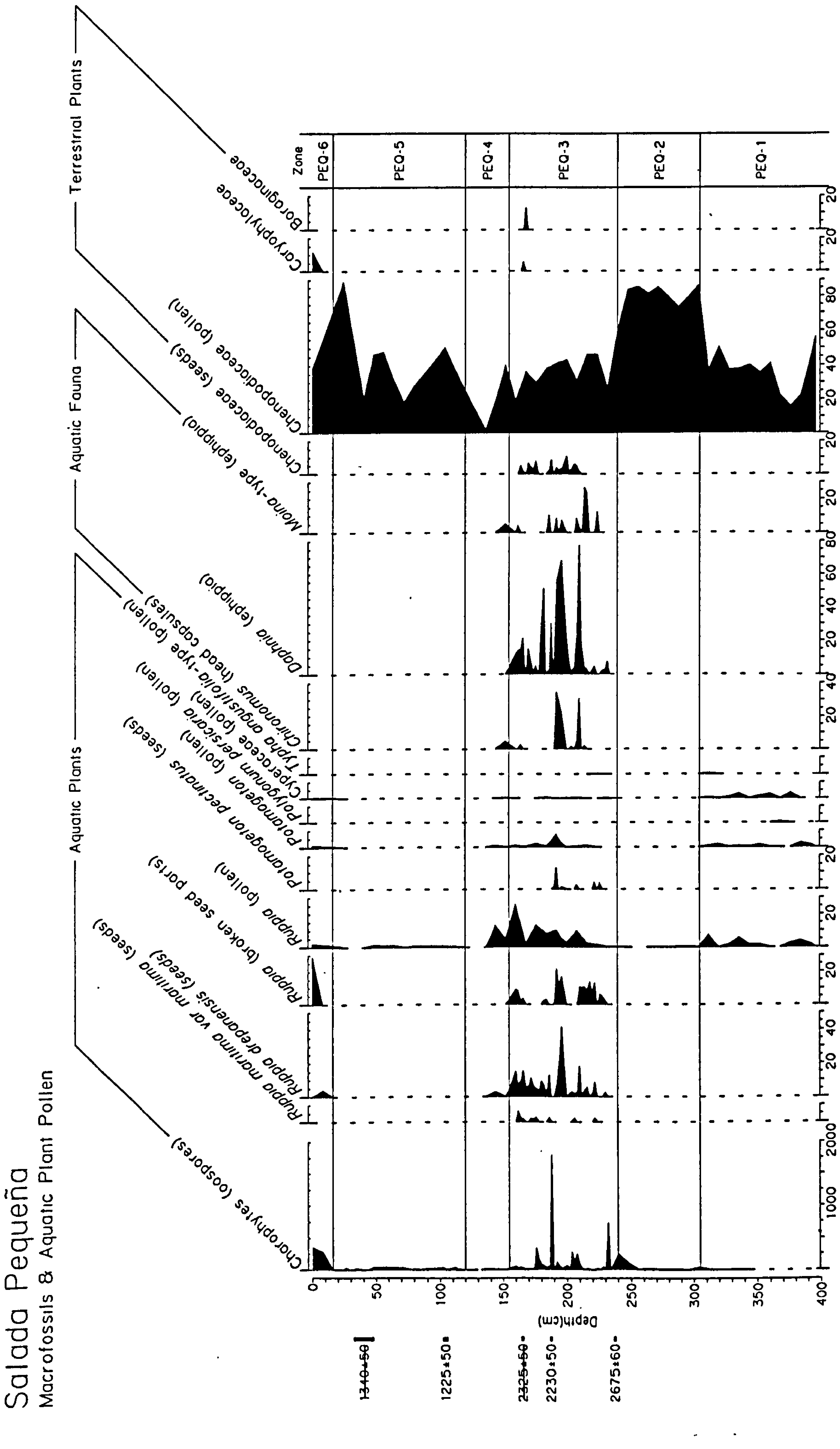


Figure 9.5.2 **Salada Pequeña: terrestrial plant pollen and charcoal**



Analysis: B A.S.Davis, Geography Dept, Newcastle University, GB

Figure 9.5.3 **Salada Pequeña: macrofossils and aquatic plant pollen**

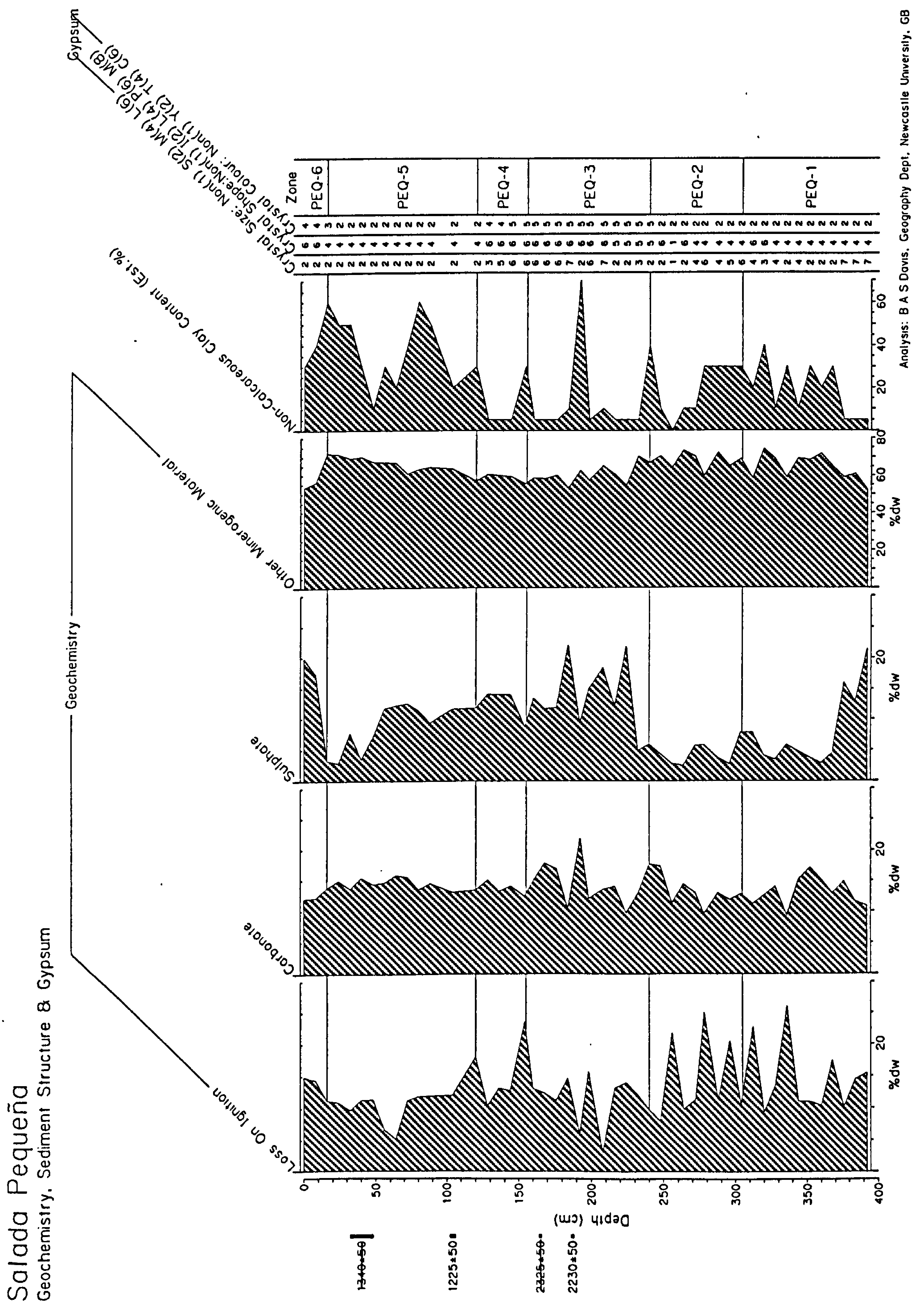


Figure 9.5.4 **Salada Pequeña: geochemistry, sediment composition and gypsum**

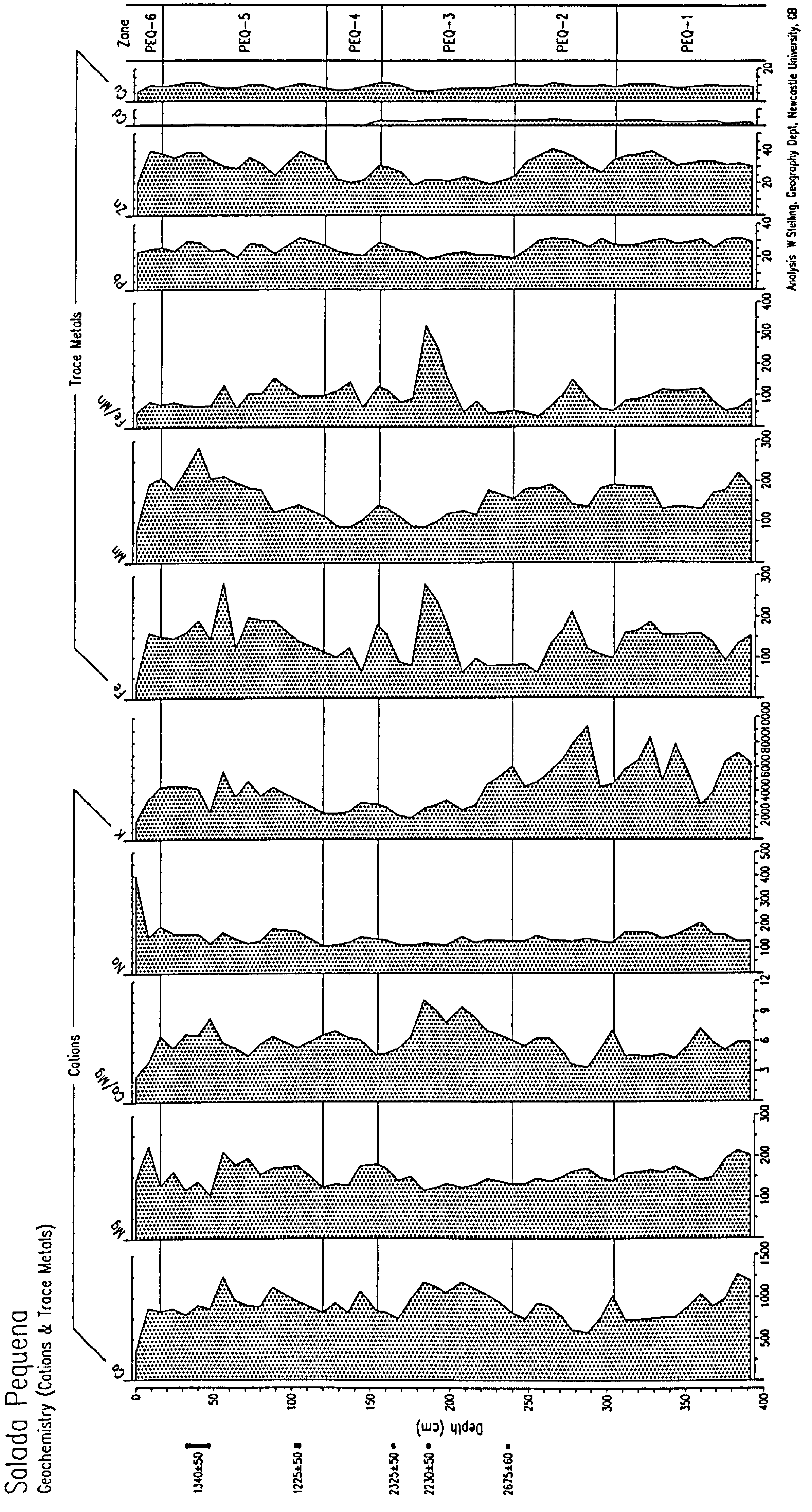


Figure 9.5.5 **Salada Pequeña: geochemistry (cations & trace metals)**

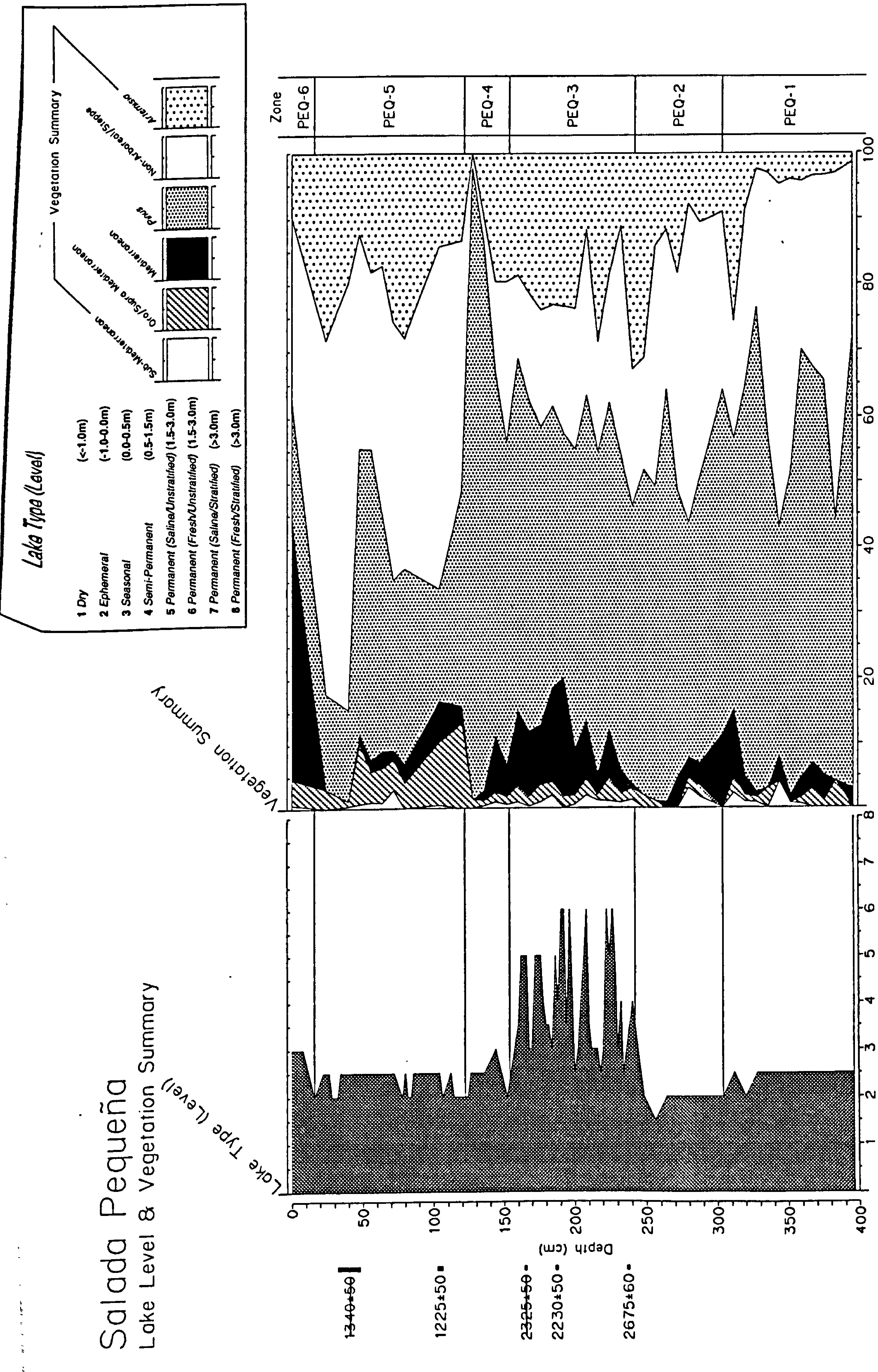


Figure 9.5.6 **Salada Pequeña: lake type (level) and vegetation summary**

9.6 Laguna Salada

9.6.1 *Site Description*

The Laguna Salada ('Salada de Chiprana') is located 10km west of Caspe at an altitude of 150m, some 29m higher than the Rio Ebro, damned in 1967 to form the Mequinenza Reservoir 2km away (*Figure 9.1.6* p154).

The laguna is the lowest in the Ebro Basin and is unique in Spain as the only natural permanent inland salt lake. Its low altitude with respect to the regional groundwater table undoubtedly explains how the lake maintains sufficient groundwater flow to sustain a depth of over 5m in an area receiving less than 300mm precipitation per year. The groundwaters entering the lake flow through Tertiary evaporites rich in gypsum (Guerro *et al*, 1989), forming lake waters unusually rich in magnesium sulphate. Sodium chloride would appear to be less significant than in other saline waters due to the lack of repeated evaporitic cycles favouring the soluble elements, and perhaps, in addition, the relative youth of the lake involved (Chapter 10). Currently, a supply of fresh water periodically enters the laguna from La Salabrosa, a small (2.8Ha) hunting laguna 100m away, artificially freshened by irrigation water (Guerrero *et al*, 1989, Balsa *et al*, 1991). Water chemistry for the Laguna Salada is shown in *table 9.1* p157.

Vegetation

Within the lake itself, *Ruppia maritima* var *maritima* and *Lamprothamnium papulosum* cover large areas of the lake shallows, down to around 3m (Guerrero *et al*, 1989). Shoreline vegetation is poorly developed, although emergents dominate neighbouring fresher water pools such as La Salobrosa, while temporary more saline pools contain *Ruppia drepanensis*. Marginal emergents consist mainly of scattered beds of *Phragmites australis*, with *Typha angustifolia* also present where overflow waters from La Salobrosa enter. The connecting ditch carrying these waters was found to be choked with *Typha dominguensis* and *Scirpus maritimus*. Vegetation immediately above the shore consists mainly of halophytes where salinity and risk of inundation is high. Chenopodiaceae dominate the lower beach, including *Salicornia ramosissimae, Suaeda maritima* and *S.vera*, while on the upper beach, *Scirpus maritimus, Spergularia, Limonium* and *Juncus sp.* can be found. *Tamarix* can also be found scattered around the lake shore, where, to the north it forms an unusual small wood of *T.canariensis* and *T.boreana* (Balsa *et al*, 1991).

The vegetation surrounding the lake is predominantly dry farmed cereals, with an increasing amount apparently coming under irrigation. Natural vegetation is restricted to rocky hilltops and slopes which lie close to the lake to the south and west. Here, small *Juniperus phoenicia* are interspersed by the occasional *Pinus halepensis*, together with *Asparagus acutifolius, Thymus sp., Cistus* and *Stipa.*

9.6.2 *Analysis & Methods*

Coring was undertaken in July 1990 from a raft moored in 4.5m of water. Sediment was recovered to a depth of 206cm. The first metre was retrieved using a Fat Livingstone corer, with the second metre and 6cm retrieved using a standard Thin Livingstone.

The core was subsampled in the laboratory at 4cm intervals for analysis of pollen, geochemistry (loss on ignition; carbonate; sulphate; lead; zinc; cadmium; copper; manganese; iron; calcium; sodium potassium and magnesium), charcoal, macrofossils and stratigraphy. In addition, macrofossil analysis was also performed on continuous 1cm slices between 48cm and 92cm from the Fat Livingstone core, and on continuous 3cm slices (with the occasional 1cm slice) between 100-140cm and 180-206cm from the Thin Livingstone cores.

9.6.3 *Dating Control*

Three AMS radiocarbon dates were obtained from a mixture of Chenopodiaceae plant remains and Caryophyllaceae seeds at 50-51cm (315±60) and 73-75cm (420±50), and charcoal from 191-194cm (5725±60). The time/depth relationship is plotted in *figure 9.6.1* p217. A hiatus in the lower part of the core is strongly suggested although its exact location is difficult to determine. Lithological evidence indicates two possible positions for a break in the sediment record, between zones LAG-1 and LAG-2, and between LAG-2 and LAG-3. The events across the junction between LAG-2 and LAG-3 however appear to be contiguous and connected. The more likely location is therefore between zones LAG-1 and LAG-2.

9.6.4 *Results*

The results are presented as follows:

Zone LAG-1 (206(Base)-192cm)

Lake Environment: Seasonal Playa (lake type 3)

Macrofossils: Ruppia drepanensis
Pollen: Cyperaceae, *Potamogeton, Ruppia*
Geochemistry: Low sulphate
Stratigraphy: Grey, lacustrine playa clays
Gypsum: Lenticular

Ruppia pollen and *Ruppia drepanensis* seeds, together with lenticular gypsum, indicate that the Laguna Salada was a seasonal playa lake at this time (lake type 3). Unusually low Chenopodiaceae pollen values (<5%TP: Total Pollen) suggest that the lake was quite large, and that the coring site was some distance from the surrounding marginal vegetation. This is similar to the situation currently found at the Salada Grande (Site Ref.No.30), which was the largest playa lake studied as part of the surface sample data set (*Figure 7.1A*). Here, Chenopodiaceae pollen values remained below 5%TP, despite a well developed marginal vegetation. Transport of Chenopodiaceae pollen to the centre of the Salada Grande is also restricted not only by distance, but also by low flooding frequency, and by the dense marginal vegetation restricting storm run-off across the lake.

Sulphate values (*ca.*14%dw) are high in comparison with other lakes studied, indicating characteristically large contributions of groundwater into the Laguna Salada. In comparison with some upper parts of the core however, sulphate levels are relatively low, reflecting the greater through-put of groundwater during periods of deeper lake water experienced later on.

Terrestrial Environment: *Pinus* & *Quercus ilex*-type Woodland

Pollen: Pinus, Quercus ilex-type
Charcoal: Low
Geochemistry: High carbonate, low trace metals

The landscape is well wooded in zone LAG-1, with arboreal pollen accounting for over 85%TTP (Total Terrestrial Pollen). The forest cover is dominated by *Pinus*, comprising over 70%TTP, but also with significant amounts of *Quercus ilex*-type (>10%TP). Other taxa present include *Juniperus* (5%TTP) and *Olea* (<2%TTP).

The low non-arboreal component consists mainly of Gramineae (*ca.*10%), including cereal/Esparto size pollen grains (>40μm), with some very large grains (>60μm). *Artemisia* values are particularly low (<5%TTP), especially when compared to levels further up the core (>20%TTP) following major deforestation (LAG-3-4).

High carbonate levels (*ca.*17%dw) may suggest some catchment erosion, although trace metal values remain low, along with disturbance indicators, such as Compositae and charcoal (<5mm²gdw).

Zone LAG-2 (192-130cm)

Lake Environment: Ephemeral/Seasonal Playa Lake (lake type 2-3)

Macrofossils: None
Pollen: Potamogeton
Geochemistry: High sulphate
Stratigraphy: Red clays
Gypsum: Lenticular

The lake becomes dryer and less saline in zone LAG-2, with evidence of aquatic macrophytes confined to low levels of *Potamogeton* pollen. Lenticular gypsum continues to indicate seasonal lake conditions (lake type 3), although the crystals become more irregular and yellow, suggesting the influence of weathering and humic acids from terrestrial vegetation (lake type 2). Chenopodiaceae pollen values remain unusually low however (<2%TP), with insufficient time during summer desiccation to invade the lake basin. Dry, oxidising lake conditions are also indicated by low pollen concentrations (although preservation was generally good), and red clays. The lake is classified therefore as transitional (type 2.5).

Terrestrial Environment: *Pinus* Woodland

Pollen: Pinus
Charcoal: High
Geochemistry: Low carbonate & trace metals

Pinus becomes almost completely dominant within the zone, reaching values of over 90%TTP. This is similar to the development of monospecific pine forests at the Hoya del Castillo (CAS-4) and Salada Pequeña (PEQ-4). Deciduous taxa almost completely disappear within the zone, indicative of a lowland Mediterranean *Pinus halepensis* forest (Chapter 8).

Charcoal values remain low for much of the zone, but peak sharply towards the end of the zone, where *Pinus* declines to less than 30%TTP. This reflects a 45%TTP reduction in arboreal taxa connected with deforestation.

Zone LAG-3 (130-45cm)

Lake Environment: Seasonal/Semi-Permanent Salt Lake (lake type 3-4)

Macrofossils: Ruppia drepanensis, Althenia
Pollen: Ruppia, Potamogeton
Geochemistry: Low Ca/Mg ratio
Stratigraphy: Grey/blue lacustrine clay
Gypsum: Prismatic

Lake levels appear to fall at first with the onset of the zone as Chenopodiaceae pollen values rise rapidly to exceed 40%TP (lake type 2), reflecting ephemeral lake conditions and the invasion of the lake basin by annual terrestrial halophytes. The overall trend, however, is of rising lake levels represented by the appearance of aquatic macrofossils of *Ruppia drepanensis* and *Althenia* (lake type 3-4). The rise in Chenopodiaceae is particularly notable due to its absence lower down the core (LAG-1-2), which may have been due to its restricted dispersal (see zone LAG-1). Rising Chenopodiaceae pollen values may in fact reflect a relative change in pollen (and seed) dispersal, caused by both an increase in flood waters, and an increase in run-off from the recently deforested catchment. New areas of the basin may also have become colonised by Chenopodiaceae as rising groundwater increased soil salinity.

Surface sample investigations of the dispersal of characteristics of terrestrial plant seeds and pollen were only undertaken on a playa lake (Chapter 6). The pattern of dispersal in more permanent lakes was not examined, although Chenopodiaceae and Caryophyllaceae seeds are commonly associated with periods of permanent water in the palaeoenvironmental record (see zones CAS-3; PEQ-3; LAG-3-4; EST-1). The reason for this seems unlikely to relate to the actual presence of terrestrial plants at the coring site, since no other evidence for desiccation (*eg*. lenticular gypsum) occurs. The alternative hypothesis must therefore be that permanent lakes provide better environments for seed dispersal (and preservation?) than temporary lakes.

Lake levels continue to rise to permanent levels early on in the zone, marked by seeds of *Ruppia maritima var maritima* (120cm) (lake type 5). *Ruppia drepanensis* then increases as water levels becomes more seasonal (lake type 3). The presence of *Althenia*, which has an extended 5 month life-cycle (Chapter 2, section 2.3.2.3), together with the dominance of prismatic gypsum, probably indicate that this period of desiccation was less than 3 months in the year. The existence of *Althenia* in the lake also suggests that the lake waters were turbid and particularly rich in chlorides (Alonso & Comelles, 1981). Evidence of high lake turbidity is supported by the lack of bottom dwelling Charophytes in the zone, despite their proliferation in the following high-water zone (LAG-4).

The Ca/Mg ratio indicates an initial period of low salinity, low magnesium calcite deposition as lake levels rise initially, followed quickly by saline, high magnesium calcite conditions as evaporitic concentration occurs.

Deforestation probably changed the hydrological balance of the lake, causing an initial rise in lake level at the beginning of the zone. Lake levels then continued to fluctuate, along with climate, throughout the zone, with declining sulphate levels, *Ruppia* pollen, and aquatic macrophytes seeds, suggesting lower lake levels towards the end of the zone. Chenopodiaceae pollen over 40%TP and stem parts of Chenopodiaceae indicate that lake levels became close to ephemeral (lake type 2) at times. Radiocarbon dating of Caryophyllaceae seeds and Chenopodiaceae plant parts permitted the dating of these low lake level periods at 50-51cm (315±60) and 73-75cm (420±50).

Terrestrial Environment: Degraded *Pinus* Matorral with *Juniperus* and *Artemisia* & Cereals/Esparto Steppe

Pollen: *Pinus, Juniperus, Artemisia,* Gramineae (>50µm)
Charcoal: Low
Geochemistry: High potassium and trace metals

The start of the zone shows a clear vegetation succession following the destruction of the original climax *Pinus* (*Pinus halepensis*?) forest by fire at the end of the previous zone. Gramineae (<40µm) responds first, increasing from 10% to 40%TTP at 130cm. This then declines as *Quercus ilex*-type (5% to 20%TTP) and Chenopodiaceae (4% to 56%TTP) peak at 126cm. Both these then decline as *Artemisia* (5% to >15%TTP) becomes established after 122cm.

The destruction of the climax pine (*Pinus halepensis*?) forest leads to the development of a typical sub-climax sclerophyllous scrub community with *Juniperus* sp, *Quercus coccifera, Phillyrea angustifolia* and Ericaceae sp, together with a variety of herbaceous matorral plants including *Rosmarinus officianalis* (*Mentha*-type), *Artemisia* and Esparto(Cereal?) grasses. Levels of *Juniperus* are high (>10%TTP) and compare with the late Holocene post-deforestation vegetation at the Salada Pequeña (PEQ-5).

The opening of the forest canopy also sees the appearance of taxa associated with cultivation such as *Olea* and *Juglans*, as well as cereal(Esparto) size Gramineae (>40µm) and *Rumex*.

More general disturbance indicators also appear, including members of the *Plantago* and Compositae families. Carbonate values are not available for most of the zone, but peaks in potassium and trace metals suggest increased erosion following clearance. High Fe/Mn ratios may also indicate catchment waterlogging (Engstrom & Wright, 1984) in the earliest part of the zone.

Zone LAG-4 (45-0cm)

Lake Environment: Permanent Saline Lake (lake type 5-7)

Macrofossils: Ruppia maritima, Lamprothamnium papulosum
Pollen: Ruppia
Geochemistry: High-low Ca/Mg ratio, high sulphate
Stratigraphy: Laminated organic mat and lacustrine clays
Gypsum: Massive & prismatic

Another large increase in groundwater level is indicated by a major increase in aquatic macrophytes at the beginning of the zone. *Ruppia maritima var maritima* re-appears, indicating permanent water (lake type 5), while deep water is suggested by a change from grey playa clays to laminated organic clays.

The rise in water level is clearly shown by a macrophyte succession from the annual, *Ruppia drepanensis* to the perennial *Ruppia maritima var maritima.* As water depth increases further, *R.maritima* is replaced by bottom dwelling Charophytes, which appear for the first time in the core. These then briefly give way to canopy forming (but low salinity tolerant) *Potamogeton pectinatus* (see Chapter 2, section 2.3.3) (lake type 6) at around 37cm as lake levels rise faster than evaporitic concentration, resulting in a period of deep, fresh water. This is shown in the ratio of Ca/Mg which rises and peaks at the same level, as low salinity, low magnesium calcite deposition dominates

After 37cm, the Ca/Mg ratio declines rapidly as high magnesium calcite replaces low magnesium calcite as evaporitic concentration causes rising lake salinity as lake levels stabilise. This is also reflected in a sharp rise in sulphate levels and stratigraphic change from organic clays to laminated algal mat and massive gypsum-type crystal structures.

The lake has now evolved into its present deep water hypersaline state at this stage in the zone. The increase in salinity of the lake waters is further emphasised by a change in Cladocera from low salinity tolerant *Daphnia* to high salinity tolerant *Moina mongolonica*, and by the virtual disappearance of *Potamogeton.*

Two further periods of low lake level (lake type 5) interrupt the establishment of the current deep, stratified saline lake (lake type 7). Both are associated with peaks in the carbonate curve and troughs in the sulphate curve at around 24 and 10cm. A change from massive to prismatic gypsum is accompanied by high levels of *Ruppia drepanensis* and low levels of *Ruppia maritima var maritima.* Rapid changes in lake level would favour the annual, *R.drepanensis*, as well as causing macrophyte deaths that would encourage phytophagous *Chironomus* and *Moina mongolonica.*

The final 6cm of the most recent sediments contain few macrophyte remains and virtually no carbonate (lake type 7). Some crystals of prismatic gypsum occur, although a decline in calcium probably reflects a change in the chemical evolution of the lake waters towards magnesium and sodium sulphate precipitation. Increasing domination of the sediment process by chemical (mainly sulphate) precipitation is offset by rising LOI values, reflecting the accumulation of organic matter within the deoxygenated chemocline.

Terrestrial Environment: *Olive* Plantations with *Artemisia* & Grass Steppe

Pollen: Olea
Charcoal: High
Geochemistry: Low trace metals

The Late Medieval expansion in olive cultivation is clearly shown in this final zone. *Olea* values increase particularly steeply after the charcoal peak at 40cm, and eventually rise to over 30%TTP (24-8cm) before declining in the last 8cm as *Pinus* increases. Overall arboreal pollen values increase in the final part of the zone from around 60%TTP, to 70%TTP.

Most of this expansion of *Olea* appears to have been at the expense of the pine and scrub component including *Juniperus* and *Phillyrea*, while many of the herbaceous elements remain. *Quercus ilex*-type appears to increase along with *Olea.*

Increasing agricultural intensification is further indicated by the stronger presence of *Plantago coronopus*, *Juglans* and *Rumex*, as well as the appearance of *Vitis*. The persistence of disturbance and openland indicators suggests continued heavy grazing and cultivation.

