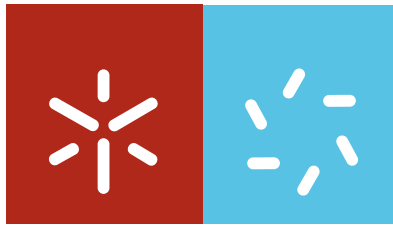Universidade do Minho
Escola de Ciências

Randi Danielsen

Late Holocene Environmental Change
at the Quiaios-Tocha coastal plain.

July 2009

Universidade do Minho
Escola de Ciências

Randi Danielsen

Late Holocene Environmental Change
at the Quiaios-Tocha coastal plain.

PhD Thesis of Science

Work accomplished under the orientation of
Professor Dr. José Eduardo Ribeiro do Rosário Mateus
e do
**Professor Dr. Pedro Alexandre Faria Fernandes
Teixeira Gomes**

July 2009

DECLARAÇÃO

Nome: Randi Danielsen

Endereço electrónico: randidanielsen@gmail.com   Telefone: 968 388 406

Número do Bilhete de Identidade: N - 0002071

Título da Tese de Doutoramento
Late Holocene Environmental Change at the Quiaios – Tocha Coastal Plain

Orientador(es):
Professor Doutor Pedro Alexandre Faria Fernandes Teixeira Gomes
Professor Doutor José Eduardo Ribeiro do Rosário Mateus

Ano de conclusão: 2009

Designação do Ramo de Conhecimento do Doutoramento:
Ciências

É AUTORIZADA A REPRODUÇÃO INTEGRAL DESTA TESE/TRABALHO APENAS PARA EFEITOS DE INVESTIGAÇÃO, MEDIANTE DECLARAÇÃO ESCRITA DO INTERESSADO, QUE A TAL SE COMPROMETE;

Universidade do Minho, ___/___/_____

Assinatura: _____

I would also like to thank Carol Preston for her kind help with proof reading and improvement of my English. Thanks to Jan Berge, University of Bergen, for letting me use his photo of *Erica tetralix* as a chapter divider.

Finally, I wish to give my gratitude to my family and friends who had patience with me through all these years as a student.

Late Holocene Environmental Change at the Quiaios-Tocha coastal plain

Abstract

This thesis concerns the palynological investigation of organic sediment series of coastal mire deposits along a transect of sites from the sea to the inland old dune fields, including lagoons, wetlands and lakes. The results have been integrated in an extended view of landscape evolution, taking into consideration many sources of information such as those from coastal geomorphology, sedimentology, malacology and finally from regional history.

For the last millennia (Middle/Late Holocene) patterns of local and regional vegetation change, concerning the vascular plants and the wetland micro-communities (fungi/algae) have been described and partly dated, giving rise to a scheme of palaeohydrological evolution of the waterbodies in the context of palaeoecological evolution. This is primarily palaeovegetational and palaeohydrological in character, but has been used to give new insight into coastal evolution in general such as phases of aeolian activity and dune building, earlier coast line and related sea level. In addition aspects of human impact have been considered.

The obtained data shows that during Prehistoric times the region was covered with a forest of pine (*Pinus* spp.) and oak (*Quercus* spp.). Some time between 4000 and 1600 years BP the region was progressively deforested and a semi-natural heathland developed dominated by species from the Ericaceae, probably maintained by cutting, burning and grazing. Later on this heathland and dune vegetation was degraded by an intense destabilisation and immigration of dunes and a subsequent desertification. This phenomenon was connected to the deteriorating climate during the Little Ice Age (LIA) and possibly a consequence of an increasing over-grazing towards modern times.

This eventually led to reforestation efforts initiated in the vicinity c 300 years ago and locally on the coastal fringe to the west of the lakes, as late as between 1924 and 1940.

Palaeolimnological implications of the palynological records of hygrophilous taxa and micro-communities of algae (and fungi), such as *Pediastrum*, gave new and interesting information about the history of the studied lakes. The record of local-scale vegetation patterns was utilized to

reconstruct the evolution of the environment in and around the lakes. Initially the sites were wetland areas similar to the dune slacks and seasonal pools found in the region at present. Formation of the two investigated lakes, Lake Vela and Lake Braças as permanent open water lakes, occurred relatively synchronously between 1723 and 1866 AD in response to the same regional geo-hydrological and climatic forcing.

Biotic and abiotic dissimilarities between the two lakes seem to have existed from the time of lake formation until today, with one of the lakes (Vela) being more alkaline and more eutrophic than the other. Contemporary knowledge of the ecological requirements of vascular plants and algae permits an attempt to elucidate these differences. The dissimilarities were probably caused by variations in water flux- direction and velocity and in agricultural intensity in the vicinity of the lakes.

In this work an apparently close relation between lake formation and aeolian activity and accumulation of sand dunes at the western banks of the lakes, was found. The three generations of dunes identified for the region by geomorphologists, were observed as truncated dunes, parabolic dunes and transverse/oblique dunes. The last generation associated with an intense migration of sand until the western banks of the present lakes, is presumably closely linked to lake formation at the Vela/Braças sites.

At the westernmost part of the littoral fringe lagoonal deposits were encountered. Analysis of these deposits suggest an end to the Flandrian transgression at a sea level similar to the present one c 5000 years BP at which time the coast line was c 1 km further inland compared to the actual situation. The following progradation of the coast line, that occurred c 4000 years ago, may have been related to the formation of a protective sand barrier giving rise to the establishment of brackish water lagoons to the east of the barrier.

Alterações Ambientais na Planície Costeira de Quiaios-Tocha durante o Holocénico Recente

Resumo

Esta tese constrói-se em torno de investigação palinólogica de séries de sedimentos orgânicos de depósitos costeiros de origem palustre ao longo de um percurso linear desde o mar até aos campos de dunas interiores preservados em lagunas, pântanos e lagoas. Os resultados foram investigados numa visão mais alargada de evolução paisagística tendo em consideração outras fontes de informação como as que decorrem dos estudos de geomorfologia, sedimentologia e malacologia das formações costeiras e da história regional.

Para os últimos milénios (Holocénico Médio/Recente), foram descritos padrões de mudança da vegetação local e regional envolvendo quer as plantas vasculares quer as micro-comunidades palustres de algas e fungos, que foram sumariamente datadas, resultando num esquema de evolução palaeoecológica para esta faixa costeira. Trata-se de um esquema primariamente palaeovegetacional e palaeo hidrológico mas que permite lançar luz sobre aspectos da evolução costeira em geral, como sejam a identificação de fases de actividade eólica, construção dunar, e evolução da linha da costa e do nível do mar. Por fim aspectos da humanização da paisagem foram ainda abordados.

Os dados obtidos mostram que durante a Pré-história a região teria sido inicialmente ocupada por matas de pinheiro (*Pinus* spp.) e carvalho (*Quercus* spp.). Entre 4000 e 1600 anos BP, assistimos à progressiva desflorestação da região e ao desenvolvimento de uma vegetação semi-natural arbustiva dominado por Ericáceas, provavelmente mantida por corte, fogo e pressão pastoril. Mais tarde assistimos à degradação desta paisagem de charnecas e matos pela intensa destabilização e imigração dunar e consequente desertificação. Este fenómeno esteve ligado à deterioração climática da Pequena Idade do Gelo (LIA) e possivelmente é uma consequência da acentuada sobre-pastagem durante a Época Moderna.

Esta situação levou ao processo da reflorestação que começou na região há cerca de 300 anos e mais tarde entre 1924 e 1940, localmente em toda a faixa costeira a ocidente das lagoas.

As implicações paleolimnológicas dos dados palinológicos relativos à vegetação higrofita e às micro-comunidades de algas (e fungos), como por exemplo de *Pediastrum*, forneceram informação nova e interessante sobre a história das lagoas estudadas. O registo dos padrões da vegetação à escala local permitiu evidenciar a evolução da estrutura da vegetação palustre no interior e margem das sistemas paludosos e a sua especificidade. Inicialmente os sítios consistiam em depressões húmidas de carácter intradunar podendo sazonalmente assumir o aspecto de charcos. A formação das duas lagoas investigadas, Lagoa da Vela e Lagoa das Braças, enquanto corpos de água livre permanente, ocorreu de forma relativamente sincronizada entre 1723 e 1866 AD como resposta à mesma força geo-hidrológica e climática regional.

As diferenças bióticas e abióticas entre as duas lagoas parecem ter existido desde o tempo da sua formação até à actualidade, com uma das lagoas (Vela) a apresentar maior alcalinidade e eutrofização do que a outra. O conhecimento actual das preferências ecológicas das plantas vasculares e mais especificamente das algas, permite tentativamente elucidar as diferenças entre as duas lagoas. Estas diferenças foram causadas provavelmente por variações na direcção e velocidade do fluxo da água e pela intensidade da agricultura nas proximidades das suas margens.

Neste trabalho foi encontrada uma aparente relação próxima entre a formação das lagoas e a actividade eólica e a acumulação das dunas de areia nos bancos ocidentais das lagoas. Das três gerações de dunas identificadas na região pelos geomorfologos, a saber – dunas truncadas, dunas parabólicas e dunas transversas/obliquas – a última geração que está associada a uma intensa migração de areias para junto das actuais lagoas, esteve muito provavelmente relacionada com a formação lacustre da Vela e Braças.

Foram também encontrados depósitos lagunares entre 0 e 1 km da linha de costa actual. A análise destes depósitos sugere um limite final à transgressão Flandriana ao nível do mar semelhante ao presente há aproximadamente 5000 anos BP, altura em que a linha da costa estava aproximadamente a 1 km de distância para o interior comparativamente com a sua localização actual. A posterior progradação da linha da costa que aconteceu há cerca de 4000 anos, poderá estar relacionada com a formação de uma barreira protectora de areia e que deu origem a uma laguna salobra no lado oriental da barreira.

CONTENTS

CHAPTER 4

Holocene interplay between a dune field and coastal lakes in the

CHAPTER 5

Final discussion

List of figures

List of tables

Chapter 4

GENERAL INTRODUCTION

The palynological approach

The investigation of pollen and other plant micro-remains preserved in past soils and limnic sediments and the subsequent reconstruction of former vegetation and environment conditions through interpretation of the findings, is the main principle of palynology. Resilience of the pollen grain, vast pollen production and relatively homogenous dispersal and deposition are the principles on which the method is based. Pollen production varies with dispersal strategy; wind-pollinated (anemophilous) species producing much larger quantities of pollen than insect-pollinated (entomophilous) and self-pollinated (autogamous / cleistogamous) species. Absence of pollen of an anemophilous species implies that there is relatively low probability that the plant grew in the local or extra-local environment (Fig.1), (sensu. Janssen, 1973). This assumption, however, does not apply to the absence of pollen of entomophilous or autogamous species, whose presence on the other hand means that the species almost definitely grew locally.
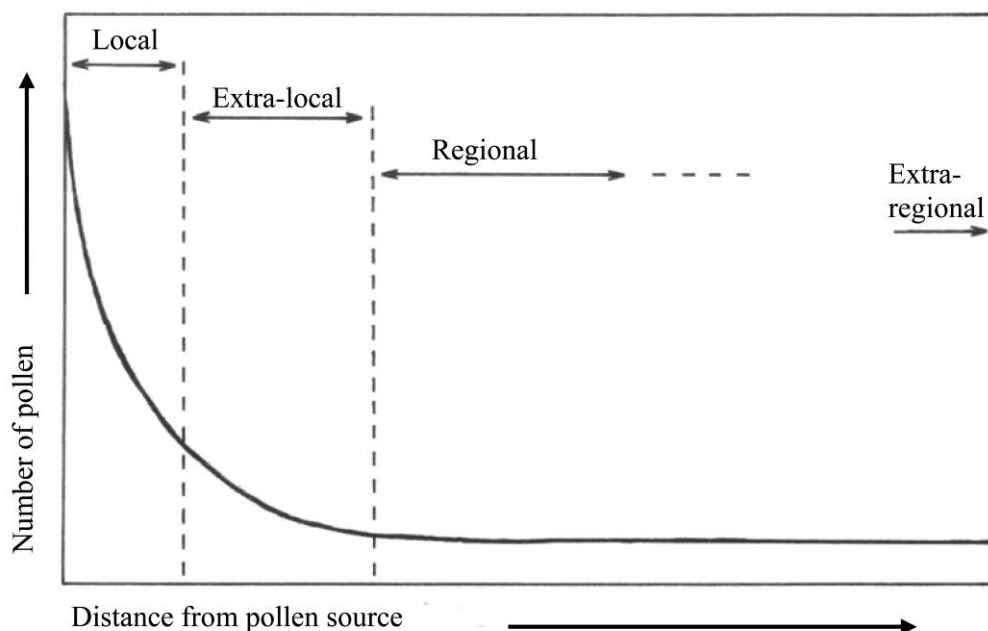
Fig.1. Principles of pollen deposition. Redrawn from Janssen, 1973

Identification of pollen down to the lowest possible taxonomic level is essential for the interpretation and reconstruction of the flora, vegetation and environment. There is, however, no direct relation between pollen assemblages and vegetation, and interpretation must be based on comprehension of all the different factors influencing the pollen from production, through dispersal, deposition and preservation until sampling and analysis (Fig.2). Knowledge of ecologic

demands of individual plants and plant communities may secondarily be applied to deduce causal conditions like climate, cultural activity and geologic events.
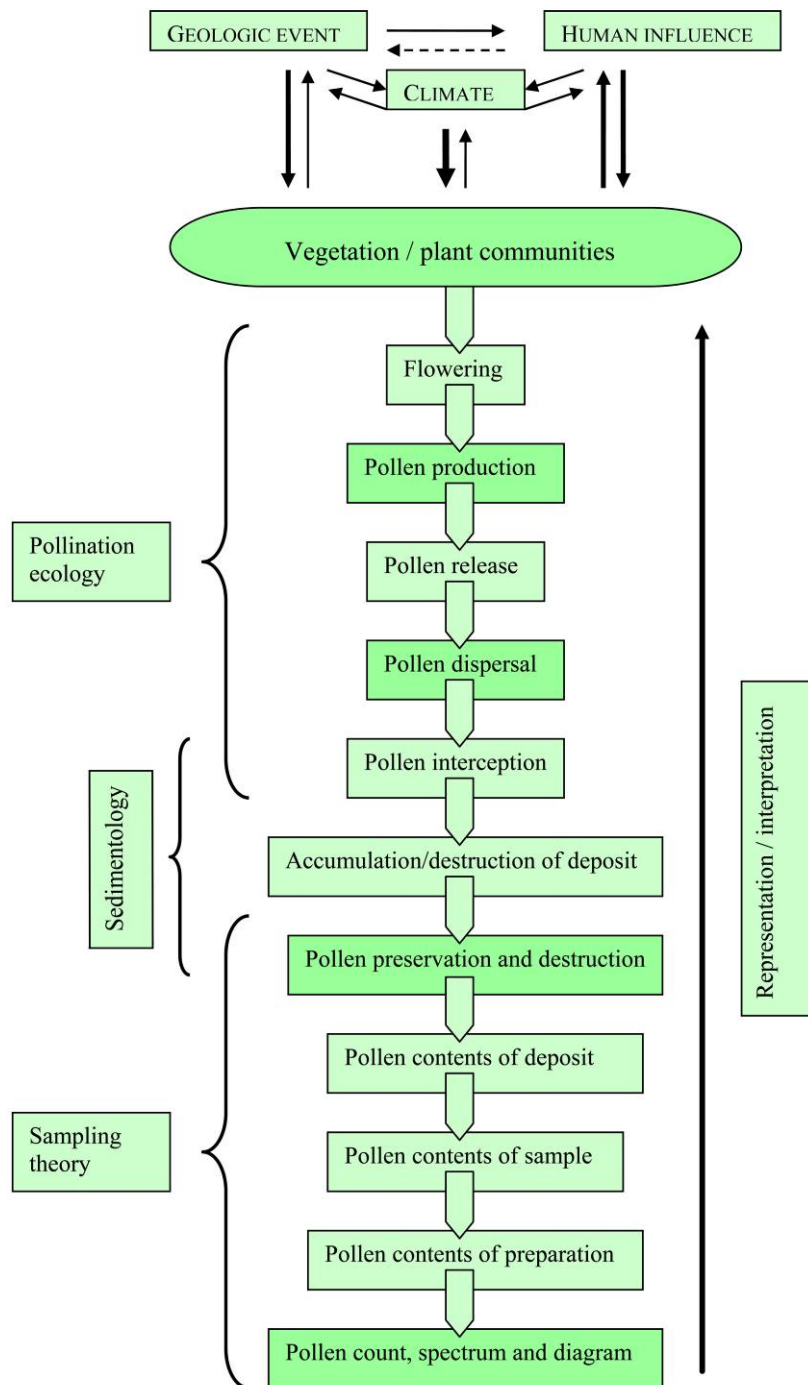
Fig.2. Flowchart of pollen analysis. Redrawn from Fægri *et al.,* 1989

From a European perspective relatively few palynological investigations exist regarding vegetation in Holocene Portugal (Mateus & Queiroz, 1993). Pollen preservation requires humid, anaerobic soils found in wetland and lake sediments as well as in lagoonal and marine deposits.

Palynological analyses of marine cores record the vegetation of a very large region and give information about past vegetation on a continental scale. For more detailed knowledge about a limited geographical area, sediments from lakes, wetlands or lagoons must be used. In some parts of Portugal these types of habitats are missing.

Two regions that have been extensively studied though are the Serra da Estrela (Romariz, 1950; Janssen and Woldringh, 1981, van den Brink and Janssen, 1985; van der Knaap and van Leeuwen, 1995; van der Knaap and van Leeuwen, 1997) and north-western Alentejo (Mateus, 1989; Mateus, 1992; Queiroz, 1989; 1999; Queiroz and Mateus, 1994). Other more scattered studies exist from Boca do Rio (Algarve) (Allen, 2003), from the lower Tagus valley (van Leeuwaarden and Janssen, 1985), from Nazaré, (Gomes, 2007) and from north-western Portugal (Ramil-Rego and Gomez Orellana, 1996; Gomez Orellana, *et al.*, 2001).

Apart from the preliminary pollen investigation south of Nazaré (Gomes, 2007), there is no other Holocene palynological investigation from central-littoral Portugal. On that account the current investigation is a contribution to fill the resultant information gap for the comprehension of Holocene vegetation history and environmental development of this region.

Study area

The littoral fringe of central Portugal is extensively covered by sand dunes, in places reaching up to 10 km inland. Most of these dune systems were probably formed during Pleistocene and Holocene (Carvalho, 1954; 1964; Granja, 1990; 1999; Granja & Carvalho, 1992; Granja & de Groot, 1996; Granja *et al.,* 1996; 2008; Clarke and Rendell, 2006) and consist of various dune formations or fields with distinctive morphology, such as; littoral dunes, parabolic dunes, transverse/oblique dunes and further inland, abraded dunes.