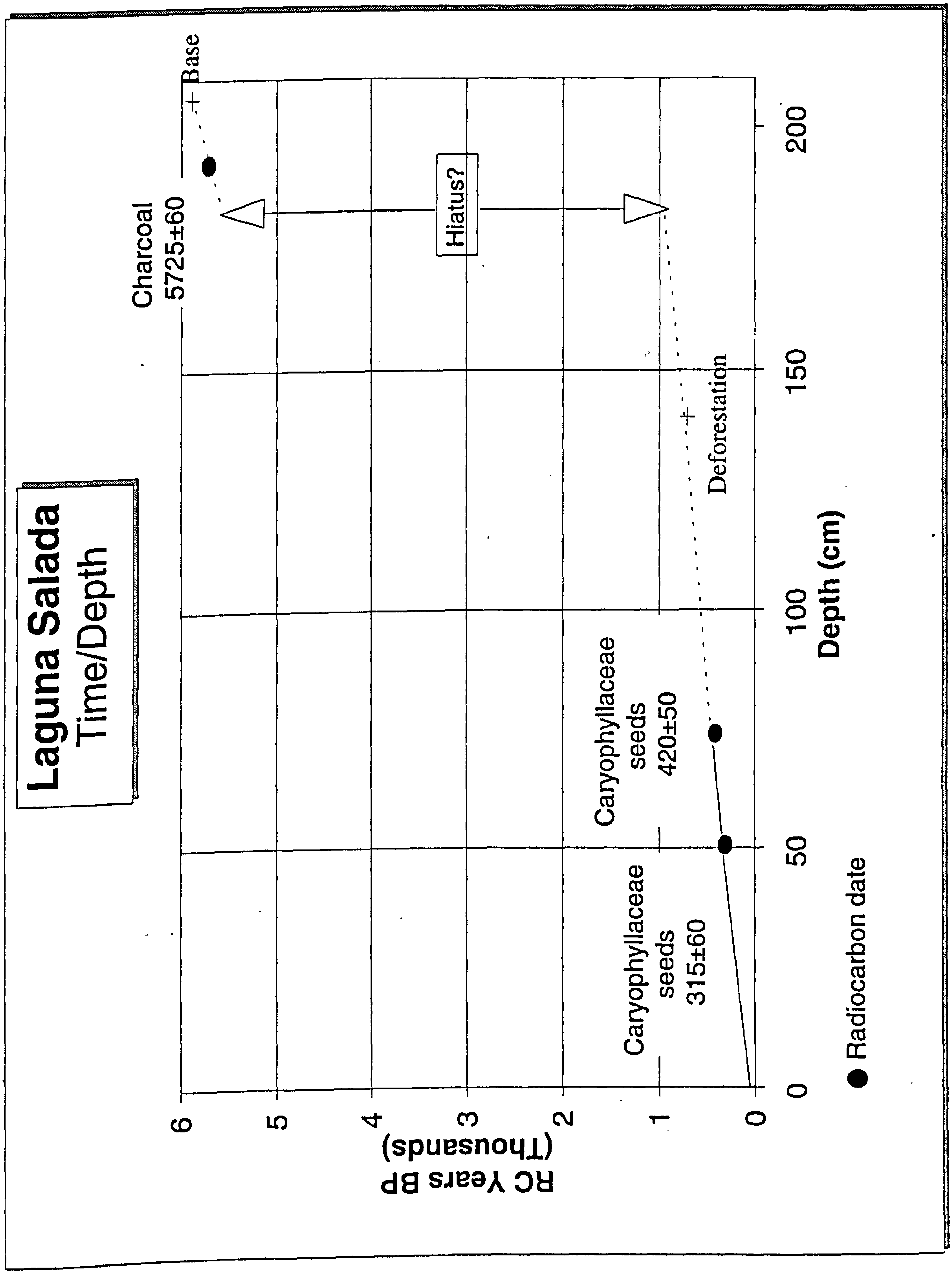


Figure 9.6.1 Laguna Salada: radiocarbon time/depth curve

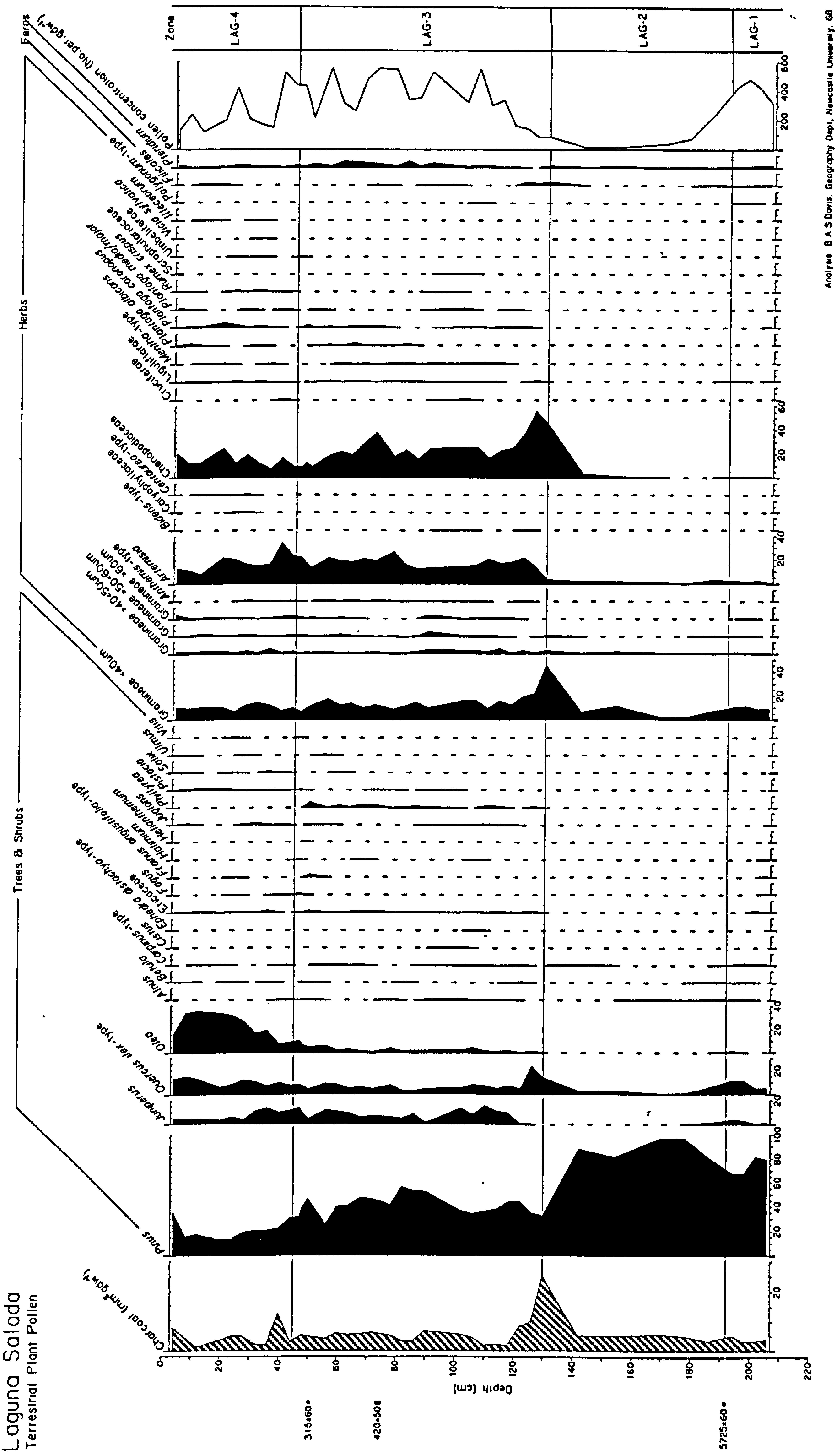


Figure 9.6.2 **Laguna Salada: terrestrial plant pollen and charcoal**

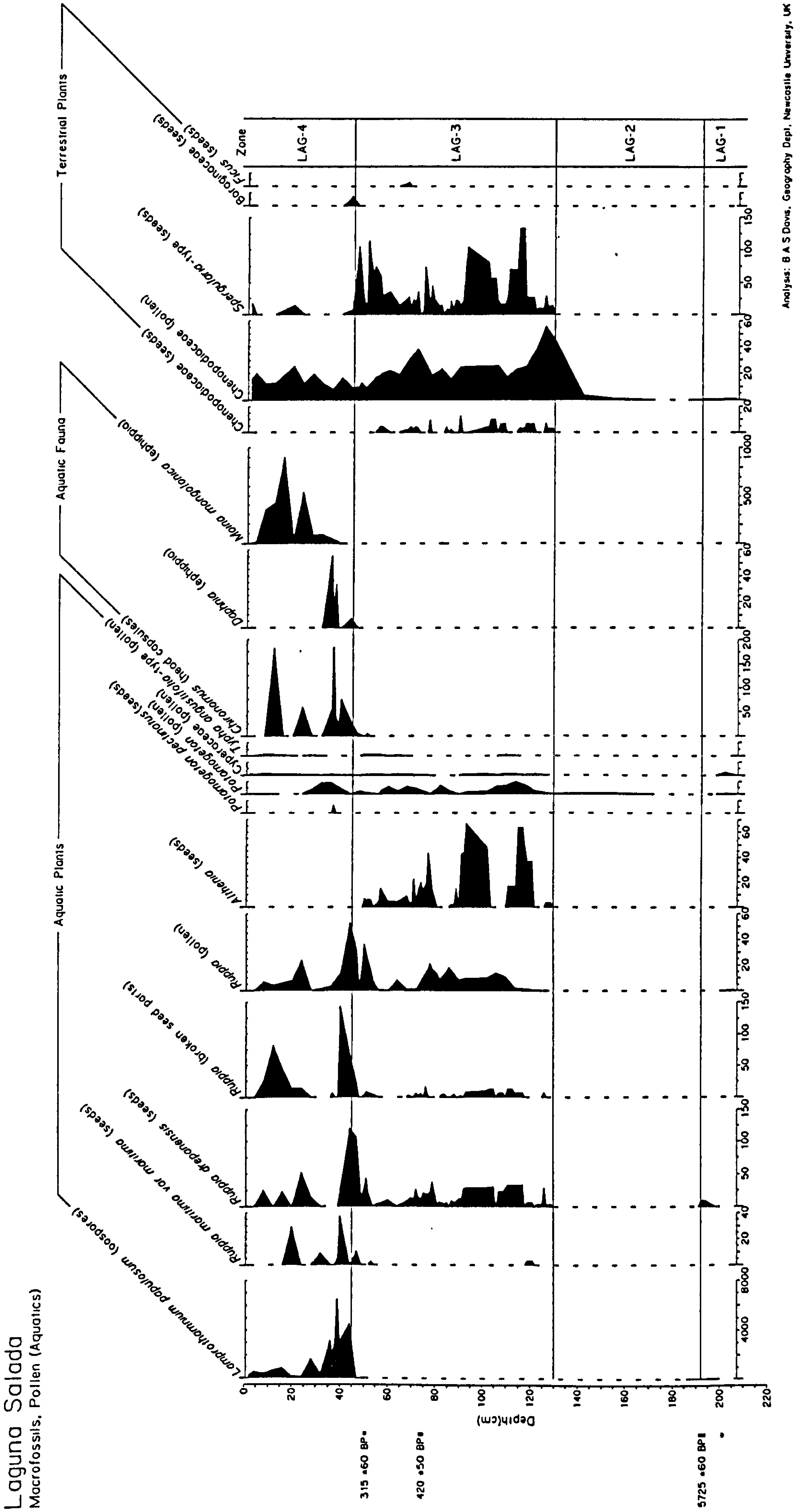


Figure 9.6.3 **Laguna Salada: macrofossils and aquatic plant pollen**

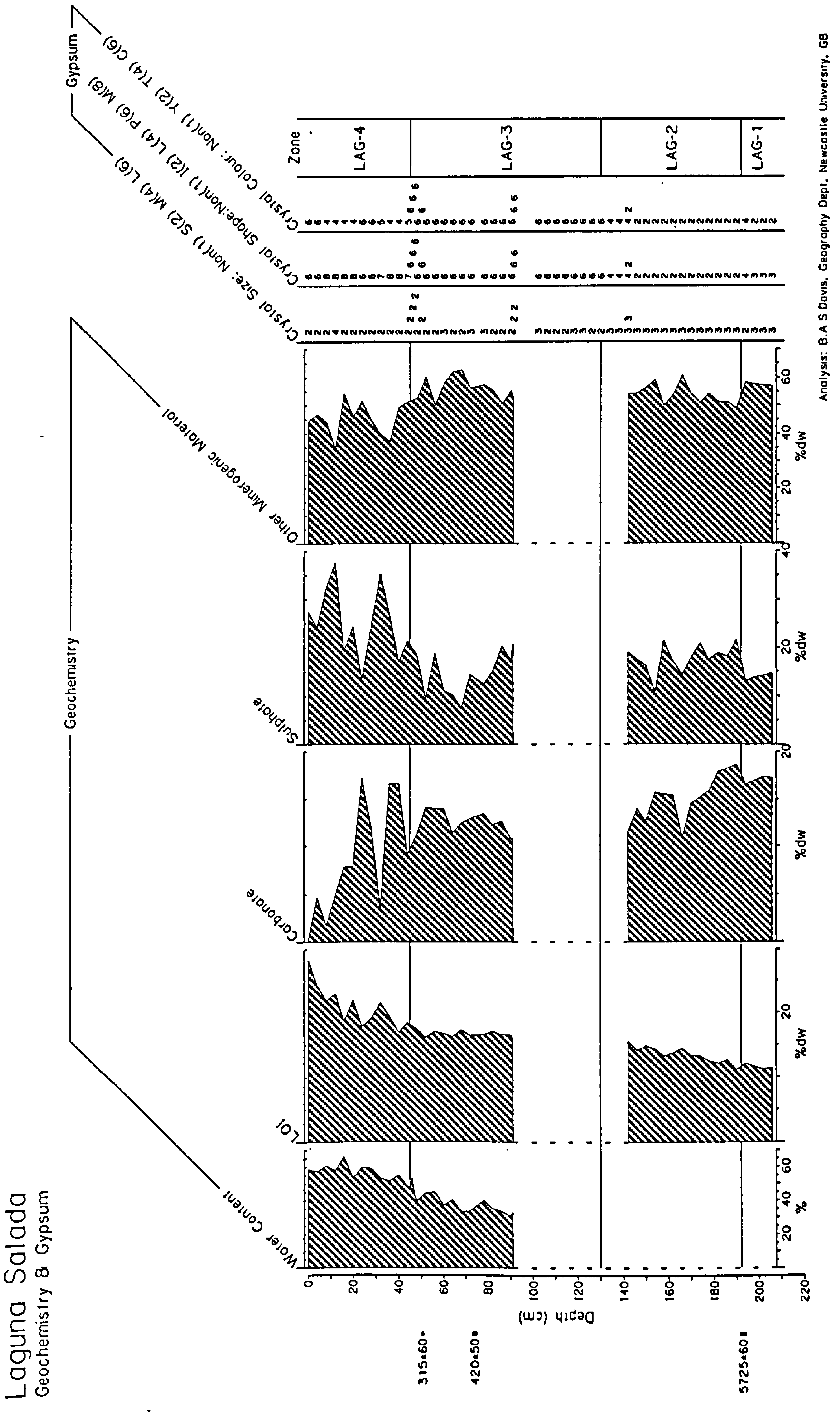


Figure 9.6.4 **Laguna Salada: geochemistry, sediment composition and gypsum**

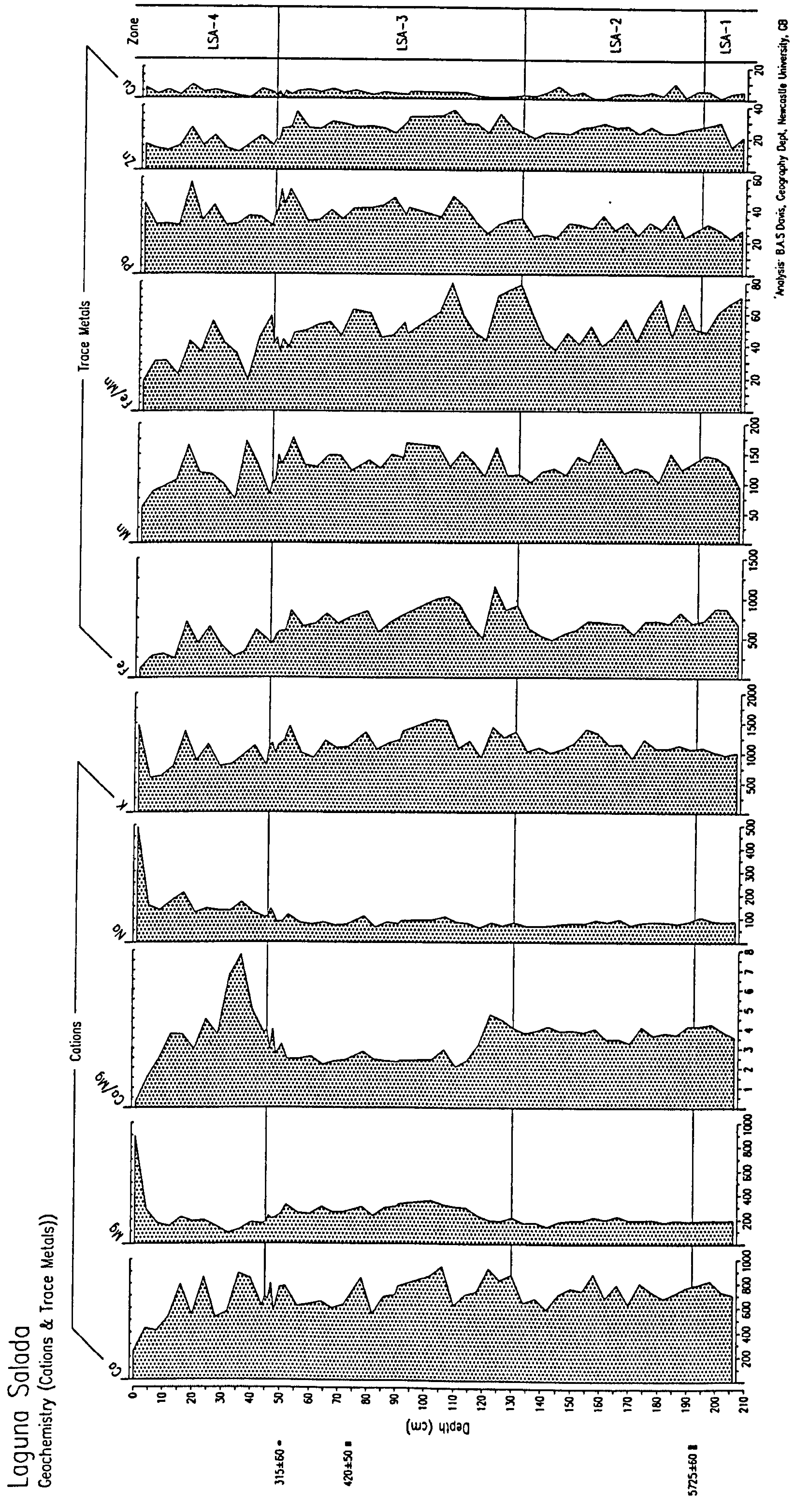


Figure 9.6.5 **Laguna Salada: geochemistry (cations & trace metals)**

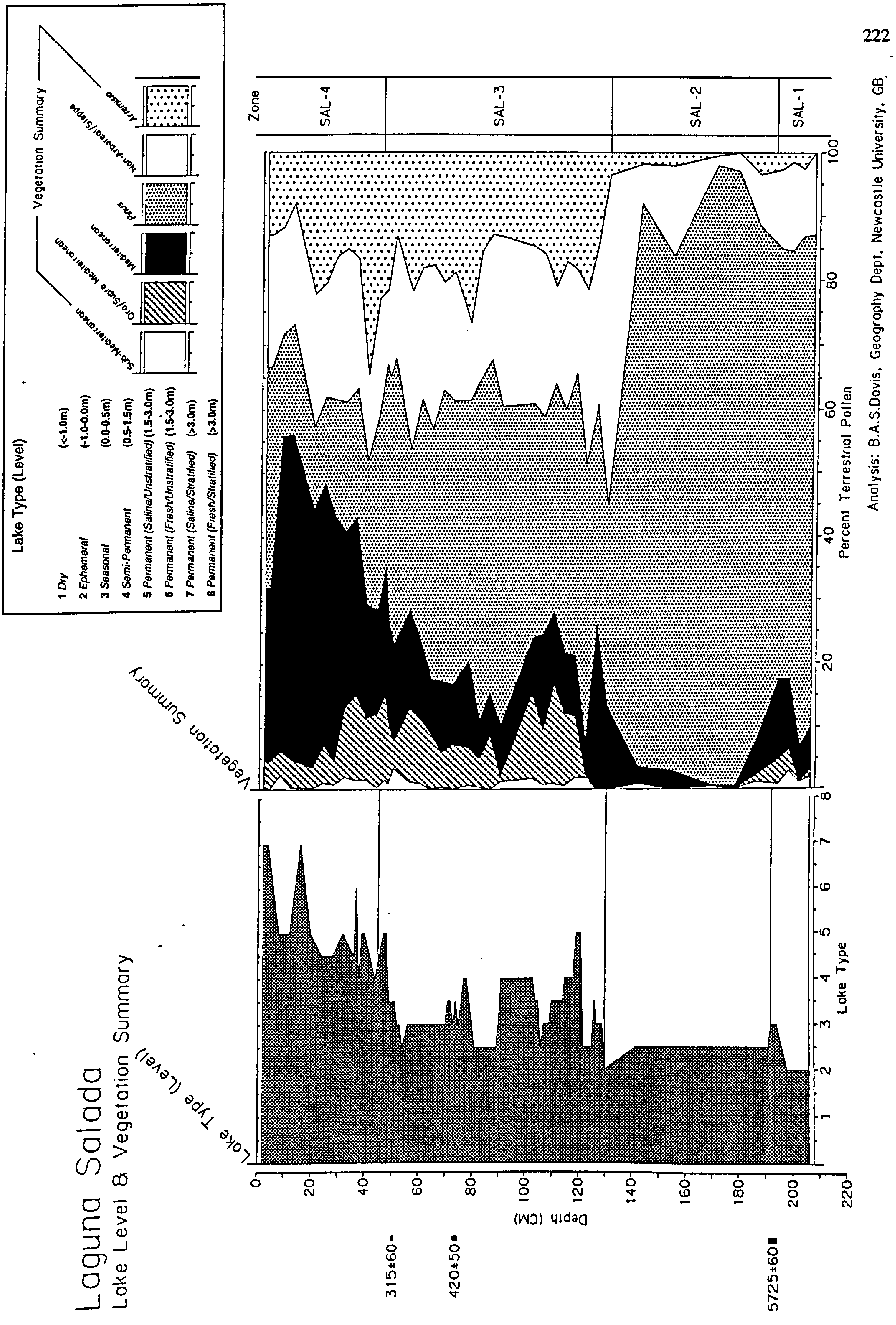


Figure 9.6.6 **Laguna Salada: lake type (level) and vegetation summary**

9.7 Laguna Gallocanta

9.7.1 Site Description

Although probably linked by deep subsurface flows to the Ebro Basin, the Laguna Gallocanta lies at the lowest point of a separate endoreic depression of some 500km^2 (*Figure 9.1.7* p155). It forms the largest natural inland lake in Spain covering 1330Ha, with a width of 2.5km and length of 6.0km in most years, although this can change substantially with fluctuations in water level. The lake is shallow (<2.0m) and hypersaline but its position on the semi-arid/semi-humid boundary ensures the permanence of its waters. It has been recorded as drying out four times this Century (Comín *et al.*, 1990a), the last time in 1984/85.

In such an arid landscape, the lake is very important as a winter stop-over resource for migratory waterfowl, including the European crane. Dramatic fluctuations in the number of birds from year to year reflect changes in aquatic vegetation linked to salinity and water depth. Over 200,000 birds were estimated to have visited in 1978 when the lake was over 2m deep, but this had declined along with lake level to only 50,000 in 1981 (Grunfeld, 1988). In 1985 the laguna became a National Game Reserve and is protected as a Bird sanctuary under EEC legislation (EEC directive 409/79).

Climate

Lying at an altitude of 1000m, the climate is more montane than that of the central Ebro Basin, with colder winters and cooler summers reflected in a mean annual temperature 5°C lower at 11°C (Biel & Garcia, 1962). Temperatures in winter average only around 3°C with frequent frosts, while in summer they rise to over 22°C (Monserrat & Gomez, 1983). Annual precipitation is higher at 500mm (although with wide interannual fluctuations), which together with the depressed PEt combine to produce net annual evaporative loss from the lake approximately equal to runoff and groundwater inputs.

Geology

The origins of the Gallocanta depression are primarily tectonic, with fault controlled scarp slopes separating the Palaeozoic hills to the east and north from the Mesozoic plains to the northwest and southwest (Calvo *et al*, 1978). The basal sediments of the lake are impermeable Keuper marls from the Trias, however much of the plains are Miocene limestones and conglomerates (Aranguren & Suádrez, 1973) over which the inflow waters flow and gain minerals.

Geomorphology

The lake occupies a gently sloping basin, steepening 3km to the east against the Sierra de Santa Cruz (1391m). Ephemeral arroyos extend down from these hills, forming broad alluvial fans at the break of slope before reaching the lake itself. The Rambla de la Hoz de los Poznelos enters the lake from the plains to the west on the opposite shore and represents an important supply of freshwater to the lake for much of the year. Low gradients and flow levels however provide little erosive and transportational power and lake sedimentation is dominated by chemical precipitates. The prevailing northwesterly wind can be very strong at times over the treeless steppe, and large amounts of precipitated salts can be lost by deflation following desiccation (Comín *et al.*, 1990a). An extensive terrace surrounds the current lake marking a former ancient shoreline equivalent to a lake four times its present area.

Hydrology

The hydrology and hydrogeochemistry of Laguna Gallocanta has been studied in detail by Comín *et al.* (1983), Comín *et al.* (1990a) and Comín *et al.* (1990b). Inputs and outputs to the lake remain approximately equal in most years, maintaining lake level at around 100cm. A small change in the hydrological balance such as a reduction in rainfall however, as happened around 1983, is sufficient to reduce the lake to an ephemeral or seasonal playa. This was the fourth time this Century that desiccation is known to have occurred (Comín *et al.*, 1990a). Transition to this state has been calculated by Comín *et al.* (1990b) as equivalent to a 250mm drop in annual rainfall or a mere 6.6% increase in evaporation. With such a sensitive hydrology it is no surprise to find that Laguna Gallocanta shows distinct seasonal (20-50cm) and interseasonal (0-200cm) fluctuations in water level.

Hydrogeochemistry

The hydrologicaly closed nature of the basin, together with the catchment geology, the lakes shallow depth, and the degree of evaporative concentration, mean that lake waters are very saline. Salinity varies greatly with water depth from around 16%oTDS at 2.0m in 1977 to 500-600%oTDS just prior to desiccation in 1984 (Comín *et al.*, 1990a).

Lake waters are dominated by sodium and chloride ions according to the Eugster & Hardie (1978) classification: Na-Mg-Cl-(SO_4) (Comín *et al.*, 1983). Water chemistry information is displayed in *table 9.1* p157.

Carbonates and sulphates dominate the lake sediments, with some detrital quartz and silicates. Gypsum and dolomite occur at the lake centre, while calcite and aragonite predominate towards the shore (Comin *et al.*, 1990a).

Vegetation

The catchment of the lake is dominated by the dry farming of cereals which in many areas extend to the lake shore. In recent years the area dedicated to cultivation has increased considerably as saline wetlands around the lake have been progressively drained and ploughed up. The area to the west of the lake was drained in the 1970's for sugar beet cultivation (Comín *et al.*, 1983) and the large playa lake of Laguna de Zaida (210Ha), 4km northwest of Laguna Gallocanta, has recently been converted to agriculture in 1991.

Towards the mountains and on the limestone areas of the plain there are areas of dry pasture and some fields of thyme. *Quercus faginea* and *Q. pyrenaica* occur on the mountain slopes, together with *Q.ilex* and plantations of pines.

No woodland occurs around the shores of the lake, and emergent macrophyte vegetation is largely restricted to an area cut offfrom the main lake to the south called Lagunazos de Tornos. Comín *et al.* (1983) report *Salicornia ramosissima* and *Scirpus maritimus* from this area.

During periods of high water, when salinity is relatively low, large areas of the lake bottom can become covered with aquatic macrophytes, particularly charophytes. In 1915, Reyes Prosper reported finding *Chara foetida*, *Chara hispida* around the lake and *Ruppia maritima var. drepanensis* present in the lake waters. During the highwater period of 1977, Comín *et al.* (1983) reported *Lamprothamnium papulosum* and *Chara galiodes* covering large areas of the lake bottom, with other macrophytes restricted to the areas around freshwater inflows, namely *Potamogeton pectinatus*, *Ruppia drepanensis*, *Groenlandia densa*, *Chara hispida var. major* and *Zannichellia pallustris f.gibberosa*

As the lake level declined to eventually dry out completely in 1984, *Lamprothamnium* and *Chara* were last noted in September 1980 when water depth was 110cm and salinity 37‰TDS (Comín *et al.*, 1983).

9.7.2 *Analysis & Methods*

Coring was performed in July 1990 using a Kayak corer from the back of a moored boat in 1.0m of water near the centre of the lake. 22cm of sediment was recovered and cut into 1cm slices in the field. Analysis was performed continuously at each level for geochemistry (loss on ignition; carbonate; sulphate), macrofossils and stratigraphy. Pollen and microscopic charcoal analysis was performed on every other level, at 2cm intervals. The lack of sediment in the upper 3cm limited the application of these techniques to just pollen, charcoal and macrofossils.

9.7.3 *Dating Control*

No material was available for radiocarbon dating, although the olive rise (*ca.*0.4 BP) is clearly identifiable at 14-15cm from the pollen record.

9.7.4 Results

The results are presented as follows:

Figure 9.7.1:	Terrestrial Plant Pollen & Charcoal	p230
Figure 9.7.2:	Macrofossils & Aquatic Plant Pollen	p231

Zone GAL-2 (21-14cm)

Lake Environment: Seasonal/Semi-Permanent Salt Lake (lake type 3-4)

Macrofossils: Charophytes, *Moina mongolonica*
Pollen: Ruppia, Potamogeton
Geochemistry: High sulphate & carbonate
Stratigraphy: Grey playa clays
Gypsum: Lenticular

Aquatic plant macrofossils are infrequent throughout the zone, with Charophytes dominant (lake type 4), but in low numbers (50-200per 100g dw). The lake would appear to have dried out completely between 19-20cm, with a sharp peak in the sulphate curve coinciding with lenticular gypsum (lake type 2 or 3). Chenopodiaceae pollen does not show any response to this desiccation event, or others shown later in the core, and maintains low percentages (<10%TP: Total Pollen) throughout. This may indicate that conditions have never been suitable for colonisation of the lake floor by terrestrial halophytes, and confirms current observations that expansion of the distant (1km) lake marginal vegetation is restricted by the precipitation of a thick salt crust when lake levels are low.

High levels of *Ruppia* (>30%TP) and *Potamogeton* (>15%TP) pollen occur within the zone, but few seed remains, suggesting that large amounts of aquatic vegetation existed at the margins of the lake, away from the central coring site. This vegetation is typical of relatively low salinity conditions, while the Charophytes and Cladoceran, *Moina mongolonica,* found within the sediments, are tolerant of high salinity conditions. The differential distribution of these indicators, according to their salinity tolerance, can be explained by high periodicity in lake level, with flooding and salt dissolution alternating with desiccation and salt precipitation.

As lake levels fall, greater salt accumulation occurs within the centre of the lake, where a progressively shrinking and more concentrated brine precipitates salts according to the evaporitic series of the lake water. The most soluble salts are always the last to be precipitated (in the centre of the lake), and the first to be redissolved again when lake levels start to rise. The salts at the margins of the lake are the least soluble minerals, which only redissolve slowly with flooding. Rapid fluctuations of lake level (with almost annual desiccation) give rise to lower salinity lake waters than would develop under permanent lake conditions due to dissolution time lag at the onset of each flooding period, as well as the restricted time for evaporitic concentration before desiccation occurs again.

Lake salinity is therefore highest at the centre of the lake where the most soluble salts accumulate, and lowest at the lake margins where fewer and less soluble salts, as well as freshwater inflows, occur. These differences tend to equalise over long periods of lake flooding (>1 year), but remain particularly strong in the short term (<1 year). The rapidly fluctuating water levels within the zone indicated by lenticular gypsum, suggest that repeated flood-dry cycles would have emphasised the differential distribution of lake salinity. This would confirm the observed distribution of lake fauna and biota apparent in the palaeolimnological record.

Terrestrial Environment: (*Pinus* Woodland) Grass Steppe

Pollen: *Pinus, Juniperus, Ephedra distachya*-type
Charcoal: High
Geochemistry: High carbonate

Overall, the pollen evidence indicates a floral composition much the same as the present day open grass steppe environment. The arboreal pollen component remains at between 70-80%TTP (Total Terrestrial Pollen) throughout the core, with only small changes in the woodland mix.

Juniperus (>10%TTP) and *Ephedra distachya*-type (<2%TTP) characterise the early part of the zone, with *Quercus ilex*-type (>20%TTP) replacing *Juniperus* towards the end. The *Juniperus-Ephedra* association is one that is also found in the early Holocene at the Laguna Guallar (GUA-1) and Hoya del Castillo (CAS-1).

Non-arboreal taxa are dominated by the grasses (>20%TTP), which include a high percentage of large cereal/Esparto pollen grain sizes (>40µm). Sustained levels of *Olea* (2-3%TTP) probably indicate low levels of olive cultivation, with anthropogenic disturbance suggested by high charcoal levels, although this may be a result of slow sediment accumulation since charcoal tends to mirror pollen concentration. *Artemisia* levels are highest in this zone (>5%TTP) compared to the upper parts of the core, where it declines progressively.

Zone GAL-2 (15-8cm)

Lake Environment: Seasonal/Permanent Salt Lake (lake type 3-5)

Macrofossils: Ruppia maritima var maritima, Ruppia drepanensis
Pollen: Ruppia
Geochemistry: Clastics ('other minerogenic material') to carbonates to sulphates
Stratigraphy: Organic-clays to lenticular gypsum

Rising lake levels in the second zone are indicated by the disappearance of lenticular gypsum and playa clays. These are replaced by organic clays and abundant macrofossils, including seeds of *Ruppia maritima* var *maritima*, indicating permanent lake conditions (lake type 5). The widespread colonisation of large areas of the lake by this vegetatively reproducing perennial species of *Ruppia* probably explains fall in *Ruppia* pollen values (<20%TP). *Potamogeton* pollen values also decline, reflecting fewer low salinity periods due to reduced flood-dry frequency (see GAL-1) and prolonged evaporitic concentration.

Ruppia maritima var maritima is replaced by declining levels of *Ruppia drepanensis* as salinity levels increase and carbonate values rise after 14cm. Annual growth and decline of locally growing *Ruppia drepanensis*, together with the death of other macrophytes less adapted to the increasing salinity, may have released nutrients into the lake waters causing algal blooms and population explosions of Cladocera and *Chironomus*. Lake fauna peak at around 11cm, following the onset of the earlier decline in aquatic macrophytes.

Levels of Charophytes remain low throughout the zone (<150 per 100g dw), perhaps unable to compete against *Ruppia* due to low lake water salinity and heightened organic and inorganic (through carbonate precipitation) turbidity.

The end of the zone is marked by declining carbonate precipitation and increasing sulphate precipitation as salinity rises and lake levels fall. Cladocera and *Chironomus* similarly diminish as macrophytes decline further. Lenticular gypsum again indicates lake desiccation (lake type 2 or 3) at between 8-10cm, coinciding with a peak in sulphate levels.

Terrestrial Environment: (*Pinus* Woodland) Cultivated Grass Steppe

Pollen: Olea, Cannabis sativa, Gramineae (>50µm)
Charcoal: Low

The late medieval expansion in olive cultivation is clearly shown at the beginning of the zone, together with the appearance of many other anthropogenic indicators. *Cannabis sativa* shows particularly high values. This pollen type is not found at sites in the Central Ebro Basin.

Further agricultural intensification is suggested by the appearance of *Juglans* and increase in very large Gramineae (>60µm), either reflecting cultivation of cereals or the extension of Esparto grassland. The coincidental appearance of *Rumex* and the lack of response in the smaller Gramineae perhaps suggests the former rather than the latter.

Zone GAL-3 (8-0cm)

Lake Environment: Semi-Permanent Salt Lake (lake type 4)

Macrofossils: Charophytes
Pollen: Ruppia
Geochemistry: Clastics ('other minerogenic material')
Stratigraphy: Organic clays

Rising lake levels are again indicated at the beginning of this third zone, with a decline in evaporites and increase in clastic sediments ('other minerogenic material'). Increasing *Ruppia drepanensis* and declining *Moina mongolonica* indicates a low salinity but seasonally fluctuating lake environment. The high values of *Ruppia* pollen (>30%TP) suggest that sexually reproducing *Ruppia drepanensis* dominated much of the lake floor (lake type 3). The lack of evidence of *Potamogeton*, but increasing evidence of Charophytes could possibly be a result of fewer low salinity extremes and more high salinity extremes.

Geochemical evidence is not available for the most recent sediments above 5cm, however macrofossils indicate a progression to a higher salinity environment, dominated by Charophytes and *Moina mongolonica* (lake type 4). *Ruppia* was probably confined to the less saline lake margins, although the high *Ruppia* pollen values and amount of transported broken seeds suggest a significant presence within the lake.

Finally, a general decline in lake level and shift to a high salinity environment is indicated at around 2cm, with a decrease in macrophytes and an increase in *Moina mongolonica.*

Terrestrial Environment: (*Pinus* Woodland) Grass Steppe

Pollen: Pinus, Olea
Charcoal: Low

Little change in the regional vegetation is shown between this zone and the last until the final 4cm. Here, cereals (Gramineae >60μm?), *Cannabis* and *Rumex* pollen diminish, indicating a reduction in cultivation in the area. The decline of *Olea* follows somewhat later, together with *Quercus ilex*-type, whose replacement by *Pinus* may be a result of recent reafforestation this Century.

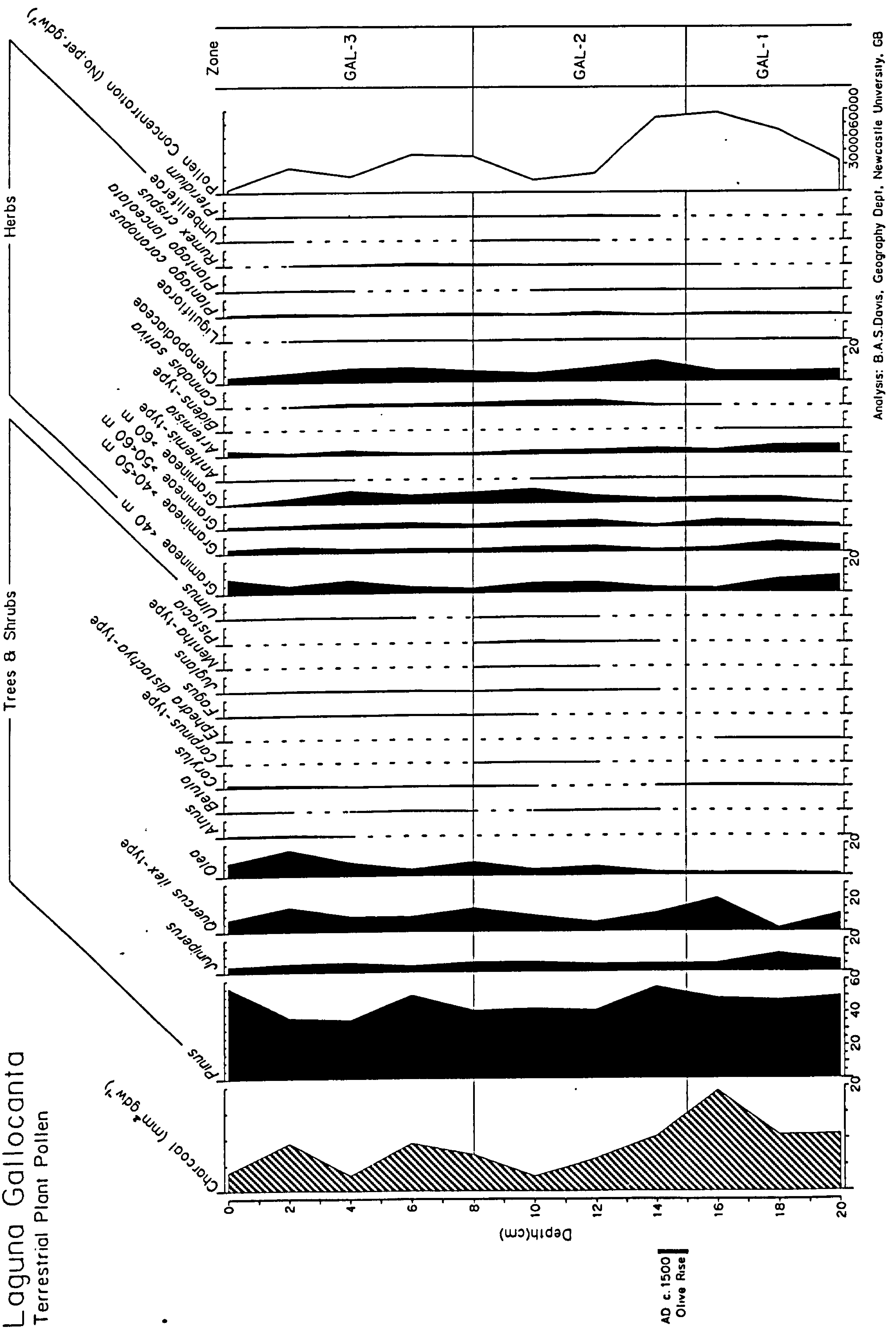


Figure 9.7.1 **Laguna Gallocanta: terrestrial plant pollen and charcoal**

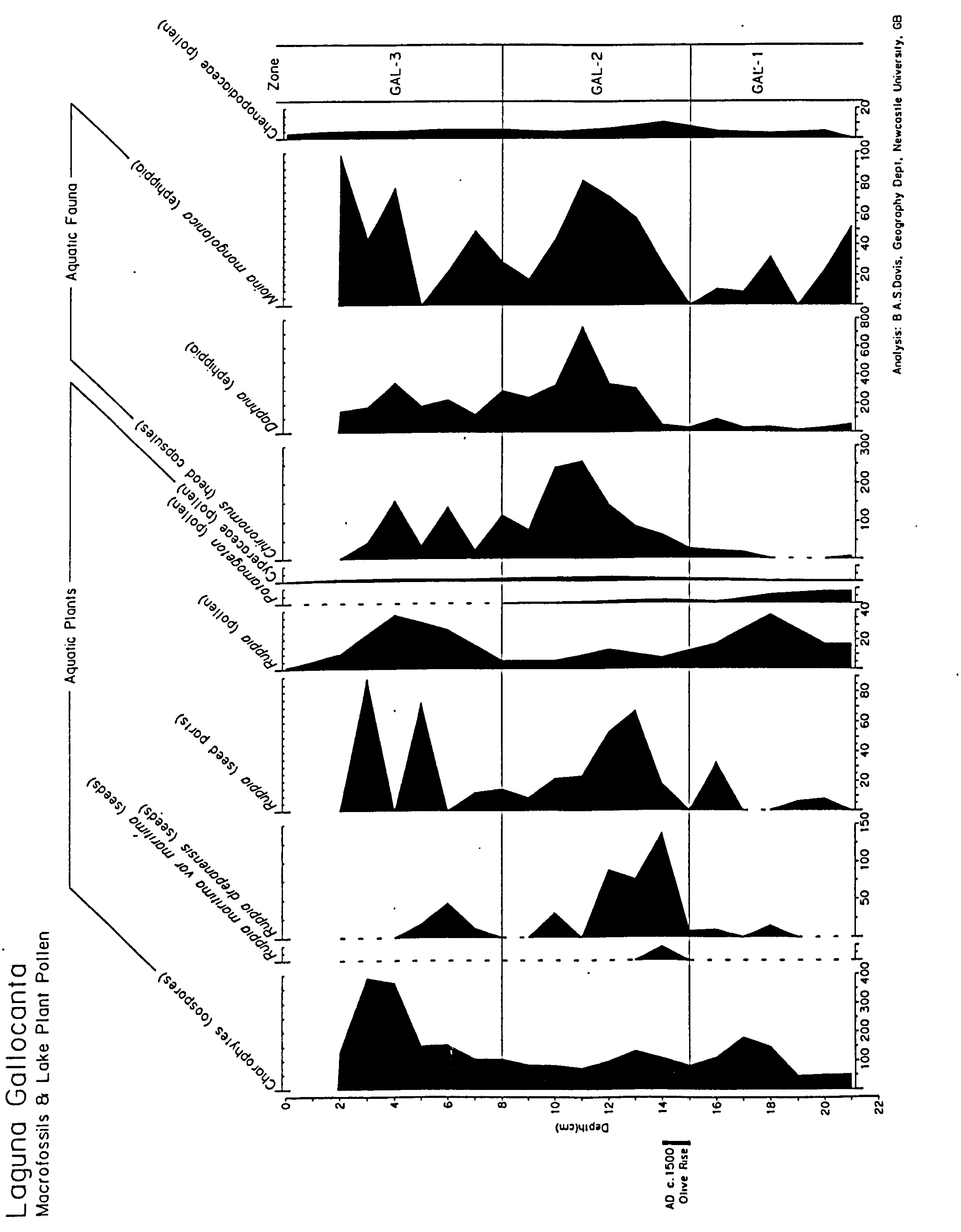


Figure 9.7.2 **Laguna Gallocanta: macrofossils and aquatic plant pollen**

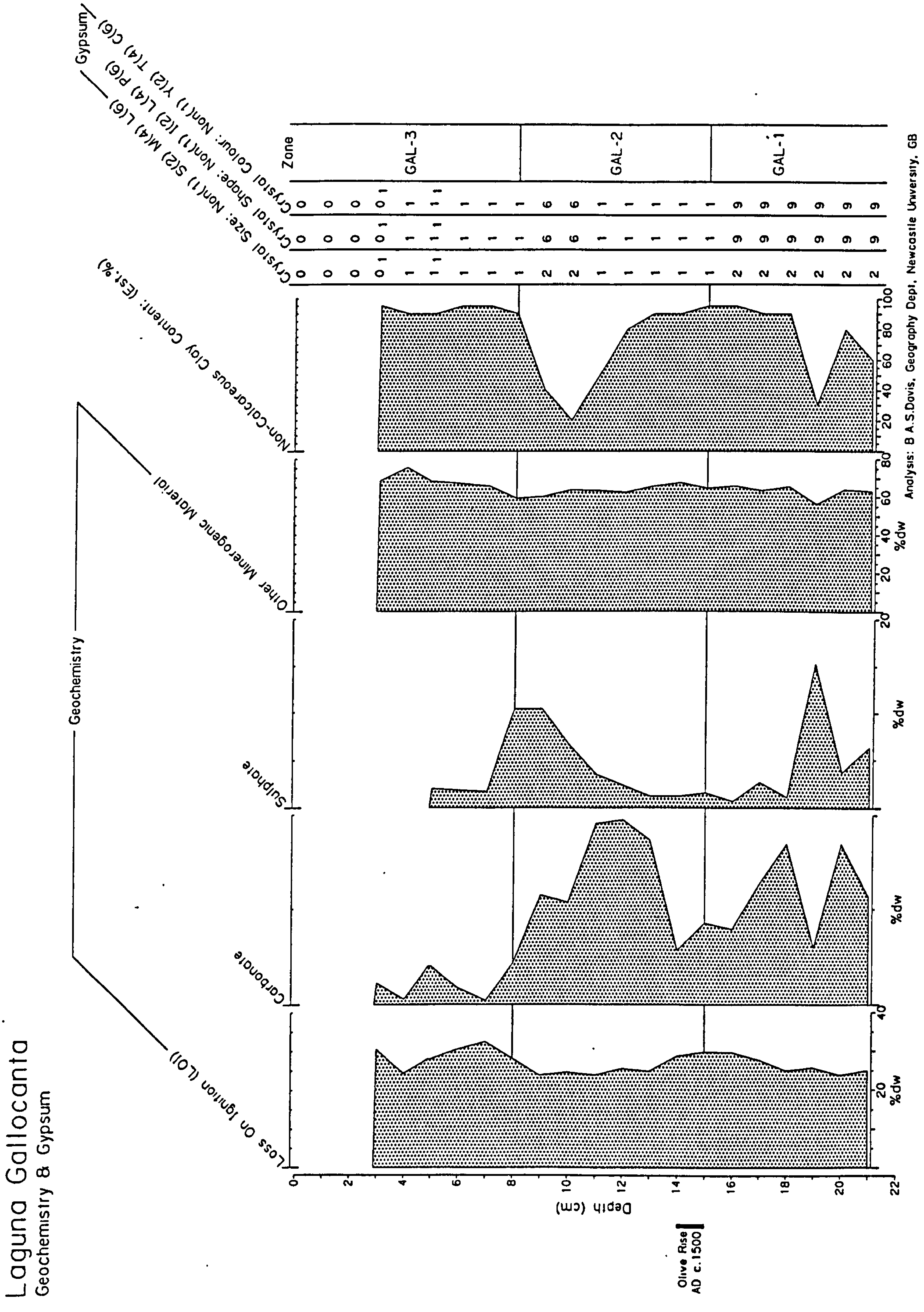


Figure 9.7.3 **Laguna Gallocanta: geochemistry, sediment composition and gypsum**

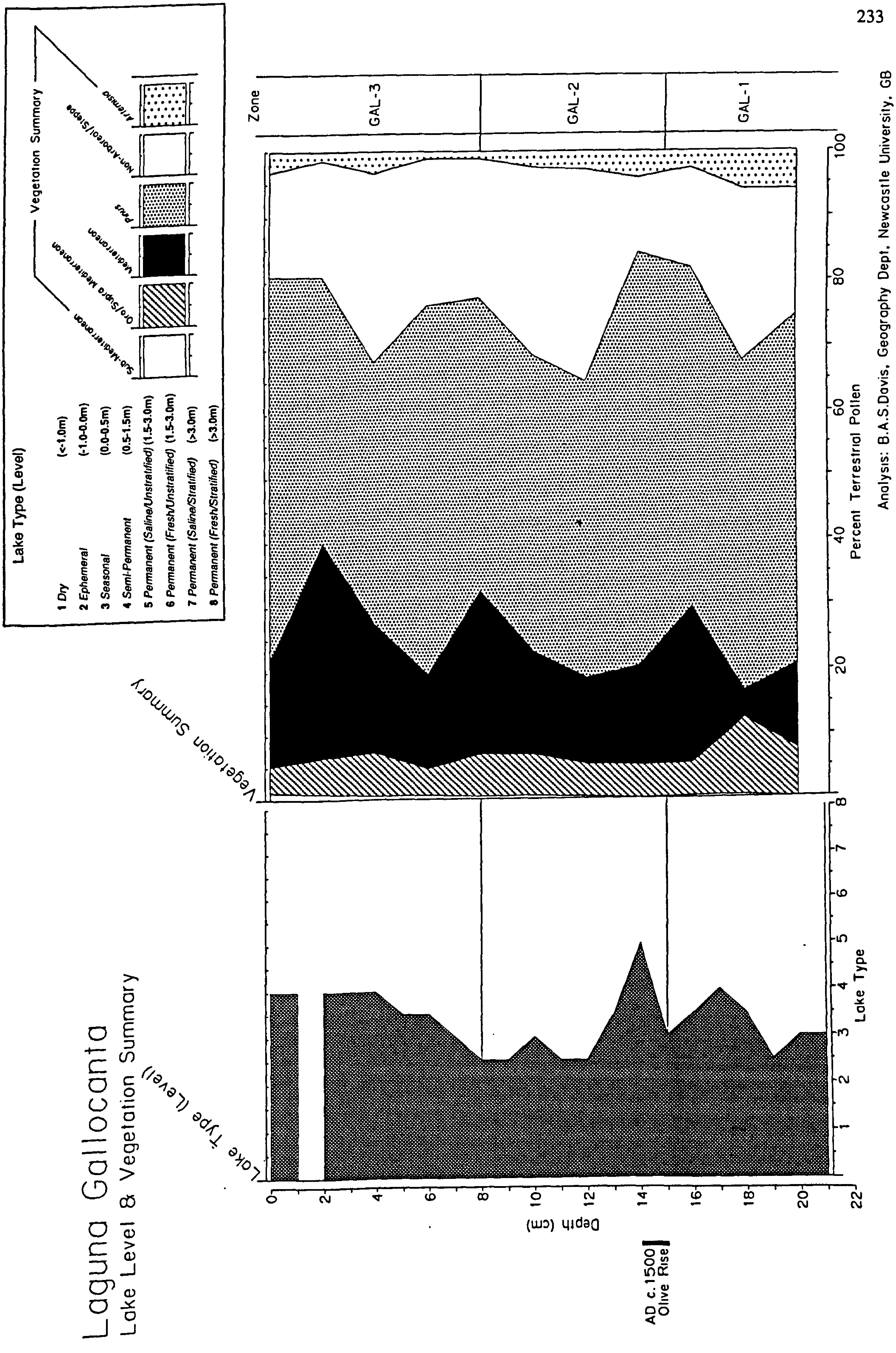


Figure 9.7.4 **Laguna Gallocanta: lake type (level) and vegetation summary**

9.8 La Estanca

9.8.1 *Site Description*

La Estanca is an artificial reservoir 2km north of the playa lakes of Salada Pequeña and Salada Grande, and 4km west of the town of Alcañiz (*Figure 9.1.5* p153). It lies at an altitude of 330m and covers an area of 87.5Ha to a maximum depth of 14m near the dam. Most of the lake basin however grades gently between 4.0 and 5.0m water depth.

An inflow of water from the Rio Guadalope along a small canal called '*la Acequia Vieja*' ensures that water levels remain high throughout the year and the lake water remains fresh. The outflow is mainly used for irrigation of the *huertas* surrounding Alcañiz, and for pumping across the Rio Regallo watershed to irrigate the Valmuel area to the west.

Originally, La Estanca is thought to have been a playa lake similar to the Salada Pequeña and Salada Grande. Benavente (1987, 1988) quotes Bardavíu ('Poblados iberos de Alcañiz', 1925) as suggesting both that an artificial reservoir existed in Iberian times at La Estanca, and that the canal '*la Acequia Vieja*' may date before the Muslim period. Permanent freshwaters have certainly been present at La Estanca since before the 17th Century, since the lake was renown at this time for its fish and aquatic birds (Benavente, 1987, 1988). The reservoir was raised after 1931 by the 'Confederación Hidrográfica del Ebro', increasing its capacity by 7.0Mil m^3, from its original 3.5Mil m^3 (Alonso & Comelles, 1985).

Water chemistry reflects the predominantly freshwater nature of the reservoir although it remains slightly mineralised. The predominance of sulphate over chlorides reflects the lack of evaporitic concentration. Alonso (1985) reports the lake waters as clear (low turbidity), with little eutrophication and no contamination from pollutants. Water chemistry data is presented in *table 9.1* p157.

Large changes in water level restrict the development of littoral vegetation and only limited evidence of macrophyte remains (Charophytes) could be found in the deeper parts of the reservoir (4-5m). Alonso & Comelles (1985) mention a number of macrophytes found present in the lake including *Potamogeton lucens*, *Potamogeten pectinatus*, *Polygonum amphibium* and *Chara vulgaris*. Shoreline vegetation was found to be mainly composed of beds of *Scirpus lacustris* and *Typha angustifolia*. Braun-Blanquet (1957) quotes Loscos & Pardo as finding six species of *Potamogeton* in La Estanca, including *P.crispus*, *P.trichoides*, *P.densus*, *P.lucens* and *P.natans*.

Dry cereal cultivation reaches the lake edge to the west, while olives grow on the hills to the north and irrigated crops below the dam to the east. The south shore has been planted with pines and other trees to provide shade for recreation, with further recent reafforestation on the hills behind.

9.8.2 *Analysis & Methods*

Coring was undertaken from a moored raft in the centre of the lake in 4.0m of water. The first drive to 82cm was taken using a Fat Livingstone corer, while the second and third drives down to 193cm were taken with a Thin Livingstone. The Fat Livingstone core was extruded into 1cm slices in the field while the Thin Livingstone core was stored in drainpipe in 50cm sections.

The core was subsampled in the laboratory at 4cm intervals for analysis of pollen, geochemistry (loss on ignition; carbonate; sulphate), charcoal, macrofossils and stratigraphy. In addition, macrofossil analysis was also performed on continuous 3cm slices between 85-100cm, 155-165cm and 180-193cm from the Thin Livingstone core (with the occasional 1cm slice).

9.8.3 *Dating Control*

Two AMS radiocarbon dates were obtained from Chenopodiaceae seeds at 162-165cm (430±50), and 182-185cm (470±50). The time/depth relationship is plotted in *figure 9.8.1.*

9.8.4 *Results*

The results are presented as follows:

Zone EST-1 (195-160cm)

Lake Environment: Ephemeral Playa Lake (lake type 2)

Macrofossils: Chenopodiaceae
Pollen: Chenopodiaceae
Geochemistry: Low LOI and carbonate
Stratigraphy: Grey playa clays

High Chenopodiaceae pollen values (>40%TP: Total Pollen), the presence of Chenopodiaceae seeds (>300per 100g dw), and the lack of aquatic pollen and macrofossils, indicate that La Estanca was originally an ephemeral lake (lake type 2), before it was a reservoir. Terrestrial halophytes, such as Chenopodiaceae, grew across the entire lake floor at this time, including the central coring site.

Low sulphate levels (<1%dw) and a lack of gypsum crystals suggest leaching of the sediments by free draining meteoric waters, and confirm only infrequent flooding.

The end of the zone is marked by the appearance of aquatic macrophytes associated with rising lake levels following dam construction. This is dealt with more fully in the following zone (EST-2).

Terrestrial Environment: Degraded Pine Matorral with *Pistacia* and *Artemisia* Steppe

Pollen: Pinus, Pistacia, Artemisia, Compositae
Charcoal: High

The low arboreal pollen component (<40%TTP: Total Terrestrial Pollen) compared to the following two zones (*ca.*65%TTP) indicates that openland was originally much more extensive in this earliest zone. This reflects a relative shift in pollen source area, as the open land represented by the dry lake basin became flooded and the regional pollen rain became proportionately more important. It should be noted that Chenopodiaceae, which would compose a large part of the vegetation covering the dry lake, is not included in the sum for terrestrial pollen and should not therefore affect the relative proportions of the other terrestrial taxa.

Pinus (*ca.*30%TTP) and *Pistacia* (*ca.*>5%TTP) represent the main arboreal taxa, suggesting a degraded matorral scrub. *Pinus* values decline temporarily with a marked peak in the charcoal curve at around 184cm. This clearance episode sees an increase *Pistacia* and the first signs of *Olea* cultivation (>5%TTP). *Juglans* is also present at slightly higher levels (<3%TTP) than later in the core.

A second period of disturbance occurs at the very end of the zone (162cm) where *Pinus* virtually disappears temporarily, while *Juniperus* peaks (>40%TTP). The replacement of *Pinus* by *Juniperus* is not, however, accompanied by any significant change in charcoal levels. This may instead represent taphonomic differences and differential deposition associated with shallow, seasonal (lake type 3: see next zone), lake conditions immediately following dam construction. This has been highlighted in the case of *Olea* and *Pinus* in Chapter 6, where the later flowering of the two, *Olea*, is found washed to the centre of the basin as the lake dries up in late spring. In zone EST-1, the place of *Olea* may have been taken by *Juniperus*, which flowers at a similar time of year (Mateo, 1987) and which forms a much greater part of the surrounding vegetation than *Olea* at this time. *Pinus* pollen falling on the lake in early Spring may have been blown to the lake margins by the wind, while *Juniperus* pollen falling on the dry lake bed in late Spring would have been washed to the central coring site by run-off waters from late season storms.

Other anthropogenic indicators are relatively few, with low amounts of large Gramineae (>40μm) characteristic of cereal cultivation (or Esparto steppe), particularly when compared to the following zones. Herbaceous taxa include significant levels of Compositae and *Plantago media/major*, indicating disturbed conditions, and probably reflecting colonisation of the dry lake bed environment.

Radiocarbon dates obtained from Chenopodiaceae seeds indicate that the peak in charcoal occurred just after 470±50BP (Cal.AD 1432), and that the water level was raised at around 430±50BP (Cal.AD 1441).

Zone EST-2 (160-100cm)

Lake Environment: Low Input/Output, Shallow, Freshwater Reservoir (lake type 6)

Macrofossils: *Daphnia*, Moinidae, *Chironomus*
Pollen: *Myriophyllum spicatum*, *Ranunculus*, *Potamogeton*
Geochemistry: High LOI
Stratigraphy: Laminated with rhizome mat and reed stem remains

The appearance of aquatic macrophytes at the onset of the zone marks a sharp rise in lake level associated with dam construction. This is accompanied by a stratigraphic change to laminated organic sediments with reed stems and rhizomous remains.

The first aquatic macrofossils occur at the end of the preceding zone (EST-1), from 166cm onwards. These occur along with high levels of Chenopodiaceae and suggest that lake filling was at first intermittent (lake type 3). The pollen record and stratigraphic record around this period (166-160cm) remains heterogeneous and does not indicate the kind of sediment mixing that may also have accounted for the coincidental appearance of terrestrial and aquatic plants.

Aquatic plant succession following the onset of lake filling is indicated by seeds of annuals such as *Potamogeton pectinatus* (>15per 100g dw), *Chara vulgaris* (*ca.*500per 100g dw) and *Ranunculus* (>25per 100g dw), adapted to temporary and lightly mineralised lake conditions. Moinidae and *Chironomous* also appear for the first time as lake nutrient levels increase following the decay of flooded terrestrial vegetation. The presence of Tanytarsini however indicates that the lake was initially well oxygenated (Chapter 3).

After 160cm, Tanytarsini disappear along with *P.pectinatus*, with seed evidence confined to *Ranunculus*, which then declines after 150cm. The lack of seeds after this point may be due to the development of deep or turbid water restricting the development of macrophytes in the central part of the lake. High (organic?) turbidity of the lake waters is supported by low levels of bottom dwelling *Chara vulgaris* in this zone of the core, as well as high levels of phytophagous Chironomids and detritivores such as *Chironomus*.

The pollen of aquatic plants is more widely dispersed and indicates that the perennial, *Myriophyllum spicatum*, dominated the lake between 160-154cm, rising to values of over 35%TP. This then declines to values less than 3%TP, while *Potamogeton* pollen remains relatively high at around 8%TP. The establishment of *Potamogeton* as the dominant submerged macrophyte may be related to its ability to withstand high turbidity water conditions (Chapter 2).

The emergent vegetation (*Typha angustifolia*-type) takes longer to become established and is probably restricted to the lake margins by the depth of water (>2.0m). Levels (*ca.*15%TP) are less than those in the upper parts of the core (20-30%TP) when lake levels became deeper. This may be attributable to large fluctuations in lake level in this early period, resulting in periodic desiccation of marginal vegetation.

Organic content levels (LOI: *ca.*10%dw) are the highest within the core, having risen from less than 4%dw in the previous zone. The lake at this stage probably has a low input and output of water, allowing the build-up of nutrients and a productive, shallow, freshwater ecosystem to develop.

Terrestrial Environment: Olive & Cereal Cultivation (Grazing?)

Pollen: Juniperus, Olea, Gramineae >50μm, *Plantago* sp
Charcoal: Low

The onset of the Late-Medieval expansion of olive at the beginning of the zone sees the start of the *Olea* rise. Large size Gramineae (>40μm) also appear, indicating the development of cereal cultivation or Esparto steppe. This may indicate the former since it is accompanied by a noticeable increased in ruderals such as *Plantago*. Pastoral farming may also have been important since the high level of *Juniperus* (>15%TTP) suggests sustained grazing pressure. No new clearance is indicated since arboreal pollen values remain steady at around 65%TTP, and charcoal values remain low. Increased catchment stability may be suggested by a sharp drop in Compositae compared to the previous zone (EST-1), but this probably reflects the disappearance of the dry lake bed habitat.

Zone EST-3 (100-25cm)

Lake Environment: High Input/Output Shallow Freshwater Reservoir (lake type 6)

Macrofossils: Chara vulgaris

Pollen: *Typha angustifolia*-type
Geochemistry: High carbonate
Stratigraphy: Laminated reduced organic clays

Chara vulgaris becomes the dominant macrophyte in zone EST-3 as the pollen of *Potamogeton* declines. Calcified oospores of *C.vulgaris* increase from around 300per 100g dw in zone EST-2, to over 1500per 100g dw in zone EST-3. The expansion of *Chara* is accompanied by a 10%dw increase in carbonate to over 45%dw as a result of biogenic calcite precipitation.

The rapid accumulation of marl causes the concentration of pollen to fall below countable levels in the lower levels of the zone (100-72cm). The appearance of *Najas flexilis* and Tanytarsini at this time supports the establishment of a clear, oligotrophic, hardwater lake. The reduced nutrient content and lake productivity of this type of lake is reflected in lower LOI values, and a reduction in Cladocera and *Chironomus* compared to the previous zone.

Pollen from emergent vegetation shows an increase in *Typha angustifolia*-type to over 15%TP, while that of Cyperaceae declines to below 4%TP. The overall increase in emergent macrophytes may be due to the stabilisation of lake levels, while the shift from Cyperaceae (*Scirpus/Phragmites*) to *Typha* may suggest a decline in lake salinity (see Chapter 2).

The change in the nature of the lake (reservoir) from a turbid, and possibly lightly saline and eutrophic lake, to a clear, oligotrophic, freshwater lake, may have been as a result of the reduced residence time of lake water. Construction of a new supply canal, or the lining and enlargement of an existing supply canal from the Rio Guadalope would have provided more water to flow into the lake. The continued presence of oospores and seeds of submerged macrophytes does not indicate that this resulted in a major increase in water depth, although the increase in marginal vegetation suggests that water levels were stabilised. Increased input of lake water was therefore compensated for by an increase in output of water from the lake for irrigation. This is supported by the terrestrial pollen record which suggests a continued increase in agricultural intensification and irrigated huertas, indicated by a huge expansion in olive cultivation.

Terrestrial Environment: *Olive* Plantations with Cereal Cultivation (Grass Steppe)

Pollen: *Olea*, Gramineae (>40μm), *Plantago* sp
Charcoal: Low

Olive cultivation continues to expand throughout the zone, with *Olea* reaching a peak at 40cm (37%TTP). This is largely achieved through the loss of *Juniperus* and *Pinus*, which both decline during this period. The maximum value of *Olea* is close to that experienced at the Laguna Salada (35%TTP) in zone LAG-4, which also shows similar reduction in *Juniperus* and *Pinus*. The end of zone EST-3 sees the start of the modern decline in *Olea* and increase in *Pinus*.

The non-arboreal component shows comparatively little change from the previous zone, with similar levels of large Gramineae (>40μm) (cereals/Esparto), with perhaps a small (*ca.5*%TTP) increase in smaller sized grasses (<40μm).

Zone EST-4 (25-0cm)

Lake Environment: High Input/Output Deep Freshwater Reservoir

Macrofossils: Very low
Pollen: *Potamogeton*, *Typha angustifolia*-type
Geochemistry: Low carbonate
Stratigraphy: Laminated organic clays

A sharp decline in *Chara vulgaris* and the disappearance of the seeds of other submerged macrophytes suggests higher lake levels (>3.0m) allowing stratification to occur and the formation of an anoxic hypolimnion (lake type 8). This was probably as a result of construction of a new dam in 1931, which doubled the capacity of the reservoir from 3.5Mil m^3 to 7.0Mil m^3 (Alonso & Comelles, 1985).

A peak in Cladocera as *Chara* declines at the end of the preceding zone was probably a response to the temporary increase in nutrients as a result of the initial death of aquatic and terrestrial vegetation as lake levels were raised.

Terrestrial Environment: Degraded *Olive* Plantations with Cereal Cultivation (Grass Steppe)

Pollen: *Pinus*, *Olea*, Gramineae (>50μm), *Plantago* sp
Charcoal: Low

The decline of olive plantations this Century is clearly shown as *Olea* values drop to below 20%TTP. *Pinus* expands over the same period to over 40%TTP. The rise of *Pinus* may reflect its invasion of old olive groves or the recent expansion of pine reafforestation. Further agricultural decline is also indicated by the disappearance of *Juglans*.

The openland environment remains little changed from the previous zone, with large Gramineae (>40μm) indicative of cereal cultivation or Esparto grass steppe. *Artemisia* continues to decline from the previous zone, to only 7%TTP.