The study area is located in northern-central littoral Portugal and comprises the dune fields to the north of Figueira da Foz and Serra da Boa Viagem (Fig.3).
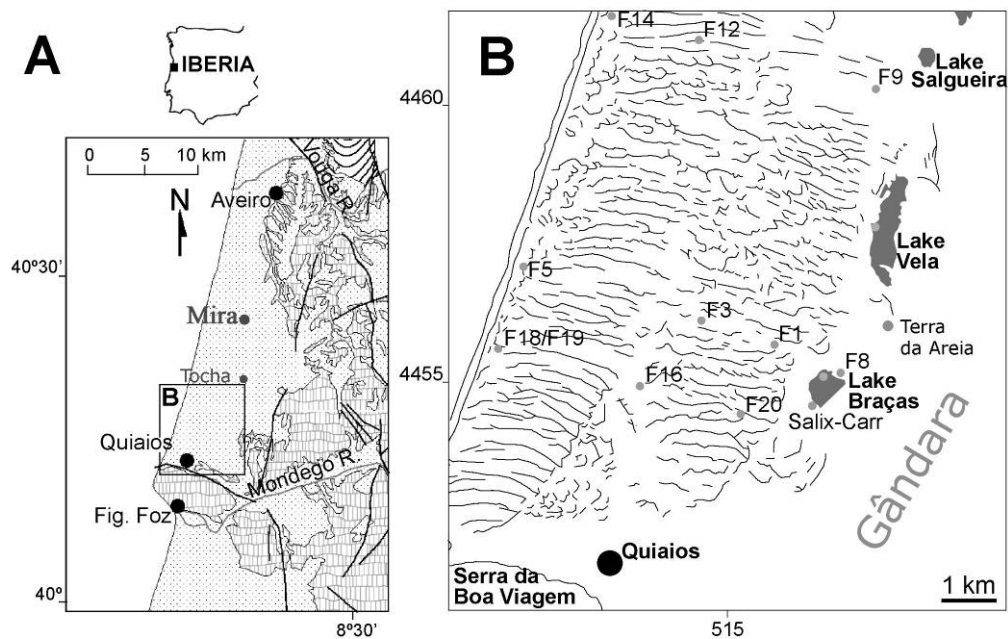
Fig.3. Map of the investigated region

The region is characterized by a maritime climate with low thermal amplitude and with mild winters and cool summers. Mean annual temperature maximum is 19.5°C and minimum is 9.2°C. Annual precipitation is around 1000 mm, however, with considerable irregularity from year to year. North to northwest winds are most frequent especially in the hottest months. In the colder months winds from the south-western quadrant (SW, S and W) are the strongest and most frequent (Almeida, 1995).

Phytogeographically, the region is situated in a transitional sector between an Atlantic vegetation zone in the northwest of Portugal and a Mediterranean zone in the south (Albuquerque, 1954; Rivas-Martínez, 1973).

A row of lakes is found in the eastern sector of the investigated area at around 45 m above sea level. They form the division between two vegetation zones. To the west vegetation is a planted *Pinus pinaster* forest mixed with *Pinus pinea*, *Acacia longifolia* and *A. melanoxylon*. The undercover vegetation is rich, dominated by psamophilous species characteristic of the coastal regosols such as *Corema album*, *Ulex europeus*, *Halimium commutatum* and *H. halimifolium*. *Calluna vulgaris* and *Lavandula stoechas* have a larger importance in older dune systems with more developed soils. To the east of the lakes, in the so-called Gândara plain, there are agricultural fields with *Zea mays*, *Secale cereale*, *Triticum aestivum* and other grass species harvested for animal fodder.

The highland of Serra da Boa Viagem has been inhabited since the Neolithic (5th - 4th Century BC) as shown by numerous dolmens (Santos Rocha, 1888-1900, Mesquita de Figueiredo, 1943, Guerra & Ferreira, 1974). Several Iron Age and Roman settlements have been registered as well (Santos Rocha, 1909, Guerra & Ferreira, 1971, Reigota, 2000). During historical time it is known that between the two nuclei, Quiaios (first mentioned in 807 AD) and Mira (1095 AD), there was a vast uninhabited area (Gândara) until around the 17th Century (Cravidão, 1992). Historical documents from the 16th Century mentions that the barren region between Cantanhede and the sea was used as winter pastures for kettle/sheep flocks from mountainous areas of Beira; "*a faixa entre Cantanhede e o mar, era uma mancha de deserto baldio, a Gândara, que se prolongava quase até Aveiro e onde vinham invernar os rebanhos da serra da Beira.*" (Gil, 1965, p. 85). In the 200 years following the 17th Century the district east of the investigated area was transformed into an intensely occupied territory (Cravidão, 1992).

The development of the dune field was episodic and influenced by conditions related to vegetation cover, climate, sea level and sediment input and human activity. Three dune generations have been recognized in the region (Almeida, 1995; Noivo, 1996) and similar geomorphology of the dunes has been ascribed to the same aeolian disruptive phase. The truncated dunes of the Gândara plain are considered of Pleistocene origin (Carvalho, 1964). The transverse/oblique dunes were formed during the last dune generation and the parabolic dunes at some stage between the two aeolian phases (Almeida 1995; Noivo, 1996).

Episodic sand invasions have caused recurring problems for human activities and agriculture along the Portuguese littoral, and stabilization measures to reduce this threat occurred already in the 13th Century when a royal decree ordered the planting of forests. In the investigated area reforestation started later. Northwest of the village of Quiaios a small triangular protective forest had been planted prior to 1773 (Fig.4), and was reportedly cut in 1845 (Pestana, 1926; Rei, 1940). It was replanted in 1856 when sand again threatened agricultural fields near the village. However, the main reforestation of the western dunes started as late as in 1924 (Pestana, 1926), initially by planting around the two lakes, Lake Vela and Lake Braças. The major part of the area was planted in the years following 1936 (Fig.5, left).

Fig.4. Cape Mondego with the triangular protective forest northwest of Quiaios (Serra *et al.* 1773), (Instituto Geográfico e Cadastral Português)
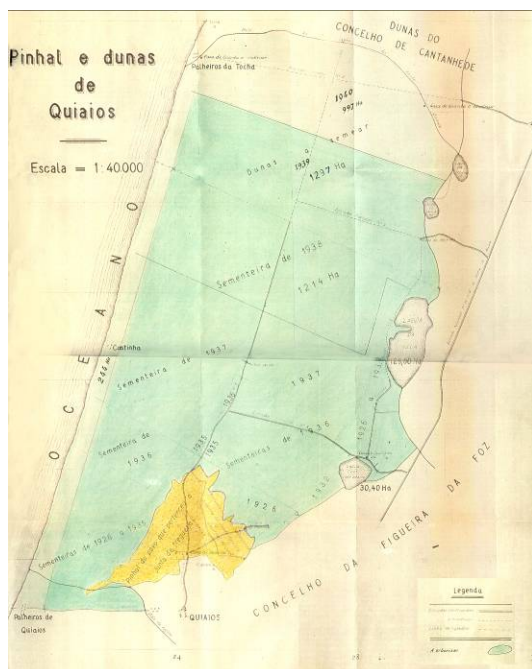
Fig.5. Reforestation effort in the dune fields

     Left: Map of reforestation (Direcção Geral dos Serviços Florestais e Aquícolas, 1939)

     Right: Photos from the plantation effort in the region (Câmara Municipal de Mira)

The reforestation project was an incredible effort involving a huge number of people and resources (Fig.5, right). Scrubs were cut in nearby forests and transported to the desert- like landscape of the region. A variety of shrubs and trees were planted (Almeida, 1995) with the objective to build up stable soil conditions for the future forest. Protective fences (ripados) were constructed and gradually lifted up behind the foredune to stabilize the migrating sand.

The reforestation remedy was effective in stabilizing the sand dunes, and littoral Portugal nowadays is characterized by this planted pine forest. Little is, however, known about past natural vegetation cover and dynamics of vegetation history in the region. Several theories, however, exist regarding the natural vegetation. Chodat (1913) considered *Pinus pinea* to be the original forest species of the sand dunes. Morais (1940) followed the same idea, supported by several discoveries of buried remains of this species by the local Forest Services during reforestation. Other authors have suggested that the natural dune vegetation was dominated by *Arbutus unedo* and *Quercus coccifera* (Braun-Blanquet *et al.*, 1956; Duvigneaud, 1962).

Objectives of the thesis

Stratigraphy of dunes records environmental and cultural changes during their formation. Lake deposits and palaeosols formed under stable conditions covered and interleaved with sandy aeolian layers from periods of sand drift are useful from a palynological perspective. Samples for this palynological investigation were extracted from the two lakes; Lake Vela and Lake Braças, and from exposed or sand covered, organic layers (palaeo-horizons) throughout the dune field west of the lakes (Fig.1).

The landscape in the Quiaios – Tocha region was shaped and reshaped in an interaction between many environmental factors. The scope of my investigation was to illuminate aspects of past natural vegetation cover and vegetation history as well as lake history dynamics in order to secondarily deduce causal conditions due to changes in:

- climate
- human activity

- aeolian activity
- dune dynamics
- coast line
- sea level

The main challenge was to resolve some of the assumed problems and discordances around these themes and contribute to the understanding of the underlying processes shaping and changing the environment.

Although the last phases of the reforestation venture were completed as late as in the middle of the 20th Century, recent encroachments in this ecologically volatile region suggest weak memory and unwillingness to learn from the past. It was therefore hoped that knowledge about past processes could assist in and improve assessment of future projects along the Portuguese coast.

Thesis structure

This thesis is composed of five chapters. Chapter 2-4 consist of three articles submitted to and published (two of them) by SCI journals.

Chapter 1

In this chapter a general introduction is presented of the method of palynology and previous palynological research done in Portugal. A description of the area and the objectives of the study are also given.

Chapter 2

The article provides a general outline of the vegetation history of the region during the last 1600 years. The discussion incorporates themes concerning lake formation, dune generations, forest history and cultural activity in the region.

Chapter 3

This chapter contains the local ecological history of the two main lakes of the region – Vela and Braças. Local and aquatic vegetation and particularly algal flora show distinct patterns of variation. These variations imply changes in lake level, nutrient level and surrounding environment through time. Differences between the two lakes since formation are elucidated and discussed.

Chapter 4

This chapter shows how additional palynological analyses of palaeosols and lake and lagoon sediments from the western fringe and its dune field have expanded the framework of evidence of the past environment both in time and space. The elucidated topics concern regional vegetation history, coastline and sea-level changes, formation and destruction of a coastal lagoon(s), lake genesis and displacement and aeolian activity and dune formation through the last 4-5000 years.

Chapter 5

A general discussion of the main results of the investigation is presented in this chapter. Advantages and importance of proposed future investigation is considered.

References

Allen, H.D., 2003. A transient coastal wetland: from estuarine to supratidal conditions in less than 2000 years – Boca do Rio, Algarve, Portugal. Land degradation & development 14, 265-283.

Albuquerque, J.P.M., 1954. Carta ecológica de Portugal. Ministério da Economia, Lisboa, Portugal. 58 p. Map 1/500 000.

Almeida, A.C., 1995. Dunas de Quiaios, Gândara e Serra da Boa Viagem. Uma abordagem ecológica da paisagem. PhD Thesis, University of Coimbra, Portugal. 305 p.

Braun-Blanquet, J., Pinto da Silva, A.R., Roseira, A., 1956. Résultats de deux excursions géobotaniques à travers le Portugal septentrional et moyen II — Chenaies à feuilles caduques (Quercion occidentale) et chenaies à feuilles persistantes (Quercion fagineae) au Portugal, XVIII. Agronomia Lusitana, Lisboa. Fasc.III., pp. 167–235.

10

Carvalho, G.S., 1954. A Gândara (Portugal) e as Landes da Gasconha (Franca). Memórias e Notícias, Museu Mineralógico e Geológico da Universidade de Coimbra, 37, 21-36.

Carvalho, G.S., 1964. Areias da Gãndara (Portugal). Uma formação eólica Quaternária. Publicações do Museo Mineralógico e Geológico da Faculdade de Ciências da Universidade do Porto, 81 (4), 3-32.

Clarke, M.L., Rendell, H.M., 2006. Effects of storminess, sand supply and the North Atlantic Oscillation on sand invasion and coastal dune accretion in western Portugal. The Holocene 16 (3), 341–355.

Chodat, R., 1913. Voyages d`études géobotaniques au Portugal. Le Globe, t. LII.

Cravidão, F.D., 1992. A população e o povoamento da Gândara (génese e evolução). PhD thesis, Coimbra University, Portugal. 531 p.

Duvigneaud, J., 1962. Le Portugal central et septentrional. Sa position phytogéographique, sa vegetation. In: Delvosalle, L., Duvigneaud, J. (Eds.), Itinéraires Botaniques en Espagne et au Portugal. Bruxelles. 116 p.

Fægri, K., Kaland, P.E., Krzywinski, K., 1989. Textbook of Pollen Analysis, fourth ed. John Wiley and Sons, Chichester. 328 p.

Gil, M.O. da R., 1965. Arroteias no vale do Mondego durante o século XVI. Ensaio de história agrária. Direcção Regional da Cultura, Lisbon. 147 p.

Gomes, S.D., 2007. A palinologia da Lagoa do Saloio (Nazaré, Portugal) e a evolução holocénica da região da Mata Nacional do Valado. MSc Thesis, Polytechnical institute of Tomar and University of Trás-os-Montes and Alto Douro. 128 p.

Gomez-Orellana, L., Ramil-Rego, P., Martínez Sánchez, S., 2001. Modificaciones del paisaje durante el Pleistoceno Superior – Holoceno en los territorios litorales Atlánticos del NW Ibérico. Estudos do Quaternário, 4, APEQ. Lisboa. 79-96.

Granja, H.M., 1990. Representar a geodinâmica da zona costeira: o passado e o presente; que futuro? PhD Thesis, University of Minho, Braga, Portugal. 347 p.

Granja, H.M., 1999. Evidence for Late Pleistocene and Holocene sea-level, neotectonic and climate control in the coastal zone of northwest Portugal. Geologie en Mijnbouw 77, 233-245.

Granja, H.M., Carvalho, G.S., 1992. Dunes and Holocene deposits of the coastal zone of Portugal, north Mondego Cape. In: Carter, R.W.G., Curtis, T.G.F., Sheehy-Skeffington, M.J.

(Eds.), Coastal Dunes: geomorphology, ecology and management for conservation. Proceedings of the Third European Dune Congress, Galway, Ireland, 43–50.

Granja, H.M., de Groot, T.A.M., 1996. Sea-level rise and neotectonism in a Holocene coastal environment at Cortegaça Beach (NW Portugal): A case study. Journal of Coastal Research 12/1, 160-170.

Granja, H.M., Carvalho, G.S., de Groot, T.A.M., Soares, A.M., Parish, R., 1996. Geochronology and the recent geomorphological evolution of the northwest coastal zone of Portugal. In: Taussik, J., Mitchell (Eds.), Partnership in Coastal Zone Management (Proceeding 3rd International Symposium EUROCOAST, Littoral 96, Portsmouth, U.K.). Samara Publishing Limited, Cardigan, 297–308.

Granja, H.M., de Groot, T.A.M., Costa, A.L., 2008. Evidence for Pleistocene wet aeolian dune and interdune accumulation; S. Pedro da Maceda, north-west Portugal. Sedimentology 55/5, 1203-1226.

Guerra, V.A. & Ferreira, O.V., 1971. Inventário das Estações da Idade do Ferro nos Arredores da Figueira da Foz. Actas do congresso Nacional de Arqueologia, vol. I, Coimbra, Portugal. 297-303.

Guerra, V.A. & Ferreira, O.V., 1974. Inventário dos monumentos megalíticos dos arredores da Figueira da Foz. Câmara Municipal da Figueira da Foz, 14 p.

Janssen, C.R., 1973. Local and regional pollen deposition. In: Birks, H.J.B., West, R.G. (Eds.), Quaternary Plant Ecology. Proceedings of the Fourteenth Symposium of the British Ecological Society. Blackwell, New York, pp. 31–42.

Janssen, C.R., Woldringh, R.E., 1981. A preliminary radiocarbon dated pollen sequence from the Serra da Estrela. Finisterra, XVI, 32, 299-309.

Mateus, J.E., 1989. Lagoa Travessa: A Holocene pollen diagram from the south-west coast of Portugal. Revista de Biologia, Lisboa 14, 17–93.

Mateus, J.E., 1992. Holocene and present-day ecosystems of the Carvalhal region, Southwest Portugal. PhD Thesis, Utrecht University, Netherlands. 184 p.

Mateus, J.E., Queiroz, P.F., 1993. Os estudos da vegetação Quaternária em Portugal: contextos, balanços e perspectivas. Edições Colibri, Lisboa. 105-131.

Mesquita de Figueiredo, A., 1943. A Pré-história do concelho da Figueira, foz do Mondego. Novos descobrimentos feitos nos Arquivos. Imprensa Portuguesa, Porto, Portugal. 11 p.

Morais, A.T.de, 1940. Novas áreas da fitogeografia portuguesa. Bol. Soc. Broteriana, Coimbra XIV (II Sèrie), 97–138.

Noivo, L.M., 1996. Morfologia e dinâmica sedimentar das dunas de Quiaios, Portugal. MSc Thesis, University of Aveiro, Portugal. 169 p.

Pestana, G.C.N., 1926. Relatório dos Serviços realizados nos perímetros encorporados na 5ª Regência Florestal. Relatório final do curso de engenheiro silvicultor. Tipografia Popular, Figueira da Foz, Portugal. 51 p.

Queiroz, P.F., 1989. A preliminary palaeoecological study at Estacada (Lagoa de Albufeira). Revista de Biologia, Lisboa 14, 3-15.

Queiroz, P.F., 1999. Ecologia Histórica da Paisagem do Noroeste Alentejano. PhD Thesis, University of Lisbon, Portugal. 300 p.

Queiroz, P.F., Mateus, J.E., 1994. Preliminary palynological investigation on the Holocene deposits of Lagoa de Albufeira and Lagoa de Melides, Alentejo (Portugal). Revista de Biologia Lisboa 15, 15–28.

Queiroz, P.F., Mateus, J.E., 2004. Paleoecologia Litoral entre Lisboa e Sines do Tardiglaciário aos tempos de hoje. In: Evolução geohistórica do litoral Português e fenómenos correlativos. Geologia, história, arqueologia e climatologia. Tavares, A.A., Tavares, M.J.F., Cardoso, J.L. (Eds.). Universidade Aberta. pp. 257-304.

Ramil-Rego, P., Gómez Orellana, L., 1996. Dinámica climática y biogeografica del area litoral-sublitoral de Galicia durante el Pleistoceno Superior - Holoceno. In: Ramil- Rego, P., Fernández Rodríguez, C., Rodríguez Guittián, M., (Coord.): Biogeografía Pleistocena-Holocena de la Península Ibérica, pp. 43-71.

Rei, M.A., 1940. Arborização — Alguns artigos de propaganda regionalista. Tipografia e Papelaria Costa, Figueira da Foz, Portugal. 43 p.

Reigota, J., 2000. A Gândara Antiga. CEMAR, Portugal. 474 p.

Rivas-Martínez, S., 1973. Avance sobre una síntesis corológica de la Península Ibérica, Baleares y Canárias. Anal. Inst. Bot. Cavanilles, Madrid, Spain, 30, 69-87.

Romariz, C., 1950. Contribuição da análise polinica no estudo da vegetação primitiva da Serra da Estrela. Comptes Rendus du XVI Congrés Internationale de Géographie.

Santos Rocha, A., 1888–1900. Antiguidades Pré-históricas do Concelho da Figueira. Coimbra, Imprensa da Universidade, Coimbra, Portugal. 271 p.

Santos Rocha, A., 1908. Estações Pré-Romanas da Idade do Ferro nas vizinhanças da Figueira. Imprensa Portuguesa, Porto, Portugal. 86 p.

Serra, E.G., Silva, R.F.A., Marques, T.P., 1773. Borrão de campo e planta thopografica do sitio da mina do carvão de pedra no promontório do Mondego. Instituto Geográfico e Cadastral Português, Lisbon, Portugal.

van den Brink, L.M., Janssen, C.R., 1985. The effect of human activities during cultural phases on the development of montane vegetation in the Serra da Estrela, Portugal. Review of Palaeobotany and Palynology 44, 193-215.

van der Knaap, W.O., van Leeuwen, J.F.N., 1995. Holocene vegetation succession and degradation as responses to climatic change and human activity in the Serra da Estrela, Portugal. Review of Palaeobotany and Palynology 89, 153–211.

van der Knaap, W.O., van Leeuwen, J.F.N., 1997. Late Glasial and early Holocene vegetation succession, altitudinal vegetation zonation, and climatic change in the Serra da Estrela, Portugal. Review of Palaeobotany and Palynology 97, 239-285.

van Leeuwaarden, W., Janssen, C.R., 1985. Preliminary palynological study of peat deposits near an oppidum in the lower Tagus valley, Portugal. Actas da Reunião do Quaternário Ibérico, 2, 225-236.
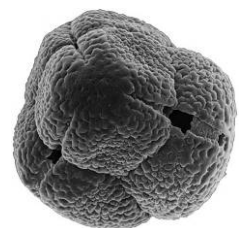
PAPER I

Palaeoecological development of the Quiaios–Mira dunes, northern-central littoral Portugal.

R. Danielsen

Universidade do Minho, Braga, Portugal / Instituto Português da Arqueologia (IPA) (Laboratório de Paleoecologia e Arqueobotânica) Lisbon, Portugal

Abstract

Pollen and non-pollen palynomorph data are presented from two lakes and two adjacent areas in the Quiaios–Mira dunes of northern-central littoral Portugal. The region consists of a large sand plain afforested in the early 20th Century in response to the threat of sand dunes advancing towards settlements and agricultural fields. The lakes are situated in the border zone between the sand plain to the west and the agricultural fields to the east.

The investigated sediments cover a period of deposition of ca. 1600 years. Initially the sites were wetland areas with changes in humidity revealed by variations in local hygrophilous vegetation and non-pollen palynomorphs. Lakes developed first in the period 1723-1866 AD seemingly as a direct result of sand dunes moving in from the west and interfering with the hydrological drainage system.

Vegetation in the region was an open heathland from 1630 BP (420 AD) until around 1720 AD when reforestation, in the form of pine plantations, occurred. Anthropogenic influence on the vegetation (grazing and agriculture) is detected early in some of the diagrams but is more prevalent in the upper part following the reforestation 200-300 years ago.

Various periods of strong aeolian activity are reflected through sand layers, suggesting multiple sand invasions and dune generations.

Keywords: palynology, littoral lakes, north-central Portugal, palaeoecology, anthropogenic influence, sand dunes.

1. Introduction

Approximately 60 % of the Portuguese coast is occupied by sand dunes. In this sand dune area, the Quiaios–Mira dunes in northern-central Portugal between Cape Mondego and Mira represent one of the major uninterrupted aeolian sand plains in Portugal (Cruz, 1984). The development of this dune field was discontinuous and influenced by conditions related to climate, sea level, sediment input, vegetation cover and human activity. Sediment stratigraphy of the dunes records environmental and cultural changes during the evolution of the dunes. Several sandy aeolian layers from periods of sand drift are intercalated with lake deposits and palaeosols formed under stable environmental conditions (Castilho *et al.*, 2007).

A string of shallow lakes (the Quiaios lakes) are found in the transition zone between Holocene transverse WNW-ESE oriented sand dunes to the west, and older dunes, possibly Pleistocene dunes (Carvalho, 1964), to the east. The eastern dune area is called the Gândara plain and sustains intense agriculture at present.

An inland sand invasion threat into the eastern agricultural fields and villages at the beginning of the 20th Century resulted in a huge reforestation of the western dunes from 1926 to 1940. At present they support a large pine forest dominated by *Pinus pinaster*. Little is known about its past vegetation cover.

Various theories have been proposed about the development of the region regarding past vegetation cover, coastline dynamics, genesis of the lakes and dune systems, but these theories partly diverge. Chodat (1913) considered *Pinus pinea* to be the original forest species of the sand dunes. Morais (1940) followed the same idea, supported by several discoveries of buried remains of this species by the local Forest Services during reforestation. Other authors have suggested that the natural dune vegetation was dominated by *Arbutus unedo* and *Quercus coccifera* (Braun-Blanquet *et al.*, 1956; Duvigneaud, 1962). A theory regarding coastline dynamics concludes that around 3000 BP the coastline was close to the lakes. According to many authors (Abecassis, 1961; Noivo, 1996; Dias *et al.,* 1997; 2000) the western dunes are believed to have formed since then by progradation of the coastline 6-7km westwards due to sand accumulation caused by the groyne effect produced by the natural promontory of Cape Mondego. The lakes according to Noivo (1996) are consequently considered to be remnants of an old marshy littoral zone. Almeida (1995), however, suggests that they were formed synchronously and as a direct result of the last dune generation, believed to have originated due

to the climatic deterioration and sea level regression during the Little Ice Age (LIA). Sand dunes are thought to have blocked natural drainage channels seawards and caused flooding and lake formation in the lower parts to the immediate eastern limit of the sand dunes (Almeida, 1995). The region is presumably characterized by three major dune generations since the Pleistocene (Almeida, 1995; Noivo, 1996).

Presented here are the results from a palynological investigation of two of the Quiaios lakes, Vela and Braças, supported by cores from two adjacent areas.

The main objectives of this study are to detect past changes in vegetation reflected by variations in pollen assemblages through time, to determine if the origin of these changes were climatically and/or anthropogenically induced and also to reveal the background for and the timing of genesis of the lakes.

2. Description of the study area

The investigated area is situated north of the town of Figueira da Foz between the parallels 40° 14´ and 40° 17´ N and the meridians 8° 49´and 8° 47´ W (International Geographic System – WGS84) (Fig. 1).
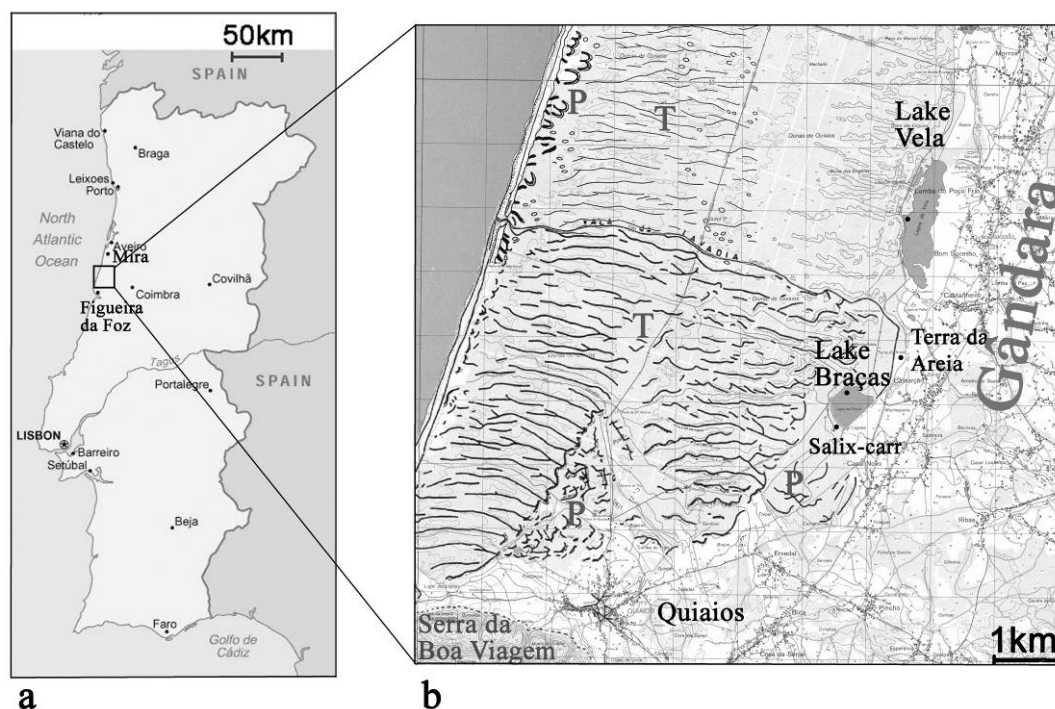
Fig.1 a) Portugal b) Investigated area. P-parabolic dunes T-transversal dunes (dune crests from Almeida, 1995 and Noivo, 1996)

2.1. History

The highlands of Serra da Boa Viagem between Figueira da Foz and the Quiaios – Mira dunes have been inhabited since the Neolithic (5th - 4th Century BC) as shown by numerous local dolmens (Santos Rocha, 1888-1900; Mesquita de Figueiredo, 1943; Guerra and Ferreira, 1974). Several Iron Age and Roman settlements were present as well (Santos Rocha, 1908; Guerra and Ferreira, 1971; Reigota, 2000). During historical time it is known that between the two nuclei, Quiaios (first mentioned in 807 AD) and Mira (1095 AD), there was a vast uninhabited area until around the 17th Century (Cravidão, 1992). In the following 200 years the Gândara was transformed into an intensely occupied territory.

2.2. Climate

The investigated area is characterized by a maritime climate with mild winters and cool summers. The thermal amplitude is low and advection fog is frequent during summer mornings (Daveau, 1980). The minimum average temperature of the coldest month is 4,8°C and the maximum average of the warmest month is 24,2°C (Daveau *op. cit.*). The region has, according to the bioclimatic zonation belts of Rivas-Martínez *et al.*, (1990), a Mesomediterranean sub-humid bioclimate. In the summer NW winds have the highest velocity and are more frequent than in other seasons. In the winter SW winds are predominant (Almeida, 1995).

2.3. Vegetation

Phytogeographically, the region is situated in a transition sector between an Atlantic vegetation zone in the north and a Mediterranean zone in the south (Albuquerque, 1954; Rivas-Martínez, 1973).

At the beginning of the 20th Century little remained of the natural vegetation and the landscape was like a desert with only small patches of pine forest partly covered by sand. The largest remaining forest was the triangular shaped pine-forest called "Pinhal do Povo" (Fig.2) planted to protect the village of Quiaios.

Fig.2 Above: View towards north from Serra da Boa Viagem around 1930. **Below**: The same view at present

Today the vegetation to the west of the lakes is a planted *Pinus pinaster* forest mixed with *Pinus pinea, Acacia longifolia* and *A. melanoxylon*. The undercover vegetation is rich, dominated by psamophilous species belonging to the phytosociological alliance of *Coremion albi* (Rothmaler 1943) with *Corema album, Ulex europeus, Halimium commutatum* and *H. halimifolium*. *Calluna vulgaris* and *Lavandula stoechas* have a larger importance in older dune systems. To the east of the lakes there are agricultural fields with *Zea mays, Secale cereale, Triticum aestivum* and other grass species harvested for animal fodder.

The forest vegetation surrounding the lakes consist of various introduced species; the *Acacia* species *A. longifolia, A. melanoxylon, A. dealbata, A. retinodes* and *Taxodium distichum, Casuarina equisetifolia, Platanus orientalis, Quercus palustris* and *Eucalyptus globulus* while *Populus alba, Fraxinus angustifolium, Ulmus minor, Salix atrocinerea* and *S. arenaria* constitute a potentially native element of the riparian forest.

The dominant natural and semi-natural vegetation around Lake Vela belongs to the alliance *Magnocaricion elatae* (Koch 1926) and the association *Cladietum marisci* (Allorge 1922) Zobrist 1939, with *Cladium mariscus, Lythrum salicaria, Mentha suaveolens, Schoenus nigricans* and *Hydrocotyle vulgaris* as the characteristic species. Around Lake Braças the vegetation is dominated by species belonging to the alliance *Phragmition communis* (Koch 1926). The association *Typho angustifoliae-Phragmitetum australis* (Tüxen and Preising 1942) Rivas-Martínez, Báscones, T.E. Díaz, Fernadez-González and Loidi 1991, predominates with

20

Phragmites australis, Typha latifolia and *Scirpus lacustris* (Martins, 1999). *Myrica gale* is found in a limited zone at Lake Braças´ southern bank. The aquatic vegetation in both lakes includes species from the alliances *Nymphaeion albae* (Oberdorfer 1957) and *Lemnion minoris* (Tüxen ex. O. Bolòs and Masclans 1955) with the respective associations 1; *Myriophyllo-Nupharetum lutei* (Koch 1926) dominated by *Nymphaea alba* and the exotic species *Myriophyllum aquaticum* and 2; *Lemnetum minoris* (Oberdorfer 1957) with *Lemna minor* and *Azolla caroliniana* (Martins *op. cit*.).

2.4. Geomorphology and soils

The dunes extend up to 7km inland from the coastline and due to a gradually sloping Mesocenozoic basement, reach elevations of up to ca. 60m.a.s.l. The morphology of the younger dunes is still preserved in many cases. The fore-dune is a fairly continuous ridge reportedly related to human intervention, through the erection of a wooden fence (Almeida, 1995). From the beach inland wards, behind the fore-dune, the most common dune forms are transverse and parabolic dunes (Almeida, 1995; Noivo, 1996; Clarke and Rendall, 2006). In the "Pinhal do Povo" parabolic and blow-out dunes exist as their vegetation cover protected them from sand invasion during more recent dune generations (Almeida, 1995).

From a pedological point of view, dystric regosols are dominant to the west of the lakes (Cardoso *et al*., 1971) replaced by detrital, non-calcaric podzolic soils to the east. Soil thickness is less than 10cm in most of the area to the west of the lakes (Almeida *op. cit*.) barely covering the sand. The sand deposits may however reach magnitudes of 35m. Dune crests of altitudes up to 18m (Noivo, 1996) above the interdunal flats are common and sand deposits below the flats, in places intercalated with palaeosols, may reach depths of ca. 16m (Castilho *et al*., 2007).

3. Field and laboratory methods

3.1. Fieldwork

During this study four cores were palynologically analyzed. The two main cores were extracted in Lake Vela (06/09/2004) and Lake Braças (29/12/2003) north of Quiaios village. Both Lake Vela and Lake Braças are shallow (max. 2m water depth), eutrophic lakes situated 6–7km to the

east of the coastline at an altitude of ca. 45m.a.s.l. Lake Vela is 475m wide and 2km long while Lake Braças has the same width but is 650m long. A large amount of sediment was extracted from Lake Braças in 1993. The core from this basin was obtained in a presumably undisturbed area. A 1m long Livingstone corer with 6cm diameter was used for extraction of both main cores. Water level in the lakes is determined by freatic level of the surrounding dunes and thus directly affected by eventual changes in the climate, dune geomorphical fluctuations or anthropogenic influence leading to water table variations.

A supplementary peat monolith was cut out from Lake Braças´ southern margin in a Salix-carr (26/09/2004) in order to control for possible disturbances of the main core.

In addition a core was collected from Terra da Areia (09/09/2004), a dry flattened depression located between the two lakes. Here a bottom filling mechanical hammer corer was used with 1m long replaceable steel tubes of decreasing diameter. The motive of this additional record was to investigate the possibility of a larger lake system in the past, integrating both modern systems.

An iron pan, "sorraipa", is found at varying depths in most of the area and neither hammer corer nor Livingstone corer managed to penetrate this layer. Layers of sand also complicated the coring.

3.2. Laboratory work

Samples were extracted at ca. 2cm intervals. In Terra da Areia the space between samples varied due to sandy layers devoid of pollen and as a result of disturbed sediment between the 1m tubes (debris from borehole wall).

The samples were subjected to standard laboratory treatment including HF exposure for 48 hours. Exotic *Lycopodium* spore tablets were added to permit the calculation of pollen concentration data.

Pollen and non-pollen palynomorphs (NPP) were analyzed. The minimum sum of regional pollen was 250 whenever possible. In some cases this was unachievable due to low pollen content (in sandy samples).

Selected samples were dated by Beta Analytic Inc. (Miami, USA) and by the "Instituto Tecnológico e Nuclear" (Lisbon, Portugal).

3.3. Pollen and microfossil identification and diagrams.

Pollen was identified with the help of the keys of Moore *et al.* (1991), Fægri *et al.* (1989), Northwest European Pollen Flora parts I-VI (Punt, 1976; Punt and Clarke, 1980, 1981, 1984; Punt *et al.*, 1988; Punt and Blackmore, 1991), the Ericales key of Mateus (1989a) and the Cistaceae key of Queiroz, (1999). The identification of Quercus pollen was done according to an identification key prepared by José Mateus and Paula Queiroz, Instituto Português de Arqueologia (IPA), Lisbon, based on the work of Saenz de Rivas (1973). In addition direct comparison with modern reference material was possible through the use of the pollen reference collection of the Laboratory of Palaeoecology and Archeobotany in Lisbon.

For the genus *Pediastrum* the key of Komárek, J. and Jankovská, V. (2001) was used and for other non-pollen palynomorphs (NPP) the supplement in Mateus (1992) and various articles by van Geel (van Geel, 1976a,b, 1978 and van Geel *et al.*, 1983; van Geel *et al.*, 1989) were consulted.

Pollen and microfossil data are presented in percentage pollen diagrams. All data were calculated as percentages of total regional pollen (TRP) including pollen from dry-soil taxa with the exception of *Pinus* and taxa occupying the lake margins. Pollen from *Pinus*, pollen from local taxa (mainly hygrophilous) and NPP are expressed as percentages of TRP. The pollen diagrams were constructed using Tilia and Tilia graph (Grimm, 1991-1993). The diagrams have been divided into regional pollen assemblage zones (PAZ) and local pollen zones delimited by visual inspection based on major changes in the regional and local pollen curves. The boundaries of zones marked with Roman numbers (solid lines) mark changes in the regional vegetation. Local zones marked with Arabic numbers (interrupted lines) are based on changes in aquatic and hygrophilous marsh vegetation.

4. Results

4.1. Lithology

Sediments of all four cores were characterized by a mixture of sand and organic mud in various proportions. In the lake sediments mineral content gradually increased downwards.

In the Salix-carr monolith wastewater discharges from a nearby hydrological station seemed to have influenced the top sediment of the monolith and hence the top of the monolith was not analyzed. The base reached an iron pan layer.

In Terra da Areia the bottom sandy sediment (20cm) was lost at extraction. The upper part of this core was not used since above the top muddy layer, at 78-79cm depth, there was ca. half a metre of sterile aeolian sand covered by 36cm of disturbed surface sediment showing the effect of agricultural activity in the near vicinity.

4.2. Chronology

Three samples were radiocarbon dated, two from the base of the organic sequences from Lake Vela and Salix-carr, the third a wood sample from Lake Braças (Table 1). All dates quoted as BP are conventional ^{14}C years.

Table 1 – ^{14}C datings

Lab. ref.	Site	Depth	Sample type	Conv. ^{14}C years BP	Calibrated age		Calibration method
					1σ (AD)	2σ (AD)	
Beta-2051 49	L.Vela	76,5-84cm	Organic mat.	1630±40 BP	383-441, 454-460, 484-532	268-271, 335-540	CALIB 5.0* INTCAL04. 14C**
Sac-2038	Salix-carr	63-66cm	Organic mat.	1510±230 BP	255-308, 311-718, 743-769	26-42, 47-994	CALIB 5.0* INTCAL04. 14C**
Sac-2154	L. Braças		Wood (*Erica erigena*)	180±35 BP	1665-1684, 1733-1785, 1794-1807, 1928-1951	1650-1698, 1723-1816, 1834-1879, 1916-1952	CALIB 5.0* INTCAL04. 14C**

*(Stuiver and Reimer, 1993)
** (Reimer *et al.,* 2004)

4.3. Vegetation changes

4.3.1. Regional (extra-local) vegetation development

Three regional pollen assemblage zones are recognized and three of the four diagrams include all zones (Fig.3, 4, 5 and 6). Regional pollen zones are considered reflections of

synchronous changes in the regional vegetation. In PAZ I and PAZ II all four sites were seasonally inundated wetland areas and the pollen rain was probably strongly influenced by extra-local and local vegetation (as defined by Janssen, 1973).