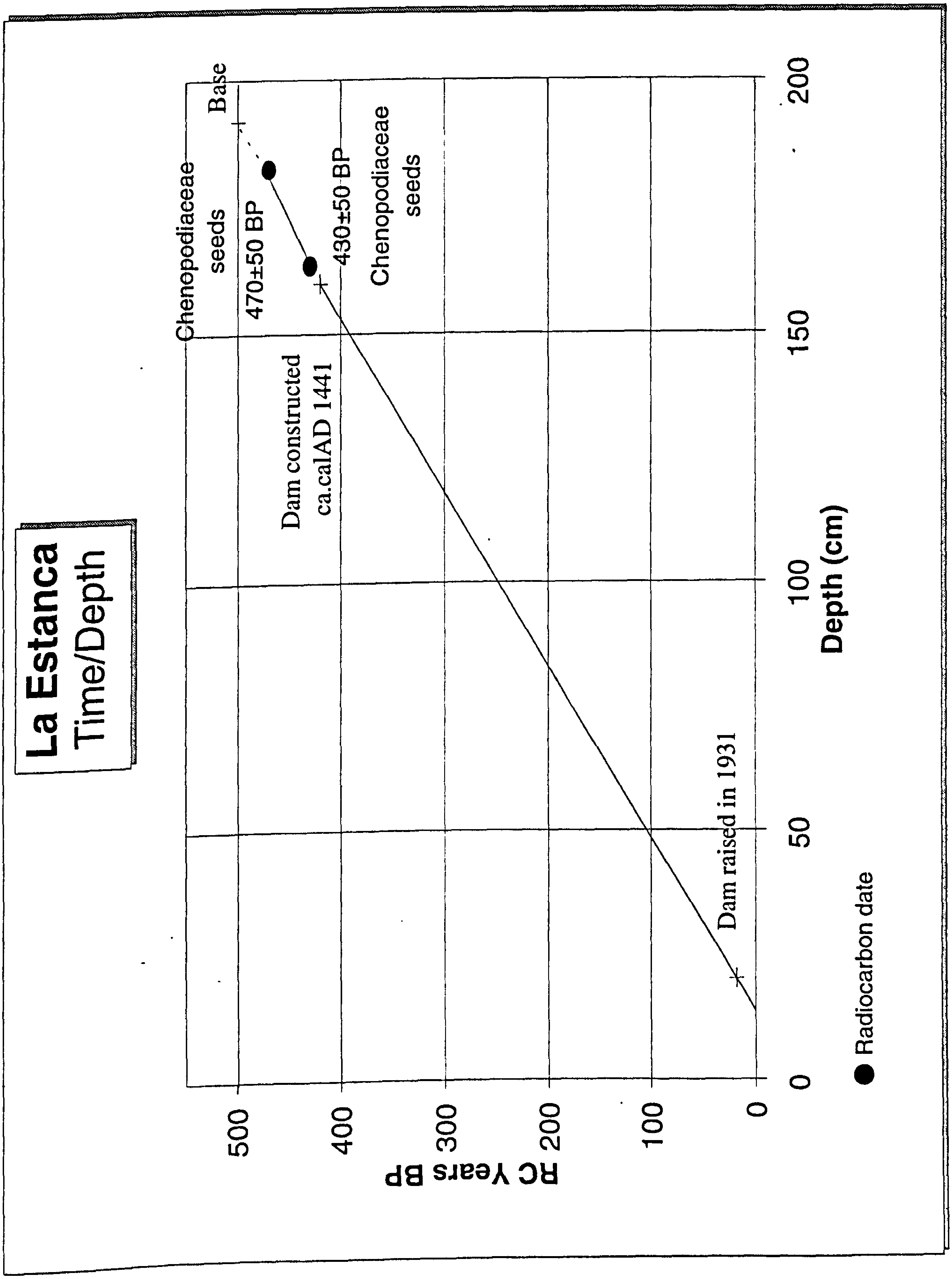


Figure 9.8.1 **La Estanca: radiocarbon time/depth curve**

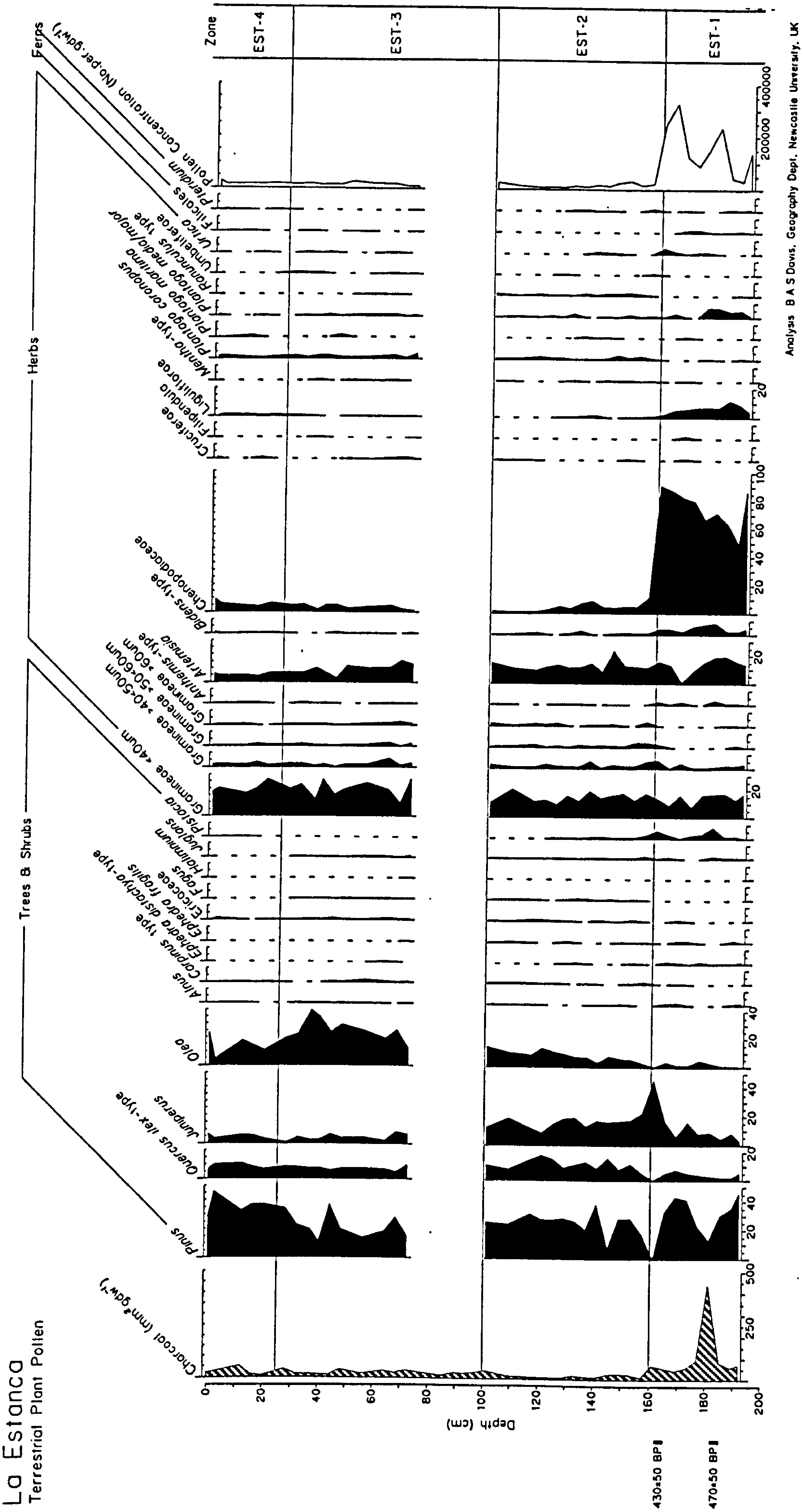


Figure 9.8.2 **La Estanca: terrestrial plant pollen and charcoal**

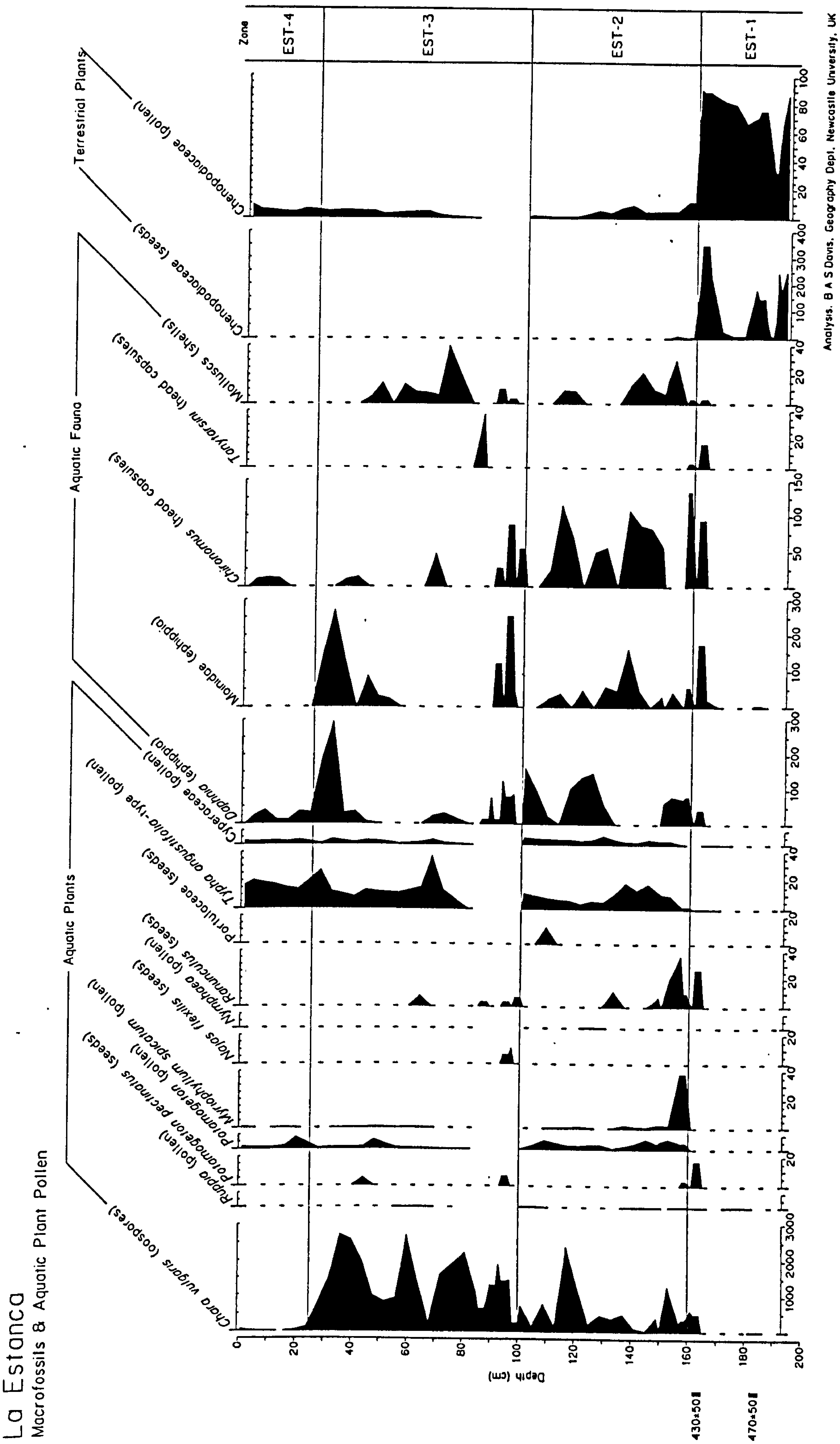


Figure 9.8.3 **La Estanca: macrofossils and aquatic plant pollen**

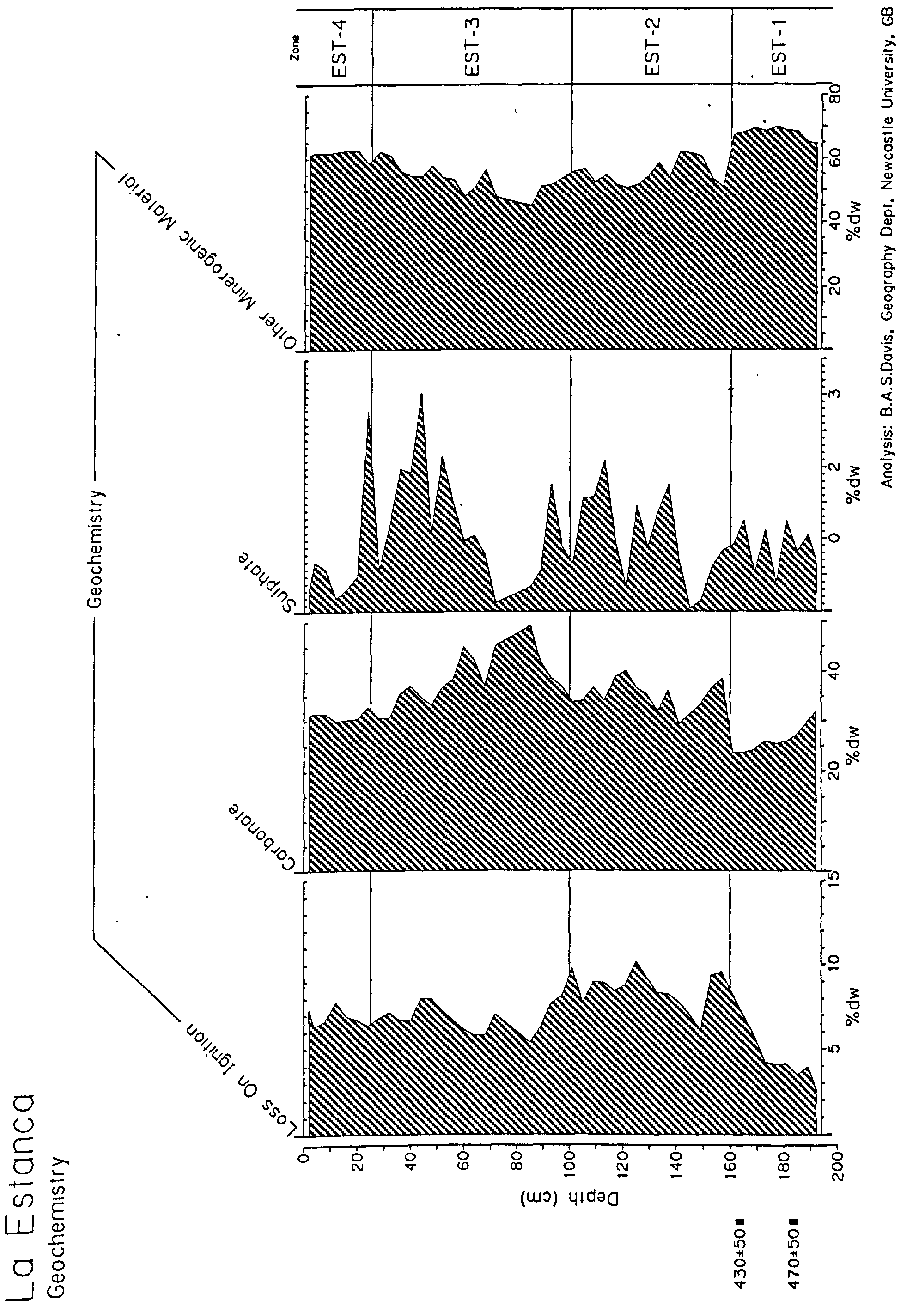


Figure 9.8.4 **La Estanca: geochemistry**

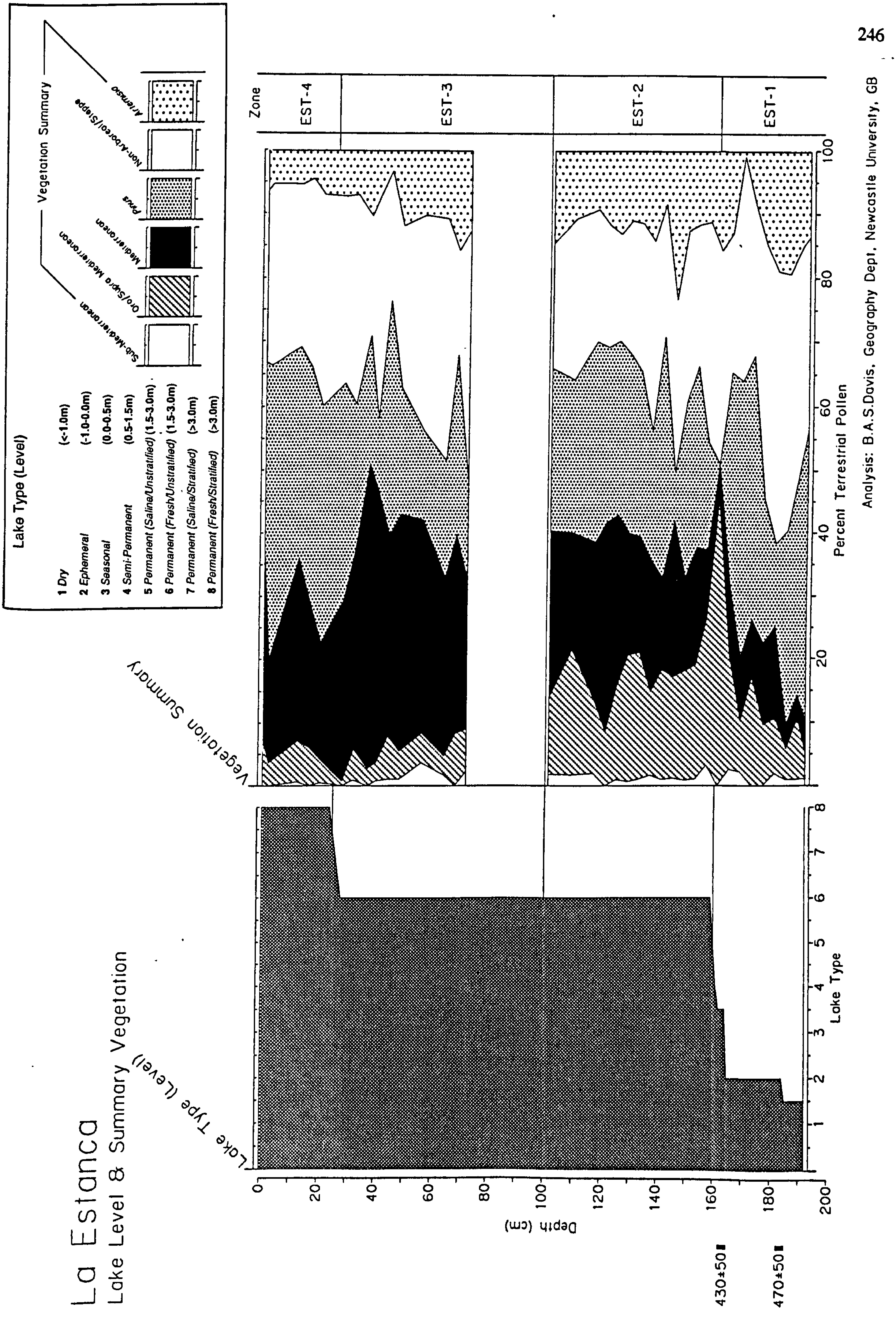


Figure 9.8.5 **La Estanca: lake type (level) and vegetation summary**

Chapter 10

Discussion

10.1 Abstract

Early Holocene: The central Ebro Basin was originally covered by an extensive forest of Juniperus thurifera from <9.3-8.6Kyr BP, which later gave way to pine and evergreen oak between 8.6-7.2Kyr BP. Lake levels over this period were higher and more permanent than today. Climatic conditions were cool, dry, and markedly continental during the earlier period, with low evapotranspiration. The second period is marked by warmer, wetter conditions with high evapotranspiration. A regional scale early Neolithic clearance (arable?) event is shown between 7.7-7.3Kyr BP.

Mid Holocene: Pinus halepensis forest expanded to cover the central Ebro Basin between 7.2-5.4Kyr BP, accompanied by lower groundwater levels due to reduced winter rainfall and high evapotranspiration. After 5.4Kyr BP, increasing aridity caused a reduction in both forest cover and lake levels. Between <4.0-2.7Kyr BP a climate of high summer storm frequency became established, although winters remained particularly dry. Winter rainfall recovers as lake levels peak during Iberian-Roman times, between 2.7-1.8Kyr BP. This is accompanied by high population densities, intensive arable agriculture and sylviculture. Rapid depopulation occurs with a fall in lake level and restoration of pine (P.halepensis) forest at 1.8Kyr BP.

Late Holocene: Destruction of the P.halepensis forest by fire occurs at around 1.4Kyr BP as agriculture changes to extensive pastoral farming during the Visigoth and Muslim eras. The late Medieval (0.4Kyr BP) sees a change to modern intensive arable farming and sylviculture (cereals, olive, fig, hemp, vine). A recent rise in lake levels (0.4-0.0Kyr BP) has occurred throughout the Ebro Basin that may be linked to an increasingly 'Mediterranean' climate similar to Iberian-Roman times.

10.2 Introduction

The reconstruction of the Holocene palaeoenvironmental history of the Central Ebro Basin is based on the analysis of 7 cores from 7 lakes, supported by 14 AMS radiocarbon dates. No single site contains a complete palaeoenvironmental record for the entire Holocene. The Hoya del Castillo probably underwent continuous sediment accumulation throughout the Holocene (from *ca.*10.Kyr BP?), but low water levels in the middle and late Holocene (after *ca.*4.6Kyr BP) caused a hiatus in the pollen record. A longer hiatus in the sediment record occurs during this time at the Laguna Guallar between *ca.*7.2-4.1Kyr BP), although here, sediment accumulation probably restarted at the same time as the Salada Pequeña (from 4.5Kyr BP). A hiatus may also interrupt the record near the base of the Laguna Salada (between *ca.*5.6-1.6?Kyr BP) (see Chapter 9, section 9.6.3). Two further AMS radiocarbon dates have been disregarded at the Salada Pequeña due to probable reworking and contamination (see Chapter 9, section 9.5.3). Sediment accumulation at the Salada Pequeña has probably been continuous from its base to the present, providing a high resolution record for the mid-late Holocene (12yr/cm), similar to the one provided by the Hoya del Castillo for the early Holocene (15yr/cm). Other sites become available for the final period of the Holocene, including the Laguna Salada (from 1.6?Kyr BP), Laguna Gallocanta (from 0.7Kyr BP) and La Estanca (from 0.5Kyr BP). No independent dating control is available for the La Salineta, although pollen evidence indicates that it probably covers the mid-late Holocene.

A summary of core correlation, dating and zones is provided in *figure 9.1.8* p156. This information has been used to plot lake type (level) and vegetation summary against time (radiocarbon years) for the six dated cores (*Figure 9.1.1* p149). A linear relationship was generally assumed to exist between time and depth, with adjustments made for suspected hiatuses. The following time zones are based around this approximate dating framework, with zonation intended as an aid to description of the main palaeoenvironmental events.

10.3 Early Holocene

10.3.1 *<9.2Kyr BP*

Environment:
Semi-desert *Ephedra distachya*-type, *Juniperus* & *Artemisia* steppe
Low groundwater, high run-off/erosion

Cores and zones represented:
Laguna Guallar: **GUA-1**
Hoya del Castillo: **CAS-1**

Terrestrial Environment

The Late Glacial in the Central Ebro Basin was probably characterised by semi-desert conditions. Low precipitation would have been more of a limiting factor on vegetation than temperature since arboreal communities of *Betula*, *Juniperus* and *Pinus* were already becoming well established at high altitudes sites in the Pyrenees after 13 Kyr BP (Montserrat Marti, 1992). Despite this developing woodland cover, a large proportion of xerophytic taxa such as Chenopodiaceae, *Artemisia* and Gramineae still remained at sites in the Pyrenees throughout the Late Glacial, particularly at locations in the Mediterranean zone away from the Atlantic (Jalut *et al*, 1992). Semi-arid conditions in the high Pyrenees would confirm even greater aridity at the opposite end of the regional precipitation gradient in the Central Ebro Basin. This was probably even more so during

Full Glacial conditions, and during the Younger Dryas (11-10Kyr BP), when aridity temporarily increased in the Pyrenees before climate conditions finally ameliorated at the onset of the Holocene.

The start of the pollen record from the Central Ebro Basin is estimated at around 9.3Kyr BP. The terrestrial pollen at this point indicates a well developed open steppe woodland of *Ephedra distachya*-type and *Juniperus*, together with *Artemisia*, Gramineae and Chenopodiaceae. This *Ephedra-Juniperus* community is almost identical to that which characterises the last phase of the glacial period (15-13Kyr BP) and Younger Dryas (11-10Kyr BP) at sites in the southern and eastern Pyrenees (Montserrat Marti, 1992; Pérez-Obiol & Juliá, 1992), as well as at Padul, 480km south (Pons & Reille, 1988). Dating control for this period for sites in the Central Ebro Basin is based on extrapolation from a date of 8855±80BP for the later peak in *Juniperus*. Although the chronology may therefore be tentative, the fact that *Juniperus* was still present in such large amounts so late into the Holocene supports the conclusion that the delayed development of the extreme xeric *Ephedra-Juniperus* community reflects the greater aridity of the Ebro Basin. This contrasts with the wetter, upland locations, where other studies have been undertaken, which by the early Holocene were beginning to see the appearance of broad leaved forest communities.

Temperatures were relatively warm in the Central Ebro Basin and unlikely to have been limiting since typical thermophilious Mediterranean taxa such as *Olea* and Evergreen Oak (*Quercus ilex*-type) occur throughout this early period at both sites. This appears to confirm the idea that climatic dryness rather than temperature was the limiting factor to vegetation development in the region during the post-glacial (Jalut *et al*, 1992).

Lake Environment

Increasing precipitation after the Late Glacial probably tipped the balance from net deflation to net accumulation within the lake basins, provoking the build up of evaporitic salts and eroded sediments from the basin catchments. The rise in groundwater levels maintained moisture levels within the lake surface sediments throughout the year, preventing them from drying out during the summer and becoming exposed to wind action.

The sediment record at the Hoya del Castillo predates the pollen record, with sediment probably accumulating from around the start of the Holocene (*ca.*10.0Kyr BP). Stratigraphic and geochemical evidence indicates that lake levels were low and ephemeral during this period (lake type 1-2). Conditions were highly arid, with poor vegetation and oxidising conditions suggested by pedogenesis and lack of pollen in the sediments of the Hoya del Castillo. Depressed LOI values also suggest low organic productivity, while catchment erosion is indicated by high carbonate values.

As lake levels gradually started to rise in the early Holocene, then so conditions became more favourable for pollen and macrofossil preservation. This is reflected in the timing of the start of the pollen record (*ca.*9.3Kyr BP), which occurred slightly earlier at the Laguna Gualiar where the lake was semi-permanent (lake type 4), than at the Hoya del Castillo where the lake was only seasonal (lake type 3).

The Laguna Guallar displays consistently deeper lake levels than the Hoya del Castillo throughout the early Holocene period, reflecting a difference that persists to the present day. This can be partly explained by the lower precipitation experienced at the Hoya del Castillo due to its location at the more arid end of the precipitation gradient across the basin. The main result of this is a lower groundwater surface within the region of the Hoya del Castillo. Reduced groundwater inputs into the Hoya del Castillo are however partly compensated for by a more developed surficial drainage system which currently feeds a small ephemeral stream that enters the lake from the west. The greater levels of surface run-off at the Hoya del Castillo has led to higher inputs of eroded material from the lake catchment and less evaporite deposition from the evaporation of mineral-rich groundwaters. Sediments deposited at the Hoya del Castillo are therefore significantly lower in sulphates and higher in detrital carbonates and other minerogenic material than sediments at the Laguna Guallar. Inwash from catchment erosion at the Hoya del Castillo has resulted in higher rates of sediment deposition in comparison with the Laguna Guallar and therefore a higher resolution record. Similarly, surface run-off at the Hoya del Castillo has sustained sediment accumulation and lake levels throughout most of the Holocene independent of changes in winter rainfall and groundwater recharge. This is in contrast with the Laguna Guallar where reduced winter recharge and lower groundwater levels in the mid-Holocene appear to have caused a hiatus in the sediment record.

10.3.2 *9.2Kyr-8.6Kyr* BP

Environment:
Juniperus thurifera woodland
Fluctuating (high-low) groundwater, low run-off

Cores and zones represented:
Laguna Guallar: **GUA-2**
Hoya del Castillo: **CAS-2**

Terrestrial Environment

By 9.2Kyr BP, the continued decline in aridity and possibly increased continentality led to the development of an extensive juniper woodland throughout the Ebro Basin, with values of *Juniperus* exceeding 50% at both the Hoya del Castillo and Laguna Guallar. This is accompanied by an increase in pollen concentration, which together with the known poor pollen dispersal of the taxa (Huntley & Birks, 1983; Stevenson, 1981) suggests a dense woodland on a regional scale. *Ephedra distachya*-type falls off markedly at this time, along with steppe indicators including *Artemisia*, Gramineae and Chenopodiaceae. This succession is in line with that shown at other sites where the *Ephedra-Juniperus* community occurs during the late-glacial, although in the Central Ebro Basin, an AMS radiocarbon date indicates the juniper peak to be firmly in the early Holocene, around 8855±80 BP. Increasing winter cold is suggested by the decline of already low levels of thermophilous Mediterranean taxa including the disappearance of *Olea*.

Pollen diagrams from sites at higher altitudes on the southern slopes of the Pyrenees (Montserrat, 1992) and in the Iberian Mountains (Peñalba, 1989; Stevenson unpublished) during the early Holocene indicate a similar cool, wet climate with woodlands of predominantly *Betula* and *Pinus* (identified as *P.sylvestris* at Quintanar de la Sierra). Sites to the west however, influenced more by the moderating influence of the Atlantic, show the establishment of deciduous oak and *Corylus*, the primary elements of deciduous oak woods (Costa *et al*, 1990; Hannon, 1985).

Speculation of the existence of a large juniper woodland once covering the Central Ebro Basin has been made by many authors (Braun Blanquet & Bolos, 1957; Ferrer, 1960; Terradus, 1986; Peréz-Obiol & Roure, 1991; Balsa & Montes, 1991). The name of the area, 'Los Monegros', is thought to have been derived from the Spanish *'monte negros*' (black hills), so called because of the dense, dark, juniper forests that once covered them. All that remains today are scattered stands of *Juniperus thurifera*, although more extensive woodlands of this species occurs at Retuerte, near the Sierra de Alcubierre to the north (Ferrer, 1960). The existence of *J.thurifera* in the area is thought to reflect the unusual montane and continental character of the climate in the Central Ebro Basin, exaggerated by the frequency of temperature inversions in the winter months (Terradus, 1986). This species differs markedly from other junipers that occur in the Ebro Basin, such as *J.phoenicea* and *J.oxycedrus* (Mateo, 1987) which are smaller and more commonly found associated with anthropogenic impact and the development of degraded Mediterranean matorral. *J.thurifera* currently has a relatively restricted distribution within the Iberian Peninsula, being mainly confined to the Ebro Basin, eastern La Mancha and the higher parts of the Iberian Cordillera. It is particularly associated with extreme continental Supra- or Oro- Mediterranean climate conditions, with a strong seasonal drought, high insolation, cold winters ($m = -7$ to -2) and a sub-humid precipitation regime (600-800mm) (Rivas-Martinez, 1988; Wengler & Vernet, 1992). This is reflected in the distribution of *J.thurifera* in the Western Mediterranean, where major communities are found principally in the Southern Alps, Atlas Mountains of Morocco and Iberian Mountains (Mateo, 1987). Away from these high altitude areas, scattered examples on the lowlands of the eastern Spanish Mesetas are thought to be relics of a much larger forest (Lopez-Garcia, 1985) that can now be shown to have persisted into the early Holocene upto at least 8.4Kyr BP. Current climate conditions on the eastern Meseta are markedly continental, but probably too warm and dry to form a *J.thurifera* climax community, even if anthropogenic impact was removed. The development of an extensive *J.thurifera* community at the onset of the Holocene therefore reflects climatic conditions on the Mesetas that were probably much cooler and wetter than present.

The origins of the Los Monegros name are unlikely to date from this early Holocene period, or from the recent past when extensive clearance removed most of the forest cover. The palaeoenvironmental record in the area is discontinuous for the late Holocene, but shows no signs of a *J.thurifera* forest to rival that of the early Holocene.

This may be an artefact of the poor pollen dispersal capabilities of juniper. Following the rapid retreat of the *J.thurifera* forests on the central steppes of the Ebro Basin after 8.4Kyr BP, large stands may still have persisted in sheltered locations on the slopes of the Sierra de Alcubierre. The poor pollen dispersal capabilities of *Juniperus* would have produced a much steeper decline in the palaeoecological record at the central lake sites following this retreat than may necessarily have been the case. It may well be that large areas of these hills were still covered by *Juniperus* until relatively recently but that their distance from the coring site meant that *Juniperus* pollen did not enter into the palaeoenvironmental record in any quantity. The persistence of *Juniperus* is indicated by a low (<3%TTP), but continuous level of *Juniperus* pollen throughout most of the Holocene palaeoenvironmental record in the Ebro Basin.

Perhaps of more interest however, is a notable increase of *Juniperus* at some sites (but not the Laguna Guallar) during the last millenium following major deforestation and the introduction of extensive grazing. The name 'Los Monegros' may therefore reflect this later expansion of *Juniperus*, which was favoured due to its resistance to grazing (see section 10.5).

Lake Environment

From the onset of the pollen record and rise in *Juniperus* at around 9.5Kyr BP to the decline of *Juniperus* at 8.6Kyr BP, lake levels were generally slightly lower than present at the Hoya del Castillo and higher than present at the Laguna Guallar. Lake levels increase with the decline in *Juniperus* after 8.6Kyr BP, although at the Laguna Guallar, fluctuations in lake level become increasingly more marked with periods of permanent deep water alternating with desiccation.

The seemingly contradictory record of high lake levels and xerophytic vegetation can be simply explained through the sensitivity of these groundwater fed lake systems to winter recharge (see Chapter 7, section 7.7). High evapotranspiration throughout the summer half of the year means large amounts of rainfall are necessary to reduce the hydrological deficit enough to cause groundwater recharge. During the winter half however, low insolation and reduced daytime temperatures result in low evapotranspiration and hence a greater likelihood of any precipitation resulting in net groundwater recharge. A continental climate with lower mean winter temperatures in the early Holocene, as suggested by the prevalence of *J.thurifera*, could account for higher lake levels without necessarily the need for a large increase in winter rainfall. Lower evapotranspiration in winter (and indeed most of the year) would lower the threshold required for hydrological surplus while annual precipitation levels could have remained much as today.

In contrast, lake levels at the Hoya del Castillo remain relatively low during this period, supporting the idea that higher lake levels at the Laguna Guallar were more a result of decreased winter (and summer ?) evapotranspiration rather than increased precipitation. Higher overall levels of precipitation would be expected to generate more catchment run-off and hence high lake levels at the Hoya del Castillo.

10.3.3 *8.6Kyr-7.2Kyr* BP

Environment:

Pinus & evergreen oak woodland

Anthropogenic (Early Neolithic?) clearance

High groundwater, high run-off

Cores and zones represented:

Laguna Guallar: **GUA-3**

Hoya del Castillo: **CAS-3**

Terrestrial Environment

By 8.6Kyr BP a rapid change to warmer winters occurs in the Central Ebro Basin resulting in the displacement of *Juniperus* in favour of *Pinus* and evergreen oak. This climatic amelioration is further suggested by the appearance of other typical Mediterranean pollen taxa including *Olea* and *Mentha*-type (*Rosmarinus officianalis*?). Although the latter Mediterranean taxa would imply some degree of summer drought stress, the occurrence of broadleaved trees such as *Corylus* and *Ulmus*, along with the replacement of *Artemisia* steppe with Esparto grassland, imply that this may not have been too severe.

The onset of this altithermal period is also marked regionally with a general increase in evergreen oak at Quintanar de la Sierra (1470m) (Peñalba, 1989) in the Iberian Mountains, and at Le Paul de Búbal (1115m) (Montserrat, 1992) in the Southern Pyrenees. Sites in Cantabrica to the west show an increasing diversification of species within the now established and evolving deciduous oak woodlands.

8.2-7.6Kyr BP Climatic regression

A short period of regression within this overall pattern of recovery has been identified at a number of sites in Iberia at around 8.2Kyr BP (Turner & Hannon, 1988). Deciduous oak is replaced by *Betula* at Sanabria Marsh (Hannon, 1985) and Laguna de las Sanguijuelas (Menendez Amor & Florschutz, 1961) in northwest Spain, and Lagoa Comprida (Janssen & Wooldringh, 1981; Van den Brink & Janssen, 1985) in Portugal, while at Orihuela del Tremedal (Stevenson, unpublished) in northeast Spain, it is *Pinus* that is replaced by *Betula*. A similar regression of oak is recorded at Valle de la Nava (Menendez Amor, 1968) and Padul (Pons & Reille, 1986), although it is not clear in the case of the latter to what degree this is statistical artefact, given that it is associated with a major increase in monolete fern spores which are also included in the pollen sum (Turner & Hannon, 1988). Evidence of a similar event at sites in the high Pyrenees is limited, although a distinctive decline in deciduous oak occurs at the low altitude site of Tourves (298m) on the French Levant (Nichol-Pichard, 1987). A significant drop in lake level about this time does not register much response in the vegetation of the Central Ebro Basin, although ample evidence of a later period of woodland disturbance occurs between 7.7-7.3Kyr BP.

7.7-7.3Kyr BP Neolithic clearance

This later disturbance event is accompanied by a distinctive peak in charcoal and increase in *Q.ilex*-type. This is shown most clearly in the Hoya del Castillo core which has a higher rate of sediment accumulation and higher resolution. Between around 7.7-7.3Kyr BP a marked increase in *Quercus ilex*-type occurs, accompanied by an equally marked decrease in *Pinus*. An attendant rise in charcoal concentration implicates fire as the principal agent in this degradation of the forest cover.

Firing may have occurred over a wide area over a very specific time period since a similar peak in charcoal is also apparent at the Laguna Guallar. An AMS radiocarbon date of 7485±80 at the onset of the charcoal curve at the Laguna Guallar correlates well with a date of 7325±65 for the end of the charcoal curve at the Hoya del Castillo, bracketing the most intense burning period.

The level of clearance, however, appears less than that recorded later on in the late Holocene (section 10.5) with little development of a juniper and sclerophyllous matorral. This may relate to a lower frequency of burning events, increased vegetation stability due to more humid conditions, or a lack of grazing pressure from livestock herding.

The event seems too discrete to have been caused by climatic factors, although convective summer rainfall may have produced an increased frequency of lightning strikes. Mid-Holocene increases in *Quercus ilex*-type pollen at other sites in the Mediterranean have been suggested as a direct result of Neolithic population pressure (Di Castri, 1981; Pons, 1981; Behre, 1988) and charcoal has been found in the sediments at the onset of these rises in *Q.ilex* (Tallis, 1991). The dates obtained for the charcoal peak in the Central Ebro Basin however suggest that this disturbance occurred at the very start of the Neolithic, and might even be considered to be Mesolithic. Few archaeological sites have been radiocarbon dated in the area and the timing of the development of Neolithic culture has not generally been based on any firm independent dating control. Commonly, the period of transition between Mesolithic and Neolithic cultures in the Western Mediterranean has been placed at around 6.5Kyr BP, but recent radiocarbon evidence indicates that the Neolithic may have begun much earlier (Guilane, 1979). The Ebro Basin contains many Neolithic sites, but relatively few of earlier Mesolithic or Palaeolithic communities (Benavente, 1987; Benavente *et al*, 1991). A radiocarbon date from a cave site in Velderpino (Cuenca) indicates that Neolithic communities could have existed in north-east Spain from as early as 8.0Kyr BP (Guilane, 1979).

Palaeoecological evidence of early Neolithic anthropogenic disturbance on the Barcelona plain has been described by Riera Mora (1990) as starting at 7.0Kyr BP, accompanied by small increases in charcoal (Riera & Esteban, 1993). In Southern France, charcoal was found by Triat Laval (1978) in association with anthropogenic indicators at Courthézon (Provence) at 7350±170 BP, with similar clearances found by Planchais (1985, 1987) at St Cyprien (Roussillon) around 6900 BP, and at Palavas (Provence) at 6780±80 BP.

The open woodlands and shallow lakes of the Central Ebro Basin would have offered an attractive resource to any prehistoric community at this time, as well as providing a natural migration route inland from the coast along the Rio Ebro. The agricultural reasons underlying the clearance of woodland are, however, more difficult to resolve. Cereal size pollen grains occur along with the fire event but it is difficult to accredit these to cultivation since they can easily be confused with naturally occurring wild grasses such as *Lygeum spartum*. The increase in occurrence of such grasses would reflect the natural retreat of woodland and extension of natural grassland through anthropogenic burning of the forest cover (Pyne, 1993). An overall reduction in arboreal pollen of 20%TTP (Total Terrestrial Pollen) during this clearance period compares with that of 30%TTP during the Late Bronze/Iberian Age and 60%TTP during Visigothic times (see section 10.5).

Although the overall level of clearance was less than the late Holocene Bronze Age and Visigoth period, the nature of the event draws parallels with Iberia/Roman and late Medieval/Modern intensive settled agriculture. The less extensive clearance involved indicates that burning of the woodland during this early Neolithic event was either less extensive or less frequent than later times. Burning may have occurred only every 30-50 years, allowing extensive regeneration before the next fire event (Trabaud *et al*, 1993). The higher levels of charcoal produced (approximately double late Holocene levels) cannot be explained by differences in sediment accumulation rates, and probably reflects the greater availability of combustible material in the Neolithic woodlands.

The high levels of charcoal, evergreen oak, large cereal size Gramineae (>50μm), *Plantago* and *Olea* are all characteristic of periods of settled arable agriculture (Iberia/Roman: zone PEQ-3, late Medieval/Modern: zones PEQ-6; GAL-3; EST-4) and not pastoral agriculture (Bronze Age: CAS-4; PEQ-1, Visigoth: PEQ-5; LAG-5, GAL-1; EST-1). Archaeological evidence indicates that Neolithic farming (including cereal cultivation) was already established around the coasts of eastern and southern Spain just before 8.5Kyr BP, and by 7.5Kyr BP had reached large areas of inland Spain, including the Ebro valley (Harrison, 1994). It seems possible therefore that early Neolithic farming was established in the Central Ebro Basin between 7.6-7.3Kyr BP, the end of which coincided with a sharp fall in lake levels and increasing aridity. Prior to this, high lake levels indicate that the climate was probably particularly favourable for agriculture, while the lakes themselves would have ensured food diversity, with abundant wildfowl, and although mostly too saline for fish, a useful supply of salt.

Lake Environment

Lake levels between 8.6-7.2Kyr BP reach their maximum within the Holocene at the two study sites. The warm winter temperatures indicated by the vegetation record suggest that this can no longer be explained by reduced winter evapotranspiration, and must have related to increased winter precipitation. Summer precipitation was also probably high, but with sufficient drought stress to maintain a Mediterranean flora. An overall increase in winter precipitation would have generated high levels of run-off, as well as groundwater recharge. This is supported by evidence of much higher lake levels at the Hoya del Castillo than in the previous period.

High lake levels in the early Holocene are characteristic of endoreic lakes throughout the world, reflecting a large scale surplus in the global moisture budget (P-E) (COHMAP, 1988). High lake levels in the Western Mediterranean during this period have been reported by Harrison & Digerfeldt (1993) in Iberia, Italy and Greece, Lamb *et al* (unpublished) in Morocco, and Rognon & Williams (1977) in the temperate margins of North Africa.

8.2-7.6Kyr BP Climatic regression

A period of low lake level between about 8.2-7.6Ka BP interrupts this pattern of generally high lake levels. This occurs most clearly at the Hoya del Castillo although very high sulphate levels and lenticular gypsum at the Laguna Guallar indicate rapid evaporation and desiccation. A similar lake level regression has been recorded in many lakes around this time, particularly in Northern Africa (Street-Perrott *et al*, 1985; Roberts *et al.*, 1994). The timing of lake level regression in the Ebro Basin (*ca.*8.2-7.6) is slightly earlier than that at Tigalmamine (*ca.*7.8-7.3Kyr BP) in the Moroccan Atlas (Roberts *et al.*, 1994). But compares with a similar oscillation at Lagoa Comprida in the Serra Estrella, Portugal (Harrison & Digerfeldt, 1993). The cause of this deviation may relate to an influx of cold water into the Atlantic following the final collapse of the Laurentide ice sheet (Street-Perrott & Roberts, 1983; Roberts, 1990), or alternatively, by the Broecker *et al.* (1990) quasi-cyclic oceanic salt oscillator (Roberts *et al.*, 1994).

10.4 Middle Holocene

10.4.1 *7.2Kyr-4.6Kyr* BP

Environment:
Pinus woodland
Low groundwater, low run-off

Cores and zones represented:
Laguna Guallar: Hiatus
Hoya del Castillo: CAS-4
Laguna Salada: SAL-1

Terrestrial Environment

The rise of pine

The disturbance period ends shortly after 7.3Kyr BP as lake levels begin to fall rapidly and *Pinus* starts to replace *Quercus ilex*-type. Other Mediterranean taxa also disappear along with deciduous species, suggesting a climate shift to more arid conditions. The establishment of a Mediterranean pine forest and overall reduction in non-arboreal vegetation may also reflect a reduction in anthropogenic disturbance.

Again, the Hoya del Castillo provides the clearest record with the *Pinus* peak identified at around 6.1Kyr BP. High *Pinus* values of over 80%TTP also occur at this time at the Laguna Salada, supported by a radiocarbon date of 5725±60BP. Unfortunately, the overall fall in lake levels interrupts the record at the Laguna Guallar causing a hiatus for the duration of the mid-Holocene.

Throughout most of the rest of Iberia, this mid-Holocene period is characterised by the widespread expansion of mixed oak forest (Menendez Amor & Florshutz, 1961; Vernet & Thiebault, 1987; Costa *et al*, 1990; Lopez Garcia, in print). Mid Holocene peaks in *Pinus* are restricted to sites in the Iberian mountains and along the eastern coast where *Pinus* has always occupied a more prominent role in the vegetation mosaic. *Quercus* is replaced by *Pinus* at coastal sites in the east between 6.8-6.2Kyr BP, including the Barcelona plain (Rierra, pers.comm.), Torreblanca (Castellon) (Menendez Amor, 1961a) and Ereta del Pedregal (Valencia) (Menendez Amor & Florschutz, 1961b), before *Quercus* re-establishes itself after *ca*.6.0Kyr BP. Within the Iberian mountain chain, *Pinus* rises to a mid-Holocene peak at around the same time at Orihuela del Tremedal (Stevenson, pers.comm.), Quintanar de la Sierra (Penalba, 1989), and further west in the Cantabrian mountains at Sanabria Marsh (Hannon, 1985). *Betula* also increases at the Orihuela del Tremedal at this time, between 6100±80 BP and 5660±60 BP (Stevenson, pers.comm.), supporting the idea of a shift to cooler conditions.

While the upland areas of the Iberian and Cantabrian mountains were dominated by a montane pine forest composed largely of *P.sylvestris*, the Ebro Basin at this time was probably covered by a lowland Mediterranean forest of *P.halepensis*. Forests of *P.halepensis* are typical of the arid southern Mediterranean zone, particularly on thin calcareous soils (Le Houérou, 1981) such as those of the Ebro Basin. This would correspond with the studies of charcoal by Vernet & Thiebault (1987), who found *P.halepensis* as the dominant woodland species at sites along the coastal areas of eastern Spain at this time.

Surface sample studies in the Ebro Basin (Chapter 8) also indicate that lowland Mediterranean *Pinus* forests are characterised by a lack of pollen from attendant deciduous tree taxa. Is is therefore significant perhaps that deciduous taxa ('sub-Mediterranean' in the phytoclimatic summary vegetation classification) virtually disappear during the mid Holocene *Pinus* rise.

The reason for the rise in prominence of *Pinus* in the Central Ebro Basin during the mid Holocene is not entirely clear. Lake levels indicate an increase in aridity to which *P.halepensis* would be highly adapted, however this interpretation does not necessarily fit with the decline in steppe. Increasing aridity would have brought about a decline in woodland cover, not a net increase. A possible explanation for this might be related to a decline in anthropogenic disturbance which had maintained a large area of steppe during the preceding pluvial climatic regime. Alternatively, the distribution of rainfall may have become more monsoonal, with wetter summers and drier winters (hence reducing groundwater recharge). An overall reduction in rainfall and shift to cooler winters would also have favoured pine against competition from sclerophyllous vegetation, although the lack of *Juniperus* may indicate that conditions did not become too cold. The advantage of the latter explanation of a decline in Mediterranean climate conditions and summer drought stress (even if drier overall) would be that it would also fit with the overall pattern of expansion of deciduous oak in the more humid parts of Iberia at this time.

The decline of pine

The decline of *Pinus* after 5.6Kyr BP in the Central Ebro Basin is part of an overall regression in woodland cover and increase in grass steppe. Charcoal values remain low throughout this period, suggesting that this represented a change in climate and not anthropogenic deforestation. The reappearance of sclerophyllous Mediterranean taxa such as *Quercus ilex* and *Olea* could indicate a return to Mediterranean climate conditions, with an increase in summer drought stress.

The deciduous oak woods of the mid Holocene are widely recorded as being replaced by sclerophyllous woodland throughout the Western Mediterranean at this time, between 6.0-4.0Kyr BP (Beug, 1982; Vernet & Thiebault, 1987; Pons & Reille, 1988; Mateus, 1992; Riera-Mora & Esteban-Amat, 1994). Overall tree cover also declines during this period in the Mediterranean region (Hempel, 1987). At high altitude in the southern and eastern Pyrenees, *Corylus*, *Quercus* and *Ulmus* are replaced by *Abies* and *Fagus* (Perez Obiol, 1988; Montserrat Marti, 1992).

The relative role of man or climate in bringing about this change is the subject of much debate. Evidence from the Central Ebro Basin indicates that woodland cover and lake levels declined over this period, while charcoal values remained low. *Olea* and cereal-size Gramineae re-appear, but these could well be elements of the natural vegetation which also occur at similar values as early as 9.3Kyr BP. A trend to drier Mediterranean conditions with increased summer drought stress appears to provide the most appropriate explanation. This would have favoured sclerophyllous vegetation while also enlarging the area under steppe without necessarily any anthropogenic interference.

Lake Environment

A rapid decline in lake level at both the Hoya del Castillo and Laguna Guallar indicates a reduction in winter rainfall at around 7.3Kyr BP. The fall in lake level is slightly earlier than for other (non-endoreic) lakes in Western Mediterranean (Harrison & Dingerfeldt, 1993), which decline at around 6.0Kyr BP. This early fall in lake level is however in accordance with the observation of Harrison & Dingerfeldt (1993) that lakes in the Western Mediterranean responded earlier than those in the east. A later decline in lake level does however occur at the Hoya del Castillo at around 4.6Kyr BP, with a change from seasonal to ephemeral lake conditions.

The lowering of the groundwater table at 7.3Kyr BP probably caused the cessation of evaporite deposition at the Laguna Guallar, resulting in a hiatus in the stratigraphic record that lasted until the late Holocene. Evidence from the Hoya del Castillo that lake levels continued to decline into the mid Holocene could also explain a sedimentary hiatus at the Laguna Salada between zones SAL-1 and SAL-2, dated soon after 5725±60 BP. Both these lakes currently contain deeper water than the Hoya del Castillo, indicating that they have a larger groundwater catchment and hence a larger 'amplifier' effect (chapter 7, section 7.7). The result of this is to create a greater amplitude of lake level change than lakes with smaller groundwater catchments, resulting in lower lake levels when conditions are arid, and higher lake levels when conditions are more humid. In contrast, deposition continued at the Hoya del Castillo throughout much of the Holocene as a result of the greater contribution from run-off within this catchment. Although groundwater levels were low, the larger surficial drainage system of this lake maintained water levels, and probably more importantly, a supply of sediment.

The lack of response of these two lake systems to later fluctuations in lake level recorded at the Salada Pequeña may relate simply to the fact that later increases in lake level were simply not on the same scale as those earlier on in the Holocene. The fact that the Salada Pequeña is at the less arid end of the precipitation gradient may support this idea. However, all lakes record an increase in lake level within the last few hundred years that appears to be relatively minor compared to the Iberian-Roman pluvial (see later) registered only at the Salada Pequeña. Both the Hoya del Castillo and Laguna Guallar appear to have had their hydrological response de-sensitised during the mid Holocene, which only recently has been reversed. One explanation could be related to the development of a calcrete layer evident in the soils of the central plains. Changes in the distribution of precipitation (higher storm frequency, lower overall precipitation) in the mid Holocene may have encouraged formation of a calcrete layer which would then have restricted further groundwater recharge. Calcrete layers are also reported to have formed in south east Spain between 5.1-4.6 BP (Cuenca & Walker, 1986).

10.4.2 *4.6Kyr-3.4Kyr* BP

Environment:
Open *Pinus* woodland with *Q.ilex* and grass steppe
Limited pastoral agriculture, high erosion
Low groundwater, high run-off

Core and zones represented:
Laguna Guallar: **Hiatus**
Hoya del Castillo: **CAS-5** (no pollen)
Laguna Salada: **Hiatus**
Salada Pequeña: **PEQ-1**

Terrestrial Environment

The pollen record at the Hoya del Castillo ceases at around 4.6Kyr BP following a further drop in lake level and consequent increase in oxidation within the sediments. Continuity is provided instead at the Salada

Pequeña whose basal sediments began accumulating from around 4.0Kyr BP. It is not clear why the Salada Pequeña should start accumulating sediment at this point, although deforestation could have changed the hydrological balance of the basin (see Laguna Salada in section 10.5), or increased the flow of sediment into the lake from erosion. The problem with the former, however, is that later changes in woodland, including full recovery of the woodland cover, do not correlate well with changes in lake level. Alternatively, climate change could have brought about an increase in lake level after low lake levels in the mid Holocene had caused the loss of early Holocene sediment through deflation.

The vegetation landscape at the Salada Pequeña at *ca.*4.0Kyr BP is similar to that found at the Hoya del Castillo at around 4.6Kyr BP, with an open *Pinus* woodland (although with less *Quercus ilex*-type), grass steppe and low *Artemisia*. Charcoal levels are low and although reduced in size, the woodland environment appears relatively undisturbed with few matorral indicators and relatively low charcoal.

In contrast, the openland environment appears much more disturbed with high levels of Compositae. Evidence of extensive catchment erosion is supported by high carbonate and trace metal levels (particularly potassium). Mineral magnetic measurements by Macklin *et al* (1994) on a correlated core from the same site indicate that this period was marked by erosion of catchment subsoils and bedrock, rather than topsoil.

The lack of cultivation indicators and low charcoal values suggest low levels of intensive agriculture during the Bronze Age, with an economy based primarily on livestock and pastoralism. This is in marked contrast to the early Neolithic disturbance shown at the Hoya del Castillo (zone CAS-3), and the Iberian/Roman period that occurs later on at the Salada Pequeña (zone PEQ-3). Both these episodes show high levels of charcoal, evergreen oak, large cereal size Gramineae (>50µm), *Plantago*, *Olea*, and, at the Salada Pequeña, *Juglans*. Harrison (1985) has identified this period of herding and pastoralism throughout Spain during the Bronze Age as the 'Secondary Products Revolution' or 'Policultivo Ganadero' (4.0-2.6Kyr BP). Archaeological evidence from the Central Ebro Basin confirms this theory, with detailed site excavations at Moncín (4.0-3.2Kyr BP) revealing extensive numbers of animal bones from hunting and livestock, but little evidence of plant cultivation (Harrison, 1994).

Woodland clearance in the Bronze Age is shown by the pollen record at the Salada Pequeña to have stabilised at around 65%TTP by 4.0Kyr BP. The woodland cover then remained at this level for the following 2.2Kyr, with further clearance not taking place until Visigothic and Muslim times (after 1.4Kyr BP). The onset of the decline in woodland cover in the Central Ebro Basin occurred at around 5.0Kyr BP, and coincides with the onset of a period of alluviation in the nearby Rio Regallo (Macklin *et al.*, 1994). The Salada Pequeña also indicates severe catchment erosion from at least 4.0Kyr BP, but does not suggest intense anthropogenic disturbance. Livestock grazing may have helped decrease the amount of woodland cover, but this was not intensive, and is unlikely to have destabilised the soil cover. The evidence for a possible climate cause is dealt with in the next section, but suggests an increasingly irregular and unpredictable rainfall regime. This may also help explain why a Bronze Age culture developed dependant on pastoralism, when an earlier and less advanced Neolithic culture was based on arable agriculture.

A change in the rate of erosion about this time may have brought about a change in the nature of sedimentation at both the Hoya del Castillo and the Laguna Guallar. In the case of the Laguna Guallar, this may have caused sediment to slowly start accumulating again. A change in the nature of the sediment being deposited is clearly discernible towards the top of both cores, shown by a marked increase in carbonate. Provisional analysis of other cores taken from lakes in the Los Monegros system indicates that this feature is common to them all, although the actual depth at which carbonate increases varies with sedimentation rate.

The charcoal record at both the Hoya del Castillo and Laguna Gualllar also provides further evidence that the timing of this stratigraphic change is contemporaneous between sites. The late Holocene increase in charcoal can be clearly discerned at both sites occurring a short time after the increase in carbonate deposition. The late Holocene rise in charcoal at the Salada Pequeña occurs at around 2.8Kyr BP, similar to the 2.7Kyr BP calculated age of the rise in charcoal at the Hoya del Castillo, determined from the linear extrapolation of the accumulation rate. Using the same principle, the timing of the increase in carbonate at the Hoya del Castillo is calculated at 4.0Kyr BP, close to the 4.0Kyr BP calculated for the onset of sediment accumulation at the Salada Pequeña. No comparable increase in carbonate is shown within the Salada Pequeña core, although the carbonate content of 10-15% is similar to that recorded at the top of the Hoya del Castillo core. The lack of carbonate rise at the Salada Pequeña may be a result of differences in geology between this site and the Hoya del Castillo-Los Monegros area, however, the quantity of carbonate within the Salada Pequeña core and the calculated timing of the onset of the carbonate rise suggest that the reason the rise is missing is because sediment accumulation at the Salada Pequeña occurred at, or immediately after, the carbonate rise found elsewhere.

Surface samples of soil taken from the slopes of all the lake basins cored, typically contained carbonate levels of 40-50%, while sulphate levels were less than 5%. Carbonate in hypersaline lakes in the Ebro Basin is generally a reflection of sediment inwash from catchment erosion since dilution rarely occurs to the point at which precipitation of dissolved carbonates occurs (chapter 4, section 4.6). The onset of top-soil erosion in the Late Bronze Age therefore seems the most likely explanation of the increase in carbonate. Magnetic susceptibility measurements on sediments from the Salada Pequeña suggest that intense soil erosion was indeed occurring at this time (Stevenson *et al*, 1991).

The increase in carbonate itself represents a step-wise change with few notable fluctuations once established. It therefore probably represents a threshold change in the nature of catchment conditions, perhaps linked to the loss of a protective humic layer (O horizon) to expose the mineral rich subsurface layers beneath to erosion. All eroded sediments from this point onwards would therefore contain an unusually high carbonate content compared to previously eroded sediments.

The reason for this dramatic change in catchment stability is undoubtedly connected to the loss of protective woodland cover. However, this had already been occurring progressively since at least 5.2Kyr BP at the Hoya del Castillo, along with declining lake levels, without any notable change in carbonate levels. Anthropogenic disturbance at this time appears to have been limited, with low charcoal and ruderals. The environment at the onset of the record at the Salada Pequeña however is very disturbed, with large amounts of Compositae. A climate change to drier conditions may have been responsible for the decline in woodland cover, while an increase in storm intensity/frequency may have produced periods of high intensity precipitation sufficient to cause erosion of the exposed soil surface.

An actual example of this was observed in June 1992 at the Laguna Salobral, near Cordoba in Southern Spain (see Recio-Espejo *et al*, 1985, for further site details). Record levels of torrential rain had affected Andalusia in the late Spring which had left water remaining in this shallow seasonal lake into early summer. A previous site visit in April (Reed, pers.comm.) had shown the lake to contain a thick algal mat, which by June had been covered by 12cm of fine red-brown clay sediment. The origin of this sediment was clearly evident from the fresh rills and scar marks on the surrounding slopes, at the bottom of which were large areas of reeds flattened by the force of the run-off waters. Interestingly, erosion was only evident on the recently ploughed arable land and not under the olive groves that covered the majority of the catchment. From the large pile of olive tree stumps in the corner of the field it was evident that it had only recently been converted to arable, and until recently was similarly covered in olive trees. Loss of even this relatively light tree cover (with no shrub layer) appeared sufficient to expose the land to severe erosion. Examination of a 4m core taken from the centre of the lake could find no similar episodes of such extreme catchment erosion. Carbonate analysis of the sediment above and below the algal mat showed that the eroded sediment contained much higher levels of carbonate (16.5%dw) compared to normal (9.8%dw).

High carbonate levels also occur during the earliest period of sedimentation at the Hoya del Castillo. Provisional analysis of cores from lakes in Los Monegros confirm that this is a feature common to other lakes in the area with an early Holocene record. Pollen evidence indicates that woodland cover was generally low at this time, with presumably low or absent anthropogenic disturbance. Levels of arboreal pollen during this early Holocene high carbonate (erosion) period at the Hoya del Castillo are around 65%TTP. This is similar to levels at the Salada Pequeña during the late Holocene high carbonate (erosion) period, but still less than the point at which arboreal pollen had declined to at the Hoya del Castillo prior to the rise in carbonate. It may therefore require a reduction in woodland equivalent to 65%TTP (or less) arboreal pollen before top-soil erosion will occur. This suggests that woodland cover may be as equally important as precipitation regime in causing the onset of top-soil erosion, with most erosion occurring under low precipitation (and low lake level) conditions. Clearly the feedback between precipitation and vegetation cover is important in determining the occurrence or otherwise of top-soil erosion.

Lake Environment

Falling lake levels and oxidation of pollen at the Hoya del Castillo from 4.6Kyr BP caused a short break in the environmental record before sediments started accumulating in the Salada Pequeña at around 4.0Kyr BP. A similar regression is recorded at Tigalmamine in Morocco at around 4.4-4.8Kyr BP (Roberts *et al*, 1994), and at sites in the Iberian Peninsula studied by Harrison & Digerfeldt (1993) at 4.0-5.0Kyr BP .

Rising lake levels at the Salada Pequeña after 4.0Kyr BP probably tipped the balance between net deflation and accumulation. The lake at this stage was relatively shallow and seasonal, but with unusually low sulphate levels. The low salinity of the lake waters suggests that the lake was fed not by high-salinity groundwater, but by low-salinity run-off waters. The lake today is also seasonal, but with much higher sediment sulphate levels reflecting a much higher contribution from saline groundwater.

Increasing summer storm frequency could account for high inputs of freshwater storm run-off, but limited groundwater recharge. This could also explain the high levels of catchment erosion despite a relatively well vegetated landscape and low level of anthropogenic disturbance. Overall levels of precipitation were probably slightly less than today, with a semi-arid vegetation dominated by *Pinus* and grass steppe, with very few sclerophyllous or deciduous taxa.

10.4.3 *3.4Kyr-2.7Kyr* BP

Environment:
Open *Pinus* woodland with *Artemisia*
Low groundwater, high run-off?

Cores and zones represented:
Laguna Guallar: **GUA-3**
Hoya del Castillo: **CAS-6** (no pollen)
Laguna Salada: **Hiatus**
Salada Pequeña: **PEQ-2**

Terrestrial Environment

A drier lake phase occurs between around 3.4-2.7Kyr BP, coincident with an increase in *Artemisia* and Mediterranean taxa such as *Quercus ilex*-type and *Olea*. While the increase in Mediterranean taxa is temporary, the rise of *Artemisia* is sustained for the rest of the Holocene (apart from 1.8-1.4Kyr BP when pine recovers) and closely parallels the rise in charcoal. High values of *Artemisia* also characterise the very earliest phase of the Holocene when the climate was much more arid and continental, and top soil poorly developed. The late Holocene appearance of *Artemisia* is more strongly connected with environmental degradation, matorral development and increased soil xericity caused by top-soil erosion.

Mediterranean and deciduous taxa later disappear as *Pinus* eventually dominates the arboreal component by 3.2Kyr BP. The development of a monospecific woodland of *Pinus* is in agreement with the observed drop in lake level, and confirms a climatic shift to more arid conditions. Signs of anthropogenic activity remain restricted, although charcoal values later start to increase. The continued pattern of high catchment erosion and low anthropogenic disturbance suggests that the pattern of high summer storm frequency was maintained throughout this period.

The onset of arid conditions indicated by the predominance of pine and the fall in lake level coincides with the decline of Bronze Age settlements in the Central Ebro Basin. Harrison (1994) reports that in the area of Muela de Borja, near Zaragoza, settlement density peaked between 4.0Kyr BP and 3.1Kyr BP. After this period, decline set in, with the final abandonment of the area occurring around 3.0Kyr BP.

Lake Environment

A clear drop in lake level at the Salada Pequeña occurs at around 3.4Kyr BP with a change from seasonal to ephemeral lake conditions. Prolonged desiccation during the summer months allowed the colonisation of the lake surface by Chenopodiaceae which rise to over 70% total pollen. The abruptness of this change appears to indicate that this was not due to hydroseral succession as a result of progressive basin infilling by the erosion of catchment sediments, but was in fact a climatic change to even drier winters. This conclusion is supported by the vegetation record which shows an increase *Pinus* and decrease in deciduous and Mediterranean taxa. Low sediment sulphate levels also continue to indicate that groundwater levels were low (and hence winter rainfall).

Again, this regression in lake level parallels a similar one identified at Tigalmamine in Morocco (3.5Kyr BP), as well as forming part of a more general pattern identified throughout northern Africa at this time (Roberts *et al*, 1994). Meanwhile, other lakes studied by Harrison & Digerfeldt (1993) in the Iberian Peninsula remain at a low level after declining at around 4.0-5.0Kyr BP.

10.4.4 *2.7Kyr-1.8Kyr BP*

Environment:
Quercus ilex woodland and *Artemisia*
Intensive but localised arable agriculture
High groundwater, low run-off

Cores and zones represented:
Laguna Guallar: **Hiatus**
Hoya del Castillo: **CAS-5** (no pollen)
Laguna Salada: **Hiatus**
Salada Pequeña: **PEQ-3**

Terrestrial Environment

The dry lake phase ends with a dramatic rise in lake level dated to 2675±60 BP. This is accompanied by an increase in *Quercus ilex*-type and the appearance of other Mediterranean taxa, marking a change to a warmer climate with wet winters and dry summers. This climatic amelioration coincides with a dramatic increase in anthropogenic activity. Clearance and burning activity is intensified with high peaks in the charcoal curve together with matorral development indicated by *Cistus*, Ericaceae and *Mentha*-type pollen. Increasing cultivation is suggested with the appearance of *Olea, Juglans* and large cereal-size Gramineae (>50µm). This is the first time *Juglans* is found in the pollen record and corresponds with its appearance on the Catalan coastal plain along with Greek and Phoenician traders (Riera-Mora & Esteban-Amat, 1994).

This period is associated with a considerable increase in the number of settlements in the area during the Late Iron Age and Iberian Age (van Zuidam, 1975; Benavente *et al*, 1991). The location of some of these settlements in proximity to endoreic lakes in the area has led to the suggestion that these currently seasonal saline lakes contained more permanent fresher waters around this time (Benavente, 1984). This hypothesis is confirmed by this study, which clearly indicates high water levels around this time.

The onset of favourable climatic conditions not seen since the early Holocene coincides with the first major discernible period of economic expansion in the area. Harrison (1994) has identified three periods of regional economic growth in Iberia in the Bronze Age, starting around 3.7Kyr BP in eastern Andalusia and the southern Meseta, 3.4Kyr BP in the northern Meseta, and 2.7Kyr BP in the Ebro Basin. The late development of the Ebro Basin may reflect a delay in the onset of favourable climatic conditions in the region, which was much drier during these earlier periods.

Interestingly, the evident increase in settlement number and density in the Ebro Basin, together with palaeoecological evidence of increased anthropogenic activity, does not appear to have occurred at the expense of woodland cover. The total arboreal percentage at the Salada Pequeña remains much as it was at the onset of the record around 4.5Kyr BP. Part of the explanation for this possibly relates to the high percentage of *Pinus* pollen represented in the sum, since the high pollen productivity and dispersal capabilities of pine probably make it a relatively insensitive indicator of forest thinning activities. This would however make the later reductions in *Pinus* pollen an ever more dramatic indicator of deforestation. Cultivation practices during this period are likely to have involved small scale forest clearance on the flatter, more fertile ground in the immediate vicinity of settlements. Rocky, steeper slopes would have remained with their original forest cover, similar to the *Pinus halepensis* woods of the Los Monegros uplands. Favourable climatic conditions together with a still relatively fertile soil cover probably allowed a dramatic increase in population through agricultural intensification, and arable cultivation in particular. Technological innovation was probably important at this time, with the application of the ox driven plough, new cereal and fruit crops as well as new irrigation techniques. Extensive evidence of Iberian dry farming including check dams and irrigation channels occurs at the Rio Regallo, 8km north-west of the Salada Pequeña. It appears unlikely that extensive pastoral agriculture was being employed since this would undoubtedly have led to more intense and permanent forest clearance.