The first zone (PAZ I) is characterized by low values for arboreal pollen (< 5%) and high values for heathland and wetland plants. It is represented at Vela and Salix-carr and also probably at Terra da Areia. The base of the Vela core has been dated 1630 ± 40 BP. The dating of the base from the Salix-carr monolith gave 1510 ± 230 BP indicating a relatively synchronous origin of this wetland system.

The upland vegetation reflected in this zone is interpreted as treeless open scrub vegetation with *Erica scoparia* and *E. umbellata*. The Vela and Salix-carr sites were dominated by species included in the *Halimium halimifolium* pollen type (Queiroz, 1999) with a large number of tetrads of *Halimium lasianthum,* probably reflecting extra-local or even local presence of this hygrophilous taxon. In Terra da Areia, *Calluna vulgaris* and *E. umbellata* seem to have been more common probably due to a drier habitat. Pollen from *Triticum* in Terra da Areia show agricultural activity in the vicinity in this early phase as this is a cleistogamous plant with very limited pollen dispersal. Occurrences of pollen from *Plantago lanceolata* indicate pastures.

The second zone (PAZ II), characterized by the continuous presence of pollen of scrub vegetation, is represented in all diagrams. Low representation of forest vegetation prevailed as did the dominance of pollen from heathland species such as *Erica scoparia.* A decreasing dominance of pollen from *Halimium lasianthum* was possibly caused by changing hydrological conditions towards a drier environment or as a result of natural ecological succession. Pollen values of *Calluna vulgaris* and *E. umbellata* around Terra da Areia decrease, being replaced by pollen of *E. scoparia*.

Pollen from *Olea, Cerealia* and *Zea mays* appear in PAZ II reflecting agricultural activity. Indicators of grazing also increase from this zone onwards.

The last zone (PAZ III) is characterized by major changes both in local and regional vegetation as in the algal flora of the lakes. At Vela and Braças sites permanent lakes were established at this stage.

Arboreal pollen values increase rapidly during this phase, probably due to initial afforestation of the region. Pollen of *Pinus* is most important but pollen of *Quercus spp.* also increase. Pollen of exotic taxa (*Acacia, Eucalyptus, Casuarina, Platanus*) appear in the upper part of the zone probably reflecting the reforestation since 1926. (Note that the early occurrence of *Taxodium*

pollen in the Terra da Areia diagram can be explained by contamination as sub-samples were extracted in the field during the flowering season of this tree.)

Throughout this phase there is an increase in the representation of agricultural indicators such as *Zea mays*, *Secale*, *Triticum* and *Olea*. Pollen from *Citrus*, *Castanea* and *Vitis* appear for the first time in this zone. The more recent part of the zone show peaks in algae like *Coelastrum* and *Pediastrum simplex* which are indicators of eutrophication.

4.3.2. Local vegetation development

The local zones are interpreted in terms of water-table oscillations. The terminology used for the hydrological conditions are shown in Table 2. The interpretation of the local vegetation development for the four localities is presented in Tables 3-6.

Table 2. Terminology of hydrological conditions

Lake	Wetland		
Open water	Swamp	Marsh	Wet heathland
Deeper water	Shallow water	Waterlogged to wet	Moist

In the Salix-carr profile the pollen curves of the monoseptate fungal spore T-80 IPA (cf. T-18 HDV) fluctuates throughout the diagram. These curve fluctuations are probably connected to local dry/wet phases. T-18 HDV is considered a good indicator of humid marshland (Mighall, *et al.*, 2006).

Table 3 - Local vegetation development **Lake Braças**

Local zone	Sub-zone	Depth	Local wetland system	Characteristics
B-1		43-69cm	Wet heathland	Relatively dry local hydrological conditions with *Erica erigena* in wetter parts and Poaceae, Brassicaceae, *Apium innundatum, Potentilla,* and *Mentha* occurring in the local vegetation. Few algal remains are found, mainly from members of the family Zygnemataceae (*Debarya, Mougeotia, Zygnema*).
B-2		35-43cm	Marsh and later inundation	Local pollen reflection gives an indication of conspicuous reed-swamp grass-sedge vegetation around open water, a waterlogged margin with *Cladium mariscus*, Poaceae and Cyperaceae surrounded by wet heathland with *Erica erigena* and *Myrica cf. gale*. Increased humidity is further suggested by increase in Type-18 occurrences.
	B-2a	39 -43cm	Marsh and wet heathland	This sub-zone reflects a wet heathland environment. A peak in the *E. erigena* curve may indicate a local paludification. A distinct development of hygrophilous taxa can be observed at this stage, shown by high values for Cyperaceae and with appearance of *Potamogeton, Myriophyllum* and *Botryococcus.*
	B-2b	35-39cm	Inundation / lakelet	There was probably a continuing increase of the water-table during this sub-zone resulting in death of the *E. erigena* stands (see discussion below) in central parts of the basin reflected in the diagram as a strong decline in pollen from this species. This event is also revealed by a peak in pollen from *Nymphaea* and by an increase in algal content (*Pediastrum spp., Scenedesmus*).
B-3		17-35cm	Oligotrophic lake	Lake conditions seem to have prevailed since the beginning of this zone. Algal remains are common and the green algal genus *Pediastrum* is represented by many species (*P. integrum, P. boryanum var. brevicorne, longicorne and boryanum, P. duplex var. rugulosum and P. angulosum var. angulosum).* There is a peak in *Pediastrum integrum,* an alga found mainly in oligotrophic, clear water and in dystrophic swamps (Komárek and Jankovská, 2001) indicating that initially the lake was poor in nutrients. *Erica erigena* shows a more modest and stabilized pollen curve indicating a more distant pollen source.
B-4		0-17cm	Eutrophication	Lake conditions changed into a eutrophic environment. The division into two sub-zones is based on increased nutrient content towards the sediment surface.
	B-4a	14-17cm	Eutrophic lake	Eutrophication is shown by a rapid and large increase in *Coelastrum* percentages and by presence of several varieties of *Pediastrum simplex* (Komárek and Jankovská, 2001).
	B-4b	0-14cm	Stronger eutrophication	The eutrophic conditions were further enhanced in this sub-zone as revealed by the initial peak in *Typha angustifolia* and the rapid increase in algal remains in general and of *Coelastrum* sp. in particular*.* There is also a peak in *Pediastrum boryanum var. cornutum* reported to prefer large, naturally eutrophic water bodies, not overgrown by aquatic plants (Komárek and Jankovská, *op. cit.*).

Table 4 - Local vegetation development **Lake Vela**

Local zone	Depth	Local wetland system	Characteristics
V-1	57-84cm	Wet heathland	In this zone the local vegetation seems to have been dominated by *Halimium lasianthum* some Poaceae and *Erica erigena* indicating humid (non-waterlogged) local soil conditions.
V-2	31-57cm	Marsh	Poaceae pollen dominate this zone, but *E. erigena* and *Myrica cf. gale* together with *Radiola linoides* are represented. A few pollen from *Potamogeton* and Isoetes and algae from the Zygnemataceae are the only indications that open water existed locally at least during the wet season perhaps in the form of small ponds. Pollen from marsh plants like *Mentha, Hydrocotyle* and Brassicaceae have scattered occurrences.
V-3	11-31cm	Lake environment	During this phase the wetland is rapidly transformed into a lake. Aquatic plants like *Myriophyllum, Potamogeton, Nymphaea* and *Isoetes* were common. *Botryococcus,* various *Pediastrum, Scenedesmus* and *Rivularia* dominated the algal flora of the lake. Its margins had a grass-sedge vegetation with *Erica erigena* wet heathland more inland.
V-4	0-11cm	Eutrophication	In this phase the lake seems to have undergone a eutrophication episode with *Coelastrum* appearing and a peak in *Scenedesmus. Nymphaea* values increase.

Table 5 - Local vegetation development **Salix-carr**

Local zone	Depth	Local wetland system	Characteristics
Sc-1	50-65cm	Wet heathland	During formation of this sediment, the local vegetation seems to have been a wet heathland with *Erica erigena* and *Halimium lasianthum.* Type 18 (HDV) has a peak as well.
Sc-2	44-50cm	Drier phase	In this zone Poaceae dominated the local vegetation. Pollen values from Cyperaceae and *E. erigena* and spores of Type 18 (HDV) are reduced. This could either indicate inundation or a drier phase. The almost total lack of pollen from aquatic plants and algal remains points towards the latter.
Sc-3	26-44cm	Humid wetland	In this phase there is another increase in pollen values from Cyperaceae, *E. erigena, Radiola linoides* and spores of Type 18 (HDV) and the environment was probably more humid. A decline of Type 18 (HDV) spores between ca. 27 and 32cm possibly indicates a drier period. The other pollen curves, however, do not give a clear signal about this event. The upper part of this zone shows the first occurrences of pollen from *Salix.*
Sc-4	18-26cm	Swamp/marsh	This phase clearly corresponds to the inundation phase found in Braças at the level of increase in Arboreal Pollen (AP). Algal remains of various *Pediastrum sp., Scenedesmus* and *Botryococcus* appear. Pollen from aquatic plants (*Myriophyllum* and *Nymphaea*) are found along with a reduction in pollen values from *E. erigena.*

Table 6 - Local vegetation development **Terra da Areia**

Local zone	Depth	Local wetland system	Characteristics
TA-1	285.5-305cm	Marsh/wet heathland	This zone reflects a grass-sedge vegetation with seasonal shallow basins of *Myriophyllum, Potamogeton, Hydrocotyle* and algae from the Zygnemataceae and *Botryococcus. Erica erigena* has high values showing the existence of wet heathland nearby.
TA-2	263.5-285.5cm	Drier environment	The sediment has a sandy layer in this zone and pollen content indicates a drier environment. Most likely the layer is aeolian sand transported to the site at the time.
TA-3	240-263.5cm	Marsh	This zone seems to reflect a more humid and stable environment with increasing values for *Isoetes, Mentha* and Poaceae.
TA-4	121-240cm	Initial erosion and subsequent wetland development	A thin sandy layer initiates this zone and all the pollen curves have abrupt changes thereafter. This could indicate a hiatus caused by aeolian truncation of the surface and replacement of top sediment with sand. It could also have been caused by water erosion in a flood situation and peaks in pollen from hygrophilous species like Cyperaceae, *Erica erigena, Myriophyllum, Isoetes* and *Hydrocotyle* may reflect such a supply from wetter areas. During this phase a humid environment seems to have prevailed. This is suggested by relatively high values for *Myriophyllum, Botryococcus* and *Hydrocotyle.* In less humid habitats wet heathland with *Erica erigena* and wetland with *Halimium lasianthum* existed*.* At the transition to the next zone there is a ca. 50 cm sand deposit without preserved pollen.
TA-5	78-121cm	Sand deposition followed by wetter conditions	As in the other samples this zone shows a paludification after a period of (probably) aeolian sand transport. Clear lake sediment is not found, but peak values for Cyperaceae and Poaceae indicate grass-sedge vegetation surrounding wetter and deeper basins with *Isoetes* and *Nymphaea*.

4.3.3. Correlation regional/local vegetation development

In Table 7 an attempt is made to correlate regional and local changes, on the basis of boundaries as time equivalent features, despite the low number of ^{14}C datings. In PAZ I, all habitats had typical wetland vegetation. An intermediary drier phase is detected in the Terra da Areia deposit. In PAZ II abrupt changes in the pollen assemblages of Terra da Areia indicate aeolian activity or supply of flood deposits. The sites maintained their wetland vegetation but a drier phase is recognized between two humid phases in the Salix-carr. A sand layer indicating aeolian sand drift at the transition to PAZ III is found in the sediments from Lake Vela, Salix-carr and Terra da Areia. In Lake Braças peaks in the *E. erigena* and Cyperaceae curves show a strong paludification at the time of this transition. During PAZ III all sites experienced an increased water

table resulting in the formation of lakes in Braças and Vela sites and wetter environments in Salix-carr and Terra da Areia.

Table 7 – Correlation of regional and local zones

Regional zones	Local zones Vela	Local zones Braças	Local zones Salix-carr	Local zones Terra da Areia	Palaeo environment
PAZ III Reforestation and lake development	**V-4** Eutrophic lake **V-3** Lake	**B-4** Eutrophic lake **B-3** Oligotrophic lake **B-2** Marsh and later inundation	**Sc-4** Swamp/marsh	**TA-5** More humid wetland with some open water	**Eutrophi-cation** **Inundation/ Lake formation**
PAZ II *Erica scoparia* heathland	Sand layer **V-2** Marsh **V-1** Wet heathland	**B-1** Wet heathland	Sand layer **Sc-3** Humid wetland **Sc-2** Drier phase **Sc-1** Wet heathland	Sand layer **TA-4** Humid wetland Aeolian sand deposition **TA-3** Marsh	**Aeolian activity** **Wetland** **Aeolian activity** **Wetland**
PAZ I *Halimium, E. scoparia, E. umbellata, Calluna* heathland	**V-1** Wet heathland		**Sc-1** Wet heathland	**TA-3** Marsh **TA-2** Sand layer **TA-1** Marsh/wet heathland (sandy sediment lost at extraction)	**Wetland** **Aeolian activity** **Wetland** **Aeolian activity** **Ironpan formation**

5. Discussion

The investigation revealed that the Vela and Braças sites initially were humid depressions or seasonally inundated wetland systems (PAZ I and II) that only later became lakes (PAZ III). Care therefore has to be taken in reconstructing contemporary vegetation from these assemblages as the pollen rain ratio of local to regional pollen can be expected to vary when the sediments change from wetland soil to lake sediment. The smaller the lake, pond, bog or wetland in which

pollen is deposited, the stronger is the local element (Heide, 1984). An attempt has been made to exclude local pollen from the total regional pollen (TRP) sum. It is, however, possible that pollen from certain families (Ericaceae, Cistaceae), included as regional pollen, may contain local or extra-local taxa.

Investigation of palaeosols from a larger part of the region (Castilho, *et al.,* 2007), nonetheless, confirms that the pollen reflection of the regional vegetation was not obscured by this local overrepresentation in PAZ I and II but on the contrary it is representative for a large part of the region.

5.1. Palaeohydrology of the lake basins

Paludification of the Vela and Braças wetland system started around 1630 BP (420 AD), the sites initially being shallow, oligotrophic seasonal basins, inundated in the wet seasons. Poor representation of algae and aquatic plants contributes to this idea as does the apparent low sedimentation rate, the latter being suggested by the fact that pollen from *Zea mays* is found 26cm above the dated bottom sample of Lake Vela. This indicates the age of this level to be equal to or younger than the first quarter of the 16th Century ("Revolução do Milho", Ribeiro, 1967). Maximum sedimentation rate is hence 0,24 mm/year.

The initial paludification may be explained both by climate and vegetation change. Palynological research from North Alentejo suggests that climate around 1600 BP was very humid (Mateus, 1992; Mateus and Queiroz, 1993; Queiroz, 1999). Furthermore, climate research based on pollen and non-pollen palynomorph data from north-western Galicia in Spain (Mighall *et al.* 2006) indicates a major increase of humidity for the same period ca. 240–770 AD.

Open heathland dominated the environment in the Quiaios – Mira dunes at the time. Absence of forest may have resulted from a previous deforestation (see discussion below), an additional contribution to a raised water table attributable to subsequent decrease of evapotranspiration from the plant cover.

At the transition to PAZ II there seems to have been a slight drop in humidity even though a wetland environment persisted. During PAZ II two of the sites seem to have had an intermittent period of drier local conditions as they were affected by aeolian activity and sand drift.

In terms of hydrology, parts of these wetlands underwent drastic changes at the transition between PAZ II and III from seasonally inundated wetland, through a swamp phase and towards

the development of permanent lakes. In Braças, a swamp phase with *Erica erigena* including deeper pools with *Nymphaea, Potamogeton* and *Myriophyllum* is apparent. In Vela, Salix-carr and Terra da Areia a sandy layer immediately before lake formation reflect aeolian sand transport at the time.

Dating of this transition from swamp to lake was facilitated by the drought of 2005 and by the extraction of sediment in 1995 that led to exposure of former surface sediments. During this extraordinary dry summer Lake Braças dried out completely and trunks and roots of a shrub became exposed over most of its surface. Laboratory analysis of the wood showed that it was *E. erigena* (Fig.7) (Queiroz and van der Burgh, 1989)(confirmed by first author) and dating of a trunk gave 180 ± 35 BP (1650-1698 AD, 1723-1816 AD, 1834-1879 AD or 1916-1952 AD) as the time of the death event. This probably corresponds to the level of rapid decrease in the *E. erigena* pollen curve found immediately above the PAZ II/III transition at ca. 40cm from the top sediment in Braças. It reflects an inundation of Braças causing the death of a large number of *E. erigena*.

Fig.7

Erica erigena wood.

 a) rays

b) vessels with scalariform perforations

However, the ^{14}C date of this level is inconclusive. It is necessary to use historical data in an attempt to delimit the calibrated age to one or two of the given time intervals. The oldest interval (1650-1698 AD) is unlikely because the sediment thickness between the layer containing the first occurrence of *Zea mays* pollen in Vela and the PAZ II/III transition (27cm) is almost the same as the remaining top sediment of PAZ III (31cm). Generally sedimentation rate is larger in lakes than in seasonally inundated wetland. Secondly the Quiaios lakes appear for the first time in cartographical material in 1866 (Carta corográfica de Portugal, 1866). The last interval (1916-1952 AD) must hence be too late. This delimitation leaves us with a probable period for the genesis of the Quiaios lakes between 1723 AD and 1866 AD.

In both Lake Braças and Lake Vela, the algal development was strong and aquatic species became abundant at this transition, indicating an increased water level in the lakes. In Salix-carr and Terra da Areia, wetter conditions are reflected as well.

Development from wetland to lake may have resulted from human activity, climatic change and/or dune instability. Increased water run-off from agricultural fields due to installation of drainage ditches directed towards the lakes, a more humid climate or a time of aeolian sand transport filling in drainage channels from the west and causing obstructed drainage are all plausible causes of an increased water table. At any rate, the sand layers in Vela, Salix-carr and Terra da Areia immediately before lake development, indicate that sand drift was involved in the hydrological changes. It is probable that the transverse dunes were formed at a time shortly prior to lake formation. These dunes advanced according to Almeida (1995) until the immediate proximity of the lakes. All the lakes in the region are aligned at the eastern limit of this last dune generation, indicating a strong connection between lake and dune formation. The most recent dune-building episode identified in central Portugal is between 1770 AD and 1905 AD (Clarke and Rendell, 2006), linked to a period of predominantly negative winter North Atlantic Oscillation index (NAOi) and southward deflection of Atlantic storm tracks. This corresponds well with the deduced period of development of lake-environments in Braças and Vela. Sand drift from the west caused by deteriorating climatic conditions and increased sand supply due to lower sea level during LIA (Little Ice Age), combined with a scarce vegetation cover after deforestation and grazing, probably led to in an infilling of existing lakes. The result was an eastward migration of the lakes ultimately reaching their present location. Recent investigation of boreholes along an east-west gradient from Lake Braças to the sea, indicate lateral movement of the lakes towards the east (Castilho *et al.*, 2007.).

Eutrophication of the lakes is recognized in the upper parts of the diagrams probably connected to increased agricultural activity in nearby regions.