The nature and intensity of agriculture during this period corresponds closely with the pattern found by Riera-Mora & Esteban-Amat (1994) along the Catalan coastal plain. Archaeo-botanical and pollen evidence indicates intensive agriculture during the Iberian Age in the region, with widespread cereal and fruit cultivation. This corresponds however with relatively little change in the AP:NAP ratio, suggesting arable agriculture was developed without the extensive woodland clearance that was to characterise the late Holocene.

Despite an evident increase in precipitation, catchment erosion around the Salada Pequeña declines during this period. This coincides with river alluviation and hillslope fan accumulation recorded throughout the

Ebro Basin between 2.7-2.2Kyr BP (Gutíerrez-Elorza & Peña-Monné, 1989; Julian *et al.*, 1991) and 2.5-1.8Kyr BP (van Zuidam, 1975). At the nearby Rio Regallo, studied by Macklin *et al.* (1994), alluviation continued from early Bronze Age times through to *ca.*1.7Kyr BP, interrupted only by a brief period of incision between 2.5-2.4Kyr BP.

Lake Environment

The Salada Pequeña is currently a seasonal hypersaline playa lake, however during this humid phase, from 2.7-1.8 Kyr BP, it became permanent and reached depths of over 2.5m. This could only be achieved through large inputs of saline groundwater which is reflected in high sulphate levels within the sediments. Unusually however, macrophyte evidence of *Potamogeton pectinatus* seeds indicates periods of shallow, low salinity water within the lake. This contradicts the vegetation record which suggests long, warm, dry summers with high evapotranspiration likely to quickly concentrate lake waters and raise water salinity. The calculated maximum depth however is close to the 3.0m level at which lake overflow would occur into the Salada Grande, located at an altitude 7.0m below the Salada Pequeña, and within the same hydrological basin. It appears possible therefore that unlike the Hoya del Castillo and Laguna Guallar, overflow did occur in the Salada Pequeña during wet phases allowing some degree of 'flushing' of lake salts. This process may have delayed the lakes progression to a saline lake since *Ruppia maritima* var *maritima* does not occur in any quantity until after 2230±50, when *P.pectinatus* disappears.

A general rise in lake levels just before 2.0Kyr BP is registered at many lakes in northern Africa (Roberts et al, 1994), and Iberia (Harrison & Digerfeldt, 1993), although to lower levels than those experienced in the mid or early Holocene.

10.5 Late Holocene

10.5.1 *1.8Kyr-1.4Kyr BP*

Environment:
Re-establishment of dense *Pinus* woodland
Little anthropogenic disturbance
High groundwater, low run-off

Cores and zones represented:
Laguna Guallar: **Hiatus**
Hoya del Castillo: **CAS-6** (no pollen)
Laguna Salada: **SAL-2?**
Salada Pequeña: **PEQ-4**

Terrestrial Environment

The high lake level phase lasted until around 1.8Kyr BP, whereupon lake levels fell rapidly and pine woodland expanded considerably. Almost complete recovery of the woodland cover occurred, with values of *Pinus* pollen reaching over 90% TTP, similar to the mid-Holocene. Signs of anthropogenic activity are limited and almost complete depopulation of the area appears to have occurred at this time, with much reduced charcoal levels and only the occasional cereal-size Gramineae.

The rise of *Pinus* (*P.halepensis*) and fall in lake levels is similar to that of the mid Holocene, with a return to more arid conditions. This regression in climate appears to have been disastrous for agriculture and was undoubtedly accompanied by social and economic upheaval, causing rapid depopulation.

Archaeological evidence indicates that there was a considerable reduction in settlement density during Roman times around the Salada Pequeña (Benevante *et al*, 1991), and in the Ebro Basin generally. This has been interpreted by Harrison (1988) as a result of Roman political strategy to gain control over the indigenous population by gathering them into fewer, more easily controlled settlements. However, rural depopulation may also have been encouraged by the consistent failure of crops and cropping techniques with increasing aridity. A climate change to drier, and possibly cooler, conditions would have resulted in an increased frequency of spring frosts resulting in damage to fruit crops, while late spring rains could have devastated the winter wheat harvest.

Despite this shift to drier conditions, the basin catchment remained stable with little erosion. Without anthropogenic disturbance, the natural recovery of pine woodland appears to have successfully maintained catchment stability. Elsewhere, on slopes and in river systems filled by sediment that accumulated during the previous pluvial period, the change to a more arid climate is marked by the the onset of incision (van Zuidam, 1975; Gutíerrez-Elorza & Peña-Monné, 1989; Julian *et al.*, 1991; Macklin *et al.*, 1994).

Lake Environment

Lake levels at the Salada Pequeña remain seasonal or ephemeral after falling from their high point at around 1.8Kyr BP. The re-establishment of forest cover is not accompanied by any particular response from the hydrological system other than to confirm the climatic shift to drier conditions suggested by the establishment of a monospecific *P.halepensis* woodland. High sulphate levels indicate that groundwater levels remained sufficiently close to the surface to allow the evaporation of mineral salts. The height of the groundwater distinguishes this period of ephemeral/seasonal lake water from the similar earlier period between 4.0-2.7Kyr BP at the Salada Pequeña. The latter reflected high inputs of low-salinity runoff waters sustaining a submerged vegetation including *Potamogeton*, and an emergent vegetation of *Scirpus/Phragmites* and *Typha*, intolerant of high water salinity. This later period however sees the establishment of a playa lake with *Ruppia* alone, sustained instead by high salinity groundwater flows. This would imply that the distribution of annual rainfall was significantly different between the two periods. Groundwater recharge is particularly sensitive to winter rainfall and is best maintained by a Mediterranean climate with rainfall concentrated in the winter when temperatures, and therefore evapotranspiration, are at their lowest. Rainfall that could maintain lake levels without causing groundwater recharge would have to be concentrated in the summer to buffer against high temperatures and evapotranspiration. This could also be achieved through short periods of intense rainfall that would not allow the soil to reach capacity and permit percolation into the aquifer.

The period 2.6-0.0 can therefore be characterised by a semi-arid Mediterranean climate with wet winters and dry summers (high groundwater, high/low runoff), while the period <4.0-2.7Kyr reflects a more monsoonal regime with dry winters and stormier summers (low groundwater, high runoff).

10.5.2 *1.4Kyr-0.4Kyr BP*

Environment:
Open Juniper matorral with Pine and *Artemisia*
Major deforestation, extensive grazing
Low groundwater, high run-off

Cores & zones represented:
Laguna Guallar: **GUA-4**
Hoya del Castillo: **CAS-6** (no pollen)
Laguna Salada: **SAL-3**
Salada Pequeña: **PEQ-5**
Laguna Gallocanta: **GAL-1**
La Estanca: **EST-1**

Terrestrial Environment

The woodland recovery at the Salada Pequeña lasts only to around 1.4Kyr BP, when rising charcoal values coincide with rapid deforestation. During this clearance period, the arboreal pollen contribution declines from 90%TTP, to only 40% TTP by 1225±50 BP, compared to a minimum of 60%TTP before the reforestation period. A similar rapid deforestation is also recorded at the Laguna Salada, although the dating of this event is less secure.

The onset of major deforestation during Visigothic times, between 1.5-1.2Kyr BP, can be identified in many pollen diagrams throughout Spain. One indication of the extent of these clearances is the fact that many mountain sites experience their first loss of woodland since the onset of the Holocene (Montserrat, 1992; Vasquez Gomez, 1992; Gill Garcia, 1992; Franco, pers.comm.). The establishment of high mountain pastures can be linked to the development of transhumance and the increasing role of nomadic pastoralism in the agricultural economy. Clearances at lower altitudes at this time, including the southern Meseta (Lopez-Garcia et al, 1986), Catalan coastal plain (Riera-Mora & Esteban-Amat, 1994), and Ebro Basin, are not associated with increases in cultivation, but rather the development of xerophytic scrub and ruderals indicative of heavy grazing.

At the Salada Pequeña and Laguna Salada, deforestation is followed by the development of a xerophytic scrub community and matorral. Unlike earlier clearance episodes however, *Juniperus* forms a much more dominant role within the shrub layer in the late Holocene after c.1.3Kyr BP. In comparison, the presence of *Quercus ilex*-type (*Q.coccifera*?) is limited, suggesting that fire is not the main determining factor on vegetation development since it is widely noted for its resistance to fire (Trabaud, 1981), while *Juniperus* is not (Huntley & Birks, 1983). The role of climate cannot be discounted however, since junipers are both more resistant to cold and aridity than *Q.coccifera* (Le Houérou, 1981). Aridity would appear to be more important than temperature in this respect since thermophilious Mediterranean taxa, including *Olea*, also occur at this time.

The dominance of juniper in the late Holocene could be related to differences in agricultural practices, and the introduction of livestock grazing in particular. Early agriculture during the Late Iron, Iberian and Roman Ages was associated with high population densities. In comparison, the amount of land cleared for agriculture was relatively small, and consequently must have been farmed intensively in order to sustain such a large population. Only arable crops could have yielded a sufficient return, helped no doubt by a soil that was probably still deep and fertile, and a benign climate. By Visigothic times, the settlement density had fallen considerably (Benavente *et al*, 1991), reflecting both a general reduction in overall population, and the need for larger defensive settlements due to the political instability of the era. Arable farming was still practised close to settlements, but declining yields from eroded soils and competition from extensive livestock farming probably limited its use. Forest felling was no longer limited to the clearance of small areas of level, fertile ground for arable farming, but also extended into previously untouched rocky and relatively infertile hillsides and steep slopes. This more extensive deforestation made more land available for the grazing of sheep and goats, while persistent browsing and repeated firing to encourage new growth changed the nature of the remaining vegetation. Areas of natural, climax forest in hilly areas were replaced with a sub-climax or matorral community on a much depleted soil, while the more fertile grasslands of the plains saw a change from grasses and Leguminosae to less productive ruderals, including *Artemisia*, Chenopodiaceae and *Plantago*. A mainly sedentary arable society during Iberian and Roman times was therefore replaced with a pastoral and nomadic lifestyle during later Visigothic times. This change became accentuated with the Moslem conquest of Iberia in the 8th Century and the importation of an agricultural creed based on Islamic principles of common grazing of uncultivated land with wealth and status measured by the quantity, not quality, of livestock (Tallis, 1991).

The level of woodland clearance at the Laguna Salada during this period (*ca.*1.4-0.7Kyr BP) was less intense than the Salada Pequeña, with a reduction in the arboreal pollen contribution from 90% to only 60%. This probably reflects the limited history of anthropogenic disturbance at the Laguna Salada which may have kept its forest cover from the mid-Holocene, dated to before 5725±60 BP. The possibility of a hiatus in the record between these two dates cannot be eliminated, however, the sequence of events during the deforestation episode does suggest a contiguous record around this period. In particular, the peak in charcoal and reduction in *Pinus* pollen is accompanied by a short-term rise in fire resistant *Quercus-ilex*-type and Gramineae, encouraged by the release of nutrients caused by burning. Rapid depletion of these nutrients and erosion of the soil cover later sees the replacement of these taxa with xerophytic scrub of *Juniperus* and *Artemisia.* Infilling by eroded sediments also causes a short-term reduction in lake level, allowing the colonisation of the lake surface by Chenopodiaceae.

The extent of the clearance event at the Laguna Salada suggests parallels with the deforestation event at the Salada Pequeña, dated to 1.4Kyr BP. Extrapolation of the sediment accumulation rate suggested by the two radiocarbon dates further up the core at the Laguna Salada however gives a later date of between 7.0-8.0Kyr BP. This discrepancy may have been caused by a much slower rate of accumulation during the initial stages of the lake level rise at the Laguna Salada. Alternatively, comparison can be made with a second clearance episode at the Salada Pequeña at around 0.7Kyr BP, prior to the olive rise, which also coincides with a decline in lake level expansion of Chenopodiaceae.

Lake Environment

Lake levels at the Salada Pequeña remain low throughout this clearance episode, fluctuating only between seasonal and ephemeral conditions. In contrast, the Laguna Salada shows a much more marked response to deforestation with first a drop, then a rapid rise in lake level.

The initial fall in lake level at the Laguna Salada can be interpreted as a result of sediment inwash from slopes recently denuded of tree cover. Following this relative drop in lake level, water depth increases *ca.*2.5m to form a semi-permanent lake. The destruction of forest cover was clearly translated into increased groundwater recharge and run-off, dramatically transforming the hydrology of the lake catchment. This artificial alteration of catchment hydrology can be seen as a step wise change in the sensitivity of the catchment to natural climate change. Changes in lake level from the point at which the new equilibrium is reached can therefore be interpreted as a climate response assuming no new major vegetation changes.

The effects of changes in vegetation on catchment hydrology has spawned a huge literature, although generally, a reduction in catchment vegetation will generate an increase in water yield, and vice-versa (Bosch & Hewlett, 1982). Under similar climate and vegetational conditions in Australia, Ruprecht *et al* (1991) found a major recharge of groundwater following forest thinning, resulting in an extension of the duration of the seasonal groundwater aquifer from 2 to 6 months and a four-fold increase in winter stream baseflow. Alteration of the groundwater balance due to clearance of the native vegetation has also been identified as causing a rise in groundwater in the Murray Basin, Australia (Simpson & Herczeg, 1991).

The effect of forest clearance at the Laguna Salada can be estimated as equivalent to a 48.6% (9.38mm) increase in annual effective precipitation (see chapter 7, section 7.7) assuming climatic conditions similar to the present day. Such a large impact obviously has implications in deriving climate histories from lakes that may be equally influenced by minor changes in catchment vegetation.

10.5.3 *0.4Kyr-0.0Kyr BP*

Environment:

Intensive arable agriculture and sylviculture
High groundwater, low run-off

Cores and zones represented:

Laguna Guallar: **GUA-5**
Hoya del Castillo: **CAS-7**
Laguna Salada: **SAL-4**
Salada Pequeña: **PEQ-5**
Laguna Gallocanta: **GAL-2, GAL-3**
La Estanca: **EST-2, EST-3**

Terrestrial Environment

The Christian reconquest and the end of the Muslim era in the 15th and 16th Century brought about a second period of clearance and a return in emphasis to settled arable agriculture. The widespread application of irrigation and deep ploughing both extended the area under cultivation and allowed the development of new crops. The most obvious sign of this agricultural intensification was the huge expansion of olive cultivation, evident in the uppermost sediments of all the cores. Other crops also appear about this time, including *Vitis* (vine) and *Ficus* (fig) at the Laguna Salada, and *Cannabis sativa* (hemp) at the Laguna Gallocanta. Cereal-type pollen reappears at the Salada Pequeña after being absent since Iberian times, while the levels of Cereal-type pollen increase markedly at the Laguna Gallocanta. In contrast, the amount of *Juniperus* declines at all sites as browsing intensity is reduced along with livestock numbers as the land area devoted to arable farming increases. However, this is also accompanied by an increase in *Quercus ilex*-type (*Q.coccifera*?) that may suggest a climatic interpretation, particularly since lake levels also increase at the same time.

The late Medieval and modern times are also marked by the restoration of catchment stability in many lake systems, after the preceding period of often intense erosion and sediment inwash. Gutíerrez-Elorza & Peña-Monné, 1989 and Julian *et al.*, 1991 have identified renewed valley floor alluviation during this period in the Ebro Basin, not seen since Iberian/Roman times. A similar post-Roman fill was identified by Macklin *et al.*, 1994, but unfortunately could not be dated.

Lake Environment

Lake levels show a universal increase within the last few hundred years at all the sites studied in the Ebro Basin. This is reflected in increased numbers of *Ruppia* seeds in the surface sediments of all the playa lake cores. This may be an artefact of differential preservation since surface samples gathered for seeds typically show a logarithmic decline in number just below the surface layers due to dilution and oxidation (Grillas *et al*, 1993). However, the evidence is not just confined to palaeoecological sources and is also supported by changes in core stratigraphy and geochemistry. Furthermore, lakes with a high sedimentation rate such as the Laguna Salada show that these changes occurred even at quite deep levels when any preservation errors should have stabilised.

At La Estanca, the dramatic increase in lake level reflects the construction of a dam and the basins conversion to a freshwater reservoir sometime soon after Cal.AD 1441. Widespread construction of irrigation schemes throughout the Ebro Basin occurred around this time, including the construction of the Aragon Imperial Canal. Building work began on the canal in 1587 and was finally completed in 1772 (Braudel, 1972). The application of surplus irrigation water over a wide land area may have helped increase groundwater recharge and so enhance lake levels. In support of this is the experience of La Mancha on the southern Meseta where irrigation waters have been extracted from the underlying aquifer rather than by the diversion of surface streams and rivers as in the Ebro Basin. At La Mancha, lake levels have consequently fallen over the same time period, with many old lake systems now converted into dry land. However, the extension of irrigated *huertas* in the Ebro Basin has been mainly confined to areas close to the main river valleys including the Zaragoza plain, and would have had little impact in areas like the Laguna Guallar in Los Monegros which sit high on the interfluves.

In areas such as this, the late Medieval agricultural revolution did bring about other changes which may nevertheless have influenced the local hydrology. The further clearance of scrub and extension of arable land would have reduced the land cover of deep rooting perennials, and replaced it instead with shallow rooting annuals such as winter wheat. This change in ground cover would have reduced the net evapotranspirational demands of the vegetation and allowed more precipitation to flow through the upper soil layer and into the underlying aquifer. The attendant increase in surface run-off would probably have been of limited impact due to the horizontal nature of much of the terrain.

A further, and possibly more important change however was the introduction of deep ploughing. It has already been mentioned that the reduction of forest cover in the Bronze Age may have led to calcrete formation within the soil regolith, preventing groundwater recharge in some areas and so 'desensitising' lake level response. Deep ploughing could have 're-sensitised' these lake systems however through destruction of the calcrete layer and the restoration of groundwater recharge. The removal of the calcrete can be witnessed today by the piles of calcrete blocks at the sides of fields in Los Monegros, or often dumped as infill into the surrounding lake basins.

Anthropogenic alteration of the hydrological system might explain some of the increases in lake level in the Central Ebro Basin, however, an increase in lake level is also evident at Laguna Gallocanta. The Laguna Gallocanta occurs on the semi-arid/sub-humid climate boundary at a higher altitude than lakes in the Central Ebro Basin. It is largely fed by run-off from its extensive basin catchment with only minor inputs from groundwater (Comín *et al*, 1990b). The effects of any anthropogenic alteration of groundwater recharge are therefore of less importance while pollen evidence indicates that the vegetation landscape has changed relatively little in the past 600 years. The implication therefore is that climate change has been the principle agent behind rising lake levels. This may also be supported by pollen evidence from sites in the Central Ebro Basin that indicate a general increase in *Q.ilex*-type over the same time period, a feature which has been associated with periods of high lake level throughout the Holocene.

Chapter 11

Conclusions

11.1 Abstract

Strengthened seasonal variation in solar radiation in the early Holocene increased the continentality of the climate of the Ebro Basin. Winters became warmer after 8.6Kyr BP as sea surface temperatures and land ice approximated to present conditions. Precipitation (available moisture) increased throughout this early period, but declined as temperatures rose in the mid Holocene. High levels of moisture associated with increased orographic (monsoonal?) precipitation and possible decreased summer temperatures found in other parts of the Mediterranean in the mid Holocene did not reach the continental interior of the Ebro Basin. An increase in westerly airflow with the decline in strength and position of the Azores high after 5.4Ky BP generated greater summer storm frequencies, although winters remained dry as the winter anticyclone persisted. Between 2.7-1.8Ky BP the influence of the winter anticyclone declined and winter precipitation increased markedly. After 1.8Kyr, aridity returned along with increased strength of the winter anticyclone and lower overall temperatures. Modern climate conditions were established after 0.4Kyr BP with a rise in winter rainfall and possibly winter temperatures.

11.1 Introduction

A summary of the main palaeoenvironmental changes affecting the Ebro Basin is given in *figure 11.1* p275. Reconstruction clearly shows that major changes occured in climate, vegetation and human impact in the region throughout the Holocene. The semi-arid central Ebro Basin can be shown to provide a more sensitive record of Holocene climate change than many other previously investigated sites in the Western Mediterranean.

The multi-disciplinary nature of this study, and particularly the independant climate record provided by lake level reconstruction, has allowed the independant assessment of many key environmental variables, such as climate, human activity, vegetation and erosion, that were previously difficult to seperate. This fact, together with the inherent sensitivity of a semi-arid environment to small changes in climate and environmental degredation show that palaeoenvironmental investigations in this, and similar parts of Spain containing endoreic lakes, can provide important new information on the development of the Mediterranean environment.

11.3 Palaeoclimate

The current climate of the central Ebro Basin is semi-arid supra-mediterranean (see Chapter 4, section 4.4). The palaeoenvironmental record indicates that there have been major changes in the climate of the basin

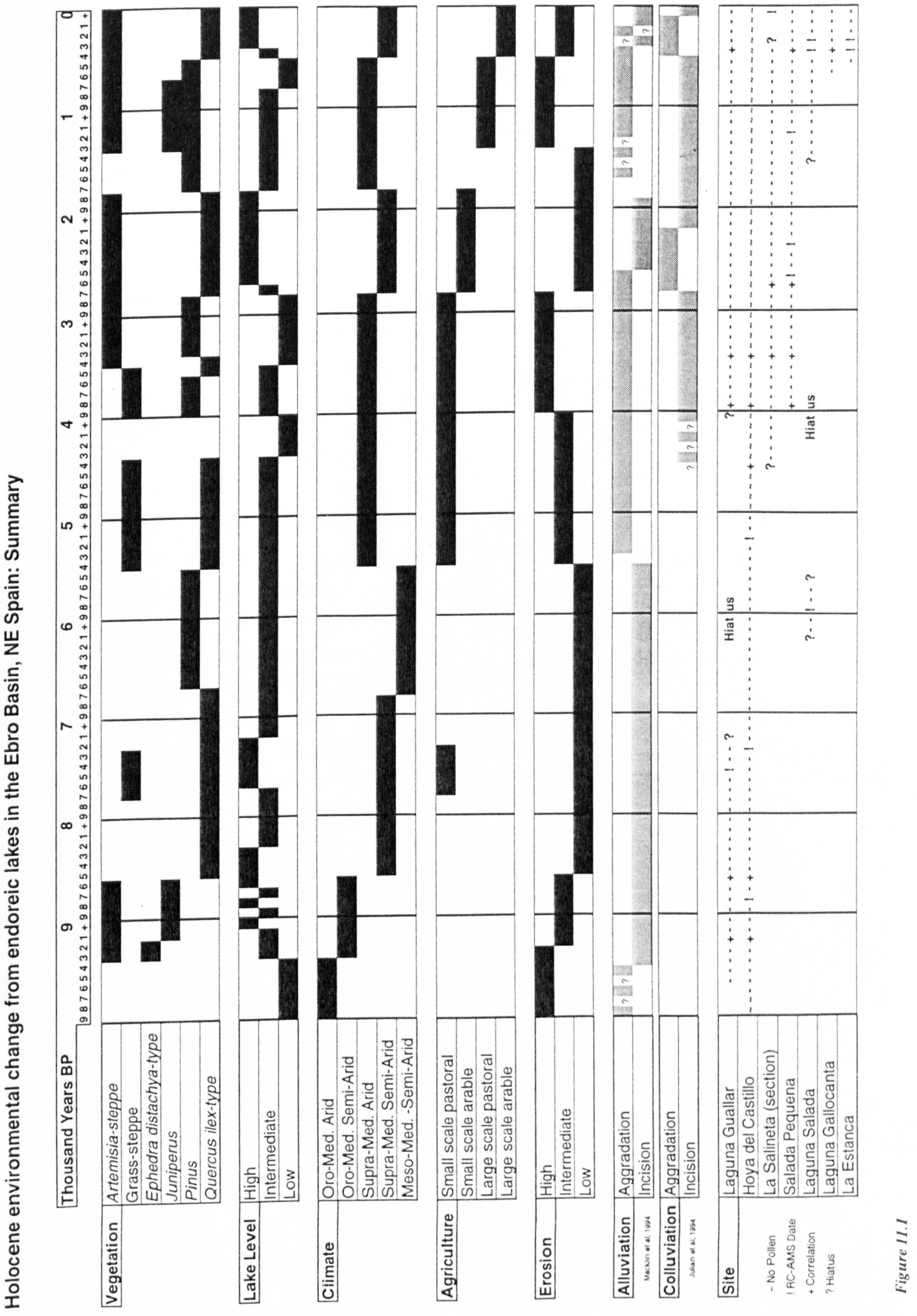


Figure 11.1 **Summary of Holocene environmental change in the Ebro Basin, NE Spain**

over the past 10.0Kyr, from extreme continental oro-mediterranean in the early holocene to arid, meso-mediterranean in the mid Holocene. Mediterranean conditions have remained throughout, with a distinct summer drought, but with large variations in winter rainfall. Temperatures have played an important part in determining evapotranspiration and levels of available moisture, being significantly colder in the first part of the Holocene, and warmer in the mid Holocene.

Early Holocene

Stabilisation of the global climate system after full glacial conditions was just about complete by the time lake formation began in the central Ebro Basin at around 10.0Kyr BP. The majority of the Wisconsin Ice Sheet had dissappeared and sea and surface temperatures were close to normal. The global radiation budget however was still significantly different, with a July perhilion and exagerated axial tilt combining to produce extreme seasonal variation in the Northern hemisphere. Higher inputs of solar radiation in summer and reduced solar inputs in winter combined to exagerate the continentality of the Ebro Basin, resulting in a vegetation (*Juniper thurifera & Artemisia*) tolerant of high aridity, cold winters and hot summers.

Cooler winter temperatures would also have led to decreased evapotranspiration at this time of year, allowing a larger proportion of winter precipitation to recharge the groundwater aquifer. High groundwater levels would have maintained lake levels throughout the warm summer months, compensating for any increased evapotranspiration. High groundwater recharge was therefore being maintained by low winter evapotranspiration rather than high precipitation, making it vulnerable to small changes in the distribution of winter precpitation. Frequent failure of these winter rains may account for large variations in lake level during this period.

A northward displacement of the subtropical anticyclone has been suggested by Guiot *et al* (1993) at this time to account for decreased precipitation in Northern Europe and increased precipitation in Western France. An accompanying poleward shift in the winter polar jet stream would also have brought the north-east of Spain into a winter rainfall regime, replacing the current pattern of spring and autumn maxima. Increased rainfall in the coldest months when evapotranspiration is at its lowest would have had the greatest effect on groundwater recharge without necessarily increasing mean annual rainfall.

As the seasonal differences in global radiation gradually declined, winter temperatures ameliorated and continentality was reduced in the Ebro Basin. This is reflected in a vegetation change from *Juniperus* to *Quercus ilex*-type and *Pinus* at around 8.6Kyr BP. Precipitation increased along with temperature, providing sufficient available moisture to raise lake levels to their highest Holocene level despite higher levels of evapotranspiration.

Rising temperatures and evapotranspiration throughout the early Holocene were therefore more than compensated for by increasing precipitation in the Ebro Basin. Low winter evapotranspiration was replaced by high precipitation as the dominant control on lake levels after 8.4Kyr BP. Inreases in precipitation helped maintain high lake levels through raising groundwater, while also increasing runoff.

Changes in the global moisture balance investigated by COHMAP memebers (1988) indicate a 25-30% increase in precipitation between 12.0-6.0Kyr BP, and seven fold increase in available moisture. High lake levels in the Ebro Basin accord with high global lake levels throughout the world during this period (Street & Grove, 1978). A temporary drop in lake levels between 8.2-7.6Kyr BP is also in agreement with similar findings in northern Africa (Roberts *et al*, 1994) and probably reflects a reduction in winter rainfall since vegetation displays little response.

Mid-Holocene

After 7.2Kyr BP, precipitation failed to keep pace with rising temperatures in the Ebro Basin and a net decline in available moisture occured with rising evapotranspiration. The sclerophyllous woodlands of the early Holocene were replaced by pine during the mid Holocene as lake levels declined and aridity increased.

This evidence would appear to contradict the widespread development of deciduous woodland throughout the Mediterranean during this period (Huntley & Prentice, 1988) as well as high lake levels in other parts of Iberia (Harrison & Digerfeldt, 1993). The wetter conditions experienced in other areas of the western mediterranean clearly did not extend to the central Ebro Basin.

The size of the Iberian Peninsula is sufficient for it to develop a small scale low pressure system during the summer as a result of high insolation over the central mesetas. This generates onshore airflow from the Atlantic or Mediterranean that results in instability and occasional summer thunderstorm activity. The dryness of the interior however usually quickly dissipates any moisture and reduces the potential precipitation yield. At around 6.0Kyr BP, higher summer insolation and consequent land-sea pressure gradient (due to differential heating) may have combined to increase the strength of the summer low pressure over the Peninsula and create greater instability. At the same time, the northward displacement of the sub-tropical high pressure system would have allowed the seasonal monsoon winds of North Africa to penetrate to higher latitudes. Font Tullot (1988) has argued that as a result, precipitation increased substantially in the southern half of the Peninsula during the summer, reducing the seasonal variation in precipitation. An enhanced Azores high at this time would also have reduced the influence of Atlantic depressions on the western margins of the Peninsula, although increased onshore air-flow would have produced localised increases in orographic precipitation in mountainous areas at the continental margins.

Rainfall approaching from the coast would therefore have been intercepted by the mountainous terrain surrounding the Ebro Basin, while monsoonal flow from the south would be quickly dissipated over the central uplands. As well as this overall reduction in precipitation, an increase in winter temperatures would further exagerate the effect on groundwater by increasing evapotranspiration and reducing the amount of winter recharge.

A change in the annual distribution of precipitation occured in the central Ebro Basin after 5.4Kyr BP. This is reflected in a change from pine to sclerophyllous vegetation and grass-steppe, but not an increase in lake level. Low winter precipitation restricted groundwater recharge while enhanced spring and autumn storm activity increased runoff and erosion after 4.0Kyr BP. The continued southward decline in the position of the Azores high and sub-tropical high pressure to their current position would have allowed the development of mid-winter high pressure over Iberia. This would have strengthened the current bi-modal distribution of precipitation and reinforced the mid-winter drought while high summer insolation would still have maintained high levels of storm activity. The decline in the Azores high would also have allowed the westward penetration of Atlantic low pressure systems into the Peninsula, precipitating further storm frequency through advection on contact with warm Mediterranean air to the east.

Storm activity declined after *ca.*3.4Kyr BP and a short period of warm winters and drier conditions prevailed until precipitation increased markedly between 2.6-1.8Kyr BP. During this pluvial period, winter rainfall increased considerably along with groundwater recharge. The climate became more 'Mediterranean' at this time, with reduced development of the winter anticyclone permitting penetration of rain bearing winds to the centre of the Ebro Basin. Precipitation was therefore distributed more evenly within the winter half of the year, although the summers remained warm and dry with a prolonged drought.

Late Holocene

Dry conditions quickly re-established themselves after 1.8Kyr BP and persisted upto late medieval times (*ca.*0.4Ky BP). Winter rainfall was greater than between ca.4.6-2.7Kyr BP allowing higher levels of groundwater recharge, but overall levels of precipitation were less. This may have represented a relative shift in evapotranspiration and available moisture due to cooler winters and/or warmer summers. The return of high levels of *Juniperus* may well support this hypothesis.

Since 0.4Kyr BP, rising lake levels and sclerophyllous vegetation suggest that the climate has got wetter, with increased winter rainfall and groundwater recharge. This trend appears to have persisted into the present century, although the low resolution of the sediment record makes this difficult to establish.

11.4 Vegetation and Human Impact

The earliest pollen records show that the central Ebro Basin at the start of the Holocene was covered by a semi-desert vegetation of *Ephedra-Juniperus-Artemisia* upto *ca.*9.2Kyr BP. The extreme continental climate conditions that characterised this period continued into the early Holocene, while rising precipitation allowed an extensive woodland of *Juniperus thurifera* to develop. The dissapearance of *Olea* during this period may indicate that conditions became colder between 9.2-8.4Kyr BP.

The climate finally ameliorated around *ca.*8.4Kyr BP with the establishment of the current supra-mediterranean vegetation of *Pinus* and *Quercus ilex*-type. The early Holocene openland flora of *Artemisia* steppe is also replaced by Mediterranean grassland including *Lygeum spartum* at this time.

The evolution of the Holocene woodland from this point is dominated by inter-changes between *Pinus* and evergreen oak, mainly in response to climate change, but also partly through anthropogenic disturbance. Evergreen oak never dominates, but does increase markedly during periods of high lake level and early woodland clearance. In particular a significant rise in *Quercus ilex*-type occurs during early Neolithic clearance (7.6-7.3Kyr BP), as well as with declining woodland cover (and lake level) after *ca.*5.4Kyr BP. Intense anthropogenic clearance after 1.4Kyr BP however favoured *Juniperus* rather than *Quercus ilex*-type. This may have been linked to a change in agricultural practice to extensive nomadic pastoralism, against which juniper may have been more resistant than evergreen oak. It is notable however that this period of juniper domination also coincides with low lake levels, and suggests that increased aridity may also have favoured juniper as the main matorral shrub.

In contrast to evergreen oak, pine (*P.halepensis*?) is favoured during periods of aridity and low lake level, reaching particular dominance in the mid and late Holocene. During two periods of low anthropogenic disturbance, pine formed a dense monospecific woodland between 6.6-5.4Kyr BP and 1.8-1.4Kyr BP. The establishment of this forest was especially rapid following the Roman-Iberian period despite earlier woodland clearance, agricultural activity and top soil erosion. The swift recolonisation by pine of an undoubtably eroded landscape more arid than today, suggests that environmental degradation was at least reversable by this stage. Furthermore, it highlights the ability of pine to rapidly re-establish itself and dominate the woodland cover once anthropogenic pressure is removed.

The high aridity of the Ebro Basin has maintained a Mediterranean schlerophyllous or acicular woodland cover throughout the Holocene. Deciduous taxa compose only a low proportion of the pollen spectra, either from long distance transport from surrounding mountains or from riverine vegetation. High levels (5-10% TTP) of deciduous pollen are more closely associated with evergreen oak than pine and support the idea that the former are linked with low aridity, and the latter with high aridity.

Anthropogenic disturbance is clearly evident during the late Mesolithic/early Neolithic in the Ebro Basin. A peak in charcoal and increase in evergreen oak and grassland between 7.6-7.3Kyr BP is evident at both sites that cover this period. This period of agricultural activity is one of the earliest ever recorded in the Western Mediterranean, and is comparable that found by Triat-Laval (1978) in Provence, southern France.

The assesment of agricultural impact is complicated by the natural occurance of many anthropogenic indicators in the vegetation of the Ebro Basin. *Olea* is present from the onset of the pollen record in the early Holocene, while large cereal-size Gramineae pollen (>50μm) is also produced by naturally occuring wild grasses such as *Lygeum spartum*. On the other hand, *Juglans* is thought to have already been native along the Catalonian coast for much of the Holocene (Rierra-Mora & Esteban-Amat, 1994), but is only recorded from Iberian-Roman times (2.6Kyr BP) in the Ebro Basin.

The large scale clearance of woodland began progressively after 5.4Kyr BP (early Bronze Age) but, unlike virtually all other reductions in forest cover, was not accompanied by an increase in charcoal. Within this declining forest cover, sclerophyllous vegetation expanded at the expense of pine although this occured during a period of low lake level. The contradictory picture of declining woodland cover, expanding sclerophyllous vegetation, low lake level and low fire frequency suggests that the reasons behind the decline in woodland cover are multifarious and linked to both climatic aridity and low impact human activity. Agriculture at this time was mainly pastoral (Harrison, 1985, 1994) and the grazing of livestock was probably a key cause of the expansion of sclerophyllous vegetation and decline in woodland cover.

Agricultural activity may have declined slightly between 3.4-2.7Kyr BP (late Bronze Age-early Iron Age) as aridity increased temporarily. An important change occurs at this point in the composition of the openland vegetation as Mediterranean grassland is replaced by *Artemisia*. High levels of *Artemisia* are maintained throughout the remainder of the Holocene with little recovery of the grassland component despite large changes in climatic regime. The loss of topsoil following the reduction in forest cover in the mid Holocene probably caused a stepwise change in environmental conditions that prevented the recovery of grassland.

A marked pluvial period between 2.7-1.8Kyr BP characterises the Iberian and Roman Age. Archaeological evidence (van Zuidam, 1975; Benavente *et al.*, 1991) indicates that the human population expanded during this period although pollen evidence shows that woodland cover did not diminish. Agricultural production instead increased through the adoption of intensive cereal farming and fruit cropping. *Juglans* appears for the first time at this point, coincidental with its appearance on the Catalonian coastal plain (Rierra-Mora & Esteban-Amat, 1994) and the establishment of the first Phoenician trading posts in the Peninsula.

A catastrophic decline in population and agricultural production accompanied the rapid return of arid conditions in the Ebro Basin around 1.8Kyr BP. Pine woodland quickly re-established itself as virtually all signs of anthropogenic activity dissappeared. Interestingly, this period coincides with the onset of the decline in the authority of Imperial Rome in the Peninsula.

Extensive clearance of the regenerated pine forest occured around 1.4Kyr BP, and reflects regional defforestation with the onset of Visigothic rule and the establishment of nomadic pastoralism. This fundamental change in the mode of agriculural production compared with the earlier Iberian-Roman period probably reflected increased aridity, declining soil fertility as a result of top soil erosion, and political instability. The importation of a northern European agricultural creed based on animal fat and dairy production may also have been important.

The level of defforestation far exceeded that of Bronze Age times and probably saw the establishment of much of the modern treeless landscape. Clearance favoured Juniper, rather than evergreen oak, at this time although the reason for this is not clear. The climate may have been too arid for oak, or alternatively, the grazing too intense. Either way, this period probably saw an expansion of juniper throughout the Ebro Basin, giving rise to the name Los Monegros (from '*monte-negros*' or 'black hills') for the juniper covered hills of the central area.

A second period of more extensive clearance occured during the Muslim occupation in the early Middle Ages (0.7Kyr BP), in which the area around the Rio Ebro at the Laguna Salada may have been defforested. This second clearance phase also saw the limited restoration of arable farming and syviculture to a level similar to Iberian-Roman times. This change in agricultural production does not appear to have occured during a particularly suitable climatic period and may have been achieved through the adoption of new agricultural practices and technologies, including irrigation.

The establishment of modern agriculture began in the 15/16th Century (0.4Kyr BP) with the massive expansion of olive plantations. This period also saw the construction of the La Estanca reservoir (*ca.*Cal.AD

1441) and the more widespread introduction of irrigation to large areas of the Ebro Basin. The extension and intensification of arable and sylviculture production was accompanied by a shift from juniper to evergreen oak matorral. This may reflect a reduction in grazing pressure with the development of arable farming, although rising lake levels suggest that the climate has become wetter over the past few hundred years.

11.5 Erosion

The independent history of climate, vegetation and anthropogenic activity provided by analysis of endoreic lake sediments provides a unique means to assess the impact of these multifarious factors on run-off and erosion recorded in nearby river systems.

Within the lake system, three main periods of catchment erosion can be identified during the Holocene:

1) <9.2Kyr BP
2) 4.0-2.7Kyr BP
3) 1.4-0.4Kyr BP

These can be related almost directly to four alluvial fills recognised by Macklin *et al.* (1994) at the Rio Regallo, located within the study area, 7km west of the Salada Pequeña, and 16km east of the Hoya del Castillo:

1) Morino unit (late-glacial-early Holocene?)
2) Ceruzuela unit (*ca.*OSL 3840-2780 BC, AMS^{14}C 2360-2200 BC)
3) Altafulla unit (*ca.*OSL 410 BP-390 AD) & Castellar unit (post Roman)

In addition, Gutíerrez-Elorza & Peña-Monne (1989) and Julian *et al.* (1991) have investigated periods of late Holocene accumulation and incision of slope deposits in the Zaragoza area, 30km north-west of the Rio Regallo. These slope deposits, dated by archaeological evidence, show the opposite response, with accumulation occurring between periods,

2) to 3) (2.7-1.4Kyr BP)
3) to Present (0.4-0.0Kyr BP)

whilst slope incision took place during the same periods:

2) *ca.*4.0-2.7Kyr BP
3) 1.4-0.4Kyr BP

The timing of these events suggests that the accumulation of sediment in lake and river systems may have taken place during slope incision, whilst the accumulation of slopes deposits took place during river incision.

The onset of Holocene valley floor alluviation was probably triggered by deforestation after 5.4Kyr BP with the introduction of small scale pastoralism during the late Neolithic/Bronze Age times. An increase in summer storm frequency after *ca.*4.0Kyr BP may also have acted to encouraged this process. Arid conditions had already become established after 7.2Kyr BP but the protective woodland cover was too complete upto 5.4Kyr BP to permit slope erosion. In contrast, a change to slope accumulation and valley floor incision around 2.7Kyr BP was not accompanied by an increase in woodland cover, but by increased (winter) precipitation and the development of small scale arable agriculture. This may have continued despite a fall in precipitation after 1.8Kyr BP, since anthropogenic pressure was removed and the temporary recovery of the natural woodland cover was allowed to occur. Valley floor alluviation restarted after 1.4Kyr BP with the onset of a second and more extensive period of clearance following the introduction of large scale pastoralism. Sedimentation probably continued until around 0.4Kyr BP, when much of the area was converted to extensive arable agriculture and incision set in. This concurs with recently recorded slope accumulation, while a rise in lake levels suggests that precipitation increased during the same time period.

Comparison with the palaeoenvironmental record provided by endoreic lake sediments therefore indicates that lake and valley floor sedimentation (slope incision) took place during periods of relatively high aridity (low lake level) and low woodland cover. While, in contrast, slope accumulation (valley floor incision), occurred when conditions were less arid (high lake level) or the woodland cover was almost complete. This conclusion reiterates that of Gutíerrez-Elorza & Peña-Monné (1989) and Macklin *et al.* (1994) in emphasising the importance of the vegetation cover in controlling the erosion process in semi-arid environments.

Appendix 1: Key to diagram units

Units

General

Radiocarbon dates: radiocarbon years before present

Terrestrial Plant Pollen & Charcoal

Charcoal: square millimetres per gram dry weight
Terrestrial plant pollen: percent of total terrrestrial plant pollen (excluding Chenopodiaceae)
Chenopodiaceae pollen: percent of total pollen (including aquatics)
Pollen concentration: number per gram dry weight

Macrofossils & Aquatic Plant Pollen

Macrofossils: number per onehundred grams dry weight
Aquatic plant pollen: percent of total pollen (including Chenopodiaceae)
Chenopodiaceae pollen: percent of total pollen (including aquatics)

Geochemistry, Sediment Structure & Gypsum

Loss on ignition: percent dry weight
Carbonate: percent dry weight
Sulphate: percent dry weight
Other minerogenic material: percent remaining after deducting % LOI, sulphate & carbonate
Organic algal mat or root mat: 0 no sample
1 no mat
2 algal mat
3 root mat
Detrital quartz: 0 no sample
1 present
2 absent
Clay pelletisation: 0 no sample
1 absent
2 present
Woody plant material: 0 no sample
1 absent
2 present
Non-calcareous clay content: estimated percent of material remaining after filtering at 180 microns
Gypsum: crystal size: 0 no sample
1 no crystals
2 small (<0.5mm)
3 mix of small and medium
4 medium (0.5-1.0mm)
5 mix of medium and large
6 large (>1.0mm)
7 mix of large and small
Gypsum: crystal shape: 0 no sample
1 no crystals
2 irregular/weathered
3 mix of irregular and lenticular
4 lenticular
5 mix of lenticular and prismatic
6 prismatic
7 mix of prismatic and massive
8 massive
Gypsum: crystal colour: 0 no sample
1 no crystals
2 yellow
3 mix of yellow and translucent
4 translucent
5 mix of translucent and transparent
6 transparent (clear)

Geochemistry (cations & trace metals)

Cations (Ca, Mg, Na, K): parts per million
Trace metals (Fe, Mn, Pb, Zn, Cd, Cu): parts per million
Ca/Mg, Fe/Mn: ratio

Lake Type (Level) & Vegetation Summary

Lake Type (Level): note: 0.5 values are transitional types
1 Dry (depth <-1.0m) water fresh/mineralised
2 Ephemeral (depth 0.0--1.0m) water mineralised
3 Seasonal (depth 0.5-0.0m) water hypersaline
4 Semi-permanent (depth 1.5-0.5m) water saline/hypersaline
5 Permanent-unstratified (depth 3.0-1.5m) water saline
6 Permanent-unstratified (depth 3.0-1.5m) water fresh/mineralised
7 Permanent-stratified (depth >3.0m) water saline
8 Permanent-stratified (depth >3.0m) water fresh
Vegetation Summary: from left to right..
sub-mediterranean
oro/supra-mediterranean
mediterranean
Pinus
steppe/openland
Artemisia

Appendix 2: Quick guide to palaeoenvironmental indicators

Terrestrial Plant Pollen & Charcoal

Charcoal: Natural or anthropogenic firing of vegetation
Pinus: Lowland Mediterranean semi-arid P.halepensis woodland (deciduous taxa <4%TTP?)
Upland Mediterranean sub-humid P.nigra/P.sylvestris woodland (deciduous taxa >4%TTP?)
Juniperus: J.thurifera: montane continental climate
J.oxycedrus/J.phoenicea: degraded matorral scrub
Quercus ilex-type: Q.ilex woodland or Q.coccifera sclerophyllousmatorral scrub
Olea: Olive cultivation (>4%TTP?) or sclerophyllous matorral scrub
Alnus, Corylus, Ulmus, Fraxinus: Typical riverine vegetation
Cistus: Fire indicator, matorral scrub
Ericaceae, Mentha-type: Degraded matorral scrub (garrigue)
Anthemis, Bidens-type, Liguliflorae: 'Compositae': disturbed ground (garrigue)
Artemisia: Semi-arid continental climate, xeric edaphic conditions
Chenopodiaceae: Salt lake marginal vegetation, xeric and disturbed environments
Gramineae <40um: Grass steppe
Gramineae >40um: Cereals or Esparto (Lygeum spartum) steppe
Plantago: Disturbed ground, xeric conditions
Pollen concentration: Sediment accumulation rate, oxidation

Macrofossils & Aquatic Plant Pollen

	Lake Type	
Charophytes (oospores):	4 & 5,6,2	Submerged: Deep & shallow calcium-rich water, low turbidity: fresh to hypersaline
Chara vulgaris (oospores):	6	Submerged: Deep , calcium-rich mineralised (but not saline) water
Lamprothamnium papulosum (oospores):	4 & 5	Submerged: Hypersaline waters
Ruppia maritima var. maritima (seeds):	5	Submerged: Permanent saline waters
Ruppia drepanensis (seeds):	3 & 5	Submerged: Seasonal or temporary saline waters
Ruppia (broken seed parts):	3 & 5	Submerged: Either of above
Potamogeton pectinatus (seeds):	6	Submerged: Mineralised (but not saline) water, tolerates high turbidity
Potamogeton (pollen):	6, 3, 8	Submerged: Often pollen but no seeds in seasonal or deep, stratified lakes
Cyperaceae (pollen):	6. 8, 3	Emergent marginal veg.: Scirpus, Phragmites etc.
Typha angustifolia-type (pollen):	6, 8, 3	Emergent marginal veg.: Typha angustifolia, Sparganium sp.
Chironomus (head capsules):	2 to 8	Benthic detrital feeder, tolerant of anoxia but not sulphide build-up (stratification)
Daphnia (ephippia):	4 & 8,6,2.	Phytophagous limnetic zooplankton
Moina-type (ephippia):	6 & 8,1	Phytophagous limnetic zooplankton
Moina mongolonica (ephippa):	4, 5	Phytophagous limnetic zooplankton
Chenopodiaceae (seeds):	1, 2	Colonisation of lake bed (coring site) by terrestrial halophytic vegetation
Chenopodiaceae (pollen):	1, 2, 3	Arid conditions, disturbance, marginal halophytic vegetation (>45%TP = above)

Geochemistry, Sediment Structure & Gypsum

		Lake Type	
Loss on ignition:		High in 7,5	Organic productivity, inorganic inwash/precipitation, oxidising or reducing conditions
Carbonate:		High in 8,6	Detrital inwash in all but type 6/8 lakes where get precipitation
Sulphate:		High in 7,5	High (sulphate rich) groundwater flow often means high gypsum
Other minerogenic material:			Sodium chlorides at the surface, otherwise mostly detrital
Organic algal mat or root mat:	**1**	3	Seasonal lakes too dry for algal mat and too saline for terrestrial vegetation
	2	7,5,4,3,8	Saline lake or deep stratified (anoxic) freshwater lake
	3	6,2,1	Shallow, unstratified freshwater lake or ephemeral or dry lake
Detrital quartz:	**1**	3	Detrital inwash
Clay pelletisation:	**2**	2	Capillary rise when groundwater close (<1.0m) to surface
Woody plant material:	**2**	2,1	Terrestrial plants covering dry/ephemeral lakes
Non-calcareous clay content:		Low in 3	Detrital inwash/Pelletisation/Organic clays
Gypsum: crystal shape:	**1**	1,8	Domination by meteoric waters without groundwater flow (dry or freshwater lakes)
	2	2	Detrital weathered gypsum, oxidising conditions
	4	3,2	Sub-surface precipitation of gypsum under evaporitic pumping (dry lake) conditions
	6	7-4	Precipitation of gypsum in free water
	8	7	Amorphous gypsum-type crystals associated with deep, saline lakes
Gypsum: crystal colour:	**2**	2	Influence of tanic/organic acids from terrestrial vegetation
	4	3	
	6	7-4	

Geochemistry (anions & trace metals)

Ca: Calcium carbonate
Mg: See Ca/Mg
Na: Sodium chloride (Note: high solubility so rarely preserved within sediment record)
K: Illite clay indicator
Ca/Mg: Amount of high-low magnesium carbonate (low ratio = evaporitic concentration)
Fe: See Fe/Mn: redox conditions
Mn: See Fe/Mn: redox conditions
Fe/Mn: Redox conditions (high ratio = reducing conditions in catchment soils etc)

Lake Type (Level) & Vegetation Summary

Lake Type (Level): note: 0.5 values are transitional types
1 Dry (depth <-1.0m) water fresh/mineralised
2 Ephemeral (depth 0.0--1.0m) water mineralised
3 Seasonal (depth 0.5-0.0m) water hypersaline
4 Semi-permanent (depth 1.5-0.5m) water saline/hypersaline
5 Permanent-unstratified (depth 3.0-1.5m) water saline
6 Permanent-unstratified (depth 3.0-1.5m) water fresh/mineralised
7 Permanent-stratified (depth >3.0m) water saline
8 Permanent-stratified (depth >3.0m) water fresh

Vegetation Summary: from left to right..

Sub-Mediterranean:	Deciduous taxa (mostly riverine type)
Oro/Supra Mediterranean:	Mostly Juniperus & low amounts of Ephedra
Mediterranean:	Mostly Quercus ilex-type
Pinus:	*Pinus*
Steppe/Openland:	Mostly grasses, Plantago, Compositae
Artemisia:	*Artemisia*

Appendix 3: Radiocarbon:Calender years calibration table (from Chambers, 1993)

Calibration table of radiocarbon ages, abbreviated from the Belfast-Seattle calibration tables in Pearson & Stuiver (1986) and Stuiver & Pearson (1986) back to 3900 BP and from the University of Washington Quaternary Isotope Laboratory Radiocarbon Calibration Program (1987, Rev. 2.0) from 4000 BP to 8000 BP.

This table is intended as a guide only; see originals for full information. The bc/ad system, which has been used in several journals, is not recommended by the international radiocarbon community (see Preface), but is still used by some authors (cf. Chapter 19). Note that ages cited as lower-case bp in other publications, are equivalent to the ages in the first column in this table.

Uncalibrated (Years BP)	*Uncalibrated (Years bc/ad)*	*Calibrated age (Cal. BC/AD)*
200 BP	ad 1750	Cal. AD 1666, 1790, 1951, 1952
300 BP	ad 1650	Cal. AD 1636
400 BP	ad 1550	Cal. AD 1460
500 BP	ad 1450	Cal. AD 1422
600 BP	ad 1350	Cal. AD 1317, 1347, 1388
700 BP	ad 1250	Cal. AD 1279
800 BP	ad 1150	Cal. AD 1245
900 BP	ad 1050	Cal. AD 1159
1000 BP	ad 950	Cal. AD 1018
1100 BP	ad 850	Cal. AD 961
1200 BP	ad 750	Cal. AD 811, 847, 851
1300 BP	ad 650	Cal. AD 681
1400 BP	ad 550	Cal. AD 673
1500 BP	ad 450	Cal. AD 561
1600 BP	ad 350	Cal. AD 429
1700 BP	ad 250	Cal. AD 343
1800 BP	ad 150	Cal. AD 227
1900 BP	ad 50	Cal. AD 87
2000 BP	50 bc	1 Cal. BC
2100 BP	150 bc	151, 149, 117 Cal. BC
2200 BP	250 bc	353, 306, 236 Cal. BC
2300 BP	350 bc	392 Cal. BC
2400 BP	450 bc	408 Cal. BC
2500 BP	550 bc	765, 673, 607, 613, 608 Cal. BC
2600 BP	650 bc	801 Cal. BC
2700 BP	750 bc	838 Cal. BC
2800 BP	850 bc	976, 965, 933 Cal. BC
2900 BP	950 bc	1093 Cal. BC
3000 BP	1050 bc	1263 Cal. BC
3100 BP	1150 bc	1406 Cal. BC
3200 BP	1250 bc	1506, 1476, 1464 Cal. BC
3300 BP	1350 bc	1607, 1554, 1543 Cal. BC
3400 BP	1450 bc	1733, 1721, 1697 Cal. BC
3500 BP	1550 bc	1877, 1834, 1824, 1793, 1788 Cal. BC
3600 BP	1650 bc	1961 Cal. BC
3700 BP	1750 bc	2133, 2067, 2047 Cal. BC
3800 BP	1850 bc	2278, 2233, 2209 Cal. BC
3900 BP	1950 bc	2457 Cal. BC
4000 BP	2050 bc	2564, 2541, 2499 Cal. BC
4100 BP	2150 bc	2855, 2824, 2657, 2640, 2619 Cal. BC
4200 BP	2250 bc	2880, 2798, 2782 Cal. BC
4300 BP	2350 bc	2915 Cal. BC
4400 BP	2450 bc	3034 Cal. BC
4500 BP	2550 bc	3307, 3235, 3177, 3163, 3134, 3112, 3110 Cal. BC
4600 BP	2650 bc	3360 Cal. BC
4700 BP	2750 bc	3504, 3406, 3384 Cal. BC
4800 BP	2850 bc	3629, 3560, 3544 Cal. BC
4900 BP	2950 bc	3697 Cal. BC
5000 BP	3050 bc	3785 Cal. BC
5100 BP	3150 bc	3957, 3838, 3826 Cal. BC
5200 BP	3250 bc	3998 Cal. BC
5300 BP	3350 bc	4220, 4200, 4147, 4110, 4088, 4060, 4048 Cal. BC
5400 BP	3450 bc	4318, 4285, 4246 Cal. BC
5500 BP	3550 bc	4353 Cal. BC
5600 BP	3650 bc	4461 Cal. BC
5700 BP	3750 bc	4572, 4564, 4536 Cal. BC
5800 BP	3850 bc	4716 Cal. BC
5900 BP	3950 bc	4787 Cal. BC
6000 BP	4050 bc	4993, 4925, 4903 Cal. BC
6100 BP	4150 bc	5053, 5013, 5008 Cal. BC
6200 BP	4250 bc	5215 Cal. BC
6300 BP	4350 bc	5240 Cal. BC
6400 BP	4450 bc	5338 Cal. BC
6500 BP	4550 bc	5474, 5435, 5426 Cal. BC
6600 BP	4650 bc	5493 Cal. BC
6700 BP	4750 bc	5619, 5595, 5538 Cal. BC
6800 BP	4850 bc	5645 Cal. BC
6900 BP	4950 bc	5741 Cal. BC
7000 BP	5050 bc	5840 Cal. BC
7100 BP	5150 bc	5975 Cal. BC
7200 BP	5250 bc	6080, 6052, 6049, 6012, 6007 Cal. BC
7300 BP	5350 bc	6117 Cal. BC
7400 BP	5450 bc	6217, 6202, 6183 Cal. BC
7500 BP	5550 bc	6389 Cal. BC
7600 BP	5650 bc	6441 Cal. BC
7700 BP	5750 bc	6553, 6542, 6487 Cal. BC
7800 BP	5850 bc	6610 Cal. BC
7900 BP	5950 bc	6703 Cal. BC
8000 BP	6050 bc	7032, 6971, 6970 Cal. BC

Appendix 4

The 'olive rise' and agricultural change in the Western Mediterranean since Iberian times; A palaeoecological perspective

10.6.1 Abstract

Palaeoecological evidence is reviewed for the development of olive cultivation in the Western Mediterranean since its introduction into Iberia by the Phoenicians around 2500 BP. Olive curves from 38 pollen diagrams covering the late Holocene are plotted against radiocarbon years to allow comparison. Early evidence of intense cultivation comes from sites in Morocco, Corsica and Southern France (2000-1300 BP), and later, in Portugal and Southern France (1300-400 BP). Values from Spanish sites increase markedly after 400 BP only to decline in the past 100 years. These changes are discussed within an economic, political and climatic framework.

10.6.2 Introduction

Marked increases in *Olea* within the late Holocene is a feature common to pollen diagrams throughout the Mediterranean region including Algeria (Ritchie, 1984), Tunisia (Ben Tiba & Reille, 1982), Egypt (Mehringer *et al.*, 1979), Greece (Bottema, 1979) and Italy (Folieri *et al.*, 1988). Further west, a much more comprehensive number of pollen diagrams has now become available from Iberia, Southern France, Corsica and Morocco which display this phenomena in more detail, including Van den Brink & Gassing (1985), Garcia Anton *et al.* (1986), Reille (1992), Garcia (1992) Gomez (1992), Mateus (1992), Toro *et al.* (1992), Davis (1994) and Franco (1994).

A general east-west trend has been recognised in the timing of this 'olive rise', with sites in the eastern Mediterranean displaying an earlier take off than those in west (Huntley & Birks, 1983). This is thought to reflect the early development of fruit cultivation practices in the east, which then spread west with trade and colonisation by the early developing agrarian civilisations. This pattern is supported by archaeological and palaeobotanical evidence of fruit presses, pruning tools, olive stones and amphora.

Early man undoubtable gathered the fruits of wild olives, however by ancient times, this opportunistic exploitation had given way to active cultivation and domestication. Olive presses dating to 3000 BP have been found widely in the Eastern Mediterranean, and presses as old as 4000 BP have been found at Thera in the Aegian (Semple, 1932).

The Phoenicians are thought to have introduced olive culture into the Western Mediterranean around 2500 years BP. Along with the vine and fig, the olive has formed a key role in Mediterranean agriculture and commerce since these ancient times. Today, the Western Mediterranean remains one of the worlds largest producers of olive based products (Economist, 1986), and olive grove monoculture represents the dominant landscape in many areas of southern Portugal, south and eastern Spain and parts of southern France.

The pattern and timing of olive cultivation in these regions has varied over time in response to a number of factors including changing agricultural practices, political stability, population pressure and market demand. The role of climate in dictating the spread of olive cultivation may also have been important.

The development of olive cultivation reflects changes in agricultural production which have dramatically altered the Mediterranean landscape. Increases in olive production have been mainly achieved through the extension of cultivation into marginal lands away from irrigated areas. Olive is a high value *secano* crop which grows well in most soils and on steep and difficult terrain. Cultivation however requires considerable agrarian organisation and effort, not just in cropping but also in construction and maintenance of terracing. New trees cannot be grown from seed and take upto twenty years to come into full production. Olive groves require manpower, capital and forward planning linked to a stable market and political situation. Olive trees cannot be moved like livestock or resown like cereals if the political or economic situation changes. Similarly, they cannot be 'stolen', but their added value to the land may have made areas of olive cultivation more likely to suffer conflict. In ancient Syria, the value of olive plantations was reflected in the rate of taxation which was 5 times that of a vineyard, and 20 times that of the best arable land (Jones, 1966).

Evidence for the timing and extent of changes in olive cultivation have so far been restricted to site specific archaeological palaeobotanical investigations and to limited historical documentation. Continuous records on a broader regional scale have only recently become available from late Holocene pollen diagrams. This appendix reviews the evidence for the pattern and timing of the 'olive rise' in the Western Mediterranean, and the anthropogenic and climatic forces that may have underlined it.

10.6.3 Olive cultivation

The olive is a native of the Mediterranean and its distribution has often been related to the northern limits of the Mediterranean climate (*Figure Appx.4.1* p288). It is well equipped to withstand the annual summer heat and drought, with small evergreen leaves and deep, widely spreading roots. The spacing of trees in orchards is dictated by soil water availability, with trees planted closer together on poor draining soils and in high rainfall areas, and more widely spaced on free draining soils and in low rainfall areas. Irrigation is not normally required except in the driest areas and with young plants with poorly developed roots. Given sufficient root development however, olive trees can often be cultivated on the most depleted of soils, and represent a particularly important *secano* or dry-farmed crop. Too much irrigation or rainfall produces poor quality fruit, and dry, hot summers are necessary to allow the fruit to mature.

Prolonged hard frost (below -10°C) is usually fatal to olive trees, causing tissues to rupture and split. Late frosts also damage the reproductive parts, although with the benefit of strong winter sunshine, olive can be found in areas with a mean temperature of 3°C during the coldest month (Walker, 1960). Unusual weather conditions can often be catastrophic, as in the hard winters of 1949-50 and 1955-56 which caused the destruction of large areas of olive trees in the Levant and Italy (Thirgood, 1981; Walker 1960). As a consequence of this constant threat, olive groves are often sited close to the ameliorating effects of the Mediterranean Sea, and at low altitude, where the risk of frost is reduced.

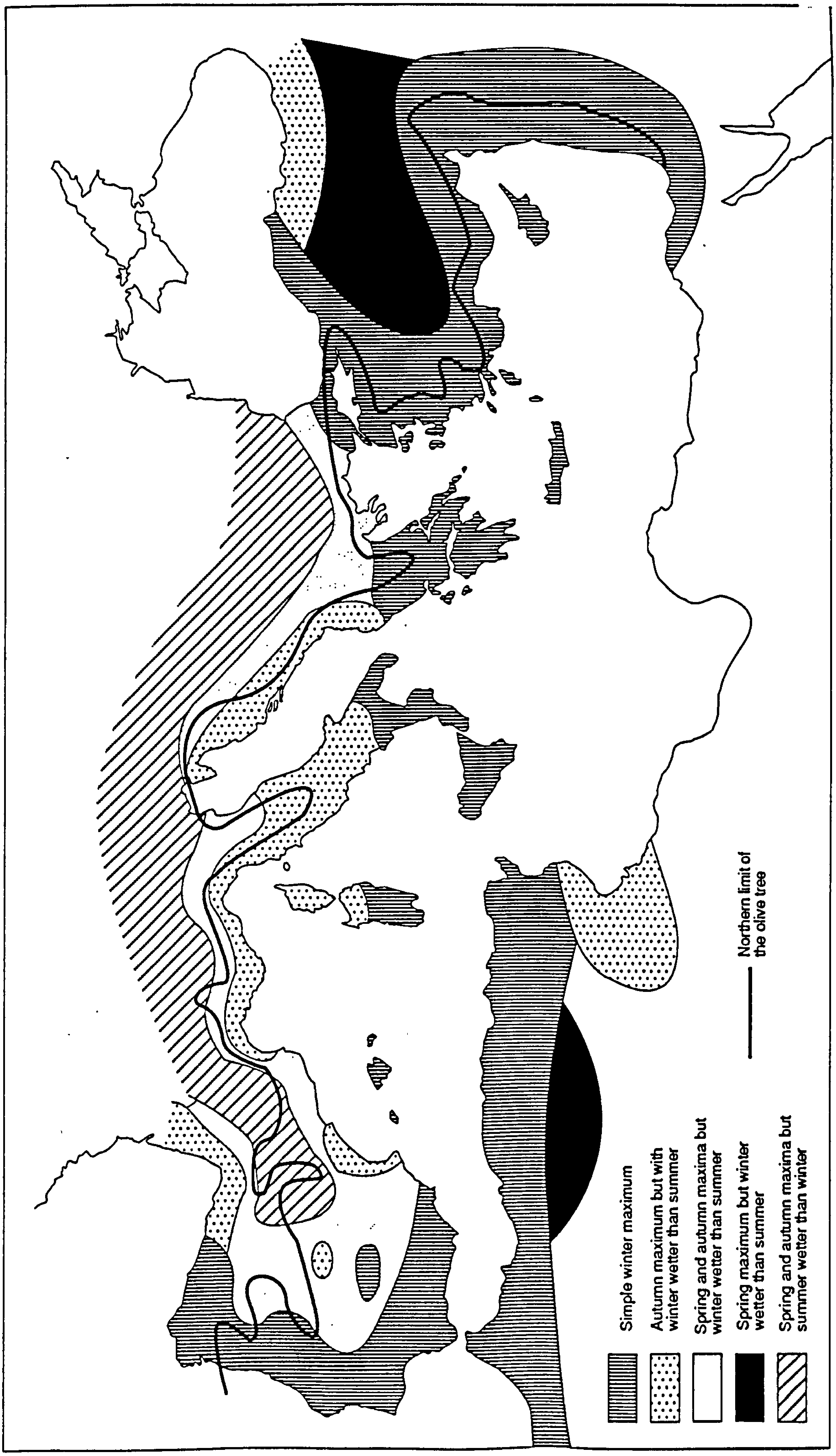


Figure Appx. 4.1 Map of the Mediterranean climate and the northern limit of the olive tree

The cultivation of olive from wild varieties and seed produces fruit of poor quality. Instead, knots and shoots are usually grown in nursery beds and transplanted (Wey, 1962). Grafting onto existing wild or cultivated trees can sometimes be employed allowing the swift introduction of better quality and more productive varieties, although cuttings do not always produce fruits. The time spent growing in a nursery allows the tree to develop a sufficiently large root network for it to be able to draw on enough moisture within the soil to survive the summer drought after transplanting.

Improved methods of cultivation have gradually reduced the time interval between planting and harvesting of the first crop. However, even when grown in an irrigated nursery under perfect conditions, a tree will still take 5-7 years to provide its first harvest, and a further 10 years before it starts to bear its maximum crop. Once established, a tree will continue to bear fruit for over half a century (Wey, 1962), although its yield will decline towards the end of its life.

Olive fruits can be utilised directly for food or as an oil for cooking, lighting or soap making. The poor pasture of the Mediterranean provides little grazing, and olive oil occupies much the same place as butter in the domestic economy (Semple, 1932). The oil is extracted using upto 3 pressings, each producing a product inferior to the last. The final pressing of kernel and skin produces the oil for soap. Leaf fodder from olive trees can supply feeding for livestock and its trimmed branches can provide a renewable fuel. Fine carvings and furniture can be made from its wood, which also makes good charcoal.

The gathering of the harvest usually takes place in December, although pruning, ploughing and manuring can be carried out throughout the year. Occasionally it may be necessary to uncover the roots and remove the suckers (Semple, 1932), especially after grafting which tends to encourage sucker development. Olive cultivation is particularly time consuming compared to other crops, requiring almost 10 times as much work as Cereals and 1.5 times as much as Vines (Delano Smith 1979). Less intensive methods can be employed but these result in a decline in both yield and quality of the crop.