There is no indication of proximity to the coastline during the period covered by the diagrams as suggested by many authors (Abecassis, 1961; Figueiredo, 1987; Noivo, 1996, Reigota, 2000).

5.2. Vegetational changes

5.2.1. Deforestation and heathland development

There are many remnants of a former forest cover in the region prior to wetland development in the Vela and Braças sites (and hence absent in the diagrams). During the opening of drainage channels and wells in the area, numerous tree trunks have been found at deeper levels under the aeolian sand (Rei, 1940; Reigota, 2000).

In the western sector of the Quiaios dunes below around 8-10 m of aeolian sand, brackish lagoonal deposits exist extending up to 1km inland from the present coastline. Pollen content in samples taken from 2 boreholes in this palaeo-lagoon reflects a mixed pine/oak forest environment (>40 % arboreal pollen) with oak as the most important of the two. A younger part of the lagoonal deposit shows continuing high frequency of arboreal pollen, although heathland plants seem to be gaining territory (Castilho *et al.*, 2007). The deposits are so far not dated but this brackish water lagoon was probably formed at the end of the Flandrian transgression when sea level stabilized and reached approximately the present level. According to the sea level curve prepared for Portugal (Dias *et al.,* 2000) this happened between 5 and 2.5 ky BP.

Furthermore, broken off mud blocks originating from a similar palaeo-lagoon are presently found on the beach in Leirosa, a comparable dune field 20km south of the Quiaios dunes, due to recent erosion of the beach. The process, also called "Inland beach migration" (Granja and Carvalho, 1998; Granja and Carvalho, 2000), is identified in various places along the Portuguese coast during the last decades, exposing older dune systems and palaeosols. The mid-layer of the Leirosa lagoonal deposit has been dated to ca. 2950 BP (Bernardes *et al.*, 2001). The mud blocks probably originate from superficial parts of the deposit and hence are younger than this mid-layer. Blocks have been analyzed for pollen and NPP (Callapez *et al.*, 2005; Callapez *et al.*, 2005a) and equally reflect a forest (>40% AP) principally composed of *Pinus* spp. and *Quercus* spp.

Mixed pine/oak forest thus seems to have predominated in the area for some time but was replaced by heathland at a later stage. Human influence (cutting, burning, pastures and agriculture) and/or climatic change led to deforestation at some point already prior to 1630 BP. The amount of settlements from Iron Age and Roman times registered in the hills nearby (Santos Rocha, 1908; Guerra and Ferreira, 1971; Reigota, 2000) points towards human activity as an important influential factor in the deforestation process. Some of the samples from the western lagoonal deposits contained pollen from *Triticum*, further indicating early human activity in the vicinity.

Palynological research from other parts of Portugal shows a similar development. Investigation from littoral northern Alentejo suggests a stepwise deforestation beginning around 6000 BP and culminating around 2000 BP when there is a maximum deforestation and overgrazing (Queiroz, 1989; Mateus, 1989; Mateus, 1992; Mateus and Queiroz, 1993; Queiroz and Mateus, 1994; Queiroz, 1999). Deforestation is followed by an increase in heathland plants like *Erica scoparia, E. umbellata, Calluna*, equal to the vegetation recognized in the initial parts of the Vela and Braças diagrams. Comparable results are found in an investigation from the Tagus valley, about 75 km NE of Lisbon (van Leeuwaarden and Janssen, 1985).

The Serra da Estrela region in eastern Portugal experienced a corresponding vegetation development (van der Knaap and van Leeuwen, 1995). Starting around 5500 BP, human influence on vegetation was limited but present as small-scale local deforestation and with some grazing. Large-scale deforestation only occurred since around 3200 BP, even though regeneration capacity was retained. Anthropogenic pressure with grazing, burning and agriculture from ca. 955 BP, caused the ultimate disappearance of forests in Serra da Estrela.

A recent palynological study from the littoral zone of Nazaré, ca. 80km south of the Quiaios area (Gomes, 2007), similarly revealed deforestation and subsequent heathland development (dated ca. 2700 BP, Gomes, *pers. commun.*).

Vegetation in the Quiaios region since ca. 1630 BP was characterized by deforested open heathland vegetation possibly with scattered occurrences of pine and oak. This scenario seems to have prevailed here as in littoral Alentejo and Serra da Estrela, as a result of intense pastoral activities maintaining an open scrubland until human intervention in the form of reforestation during the last 200 - 300 years. Infertile and sandy soils along the entire Atlantic fringe of Europe were similarly utilized as grazing ground for as much as 6000 years up to the present time (Haaland, 2002). Fodder value of evergreen heathland is high especially if regularly burned or mowed. The European practice of intentional forest

clearing to open up for pastures and the recognition of heathland as a valuable source of fodder in infertile littoral zones, seem to have reached from Norway in the north to Portugal in the south.

5.2.2. Reforestation

Reforestation of parts of the area with *Pinus* is reflected in the initial phase of PAZ III. The rapid increase in *Pinus* percentages in all four diagrams irrespective of local hydrological conditions proves a real increase of pine in the region and cannot be explained by the earlier mentioned differences in pollen rain ratio of local and regional pollen between wetland and lake sediments.

However, the chronology of reforestation is not conclusive. It is known that a pine forest owned by the crown ("Pinhal do Rei") existed in Quiaios but it is not known when it was planted. It is first included in a map from 1773 (Serra, *et al.,* 1773). The initial increase in *Pinus* pollen at the transition to PAZ III may have originated from these forested areas.

The subsequent increase in the *Pinus* curve corresponding to the level where exotic species like *Eucalyptus, Acacia, Platanus* and *Casuarina* first appear and the following high values for *Pinus* pollen almost certainly reflect the reforestation in 1926 until the present situation of a mature pine forest.

5.2.3. Agriculture

In Terra da Areia, *Triticum* pollen is found already in PAZ I suggesting nearby agriculture at an early stage. *Olea* and *Juglans* are present in the pollen rain since PAZ I as well, but their pollen may have originated from more distant cultivations. Initially low and discontinuous cereal pollen curves indicate that agriculture was scattered and more distant than today. The area was more likely utilized for pastures. This is reflected by the occurrences of pastoral indicators like *Plantago lanceolata* and coprophilous fungi (*Cercophora* and *Gelasinospora,* growing on dung of domestic animals) and by the maintenance of open heathland with no regeneration of forests throughout PAZ I and II. The first cereal pollen to appear in the Braças and Vela diagrams is *Zea mays* (in PAZ II) reflecting late introduction (or reintroduction) of agriculture in the surroundings of the lakes. In PAZ III there seems to be an agricultural intensification as pollen from *Olea,* Cerealia*, Secale, Triticum* and *Zea mays* reach a continuous and high representation in the pollen rain. The transformation of the barren Gândara into an intensely occupied territory in the 17th- 19th Century (Cravidão, 1992) may be what is reflected at the transition to PAZ III.

Algal and aquatic flora shows eutrophication of both lakes in the upper layer. Increased nutrient content towards the sediment surface is probably linked to surface runoff from nearby agricultural fields.

5.3. Sand drift and dune instability

Dune accretion and erosion depend on sediment supply, wind velocity, vegetation cover and humidity and exceeding threshold values for one or more of these factors may cause sand drift. Three dune generations (1-3) have been proposed for the region (Noivo, 1996) and similar geomorphology of the dunes has been ascribed to a synchronous origin (Fig.1).

5.3.1. Dune generation 1

The truncated dunes east of the lakes (in the Gândara plain) are thought to be the oldest and may be of Pleistocene origin (Carvalho, 1964). A distinction of these dunes was made on the criterion that they have a pedological palaeohorizon, an ironpan ("sorraipa") (Carvalho 1954; Carvalho, 1964), and they were assigned to the Würm (Weichselian) glaciation because the dunes were associated with wind-worn pebbles and Palaeolithic artefacts, as well as periglacial deposits. More recently the dunes are placed in a wider time frame ranging from the Weichselian to the Holocene (Granja and Carvalho, 1992).

5.3.2. Dune generation 2

The parabolic dunes are remnants of a dune generation of earlier origin than the WNW-ESE oriented transverse dunes and they are preserved in areas where vegetation cover was adequate to protect them against subsequent sand invasions. Dating of parabolic dunes in the region is limited to thermo-luminescence dates of parabolic dune sands near the shore and gave ages between 1145 ± 237 yr (OSL 1995) and 620 ± 128 yr (OSL 1995) (Granja *et al.,* 1996; Granja, 2002).

5.3.3. Dune generation 3

The transverse dunes belong to the most recent dune generation and their formation started around 390 years ago according to Noivo´s (1996) calculation. The cold and windy climate and sea level regression in the region during the little ice age (LIA) exposing additional sand supply, further enhanced by limited vegetation cover, is thought to have resulted in dune instability. In northern Portugal as well, sand dunes possibly generated during LIA are found to have covered medieval cemeteries (Fão – Esposende and Chafé – Viana do Castelo) (Granja, 1990; Granja and Carvalho, 1992). Historical sources describe how the inhabitants of Apúlia (Esposende) in 1586 asked royal help in their battle against sand invasion (Neiva, 1991).

In the Terra da Areia core, five layers with high sand content are recognized demonstrating an unstable local environment. They are separated by thinner muddy layers from times of more stable conditions. Starting from the top, a 34cm thick (36-70cm) aeolian sand layer is found above the mud comprising the initial sharp rise in the *Pinus* curve. This sand layer can probably be ascribed to the dune invasion at the beginning of the 20th Century that led to the large scale reforestation in 1926. The next sandy layer at 93-147cm is also identified at Lake Vela and Salix-carr. It originated from the inundation phase of the lakes and paludification of adjacent wetland areas probably in the time span 1723–1866 AD. This is approximately in accordance with Noivo´s calculations for the formation of the transverse dunes. On the basis of the sandy layers in Terra da Areia alone it is not possible to correlate the bottom sandy layers to formation of the parabolic dunes or to claim a higher number of dune generations than the three mentioned. However, it is evident that during the last 1600 years the region was subject to unstable dune sand and multiple phases of sand invasion.

6. Conclusions

In the initial phase, from around 1630 BP, the basins were seasonally inundated wetland areas whose paludification was caused by a humid climate and possibly previous deforestation. Transition to lakes, similar to the present ones, occurred at a much later stage in the time span 1723-1866 AD after a period of aeolian sand transport. In recent investigations (Castilho *et al.*, 2007) indications of eastward movement of the lakes towards their present location, are found. This was most likely a result of dunes filling in from the west affecting the drainage system of wetland and lakes consequently forcing them towards the east.

Vegetation in the region was an open heathland from 1630 BP (420 AD) until around 1720 AD. Other investigations (Callapez *et al.,* 2005; Callapez *et al.*, 2005a; Castilho *et al.*, 2007) suggest a previous forest environment that disappeared between 2.5 and 5 Ky BP. Regeneration capacity of the forest was subsequently destroyed possibly as a result of grazing and thus heathland vegetation persisted for more than one thousand years. Reforestation has only occurred during the last 2-3 centuries.

There are signs of various unstable aeolian phases suggesting multiple, more or less local sand invasions and dune generations.

Anthropogenic influence on the vegetation (grazing and agriculture) is detected early in some of the diagrams. Its representation is obviously more prevalent and consistent in their upper part particularly following the reforestation 200-300 years ago.

Acknowledgments

Fig.3 Pollen diagram Lake Braças

40
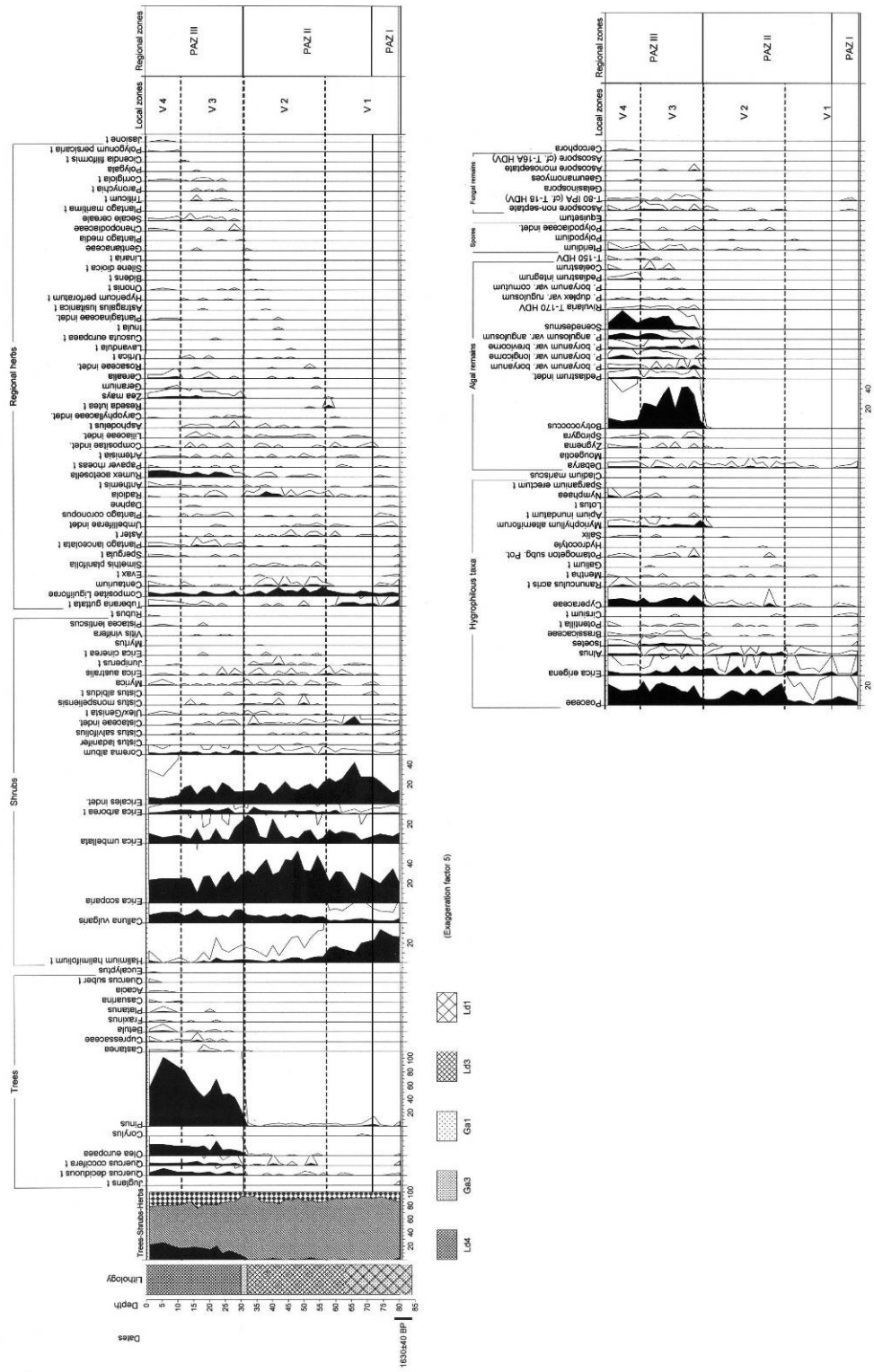
Fig.4 Pollen diagram Lake Vela

Fig.5 Pollen diagram Salix-carr

Fig.6 Pollen diagram Terra da Areia

References

Abecassis, C.K., 1961. As formações lagunares e os seus problemas de engenharia litoral. Contribuição para um estudo sistemático. Lisboa. 39-46.

Albuquerque, J.P.M., 1954. Carta ecológica de Portugal. Ministério da Economia, Lisboa, Portugal. 58 p. Map 1/500 000.

Almeida, A.C., 1995. Dunas de Quiaios, Gândara e Serra da Boa Viagem. Uma abordagem ecológica da paisagem. PhD Thesis, University of Coimbra, Portugal. 305 p.

Bernardes, C.M., Noivo, L.M., Corrochano, A., 2001. Evolution of Holocenic Coastal Dunes at Leirosa, South of Cape Mondego, Portugal. Thalassas 17(2), 47-56.

Braun-Blanquet, J. Pinto da Silva, A.R., Roseira, A., 1956. Résultats de deux excursions géobotaniques à travers le Portugal septentrional et moyen II – Chenaies à feuilles caduques (Quercion occidentale) et chenaies à feuilles persistantes (Quercion fagineae) au Portugal. Agronomia Lusitana, Lisboa, vol.XVIII. Fasc.III, 167-235.

Callapez, P.M., Paredes, R, Carvalho, M., Danielsen, R., Soares, A.F., Dinis, P., 2005. The paleolagoon of Leirosa (Figueira da Foz) and the Holocene brackish malacofauna of West Portugal. Portugala-Noticiario Malacológico–Congresso Nacional de Malacologia. Albufeira, Portugal, Portugalla, 5. pp. 17-18.

Callapez, P.M, Paredes, R., Dinis, P., Danielsen, R., Soares, A.F., Carvalho, M., 2005a. Biofacies from the Holocene paleolagoon of Leirosa (Figueira da Foz, West Central Portugal). Coastal Hope 2005. Lisbon. pp. 19-20.

Cardoso, J.C., Bessa, M.T., Marado, M.B., 1971.Carta de Solos de Atlas do Ambiente de Portugal Continental. Serviço de Reconhecimento e de Ordenamento Agrário.

Carta corográfica de Portugal, 1866. Folha 13, 1:100 000. University of Coimbra, Portugal

Carta Cabo Mondego, 1773. 1:12000. Instituto Geográfico e Cadastral. Lisbon, Portugal

Castilho, A., Danielsen, R., Dinis, P., 2007 Palaeoenvironmental development of the Quiaios – Tocha dunes based on geological and palynological investigations. Proceedings XXXV IAH Congress-Groundwater and Ecosystems, International Association of Hydrogeologists, Lisbon, Portugal, 471, pp. 1-8.

Carvalho, G.S., 1954. A Gândara (Portugal) e as Landes da Gasconha (Franca). Memórias e Notícias, Museu Mineralógico e Geológico da Universidade de Coimbra, 37, 21-36.

Carvalho, G.S., 1964. Areias da Gãndara (Portugal). Uma formação eólica Quaternária. Publicações do Museu Mineralógico e Geológico da Faculdade de Ciências da Universidade do Porto, 81 (4), 3-32.

Chodat, R., 1913. Voyages d`études géobotaniques au Portugal. Le Globe, t. LII.

Clarke, M.L., Rendell, H.M., 2006. Effects of storminess, sand supply and the North Atlantic Oscillation on sand invasion and coastal dune accretion in western Portugal. The Holocene 16(3), 341-355.

Cravidão, F.D., 1992. A população e o povoamento da Gândara (génese e evolução). PhD Thesis, University of Coimbra, Portugal. 531 p.

Cruz, C.S., 1984. Estruturas dunares litorais em Portugal. Considerações sobre fitogeodinâmica. Bol. Lig. Prot. Nat. 18/ 3, 173-205.

Daveau, S., 1980. Espaço e tempo, evolução do ambiente geográfico de Portugal ao longo dos tempos pré-históricos. Clio-Revista Centro Histórico, Universidade Lisboa 2, 13-37.

Dias, J.M.A., Rodrigues, A., Magalhães, F., 1997. Evolução da linha de costa, em Portugal, desde o Último Máximo Glaciário até à actualidade: Síntese dos conhecimentos. Estudos do Quaternário, APEQ, Lisboa. 1, 53-66.

Dias, J.M.A., Boski, T., Rodrigues, A., Magalhães, F., 2000. Coast line evolution in Portugal since the Last Glacial Maximum until present - a synthesis. Marine Geology 170, 177-186.

Duvigneaud, J., 1962. Le Portugal central et septentrional. Sa position phytogéographique, sa vegetation. In Delvosalle, L. and Duvigneaud, J., Itinéraires Botaniques en Espagne et au Portugal. Bruxelles, 116 p.

Figueiredo, M.M., 1987. Degradação paisagística da faixa costeira : uma reflexão. Locus, Revista da Associação de Investigação do Território. 2/3, 29-47.

Fægri, K., Kaland, P.E., Krzywinski, K., 1989. Textbook of Pollen Analysis, 4th edition. John Wiley and Sons, Chichester.

Gomes, S.D., 2007. A palinologia da Lagoa do Saloio (Nazaré, Portugal) e a evolução holocénica da região da Mata Nacional do Valado. MSc Thesis, Polytechnical institute of Tomar and University of Trás-os-Montes and Alto Douro. 128 p.

Granja, H.M., 1990. Representar a geodinâmica da zona costeira: o passado e o presente; que futuro? PhD Thesis, University of Minho, Braga, Portugal. 347 p.

Granja, H.M., 2002. Reconstituição paleoambiental da zona costeira, a norte da Laguna de Aveiro, desde a Idade Media até à actualidade. O Litoral em perspectiva histórica (Séc. XVI a XVIII), Instituto de História Moderna, Porto. 93-109.

Granja, H.M., Carvalho, G.S., 1992. Dunes and Holocene deposits of the coastal zone of Portugal, north Mondego Cape. In: Carter, R.W.G., Curtis, T.G.F. and Sheehy-Skeffington, M.J. (Eds.) Coastal Dunes: geomorphology, ecology and management for conservation. Proceedings of the Third European Dune Congress, Galway, Ireland. pp. 43-50.

Granja, H.M., Carvalho, G.S., 1998. The landscape of the Coastal Zone of Northwest Portugal; its degradation and management. Proceedings Fourth International Conference LITTORAL 1998, European Association for Science and Technology (EUROCOAST), Barcelona, Spain. pp.95-100.

Granja, H.M., Carvalho, G.S., 2000. Inland beach migration ("beach erosion") and the coastal zone management. Pozar, A. (Ed.) – Domac, LITTORAL 2000, Responsible Coastal Zone Management. The challenge of the 21st century. Periodium Biologorum 102 (supplement 1), Zagreb, Croatia. pp. 413-424.

Granja, H.M., Carvalho, G.S., de Groot, T., Soares, A.M., Parish, R., 1996. Geochronology and the recent geomorphological evolution of the northwest coastal zone of Portugal. In: Taussik, J. and Mitchell (Eds.), Partnership in Coastal Zone Management (Proceeding 3rd International Symposium EUROCOAST, Littoral 96, Portsmouth, U.K.) Samara Publishing Limited, Cardigan: pp. 297-308.

Guerra, V.A., Ferreira, O.V., 1971. Inventário das Estações da Idade do Ferro nos Arredores da Figueira da Foz. Actas do congresso Nacional de Arqueologia, vol. I, Coimbra, Portugal. 297-303.

Guerra, V.A., Ferreira, O.V., 1974. Inventário dos monumentos megalíticos dos arredores da Figueira da Foz. Câmara Municipal da Figueira da Foz, 14p.

Haaland, S., 2002. Fem tusen år med flammer Det europeiske lyngheilandskapet. Vigmostad /Bjørke, Bergen, Norway. 160 p.

Heide, K., 1984. Holocene pollen stratigraphy from a lake and a small pond in north-central Wisconsin, U.S.A. Palynology 8, 3-20.

Janssen, C.R., 1973. Local and regional pollen deposition. In: Birks, H.J.B. and West, R.G. (Eds.) Quaternary Plant Ecology. Proceedings of the Fourteenth Symposium of the British Ecological Society. Blackwell, New York, pp. 31–42.

Komárek, J., Jankovská, V., 2001. Review of the Green Algal Genus Pediastrum; Implication for Pollenanalytical Research. Bibliotheca Phycologica, Band 108, 127 p.

Martins, M.J.S., 1999. Estudo fitossociológico e cartográfico da paisagem vegetal natural e semi-natural do litoral centro de Portugal entre a Praia de Mira e a Figueira da Foz. MSc Thesis, University of Coimbra, Portugal. 146p.

Mateus, J.E., 1989. Lagoa Travessa: A Holocene pollen diagram from the south-west coast of Portugal. Revista de Biologia, Lisboa. 14, 17-93.

Mateus, J.E., 1989a. Pollen morphology of Portuguese Ericales. Revista de Biologia, Lisboa, 14, 135-208.

Mateus, J.E., 1992. Holocene and present-day ecosystems of the Carvalhal region, Southwest Portugal. PhD Thesis, Utrecht University, Netherlands. 184 p.

Mateus, J.E., Queiroz, P.F., 1993. Os estudos da vegetação Quaternária em Portugal: contextos, balanços e perspectivas. Edições Colibri, Lisboa. 105-131.

Mesquita de Figueiredo, A., 1943. A Pré-história do concelho da Figueira, foz do Mondego. Novos descobrimentos feitos nos Arquivos. Imprensa Portuguesa, Porto, 11p.

Mighall, T.M., Martínez Cortizas, A., Biester, H., Turner, S.E., 2006 Proxy climate and vegetation changes during the last five millennia in NW Iberia: Pollen and non-pollen palynomorph data from two ombrotrophic peat bogs in the North Western Iberian Peninsula. Review of Palaeobotany and Palynology, 141, 203–223.

Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen Analysis, 2nd edition. Blackwell Scientific Publications, London.

Morais, A. T. de, 1940. Novas áreas da fitogeografia portuguesa. Bol. Soc. Broteriana, Coimbra, XIV (II Sèrie), 97-138.

Neiva, M.A.P., 1991. Esposende – páginas de memória. Neiva (Ed.), Esposende, Portugal.

Noivo, L.M., 1996. Morfologia e dinâmica sedimentar das dunas de Quiaios, Portugal. MSc Thesis, University of Aveiro, Portugal. 169 p.

Punt, W. (Ed.), 1976. Northwest European Pollen Flora, I. Elsevier, Amsterdam. 145 p.

Punt, W., Clarke, G.C.S. (Eds.), 1980. Northwest European Pollen Flora II, Elsevier, Amsterdam, 265 p.

Punt, W., Clarke, G.S.C. (Eds.), 1981. Northwest European Pollen Flora III, Elsevier, Amsterdam, 138 p.

Punt, W., Clarke, G.S.C. (Eds.), 1984. Northwest European Pollen Flora, IV. Elsevier, Amsterdam, 369 p.

Punt, W., Blackmore, S., Clarke, G.C.S. (Eds.), 1988. Northwest European Pollen Flora, V. Elsevier, Amsterdam, 154 p.

Punt, W., Blackmore, S. (Eds.), 1991. Northwest European Pollen Flora, VI. Elsevier, Amsterdam, 275 p.

Queiroz, P.F., 1989. A preliminary palaeoecological study at Estacada (Lagoa de Albufeira). Revista de Biologia, Lisboa. 14, 3-15.

Queiroz, P.F., 1999. Ecologia Histórica da Paisagem do Noroeste Alentejano. PhD Thesis, University of Lisbon, Portugal. 300 p.

Queiroz, P.F., van der Burgh, J., 1989. Wood Anatomy of Iberian Ericales. Revista de Biologia, Lisboa.14, 95-134.

Queiroz, P.F., Mateus, J.E., 1994. Preliminary palynological investigation on the Holocene deposits of Lagoa de Albufeira and Lagoa de Melides, Alentejo (Portugal). Revista de Biologia, Lisboa.15, 15-28.

Rei, M.A., 1940. Arborização – Alguns artigos de propaganda regionalista. Biblioteca Municipal da Figueira da Foz, Portugal, 40 p.

Reigota, J., 2000.A Gândara Antiga. CEMAR, Portugal. 474 p.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Tálamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 Terrestrial Radiocarbon Age Calibration, 0–26 cal kyr BP. Radiocarbon 46 (3), 1029-1059.

Ribeiro, O., 1967. Portugal, o Mediterrâneo e o Atlântico, Esboço de relações geográficas Lisboa, Portugal. 3rd ed. 175p.

Rivas-Martínez, S., 1973. Avance sobre una síntesis corológica de la Península Ibérica, Baleares y Canárias. Anal. Inst. Bot. Cavanilles, Madrid, Spain. 30, 69-87.

Rivas-Martínez, S., Lousã, M., Diaz, T.E., Fernández-González, F., Costa, J.C., 1990. La vegetación del sur de Portugal (Sado, Alentejo y Algarve). Itinera Geobotanica 3, 5-126.

Saenz de Rivaz, C., 1973. Estudios palinológicos sobre *Quercus* de la España mediterranea. Bol. R. Soc. Espanhola Hist. Nat. (Biol.), 71, 315-329.

Santos Rocha, A., 1888-1900. Antiguidades Pré-históricas do Concelho da Figueira. Coimbra, Imprensa da Universidade, Coimbra, Portugal. 271 p.

Santos Rocha, A., 1908. Estações Pré-Romanas da Idade do Ferro nas vizinhanças da Figueira. Porto, Portugal. 86 p.

Serra, E.G., Silva R. F.A., Marques T.P., 1773. Borrão de campo e planta thopografica do sitio da mina do carvão de pedra no promontório do Mondego. Instituto Geográfico Português (IGP), Lisbon, Portugal.

Stuiver, M., Reimer, P.J., 1993. A computer program for radiocarbon age calibration. Radiocarbon 35, 215–230.

van der Knaap, W.O., van Leeuwen, J.F.N., 1995. Holocene vegetation succession and degradation as responses to climatic change and human activity in the Serra de Estrela, Portugal. Review of Palaeobotany and Palynology, 89, 153-211.

van Geel, B., 1976a. A palaeoecological study of Holocene peat bog sections, based on the analysis of pollen, spores and macro and microscopic remains of fungi, algae cormophytes and animals. Academisch proefschrift, Hugo de Vries laboratorium, Amsterdam University, Netherlands.

van Geel, B., 1976b. Fossil spores of Zygnemataceae in ditches of a prehistoric settlement in Hoogkarspel (The Netherlands). Review of Palaeobotany and Palynology, 22, 337-344.

van Geel, B., 1978. A palaeoecological study of Holocene peat bog sections in Germany and the Netherlands. Review of Palaeobotany and Palynology, 25, 1–120.

van Geel, B., Hallewas, D.P., Pals, J.P., 1983. A Late Holocene deposit under the Westfriese Zeedijk near Enkhuizen (Prov. of N-Holland, The Netherlands): palaeoecological and archaeological aspects. Review of Palaeobotany and Palynology, 38, 269-335.

van Geel, B., Coope, G.R., van der Hammen, T.,1989. Paleoecology and stratigraphy of the Lateglacial type section at Usselo (The Netherlands). Review of Palaeobotany and Palynology, 60, 25-129.

van Leeuwaarden, W., Janssen, C.R., 1985. Preliminary palynological study of peat deposits near an oppidum in the lower Tagus valley, Portugal. Actas da I Reunião do Quaternário Ibérico, 2, pp. 225-236.
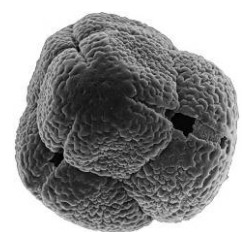
PAPER II

Dissimilarities in the recent histories of two lakes in Portugal explained by local-scale environmental processes

Randi Danielsen

Universidade do Minho, Braga, Portugal / Instituto de Gestão do Património Arquitectónico e

Arqueológico (IGESPAR), Lisbon, Portugal

Abstract

The palaeolimnology of two shallow lakes, Vela and Braças, in coastal Portugal, were investigated. The lakes are situated in a transitional area between a Holocene dune field and agricultural fields. This study focused on the local palaeoecology and palaeolimnology inferred from the stratigraphic records of pollen of hygrophilous taxa and non-pollen palynomorphs, with particular emphasis on algal remains, e.g. *Pediastrum.* The record of local-scale vegetation changes was utilized to reconstruct the evolution of the local environment in and around the lakes and to identify and explain dissimilarities between the two water bodies. Initially, the sites were wetlands similar to the dune flats and seasonal pools found in the region today. Lake genesis in both basins occurred relatively synchronously, about 2-3 centuries ago, in response to regional geo-hydrological and climatic forcing. Biotic and abiotic dissimilarities between the two lakes have existed since the time of lake formation. Knowledge of the modern ecology of local vascular plants and algae was used to elucidate differences in the recent histories of the two basins. Lake Vela has been more alkaline and displays higher trophic status than Lake Braças. Dissimilarities between the two lakes are probably explained by differences in the flow paths and amounts of input waters, with Lake Vela receiving more nutrient-rich waters from fertilized agricultural fields. Lake Braças receives greater inflow of water that passes through relatively nutrient-poor, acid soils.

Keywords: *Portugal; Pollen and NPP analysis; Pediastrum; Local-scale palaeoecology; Palaeolimnology*

Introduction

Pollen and microfossil assemblages in sediments of wetlands and lakes reflect past local and regional vegetation. The size of the sedimentary basin is the main determinant of the effective source area from which pollen is recruited (Tauber 1965; Heide 1984; Prentice 1985; Sugita 1994). The smaller the lake in which pollen is deposited, the stronger is the relative pollen contribution from local vegetation stands. In wetlands, the pollen record is dominated by local and extra-local species (*sensu* Janssen 1973). This "local overrepresentation" can reflect local-scale palaeoecological patterns, which may form the basis of a palaeo-phytosociological approach.

Holocene environmental and climatic reconstructions based on pollen sometimes include other microfossils such as algae and spores. A number of investigations have utilized algae as indicators of environmental conditions because aquatic organisms with rapid dispersal rates and short life cycles respond rapidly to changes in lake variables like nutrient availability, temperature, pH and water level. Many taxa have well-defined environmental optima and tolerances with respect to important limnological variables and their fossils can contribute to the reconstruction of past environments. *Pediastrum* is a genus of green algae (Chlorophyceae) that has proved useful in this respect (Nielsen and Sørensen 1992; Jankovská and Komárek 2000; Komárek and Jankovská 2001; Sarmaja-Korjonen *et al.* 2006). Most species form coenobia and identification is based on the morphology of the marginal cells and the cell-wall sculpture (Bigeard 1933; Parra Barrientos 1979; Nielsen and Sørensen 1992; Komárek and Jankovská 2001).

In this investigation of Lakes Braças and Vela in Portugal, lake history, local-scale vegetation development, and past environmental conditions are reconstructed using fossil remains of vascular plants and phytoplankton. Numerous studies have been carried out on the present abiotic and biotic conditions of these two lakes (Barros *et al.* 1993; Calado 1993; Vasconcelos *et al.* 1993; Barros 1994; Figueiredo 1995; Pereira 1997; Ferreira 1997; Fernandes 1999; Antunes *et al.* 2003; de Figueiredo *et al.* 2006; Abrantes *et al.* 2006a, 2006b; Abrantes 2007), but none of them reports on conditions prior to the last few decades. The objective of this investigation was to infer past changes in wetland plant communities of the two basins and to explain the causes of these variations using indicator species. Broad-scale changes in regional vegetation and environment are discussed in Danielsen (2008).

Study area
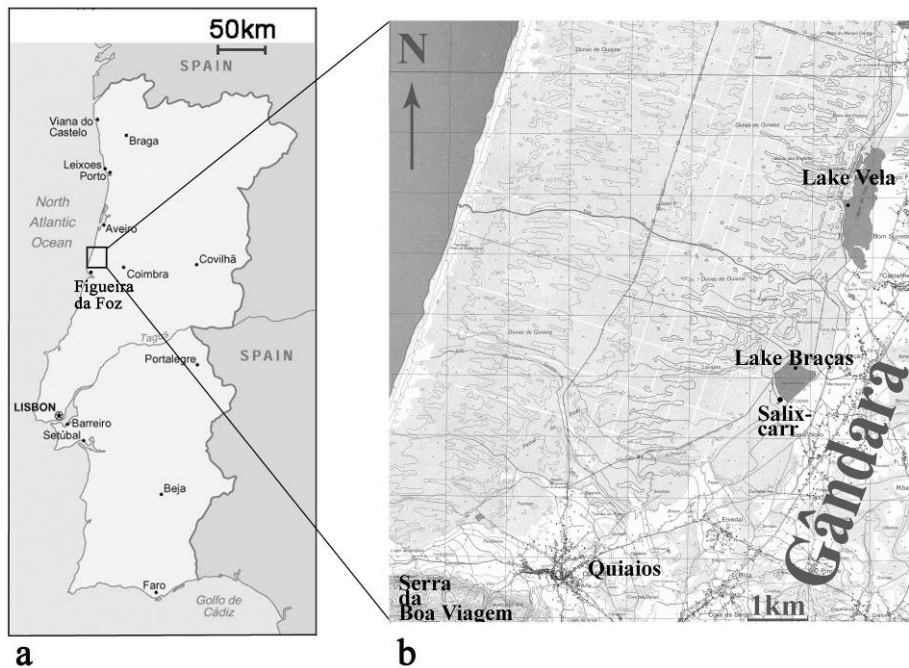
Fig.1 a) Map of Portugal, b) Inset map showing the location of the study sites

Lakes Vela and Braças are located in central coastal Portugal, between 40°15´ and 40°17´ N and 8°50´ and 8°45´ W (Fig.1) at around 45 m a.s.l., about 6 km from the coast. These are the largest of the so-called "Quiaios lakes," four water bodies that lie between a coastal sand plain to the west and an agricultural area to the east, the Gândara plain. Lake Vela is 400 m wide and 2 km long, while Lake Braças is equally wide, but is 650 m long. They are shallow, polymictic, eutrophic lakes, with water depths <2 m. Their deepest area is near their western margins. There is pollution from nearby agriculture, especially in Lake Vela, where adjacent agricultural fields receive artificial fertilizers and manure, and pesticides are used intensively for weed control (Abrantes *et al.* 2006a). Lake Vela is eutrophic, with permanently turbid water, reduced biodiversity, and recurring cyanobacterial blooms, which occasionally lead to fish kills (Abrantes 2007). Lake Braças is situated beside a hydrological station and desiccates during extremely dry summers (e.g. 1992-3, 2005-6). In 1995 sediment was removed to increase the depth of the lake.

In Lake Vela, pH values are exceptionally high, >9 in the summer (Fernandes 1999; de Figueiredo *et al.* 2006), while pH in Lake Braças is <8 for most of the year (Calado 1993; Pereira 1997; Gonçalves *et al.* 1996). This sandy region is characterized by several aquifer layers, which are enclosed by more or less impermeable units in the sediment profile (Castilho *et al.* 2007b). Water level in the lakes varies

with the phreatic level of the surrounding aquifer and is consequently affected by changes in climate, dune geomorphology, and anthropogenic influences on the water table.

The sand plain west of the lakes was forested in the period 1924-1940, and at present supports a pine forest dominated by *Pinus pinaster* Aiton. The main agricultural crops east of the lakes are *Zea mays* L., *Secale cereale* M.Bieb., *Triticum aestivum* L. and other grass species harvested for animal fodder.

Forest cover along the lake shore consists of introduced species; *Acacia longifolia* (Andr.) Willd., *A. melanoxylon* R.Br., *A. dealbata* Link, *A. retinodes* Schltdl., *Taxodium distichum* (L.) Rich., *Casuarina equisetifolia* L., *Platanus orientalis* L., *Quercus palustris* Muenchh. and *Eucalyptus globulus* Labill., while *Populus alba* L., *Fraxinus angustifolia* Vahl, *Ulmus minor* Mill., *Salix atrocinerea* Brot. and *S. arenaria* L. form elements of the potentially natural hydrophilic forest cover. The shrub *Myrica gale* L. is found exclusively in a limited zone on the southern bank of Lake Braças.