10.6.4 Methods

The Data Set

Comprehensive radiocarbon dated pollen diagrams from Iberia for the latter part of the Holocene have only recently become available. These come primarily from high altitude or coastal valley mires and peat bogs. In common with other semi-arid areas, suitable sediment sinks for environmental reconstruction are limited in the Western Mediterranean. This is particularly so for the mid-altitude range, away from the impeded drainage of the coast and the high-rainfall, deglaciated mountains. The available data set reflects this geographical bias with unfortunately little representation from eastern Spain, the central Mesetas and the Guadalquivir valley. However, this situation is likely to improve in the near future since pollen analysis is currently being undertaken on the many saline lakes in these areas (Stevenson, pers.comm.).

The limited use of lacustrine sediments has also restricted the available late Holocene record since many terrestrial sites have suffered recent disturbance. Erosion, drainage and peat cutting have meant many site records have been truncated or disturbed and only a few provide a continuous record to the present day.

Within this limited data set, principal sites in the north and west show virtually no presence of olive in their pollen profiles. This coincides well with the current northern limit of olive cultivation, where exposure to frost will damage or even kill trees and excessive cloud and moisture produces fruits of poor quality. The same restriction is true for the higher mountain ranges further south, generally above 1200m in Spain (Wey, 1962), although lower in Portugal on the Atlantic seaboard, being 750m in the Serra de Estrela (Van Den Brink & Jansen, 1985), and 400m and 500m in the Minho and Mondego valleys respectively (Walker, 1960). It is therefore surprising perhaps to find quite high values of olive pollen in such areas, presumably as a result of long-distance transport of pollen from lower altitudes.

Huntley & Birks (1984) note the relatively poor production and dispersal capabilities of olive and suggest values of 5% or above occur only when olives are growing extensively in the site catchment area. This might imply even low percentages of olive in the regional pollen rain could represent a significant olive component in the regional vegetation. Surface sample studies in south-west Spain by Stevenson (1981) suggest olive to be a high pollen producer but poor disperser. This is in contrast with other studies in Greece (Bottema, 1974), south-west Turkey (Van Zeist *et al.*, 1975) and Portugal (Mateus, 1992) where olive pollen was found to be relatively well dispersed. This has also been the opinion of other palynologists working in the Mediterranean, including Reille (1975), Beaulieu (1977), Pons & Reille (1986) and Van Den Brink & Janssen (1984). Work by Davis (1994) in the treeless steppe of Los Monegros, north-east Spain, showed olive pollen to form a consistent component in the regional pollen rain of over 10% (Total Terrestrial Pollen), despite the nearest trees being located at least 10km distant, and the nearest olive groves a further 10km away. Values increased to over 20% of total terrestrial pollen within 5km of olive groves (chapter 8, section 8.2.3.1).

The production and dispersal of olive pollen is important when assessing the likely sensitivity of the dataset given the limited geographical spread of pollen records and the distance of many of the sites from the most suitable areas for olive cultivation (*Figure Appx.4.3* p300). As an anthropogenic indicator in Mediterranean pollen diagrams, *Olea* pollen probably has an advantage in that it is more widely dispersed than *Juglans*, *Vitis* and cereal grains, and more easily identifiable than *Castanea*. Many of these other anthropogenic indicators occur in close association with *Olea* in pollen diagrams over the time period studied, reflecting the close relationship between intensive agriculture and high *Olea* values.

Data Analysis

Published pollen diagrams for the Iberian peninsular, Morocco, Corsica and parts of southern France were examined for records of *Olea* over the past 2600 years (*Table Appx.4.1* p298). Olive curves were converted into radiocarbon years and plotted against each other for comparison (*Figure Appx.4.2* p299). Only diagrams with suitable radiocarbon (or ^{210}Pb) dating control were considered. Depths were converted into uncalibrated radiocarbon years by assuming a simple linear time-depth relationship between dates. The core surface was taken to be of contemporary age unless it displayed signs of disturbance or erosion. Only undisturbed sites were used where only one radiocarbon date was available for the diagram. The locations of radiocarbon dating controls in the time series are marked together with their error bands. Unfortunately, a number of early diagrams from Spain provide only summaries of the main taxa, relegating *Olea* to the '*varia*' category. It was therefore not possible to include these studies.

10.6.5 Discussion

2600-2050 BP (Iberian & Early Roman Period)

The cultivated olive (*Olea europaea var. europaea*) is thought to have been introduced by the Phoenicians and Greeks in Spain (Bauer, 1980) and by the Romans in Portugal (Van Den Brink & Janssen, 1985). Wild olive (*Olea europaea var. sylvestris*) was probably already utilised by the indigenous peoples and pollen evidence suggests olive was present in Iberia from at least the early Holocene (Pons & Reille, 1988; Mateus, 1993, Davis, 1994). A Greek navigation guide of 530 BC provides the first documentary evidence of olives in eastern Spain (Schulten, 1957), with olive oil exports from Sagunto to Rome taking place from at least 300 BC (Pla Ballester, 1980). Clay amphoras of sufficient quality to stop olive oil turning rancid from oxidation were being manufactured in southern Spain around 550 BC, although no direct evidence, such as olive presses, have been found (Harrison, 1988).

The first signs of olive pollen occur around this time at [12] Laguna de las Madras (Stevenson & Harrison, 1992) on the south coast of Spain and [18] Hoya de Pepe Hernando (Gomez, 1992) in central Spain. Pollen values remain low however (<3%), and sites with longer sequences such as [28] Besos (Rierra, 1993) on the north-east coast of Spain, show no significant increase in *Olea* values from those experienced early on in the Holocene.

More significant levels (>3%) can be found at the coastal sites of [7] Jbel Bou Rhaba (Rielle, 1979) in Morocco, [9] Lagoa Travessa II (Mateus, 1992) in Portugal, [33] Ponts Clapets (Triat, 1975) in S.France and [36] Saleccia in Corsica.

Many of these sites show an increase in *Olea* from early on in the Holocene, while other high altitude sites start their olive curves at this point including [11] Lagoa Comprida in Portugal (Van den Brink & Janssen, 1986) and [29] La Moulinasse (Reille, 1989) in the French Pyrenees.

The spread of olive throughout the western Mediterranean at this time could be explained by a variety of factors including migration lag and climate change as well as man. The effect of man may not be just directly by introduction and cultivation, but also indirectly through forest clearance.

Evidence of favourable climate conditions at this time comes from the Ebro Basin, northeast Spain, where lake levels were significantly higher between 2600-1900 BP than at any time within the last 7000 years (chapter 10, section 10.4). The vegetation was also typically Mediterranean, with high lake levels reflecting high groundwater levels sustained by winter rainfall while the summers remained dry. The climate was therefore more 'Mediterranean' with wetter winters and long, dry summers. A favourable climate would have assisted the spread of olive against its ecological opponents, although this was probably also encouraged by anthropogenic action. *Olea* appears at this time in the Ebro Basin (*Figure Appx.4.2* p299), along with *Juglans* and cereals, consistent with the idea of agricultural intensification and the active cultivation of olive. The indirect expansion of olive through forest clearance would appear to be discounted since charcoal records from the Ebro Basin show a deforested landscape already being maintained by burning prior to the appearance of olive.

2050-1600 BP (Roman Period)

By 2050 BP, most of Iberia was under Roman rule and only Cantabria remained unconquered. Roman rule was to last another 400 years during which time a comprehensive road network was built, partly for defence and partly to link the Iberian economy into that of the Mediterranean. Demand for agricultural produce in Roman Italy could only be satisfied through the systematic importation of wheat, olive oil and wine from the Mediterranean provinces (Butzer *et al*, 1985) Large estates and latifundia (over 125 ha) were created (Delano Smith, 1979) where the ideas of Roman agronomists could be applied to the large scale production of commercial crops. Pollen percentages for olive of over 5% appear about this time in southern Italy, France and Portugal (Huntley & Birks, 1983; Mateus, 1992), and reach values of over 15% at [19] Le Vallet Neuf (Triat-Laval, 1982) in S.France, and [7] Sidi Bou Rhaba (Reille, 1979) on the Moroccan coast.

Martialis (*Epigrams*) mentions the development of similar large estates in the interior of Spain, although these were probably pastoral given the difficulties of transport and security. Olive pollen is evident in profiles from central Spain [14, 16, 19-21] although not at the high altitude site of [18] Hoyo de Pepe Hernando (Gomez, 1992), and [17] Navalguijo (Franco, 1994) on the eastern boundary of Roman rule and towards the present limit of olive cultivation. Many of the profiles available from the central Spanish mountains [16, 17, 19, 20] started to develop at the time of the Roman occupation, consistent with the idea that the wetter climatic conditions also initiated peat formation at this time.

1600-1300 BP (Visigoth Period)

Visigoth rule (AD 415-711) followed declining Roman power in the Western Mediterranean in the 5th Century AD. The period is marked by a sharp reduction in archaeological sites and materials, suggesting progressive depopulation and lower agricultural intensification. Olive declines at some sites during this period after particularly intense production during Roman times, including [32] Le Vallet Neuf (Triat-laval, 1982) in S.France and [7] Sidi Bou Rhaba (Reille, 1979) on the Moroccan coast. It would appear however that other areas of the Western Mediterranean escaped the economic and social chaos that provoked the 'Dark Ages' in northern Europe. Other sites which showed a continuous olive presence during Roman times show no signs of decline, and actually increase at [11] Lagoa Comprida in Portugal (Van den Brink & Janssen, 1985) and [31] Marsillargues in Provence (Planchais, 1982).

The lake level record from the Salada Pequeña in the Ebro Basin (*Figure 9.5.6*), northeast Spain, shows that winter rainfall declined rapidly at around 1800 BP, accompanied by a sharp reduction in agricultural activity and the restoration of pine forest. *Olea* also disappears from the pollen record (*Figure 9.5.2*) as conditions became more arid and possibly cooler.

Olive trees were highly prized by the Visigoths who actively planted new groves and traded olive oil (King, 1972). The continuation of intensive olive cultivation in some areas at period of undoubted agricultural decline and depopulation may suggest that the new invaders sought out lands of 'added value' to colonise, including those already containing olive groves.

1300-400 BP (Arab & Reconquest Period)

In 711 AD, Iberia was again invaded, this time from the south. The Arab occupation was to last until AD 1492 and is traditionally viewed as a period of great agricultural improvement and material prosperity. The new rulers allotted one-fifth of the land to peasant farmers and extracted only 20-50% of the produce. This was in contrast to the Visigoths who had treated the peasants as virtual slaves and taken upto 50-80% of their crops. The remaining four-fifths of the land not awarded to the peasants was assigned to the Emirs own followers who had a personal interest in improving it.

Agricultural surpluses of the time encouraged a resurgence in town life, with the ruling city of Córdoba attaining a population of over 500,000, by far the largest and most prosperous city in the West at the time (Barraclough, 1978). Wheat was the basic crop, supplemented by exotic foods from the Orient such as rice, peaches, figs, almonds and oranges. Commercial crops were also cultivated, such as cotton, silk, saffron, esparto, flax, hemp and wool (Jackson, 1972). Olive oil was actively traded as the 'liquid gold of Moorish Andalucia' and highly prized by Genoese merchants (Fernández Armesto, 1987).

The Arab conquest is thought to have done most to develop irrigation in the more arid south and east of the country. As in Roman times, the vast interior of the Peninsular however was thinly populated and left over to pastoralism and dry farming. To the north and west, the invading Moors "made practically no headway in the humid zone of the Iberian Penninsular" (Despois, 1961).

Olive profiles for this period from central Spain reinforce this view. Olive presence becomes more widespread and continuous but values remain low, even at low altitudes such as [14] Castillo de Calatrava (Garcia *et al*, 1986) in the Southern Meseta. Olive cultivation was more extensive than at any other time in peninsular history (Jackson, 1972) but its role in the Spanish interior was only minor. Castillians had little esteem for olives, relying mainly on lard for edible fat and had little tradition of olive growing (Fernández Armesto 1987). More sensitive sites, such as [11] Lagoa Comprida (Van Den Brink & Janssen, 1985) show a much more profound change, with a steeply rising olive curve eventually reaching values of over 20%. This occurs some 250 RC years earlier than similar increases observed by [1-6] Reille (1977) in the Moroccan Rif mountains, but coincident with sites in Southern France [31-35] which were by this time under Frank rule.

These differences may reflect the difficulties of establishing olive cultivation in marginal areas with no existing tree stocks and traditions. There is little evidence of olive prior to this period of expansion from sites in the Rif mountains. In contrast, olive would appear to have been an established part of the vegetation landscape in Southern France and Portugal, where cultivation practices introduced during Roman times may have persisted within the agrarian society.

A significant decline in the area dedicated to olive appears to have occurred at [11] Lagoa Comprida (Van den Brink & Janssen, 1985) in Portugal at around 500 BP, coinciding with a reduction in cereal pollen, and presumably marking a general decline in agricultural productivity. The establishment of the Portuguese overseas colonies around this time led to extensive migration and depopulation that may have negatively affected agricultural productivity. Sites in central Spain lying the north of the reconquest lands would have escaped the economic and social turmoil of the south, and in turn appear to show little impact from these political and agricultural changes. The southern sites of [12] Laguna de la Madres and [13] El Acebron

(Stevenson & Harrison, 1992) lie relatively far from the main olive growing region within the Guadalquivir valley, and similarly show little sign of change.

Sites in southern France show a different pattern, with sites to the west [31-32] showing a decline at around 1000 BP, while those to the east [34-35] increase. Both of these eastern sites, [34] Etang de Berre II (Laval & Medus, 1989) and [35] Etang de Berre I (Laval, Medus & Roux, 1991), show a later decline at around 400 BP that reflects a continued movement of the main area of olive cultivation away from the Rhone delta to its present eastward position (*Figure Appx.4.3* p300).

The initial decline in olive cultivation at *ca.*1000 BP came at a time of considerable political unrest in the area as repeated invasions caused the breakup of Frankish rule. From the south came the Saracens and occasionally the Vikings, while from the north, the Magyars caused greater, but shorter lived destruction. The population was at its lowest since the fall of the Roman Empire, and the cities of Marseille, Aix and Arles were abandoned (Barraclough, 1978).

The effects of this period on the agrarian economy of the area appears to have been terminal at these sites, since little recovery in olive cultivation is shown. The eastward migration of the centre of olive cultivation may reflect an increase in frequency of damaging mistral winds across the Rhone delta. The timing of this shift in olive cultivation coincides with the end of the medieval warm period in Europe and the onset of the cooling that was to lead to the Little Ice Age. Land to the east of the delta would have been sheltered from incursions of cold air and therefore presented a more favourable location for the restoration of olive cultivation as the population recovered after 900 BP.

400-200 BP (The 'Golden Age' Period)

The closing of the eastern trading routes during the 15th Century cut off supplies of spices and other oriental goods to Europe. The search for alternative routes to the Indies led to Portuguese colonisation of Madeira, the Azores and parts of Latin America. In response to these discoveries, Ferdinand and Isobella of Spain eventually decided to finance Columbus and his eventual discovery of the Americas in 1492.

The 16th Century was marked by an increasing population and rising agricultural output in Iberia. The wool and textile industry began to make Castile the economic equal of Andalucia. The lucrative trade in wine and oil to the new colonies was reinvested in the cultivation of vines and olives. It is at this point that olive curves from Spanish pollen sites start to rise prominently. Despite the difficulties of dating control and resolution, this rise appears synchronous throughout Iberia at this time, and particularly strong in the centre and north of the country.

Castilian dominance caused a fundamental centripetal shift in the concentration of political and economic power to these central and northern regions. Expansion of the wool trade and the introduction of maize also helped encourage an increase in population and the development of many central and northern cities. These growing city populations encouraged agricultural intensification in areas in the centre of the country that had previously been ignored. Many mountain areas suffered deforestation at this time (Bauer, 1991), partly to expand the area under agriculture, but also to supply timber for ship building, and wood for housing and fuel. Sites in central Spain ([14] Garcia *et al*, 1986; [21-24] Garcia, 1992; [18-20] Gomez, 1992; [16-17] Franco, 1994) and north-east Spain ([25-26] Davis, 1993) reflect these changes with increases in *Olea* to levels unprecedented at any time in the Holocene.

The great expansion of olive cultivation throughout the country in the 16th Century is perhaps unusual, since it seems to have occurred in the face of particularly unfavourable climatic conditions. This period coincides with the onset of the Little Ice Age in the Peninsular, a time of cold winters and severe frosts (Font, 1988). By the end of the Century, frosts were common place in Cordoba and Valencia, and the Guadalquivir had frozen over. Periods of heat, drought and flood were also more prevalent than in previous Centuries (Font, 1988), and it may well be that the ability of olive trees to withstand these extremes, together with a more predictable harvest generally associated with tree crops, meant greater investment in olive cultivation in preference to cereals and root crops. Periodic loss of trees during the severest weather in the early 17th Century may partly explain the slower increase during this early period than later in the 18th Century.

While olive cultivation expanded in Spain at around 400 BP, it declined notably in southern France. A dramatic fall in olive cultivation is shown at the [34-35] Etang de Berre (Laval & Medus, 1989; Laval, Medus & Roux, 1991), where an increased frequency of severe frosts during the Little Ice Age may have further restricted cultivation in the region of the Rhone delta. The olive curve also declines around this time at Canet St.Nazaire in Languedoc, to the west, where Braudel (1972) reports that frosts devastated the olive groves in the 16th Century.

While the cold weather may have been unfavourable for olive cultivation in parts of southern France during the Little Ice Age, the expansion of olive groves in the Iberian Peninsula indicates that it does not appear to have suffered from the same severe winter weather. Climate conditions in the Ebro Basin in northeast Spain appear to have been comparable with Iberian times, with higher lake levels and Mediterranean taxa suggesting wetter and warmer winters, but with a persistent summer drought.

200-0 BP (The agrarian crisis and modern times)

The 'Golden Age' of Iberian exploration, colonisation and exploitation overseas disguised two fundamental problems at home that were eventually to undermine agricultural production and Iberian world power. Depopulation to the new colonies together with a growing non-productive class of soldiers, clerics and aristocracy meant ever fewer working the land and ever more taking from it. This traditional view of impending agrarian crisis is at odds with the pattern of continued olive expansion in Spain throughout this period.

By the 18th Century, the Spanish wool industry was already in decline as a result of imported cotton and German competition. The expanding markets of north-west Europe and the overseas colonies did however increase demand for typical Mediterranean products, including wines, fruits and oils. Changes were also occurring in the pattern of land ownership and arrangements of tenure, often replacing rents based on subsistence with those involving the market and a cash return. The importance of cash crops also increased as the government sought to find taxable income to replace monies previously generated by the wool monopolies. Expropriation of church and common land in 1837 also allowed more land to be brought under intensive cultivation (Gilman & Thornes, 1985). All these factors, together with a reduced frequency of severe winter frost (Font, 1988), may have influenced the accelerated expansion in olive cultivation at this time shown at [25] Laguna Salada and [26] La Estanca in the Ebro Basin (Davis, 1993). Other sites lack the time resolution and proximity to the main areas of olive cultivation, although a similar pattern might be suggested at other Spanish sites, including [15] Laguna Grande de Gredos (Toro *et al*, 1992), [16] Navaredonda (Franco, 1994),

[18] Hoya de Pepe Hernando (Gomez, 1992) and [24] Pico de Lobo (Garcia, 1992). In south-east Spain, Oniera Mariega (in Gilman and Thornes, 1985) found documentary evidence for a 3000% increase in olive cultivation since 1752 AD in the Municipio of Montefrio. Increased cultivation of olive at this time is also shown at coastal sites in Corsica [36-37] and the Rif mountains of Morocco [1, 3-6].

In the past 100 years or so, a sharp decline in *Olea* is indicated at sites with high resolution records near the main olive cultivation areas in Portugal at [11] Lagoa Comprida (Van Den Brink & Janssen, 1985) and in north-east Spain at [25] Laguna Salada and [26] La Estanca (Davis, 1993). Rural depopulation and competition from new overseas areas of olive production are probably large factors in this decline which appears to reflect a more general decline in agricultural productivity in Spain until intensive investment in irrigation and mechanisation in the last few decades (Harrison, 1989).

10.6.6 Conclusions

Low levels of *Olea* pollen (<4%) have been identified in pollen diagrams from southern Portugal (Mateus, 1992), Spain (Pons & Reille, 1986; Davis, 1994) and Morocco (Reille, 1979) from the early Holocene onwards. Levels do not begin to exceed 4% until late Neolithic or early Bronze Age times (5500-4500 BP), when an increase in exploitation of natural wild olive occurred. In contrast to the low levels of *Olea* recorded in southern Europe, values reach almost 15% at [7] Sidi Bou Rhaba (Reille, 1979) on the Moroccan coast at this time. Similar levels at other sites do not occur until late Roman times, and can only be attributable to significant levels of olive cultivation.

Archaeological evidence indicates that the introduction of olive cultivation to southern Europe occurred with the arrival of Greek and Phoenician traders at around 2500 BP. This is confirmed by the appearance of low (<6%), but continuous levels of *Olea* pollen at this time at sites in Portugal, coastal Spain, southern France and Corsica. Unlike the Eastern Mediterranean (Huntley & Birks, 1983), there does not appear to have been any particular east-west trend to this event, with increases contemporaneous across a wide area within a period of onehundred years.

Following the establishment of Roman rule in Iberia (*ca.*2050-1600 BP), olive cultivation increased in southern Portugal, but not on the same scale as parts of southern France and coastal Morocco. The inland areas of Iberia remained poorly developed during this period, with few signs of olive.

The economic and social decline of the Visigothic era (*ca.*1600-1300 BP) sees a general reduction or stagnation of olive exploitation throughout the Western Mediterranean. This is reflected in a general shift to extensive pastoral agriculture and major woodland clearance, and marks the end of intensive olive production on the coastal plain of Morocco. A distinct increase in aridity also occurred about this time, with a sharp fall in lake level recorded in the Central Ebro Basin, north-east Spain (section 10.5).

Woodland clearance continued during the Arab occupation of Iberia, and olive cultivation was extended into the central and upland regions of the Western Mediterranean, while the coastal areas were increasingly exploited for other uses. A low, but continuous presence of *Olea* now appears for the first time in the Rif mountains of Morocco, and the central Mountains of Spain, while intensive cultivation is established in the Serra Estrela, Portugal (Van den Brink & Janssen, 1985). *Olea* declines in the coastal areas of Corsica and the Rhone delta, although intensifies at the Etang de Berre (Laval & Medus, 1989; Laval, Medus & Roux, 1991), where land drainage may have brought new areas into production

The establishment of Iberian overseas colonies and trading power in the fourteenth and fifteenth Centuries (*ca.*400 BP) coincided with a dramatic rise in olive cultivation throughout the Peninsula. Overseas migration also resulted in rural depopulation and a decline in olive production in some parts of Portugal. Other areas of previously intensive production, such as southern France, became less important as Iberia established itself as the main producer.

Olive production peaked in Iberia in the seventeenth and eighteenth Centuries, although the exact date is difficult to establish from palaeoecological evidence alone. Other areas also show an increase during this period, including coastal Corsica and the Rif mountains of Morocco. More recently, high resolution records show a decline in olive cultivation in Iberia within the last 200 years, reflecting a general trend to rural depopulation and industrialisation of the economy.

Despite the low number of sites with complete late Holocene sequences, and the distance of many from the main areas of olive production, a number of trends can still be distinguished in the development of olive cultivation in the Western Mediterranean. The pollen evidence indicates that the late Holocene olive rise is a real, but temporally and spatially discontinuous event. Regional differences occur in the timing and strength of the rise in the olive curve, reflecting changes in the extent and location of production. These changes can be seen in the rise and fall of *Olea* pollen over time, depending on site location and the economic, social and climatic factors affecting agricultural production. In determining the influence of such factors, palaeoecological evidence provides a useful continuous and independent record against which more detailed, but discontinuous and often site specific, archaeological and historical information, can be compared.

Table Appendix 4.1 **Published pollen diagrams with late Holocene olive curves from the Western Mediterranean**

Site Ref.	Site Location	Altitude	Author(s)
[1]	Jbel Tizerene	1400m	Reille (1977)
[2]	Daya Abatete, Jbel Rhesna	1270m	Reille (1977)
[3]	Sphaignes, Jbel Rhesna	1300m	Reille (1977)
[4]	Marzine, Jbel Sougna	690m	Reille (1977)
[5]	Tanakob, Jbel Sougna	840m	Reille (1977)
[6]	Jbel Bou-Hachem	1100m	Reille (1977)
[7]	Sidi Bou Rhaba	25m	Reille (1979)
[8]	Lagoa Travessa I	1.8m	Mateus (1992)
[9]	Lagoa Travessa II	1.7m	Mateus (1992)
[10]	Figueira de Baixo	2.9m	Mateus (1992)
[11]	Lagoa Comprida 2A	1600m	Van den Brink & Janssen (1985)
[12]	Laguna de las Madres	20m	Stevenson & Harrison (1992)
[13]	El Acebron	25m	Stevenson & Harrison (1992)
[14]	Castillo de Calatrava	600m	Garcia *et al* (1986)
[15]	Laguna Grande de Gredos	1960m	Toro *et al* (1992)
[16]	Navaredonda	1580m	Franco (1994)
[17]	Navalguijo	1500m	Franco (1994)
[18]	Hoya de Pepe Hernando	2020m	Gomez (1992)
[19]	Loma de Penas Creciente	1775m	Gomez (1992)
[20]	Majadas de los Hoyas	1840m	Gomez (1992)
[21]	Puerto de Morcuera PMVIII	1740m	Garcia (1992)
[22]	Puerto de Morcuera PMIII	1740m	Garcia (1992)
[23]	Puerto de Morcuera PMVII	1190m	Garcia (1992)
[24]	Pico de Lobo	2125m	Garcia (1992)
[25]	Laguna Salada	160m	Davis (1994)
[26]	La Estanca	350m	Davis (1994)
[27]	Ibon de las Ranas	2092m	Montserrat (1992)
[28]	Besos	7m	Rierra (1993)
[29]	La Moulinasse	1330m	Rielle (1989)
[30]	Canet St.Nazaire	1m	Planchais (1985)
[31]	Marsillargues	0.5m	Planchais (1983)
[32]	Le Vallet Neuf	0.1m	Triat-Laval (1982)
[33]	Ponts Clapets, Fos	0.5m	Triat (1975)
[34]	Etang de Berre II	8m	Laval & Medus (1989)
[35]	Etang de Berre I	8m	Laval, Mdus & Roux (1991)
[36]	Saleccia	15m	Reille (1992)
[37]	Etang de Crovani	8m	Reille (1988)
[38]	Etang del Sale	1m	Reille (1984)

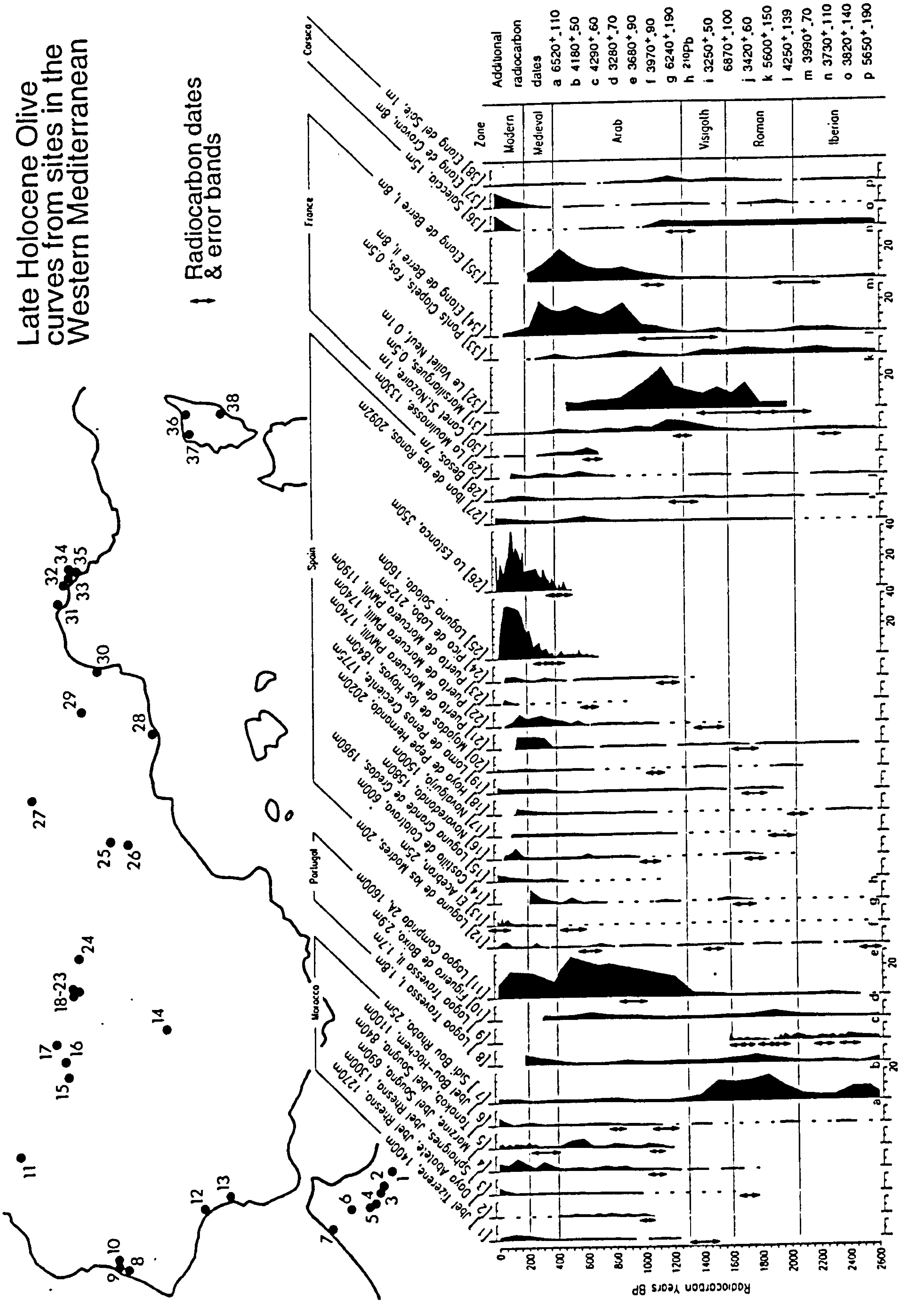


Figure Appx. 4.2 **Late Holocene olive curves from sites in the Western Mediterranean**

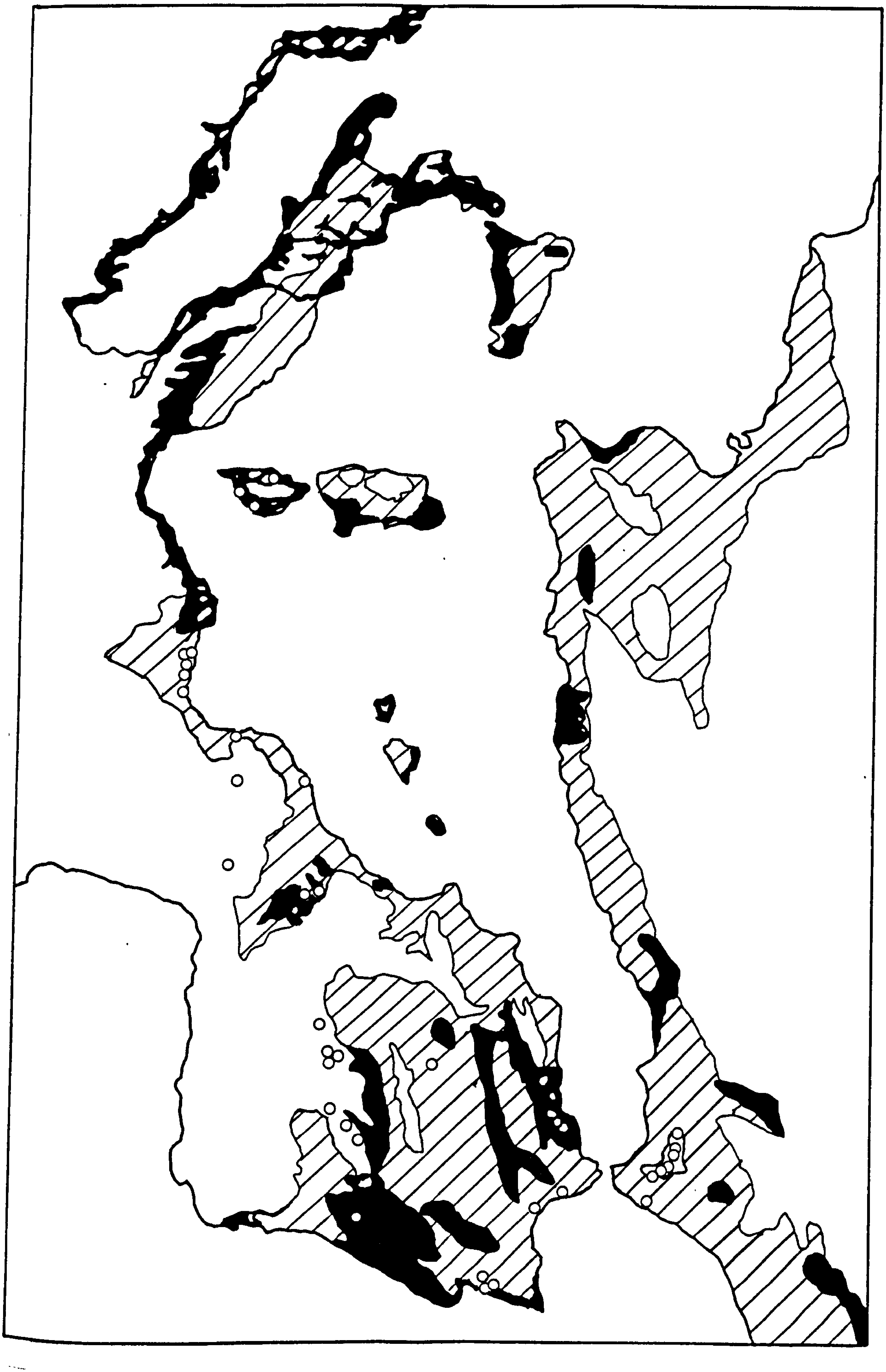


Figure Appx. 4.3 **Map of olive cultivation [illegible] Mediterranean: black areas are those of most intense olive cultivation ([illegible] ndrew, 1961)**

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