At present, the dominant eulittoral vegetation in Lake Vela belongs to the alliance Magnocaricion elatae (Koch 1926) and the association *Cladietum marisci* (Allorge 1922) Zobrist 1939, with *Cladium mariscus* (L.) Pohl, *Lythrum salicaria* L., *Mentha suaveolens* Ehrh., *Schoenus nigricans* L. and *Hydrocotyle vulgaris* L. as the characteristic species (Martins 1999). Vegetation in Lake Braças is dominated by species belonging to the alliance Phragmition communis (Koch 1926). The association *Typho angustifoliae-Phragmitetum australis* (Tüxen and Preising 1942) Rivas-Martínez, Báscones, T.E. Díaz, Fernadez-González and Loidi 1991, predominates, with *Phragmites australis* (Cav.)Trin. ex Steud., *Typha latifolia* L. and *Scirpus lacustris* L. (Martins 1999).

Aquatic macrophytes in both lakes include species from the alliances Nymphaeion albae (Oberdorfer 1957) and Lemnion minoris (Tüxen ex. O. Bolòs and Masclans 1955), with the respective associations *Myriophyllo-Nupharetum lutei* (Koch 1926) dominated by *Nymphaea alba* L. and the exotic species *Myriophyllum aquaticum* (Velloso) Verdc. and *Lemnetum minoris* (Oberdorfer 1957) with *Lemna minor* L. and *Azolla caroliniana* Willd. (Martins 1999).

The algal flora of the lakes has been reported in various studies and is summarized in Table 1.

Class	Order	Species	Author	Vela	Braças
Cyano-phyceae	Chroo-coccales	Aphanizomenon flos-aquae	Ralfs ex Bornet & Flahault	P	
		Aphanocapsa elachista var. conferta	W.West & G.S.West		P
		Aphanocapsa sp.	Nägeli	P	P
		Aphanothece castagnei	(Brébisson) Rabenhorst	P	
		Aphanothece microscópica	Nägeli	P	
		Aphanothece stagnina	(Spreng.) A.Braun	P	P
		Chroococcus dispersus	(Keissler) Lemmerm.	P	P
		Chroococcus limneticus	Lemmerm.	P	P
		Chroococcus turgidus	(Kütz.) Nägeli	P	
		Coelosphaerium kuetzingianum	Nägeli	P	
		Coelosphaerium naegelianum	Unger		P
		Gloeocapsa minima	(Keissl.) Hollerb.	P	
		Gloeocapsa minuta	(Kütz.) Hollerb.	P	
		Gomphosphaeria lacustris	Chodat	P	P
		Merismopedia punctata	Meyen	P	
		Merismopedia tenuissima	Lemmerm.	P	
		Microcystis aeruginosa	(Kütz.) Lemmerm.	P	P
		Microcystis pulverea	(Wood)Forti		P
		Microcystis viridis	(A.Braun) Lemmerm.		P
		Microcystis wesenbergii	Komárek		P
		Spirulina maior	Kütz.	P	
		Synechococcus aeruginosus	Nägeli	P	
		Synechococcus maior	Schroeter	P	
	Nosto-cales	Anabaena sp.	(Bory) Bornet & Flahault	P	P
		Lyngbya sp.	C.Agardh ex Gomont		P
		Oscillatoria chlorina	Kütz. ex Gomont		P
		Oscillatoria princeps	(Vaucher) Gomont	P	
		Oscillatoria splendida	Grev. ex Gomont	P	
		Oscillatoria sp	(Vaucher) Gomont		P
		Pseudoanabaena galeata	Böcher	P	
		Pseudanabaena papillaterminata	(Kisselev) Kukk		P
		Rivularia sp.	(C.Agardh) Bornet & Flahault		P
Eugleno-phyceae	Eugle-nales	Entosiphon ovatum	Stokes		P
		Euglena oxyuris	Schmarda		P
		Euglena sp.	Ehrenb.		P
		Heteronema acus	Dujard.		P
		Lepocinclis marssonii	Lemmerm.		P
		Lepocinclis steinii	Lemmerm.		P
		Peranema sp.	Dujard.		P
		Phacus aenigmaticus	Drezep.		P
		Phacus agilis	Skuja		P
		Phacus horridus	Pochm.		P
		Phacus skujae	Skvortsov		P
		Phacus sp.	Dujard.	P	
		Strombomonas verrucosa var. zmiewika	(Swir.) Deflandre		P
		Trachelomonas acanthostoma	Stokes		P
		Trachelomonas curta	Skv.		P
		Trachelomonas hispida	(Perty) Stein		P
		Trachelomonas hispida f. minor	V. Conforti		P
		Trachelomonas intermedia	Dangeard		P
		Trachelomonas klebsii	Deflandre		P
		Trachelomonas nexilis	Palmer		P
		Trachelomonas oblonga	Lemmerm.		P
		Trachelomonas oblonga var. T truncata	Lemmerm.		P
		Trachelomonas pusilla	Playfair		P
		Trachelomonas sp.	Ehrenb.	P	
		Trachelomonas volvocina	(Ehrenb.) Ehrenb.		P
		Trachelomonas volvocinopsis	Svirenko		P
		Trachelomonas woycickii var. pusilla	(Drezepolski) Popova		P
Chryso-phyceae		Chrysococcus minutus	(F.E.Fritsch) Nygaard		P
		Dinobryon acuminatum	Ruttner		P
		Dinobryon bavaricum	O.E.Imhof		P
		Dinobryon divergens	O.E.Imhof	P	P
		Dinobryon sertularia	Ehrenb.		P
		Mallomonas sp.	Perty	P	
		Pseudokephyrion sp.	Pascher		P
Chloro-phyceae	Volvo-cales	Chlamydomonas sp.	Ehrenb.		P
		Dysmorphococcus variabilis	Takeda		P
		Eudorina elegans	Ehrenb.	P	
		Pandorina morum	(O.Müller) Bory de Saint-Vincent	P	
	Chloro-coccales	Ankistrodesmus spiralis	(W.B.Turner) Lemmerm.	P	P
		Ankistrodesmus sp.	Corda		P
		Botryococcus braunii	Kütz.	P	P
		Coelastrum astroideum	De Not.	P	P
		Coelastrum astroideum var. rugosum	Sodern.		P
		Coelastrum indicum	W.B.Turner		P
		Coelastrum microporum	Nägeli		P
		Coelastrum pseudomicroporum	O.Korshikov		P
		Coelastrum pulchrum	Schmidle		P
		Coelastrum reticulatum	(P.A.Dang.) Senn	P	P
		Crucigenia sp.	C.Morren	P	

Class	Order	Species	Author	Vela	Braças
Chloro-phyceae		Crucigenia tetrapedia	(Kirchn.) W.West & G.S.West		P
		Dictyosphaerium pulchellum	H.C.Wood		P
		Elakatothrix gelifacta	(Chodat) Hindák	P	
		Enallax coelastroides	(Bohlin) Skuja		P
		Fusola viridis	J.Snow		P
		Golenkinia radiata	Chodat		P
		Kirchneriella contorta var. elongata	(G.M.Sm.) Komárek	P	
		Kirchneriella obesa	(W.West) Schmidle	P	P
		Kirchneriella irregularis	(G.M.Sm.) O.Korshikov	P	
		Kirchneriella lunaris	(Kirchn.) Schmidle	P	
		Korshikoviella michailovskoensis	(Elenkin) P.C.Silva	P	
		Lagerheimia subsalsa	Lemmerm.	P	
		Monoraphidium contortum.	(Thur.) Komárk.-Legn.	P	P
		Monoraphidium komarkovae	Nygaard		P
		Monoraphidium minutum	(Nägeli) Komárk.-Legn.	P	
		Nephrocytium agardhianum	Nägeli	P	
		Oocystis lacustris	Chodat	P	P
		Oocystis submarina	Lagerheim	P	P
		Pediastrum angulosum	(Ehrenb.) ex Menegh.	P	
		Pediastrum boryanum	(Turpin) Menegh.	P	P
		Pediastrum duplex var. asperum	(A.Br.) Hansg.	P	
		Pediastrum duplex var. cohaerens	Bohl.	P	P
		Pediastrum duplex var. duplex	Sulek	P	P
		Pediastrum duplex var. rugulosum	Raciborski		P
		Pediastrum simplex var. simplex	(G.M.Sm.) Komárek	P	P
		Pediastrum simplex var. echinulatum	Witte.	P	P
		Pediastrum tetras	(Ehrenb.) Ralfs	P	P
		Planktosphaeria gelatinosa	G.M.Sm.		P
		Quadrigula closterioides	(Bohlin) Printz		P
		Scenedesmus acuminatus	(Lagerh.) Chodat		P
		Scenedesmus acutus var. acutus	Meyen	P	
		Scenedesmus armatus	Chodat	P	P
		Scenedesmus bijugatus	(Turpin) Kuetzing		P
		Scenedesmus cf. spinosus	Chodat		P
		Scenedesmus ecornis	(Ehrenb.) Chodat	P	P
		Scenedesmus gutwinskii var. heterospina	Bodrogk.	P	
		Scenedesmus intermedius	Chodat	P	
		Scenedesmus oahuensis	(Lemmerm.) G.M.Sm.		P
		Scenedesmus obliquus	(Turpin) Kütz.	P	P
		Scenedesmus opoliensis var. monoensis	Chodat	P	
		Scenedesmus protuberans	F.E.Fritsch & M.F.Rich	P	
		Scenedesmus quadricaudata	Turpin	P	P
		Scenedesmus semicristatus	Uherkovich	P	
		Scenedesmus serratus	(Corda) Bohlin	P	
		Scenedesmus smithii	Teiling	P	
		Scenedesmus spinosus	Chodat	P	
		Scenedesmus tenuispina	Chodat	P	
		Schroederia sp.	Lemmerm.	P	
		Selenastrum sp.	Reinsch	P	
		Siderocelis ornata	(Fott) Fott		P
		Sphaerocystis schroeteri	Chodat	P	
		Tetradesmus lunatus	O.Korshikov		P
		Tetraedron caudatum	(Corda) Hansg.	P	P
		Tetraedron minimum	(A.Braun) Hansg.	P	P
		Tetraedron komarekii		P	
		Tetrallantos lagerheimii	Teiling		P
		Tetrastrum komarekii	Hindák	P	
	Oedogo-niales	Bulbochaete sp.	C.Agardh		P
		Oedogonium sp.	Hirn		P
	Zygnema-tales	Closterium aciculare	T.West		P
		Closterium acutum var. variabile	(Lemmerm.) Willi Krieg.	P	P
		Closterium ehrenbergii	Menegh. ex Ralfs	P	P
		Closterium setaceum	Ehrenb. ex Ralfs	P	
		Closterium parvulum	Nägeli		P
		Cosmarium depressum var. planctonicum	Reverdin		P
		Cosmarium humile var. striatum	(Gutdik) Schmidle		P
		Cosmarium phaesolus var. elevatum	Nordstedt		P
		Cosmarium sp.		P	
		Desmidium cilindricum	Greville	P	
		Euastrum oblongum	Ralfs	P	
		Euastrum verrucosum	Ehrenb. ex Ralfs		P
		Mougeotia sp.	C.Agardh	P	P
		Pleurotaenium ehrenbergii	(Bréb.) de Bary		P
		Pleurotaenium trabecula	(Ehrenb.) Nägeli		P
		Staurastrum tetracerum	(Kütz.) Ralfs ex Ralfs	P	P
		Teilingia sp.	Bourr	P	

Table 1. Present algal flora of Lake Vela and Lake Braças (based on Vasconcelos 1990; Barros et al. 1993; Calado 1993; Barros 1994; Figueiredo 1995; Pereira 1997; Fernandes 1999; de Figueiredo et al. 2006). P = present

56

Materials and methods

Field methods

Two cores, a monolith and 16 HON-Kajak (Renberg 1991) samples were analysed palynologically. A 1-m-long, 6-cm-diameter Livingstone corer was used to collect the main cores. A supplementary peat monolith was cut from the southern margin of Lake Braças in a *Salix*-carr to identify potential disturbances in the main core. Wastewater discharge from a nearby hydrological station seemed to have influenced the top sediment of the monolith and hence these upper deposits were not analysed.

Core sediments contained a mixture of sand and organic mud in various proportions. Mineral content increased downward in the cores. The sediment sequences are described according to the Troels-Smith (1955) system.

A 64-mm-diameter HON-Kajak (Renberg 1991) sampler was used to collect topmost samples of Lake Braças and every cm of the upper 16 cm of the sediment was sub-sampled. This sampler is well suited for less compacted lake sediments. Samples collected with the HON-Kajak apparatus were taken to reveal details of the last years of sedimentation in the lake.

Laboratory methods

Subsamples were extracted at ~2-cm intervals from the cores and monolith. The total volume of each HON-Kajak sample was used. Samples for pollen preparation were subjected to standard laboratory treatment including cold HF exposure for 48 hours. Pollen and non-pollen palynomorphs (NPP) were analysed. The minimum sum of regional pollen was 250 whenever possible. In some cases (e.g. sandy samples) this was unachievable due to the low pollen content.

Two bulk sediment samples and one wood sample were dated by radiocarbon (Table 2). A sample from the base of the organic sequence of Lake Vela was run by Beta Analytic Inc., Miami, USA. The other two, one from the base of the Lake Braças monolith, and a wood sample from the mid-lake core, were measured by the Instituto Tecnológico e Nuclear, Lisbon, Portugal. Dates were calibrated using CALIB 5.0 (Stuiver and Reimer 1993) and the INTCAL04 ^{14}C calibration data set (Reimer *et al.* 2004). Dates are presented as conventional (non-calibrated) ^{14}C years BP.

Table 2. Radiocarbon dates from sediments of Lake Vela and Braças, Portugal

Lab. ref.	Site	Depth	Sample type	¹⁴C years BP	Calibrated age 1σ (AD)	2σ (AD)
Beta-205149	L. Vela	76.5-84 cm	Organic material	1630±40 BP	383-441, 484-532	335-540
Sac-2038	Salix-carr, L. Braças	63-66 cm	Organic material	1510±230 BP	310-720	50-1000
Sac-2154	L. Braças		Wood (*Erica erigena*)	180±35 BP	1733-1785	1723-1816

Pollen and microfossil identification and diagrams

Pollen was identified with the keys of Moore *et al.* (1991), Fægri *et al.* (1989), Northwest European Pollen Flora, parts I-VI (Punt 1976; Punt and Clarke 1980, 1981, 1984; Punt *et al.* 1988; Punt and Blackmore 1991), the Ericales key of Mateus (1989) and the Cistaceae key from Queiroz (1999).

For the genus *Pediastrum*, the key of Komárek and Jankovská (2001) was used. The zygospores of Zygnemophyceae species *Spirogyra* (oval shape)*, Mougeotia* (spherical shape) and *Zygnema* (rectangular shape) were designated types, as these genera of filamentous zygnemophyceans can have zygospores of all forms (Medeanic *et al.* 2003). For other non-pollen palynomorphs (NPP) the supplement in Mateus (1992) and various articles by van Geel (van Geel 1976a, 1976b, 1978) and van Geel *et al.* (1983, 1989) were consulted.

Pollen and microfossil data are presented as percentage diagrams. All data were calculated as percentages of total regional po llen (TRP), including pollen of dry-soil taxa, with the exception of *Pinus* and taxa occupying the lake margins. Pollen of *Pinus*, pollen of local taxa (mainly hygrophilous) and NPP are expressed as percentages of TRP. The pollen diagrams were constructed using Tilia and Tilia Graph (Grimm 1991-1993). The diagrams were divided into regional pollen assemblage zones (PAZ) and local pollen zones delimited by visual inspection, based on major changes in the pollen curves of regional and local, hygrophilous taxa. The regional pollen is presented in condensed diagrams.

Results

Regional vegetation development

Three regional pollen assemblage zones (PAZ I-III) were identified (Danielsen 2008). In this work, however, the main focus is on local pollen and its palaeolimnological and local-scale vegetation implications. The regional vegetation development is summarized in Table 3. Regional pollen assemblage zones were used to correlate the three main diagrams in time.

Table 3. Regional pollen assemblage zones

PAZ III	Reforestation of the region. Pollen of *Pinus* were most important but pollen of *Quercus* spp. were also continuously represented. Lake development and regular high representation of indicators of agriculture and grazing were found.
PAZ II	Low representation of forest vegetation and dominance of pollen from heathland species such as *Erica scoparia* reflecting open, treeless vegetation. Pollen from *Olea,* Cerealia and *Zea mays* appeared in this zone indicating regional agricultural activity. Indicators of grazing were frequent.
PAZ I	Characterized by low values of arboreal pollen (< 5%) and high values of heathland and wetland plants. The upland vegetation reflected in this zone is interpreted as treeless open scrub vegetation with *Calluna vulgaris*, *Erica scoparia* and *E. umbellata* in a heathland mosaic, with *Halimium lasianthum* and *Erica erigena* in more humid zones.

Local vegetation development

Local vegetation is here defined as hygrophilous plants growing near or at the coring site. Ecologically, the seral communities are divided into: open water – swamp – marsh – wet heathland – carr; and temporally in the hydroseral sequences: limnic – telmatic – semiterrestric – terrestric (Table 4).

Table 4. Terminology applied to the sediment zones and hydrologic conditions in Lakes Vela and Braças, Portugal, as well as their hydroseral equivalents

Zonation terminology	Lake	Wetland			
	Open water	Swamp	Marsh	Wet heathland / shrub fen	Carr
Hydrological condition	Deeper water	Shallow water	Waterlogged to wet	Moist (non-waterlogged)	Humid
Hydroseral equivalent	Limnic	Telmatic		Semiterrestric	Terrestric

Lake Vela (Fig.2)

Zone V1

The local vegetation was dominated by wet heathland vegetation with *Halimium lasianthum* and *Erica erigena*, indicating moist (non-waterlogged) local soil conditions. Poaceae and Cyperaceae might have grown in this wetland vegetation and proliferated in wet micro-habitats. The algal flora was represented solely by *Debarya,* which probably survived in small, seasonally inundated pools (van Geel *et al.* 1989). Another indicator of temporary pools is *Isoetes*.

Zone V2

This zone is characterized by an increase in pollen of marsh plants. Poaceae percentages rise, followed by increased representation of pollen of Cyperaceae, *Radiola, Mentha* and *Myrica cf. gale. Erica erigena* is present continuously, but fluctuates, indicating its local presence in the surrounding wet heathland. *Hydrocotyle* displays scattered occurrences. Pollen of *Potamogeton,* spores of *Isoetes* and remains of Zygnemataceae (*Debarya, Mougeotia* type and *Zygnema* type) indicate periodic open-water conditions at the site.

Zone V3

During this period wetland conditions rapidly evolved into a lake environment. Semi-aquatic and aquatic plants were common and included *Isoetes, Myriophyllum, Potamogeton* and *Nymphaea.* The alga *Botryococcus* had a peak occurrence and *Pediastrum angulosum var. angulosum, P. boryanum (var. brevicorne, var. boryanum* and *var. longicorne), Scenedesmus* and *Rivularia* appeared. The lake margins may have been occupied by a swamp with *Sparganium, Apium inundatum* and a marsh with grass-sedge vegetation and *Rumex.* Wet heathland with *Erica erigena* may have characterized areas further inland. *Salix* pollen indicates it was present in the wetland forest of the region or had scattered occurrence in the lake's carr vegetation.

Sub-zone V3a

In this sub-zone *Botryococcus* dominated the algal flora. The *Erica erigena* pollen curve fluctuates, displaying peaks when *Botryococcus* decreases, possibly indicating shifts in lake water level. Remains of *Scenedesmus* are rare.

Sub-zone V3b

Scenedesmus dominated the algal flora. The genus *Coelastrum* appears in this sub-zone, suggesting eutrophication.

Zone V4

At the transition to this phase the lake experienced an abrupt and strong environmental change that negatively affected *Botryococcus* populations and favoured *Scenedesmus*. Eutrophic conditions persisted. Grass-sedge vegetation with *Rumex* was common. Aquatic vegetation was present and *Nymphaea* pollen values increase toward the top of the section.

Lake Braças (Fig.3)

Zone B1

Relatively dry local conditions existed in this zone with *Erica erigena*, *Potentilla,* and *Mentha* forming a wet heathland. Pollen of Brassicaceae and *Apium inundatum* indicate wetter spots with swamps. Few algal remains are found, mainly from the family Zygnemataceae (*Debarya, Mougeotia* type*, Zygnema* type).

Zone B2

Open water with a waterlogged, marshy margin existed, with *Cladium mariscus*, Poaceae and Cyperaceae surrounded by wet heathland with *Erica erigena* and *Myrica cf. gale*. Peaks in the representation of aquatic plants like *Potamogeton, Nymphaea* and *Myriophyllum*, suggest open water. Increased lake level is also inferred from the higher diversity and abundance of algae. *Pediastrum angulosum var. angulosum*, *P. integrum*, *P. boryanum var. boryanum*, *P. boryanum var. brevicorne* and *Scenedesmus* all have their first occurrences.

Sub-zone B2a

This sub-zone may reflect the spread of wet conditions into areas surrounding the site. A large peak in *E. erigena* suggests extensive paludification. Increased representation of hygrophilous taxa is observed at this stage, shown by high proportions of Cyperaceae and *Potamogeton* and presence of *Myriophyllum* pollen and remains of *Botryococcus.*

Sub-zone B2b

There was probably continued rise of the water table during this sub-zone, ultimately causing the death of *E. erigena* stands in the central parts of the basin, reflected in the large decline in pollen of this species. This hydrologic shift is also reflected by a peak in *Botryococcus*. Algal diversity and abundance rose, as revealed by the curves of *Scenedesmus, Pediastrum integrum, P. boryanum var. brevicorne* and *P. boryanum var. boryanum.* Pollen of *Nymphaea* shows a peak occurrence and the pollen values of *Potamogeton* decrease rapidly through this sub-zone, possibly indicating calm water conditions. Pollen of *Cladium mariscus* is common.

Zone B3

Lake conditions prevailed since the beginning of this zone. Algal remains are common and *Pediastrum* is represented by many species (*P. integrum, P. boryanum var. brevicorne, longicorne* and *boryanum, P. duplex var. rugulosum* and *P. angulosum var. angulosum). Pediastrum integrum* shows two maxima*. The sudden decline in the pollen values of *Nymphaea, Myriophyllum* and *Potamogeton* at the transition to this zone may reflect a higher water level in the lake and displacement of these taxa to other areas. *Erica erigena* shows low representation and its pollen curve is smooth, suggesting a more distant, regional pollen source.

Zone B4

The lake became eutrophic in this zone, as shown by high values of *Coelastrum* and various species of *Pediastrum*. The division into two sub-zones is based on increasing trophic state toward the sediment surface. *Botryococcus* is continuously present throughout the zone, decreasing only slightly towards the top. *Salix* became an important element in the carr vegetation that surrounded the lake.

Sub-zone B4a

Eutrophication is revealed by a peak in *Typha angustifolia* and by rapid and large increases in the representation of *Coelastrum, Pediastrum boryanum var. cornutum* and *P. duplex var. rugulosum.*

Sub-zone B4b

Trophic state was further enhanced in this sub-zone as shown by the rapid increase of algal remains in general and of *Coelastrum* in particular*. There is also a peak in *Pediastrum boryanum var. cornutum,*

P. duplex var. rugulosum and *Pediastrum simplex* (*Pediastrum simplex var. clathratum,* and *P. simplex var. echinulatum*).

Salix-carr, Lake Braças (Fig.4)

In the *Salix*-carr profile, the curve of the monoseptate fungal spore T-80 IPA (cf. T-18 HDV) is conspicuous and its fluctuations may reflect local dry/wet phases. T-18 HDV, like Cyperaceae, is believed to reflect periods of increased moisture (Mighall *et al.* 2006), but disappears under very wet conditions. In this investigation, the spore is somewhat correlated with the wet heathland species *Erica erigena*.

Zone S-c1

During formation of the sediment in this zone, the local vegetation seems to have been a wet heath with *Erica erigena* and *Halimium lasianthum.* Spores of T-18 HDV peaked.

Zone S-c2

Poaceae pollen dominated in this zone. Pollen of Cyperaceae and *E. erigena* and spores of T-18 HDV decreased. It is not clear if changes in the Poaceae curve imply inundation or a dry phase. The near total lack of pollen of aquatic plants and algal remains favours an inference for dry conditions.

Zone S-c3

In this phase there is another increase in pollen values of Cyperaceae, *E. erigena, Radiola* and spores of T-18 HDV, probably indicating a more humid local environment. The upper part of this zone shows the first occurrences of *Salix* pollen*.*

Zone S-c4

This phase clearly corresponds to the inundation phase found in Lake Braças, coincident with the increase in arboreal pollen values. Remains of various species of *Pediastrum, Scenedesmus* and *Botryococcus* appear along with pollen of aquatic plants *Myriophyllum* and *Nymphaea*.

Top sediment samples (HON-Kajak), Lake Braças (Fig.5)

This diagram was not divided into zones due to the relatively limited curve fluctuations. In general, the results correspond to a single pollen assemblage zone, both in a local and regional sense. As a whole, the sequence correlates to the last regional pollen assemblage zone (PAZ III) encountered in the other palynological sequences. It is difficult, however, to correlate in detail the surface sediment assemblage with the two other diagrams from Lake Braças.

Coelastrum maintained dominance in the algal flora throughout the diagram, showing an increase at around 13-14 cm depth. Relatively high percentages of *Pediastrum boryanum var. cornutum* and *P. duplex var. rugulosum* persist throughout the diagram. Various subspecies of *P. simplex, var. echinulatum* in particular, became more frequent in the algal flora in recent times. Pollen of aquatic species like *Nymphaea, Myriophyllum* and *Potamogeton* were present permanently, as were heterocysts of the cyanobacterium *Rivularia.* In contrast to the core diagrams, *Isoetes* spores were not found in the HON-Kajak samples.

Discussion

Local-scale vegetation patterns and hydroseral implications

Wetland phase

The regional pollen assemblage zones were used to correlate the three main diagrams in time (Table 5). The investigation revealed that the Vela and Braças sites initially were humid depressions or seasonally inundated wetland systems (PAZ I and II), periodically influenced by water-table oscillations. Conditions were possibly similar to those found in humid dune depressions and flats in the region today. Sediment accumulation in both wetland areas started around cal 400 AD (Danielsen 2008). Due to coring difficulties, the initial phase (PAZ I) was not retrieved in the core from Lake Braças, but was recovered and dated from the monolith extracted in its riparian zone (*Salix*-carr). This wetland vegetation lasted for >1000 years, initially dominated by *Halimium lasianthum* in a non-waterlogged, wet heathland environment with *Erica erigena* in areas characterized by stability and more mature stages of succession, as *Halimium lasianthum* is more related to disturbance than *Erica erigena* (Mateus pers. commun.). Decreasing dominance of *Halimium* in general, and of *H. lasianthum* in particular, at the

transition to PAZ II, was possibly caused by changing hydrological conditions or natural ecological succession. In PAZ II, a possible drier phase followed by a humid one is recognized

in the *Salix*-carr sample. Marsh vegetation, integrating species of Poaceae and Cyperaceae, existed in wetter sites, with the hygrophilous *Erica erigena* further inland.

Table 5. Regional and local pollen assemblage zones

Regional zones (Danielsen 2008)	Local zones **Vela**	Local zones **Braças**	Local zones *Salix*-carr	Palaeo-environment	Time BP
PAZ III Reforestation and lake development	**V4** Eutrophic, alkalic lake (*Scenedesmus,P. angulosum*) **V3b** Commencing eutrophication (*Scenedesmus, Botryococcus, P. angulosum*) **V3a** Oligotrophic lake (*Botryococcus*) Lake genesis	**B4b** Eutrophic lake (*Coelastrum, P. boryanum var. cornutum, P. simplex*) **B4a** Commencing eutrophication (*Typha angustifolia, Coelastrum, P. duplex var. rugulosum*) **B3** Oligotrophic lake (*P. integrum*) **B2b** Inundation and death of the *Erica erigena* (*Botryococcus, Nymphaea, Cladium mariscus*) **B2a** Wet heathland (*E. erigena, Potamogeton*)	**S-c 4** Swamp/marsh (*Scenedesmus, Pediastrum spp.*)	**Eutrophic lakes** **Eutrophi-cation** **Oligotrophic lakes** **Lake-level fluctuations?** **Inundation**	 180±35
PAZ II *Erica scoparia* heathland	Sand **V2** Marsh (Poaceae, Cyperaceae) **V1** Wet heathland	**B1** Wet heathland (Poaceae, *Erica erigena*)	Sand **S-c 3** Wet heathland (*Erica erigena*, T-18 HDV) **S-c 2** Drier phase? (Poaceae) **S-c 1** Wet heathland	**Aeolian activity** **Wetland, seasonally inundated pools**	
PAZ I *Halimium, E. scoparia, E. umbellata, Calluna* heathland	**V1** Wet heathland (*Halimium lasianthum, Erica erigena*)		**S-c 1** Wet heathland (*Halimium lasianthum, Erica erigena*, T-18 HDV)	**Wetland, seasonally inundated pools**	 1630±40
	Sand		Sand	**Aeolian activity**	

Lake phase

Palynological results from the two lakes show an unusual, "reverse" hydroseral development from semiterrestrial/telmatic stages to a limnic stage. This must have been caused by external factors. Recent

investigation of east-west boreholes from Lake Braças to the sea, indicates that sand drift was linked to the formation and lateral displacement of these lakes (Castilho *et al.* 2007a). Sand drift from the west caused by deteriorating climatic conditions during the Little Ice Age (LIA), combined with sparse vegetation cover after deforestation and grazing (Danielsen 2008), probably led to infilling of existing lakes and wetlands and impeded drainage of more inland wetland zones. The result was an eastward migration of the lakes, which ultimately reached their present location.

The formation of permanent lakes was thus a relatively recent event (PAZ III) and seems to have been approximately synchronous for both lakes, at about 200-300 years ago (Danielsen 2008). The relative pollen representation of wetland/local and of dry-soil/regional vegetation cover can be expected to have varied when the hydrological conditions changed from a wetland to an open lake. Care must therefore be taken in reconstructing contemporary vegetation from pollen assemblages. Despite the attempt to exclude local pollen from the total regional pollen (TRP) sum, it is possible that pollen of certain families (Ericaceae, Cistaceae, Poaceae) included as regional pollen, may contain local or extra-local taxa.

After lake formation, paleoenvironmental inferences based on the algal flora and the local vegetation succession vary between the two lakes, possibly due to differences in water depth or water quality. Results from a single profile within a lake, however, are difficult to interpret with respect to water-depth fluctuations. Investigations have shown that former lake levels can be constructed more reliably by using transects from the lake edge towards its centre (Digerfeldt 1986, 1988; Digerfeldt *et al.* 1997; Hannon and Gaillard 1997; Bos *et al.* 2006). Nevertheless, an attempt was made to infer variations in water level using the water-depth preferences of certain algae and variations in the relative abundances of pollen from eulittoral and sublittoral macrophytes.

Lake Vela:

Initially (V3), grass-sedge vegetation characterized the lake margin, while the presence of semi-aquatic and aquatic plants (*Isoetes, Myriophyllum alterniflorum, Potamogeton* and *Nymphaea*) suggests open water (Hannon and Gaillard 1997). Lake-level variations are indicated by fluctuations of the *Erica erigena* pollen values being negatively correlated with the values of algae. *Botryococcus* seems to have dominated the algal flora in this initial phase (V3a) while *Scenedesmus* became more abundant in the next sub-zone (V3b), suggesting eutrophication. The most important *Pediastrum* species in Lake Vela was *P. angulosum var. angulosum*, which is reported to be a rather alkaliphilic species, not occurring in peaty and acid waters (Komárek and Jankovská 2001). The next zone (V4) commenced around the time of reforestation (1924), as reflected by the pollen of exotic species (*Acacia, Eucalyptus, Platanus*). In this

zone, *Scenedesmus* reached very high values compared to *Botryococcus*, the latter apparently not well adapted to the eutrophic or polluted lake water. The continuing presence of *Pediastrum angulosum var. angulosum* throughout V3b and V4 suggests prevailing alkaline conditions.

Cyanobacterial blooms are common at present and do not favour Chlorophycean growth (de Figueiredo *et al.* 2006). This may be due to the competitive advantage and/or allelopathy of bloom-forming cyanobacteria. The toxicity of the bloom-forming cyanobacteria *Aphanizomenon flos-aquae* and *Microcystis aeruginosa* currently present in Lake Vela (Abrantes 2007) may thus have caused the observed decline of *Botryococcus* in V4. Other investigations demonstrate a decline of *Botryococcus braunii* caused by eutrophication (Smittenberg *et al.* 2003). The high pH (8.5-9) observed today cannot explain the declining values for this alga as studies have shown that *Botryococcus braunii* grows well under pH conditions between 6 and 9 (Dayananda *et al.* 2006).

Lake Braças:

Vegetation development during lake formation went through a humid heathland phase (B2a) when *Erica erigena* stands covered most of the lake area. *Myrica cf. gale* was abundant. Open water existed at the coring site, as seen by the presence of aquatics like *Potamogeton* and *Myriophyllum*. *Botryococcus* dominated the algal flora. The high abundance of *Botryococcus* and absence of other coccal green algae (e.g. *Pediastrum*) have been found to indicate extreme environments (cool, clean, oligotrophic to dystrophic water) unfavourable for the latter group (Jankovská and Komárek 2000). Colonies of *Botryococcus* have also been reported to indicate very shallow episodes (low groundwater level) as opposed to *Pediastrum*, which requires deeper water (Medeanic *et al.* 2003). The lake margins had marsh vegetation with *Cladium mariscus* and other species of Cyperaceae and Poaceae during this sub-zone. The next zone (B3) was characterized by a rapid decrease in values of both aquatic and wetland plants and a concomitant increase in coenobia of *Pediastrum,* mainly *P. integrum,* which according to Jankovská and Komárek (2000) prefers cool, clear, oligotrophic lakes, but is also reported from peaty basins (Nielsen and Sørensen 1992; Komárek and Jankovská 2001)*.* This could be an indication of increased water level and clearer water during a period of cooler, wetter conditions. The local vegetation of *Nymphaea* and sedges may have shifted to other areas of the lake with more optimal conditions for their growth during this phase.

Eutrophication is evident in the next phase (B4), probably starting at the time of local reforestation in 1924. An increase in the pollen values of *Salix* may reflect the documented planting of *Salix alba* and *S. repens* near the site (Tavares 1989). *Pediastrum boryanum var. cornutum, P. duplex var. rugulosum,*

Coelastrum and *Botryococcus* were the dominant algae, a community described in Jankovská and Komárek (2000) as common in lowland eutrophic lakes. *P. boryanum var. cornutum* is reported to prefer large, naturally eutrophic water bodies not overgrown by aquatic plants (Komárek and Jankovská 2001). *Pediastrum simplex* (*var. echinulatum, var. simplex* and *var. clathratum*) appears in this zone and is characteristic of warmer, mesotrophic to eutrophic lowland lakes (Jankovská and Komárek 2000). In the earliest phase (B4a), the large peak in *Typha angustifolia* type pollen may also reflect eutrophication. The initial peak in *Myriophyllum alterniflorum*, followed by the increase of *T. angustifolia*, may equally indicate a lake-level lowering at the coring site, recorded by a shift from the dominance of sublittoral plants to an increased number of eulittoral ones (Hannon and Gaillard 1997). A further increase in nutrient level is found in the upper sub-zone (B4b). *Coelastrum* reached very high values and dominated the algal flora completely in this sub-zone.

During the drought of 2005, Lake Braças dried out completely and trunks and roots of shrubs were exposed over most of its surface. Laboratory analysis of the wood showed that it was *E. erigena* (Queiroz and van der Burgh 1989). The trunks were probably remains of *E. erigena* stands that drowned when the water level rose. They coincide with the period when *E. erigena* decreases rapidly and aquatic plants like *Nymphaea* appear (B2b). A radiocarbon date on one of these trunks yielded an age of 180 ± 35 BP (cal 1733-1785 AD) for the time of death of the shrub. This gives an approximate time of lake origin at this locality. Presence of these relatively old trunks at the sediment surface must have been caused by sediment extraction in 1995. No trunks were present at the site of the main core, where the top sediment represented zone B4 and not zone B2, as at the trunk sites.

The 16 HON-Kajak samples from Lake Braças gave a fine resolution diagram of the recent vegetation development and revealed a partial overlap with zone B4 from the core diagram, extending the time span studied toward the present. It is, however, not possible to directly correlate the two diagrams sample by sample. The increase of *Coelastrum* at 13-14 cm may correspond to the B4a-B4b transition in the main core. Eutrophic conditions prevailed throughout the diagram, as shown by continuous high abundances of *Coelastrum*, *Pediastrum boryanum var. cornutum*, *P. duplex var. rugulosum* and *P. simplex var. echinulatum*.

The amount of *Pinus* pollen increased towards the surface of the HON-Kajak diagram, probably reflecting growth and development of the planted *Pinus pinaster* forest. Continuous presence of pollen of exotics like *Acacia, Casuarina,* Cupressaceae*, Eucalyptus* and *Platanus* throughout implies that the entire diagram originated after the 1924 reforestation.

A common feature of both lakes is that communities of *Isoetes* existed until quite recently. Plants, however, are not found in either lake today, although four species are found in the region (*I. setaceum, I. histrix, I. velatum subsp. velatum* and *I. durieui*). All four prefer temporary pools with oligotrophic to mesotrophic conditions. The relatively constant presence of spores from *Isoetes* in both lakes after lake formation and the total lack of spores in the top sediment samples (the HON-Kajak samples) indicate recent disappearance of the plant. The documented recent eutrophication in both lakes may have caused the disappearance of *Isoetes*. Light attenuation due to increased litter from riparian shrubs appears to be an important factor in reduction of both vegetative and sexual reproduction of this genus (Rhazi *et al.* 2004). It is therefore possible that the high turbidity in both lakes today impeded growth of *Isoetes* communities.

Past and present discrepancies between the lakes

Present situation

Despite the apparent similarities in the natural settings and formation of the two lakes, clear differences exist. At present, water quality in the Quiaios lakes is dissimilar, with pH, nitrate, nitrite, ammonia and conductivity higher in Lake Vela (Gonçalves *et al.* 1996; Pereira 1997; Fernandes 1999), and values for silicates higher in Lake Braças (Pereira 1997). Normally little nitrate is leached from forest and heath areas, but nitrate-containing water may move easily to areas downstream from arable land (Appelo and Postma 2005). High values of nitrate in Lake Vela indicate that neighbouring agricultural land contains high levels of this nutrient, unlike the situation at Lake Braças. pH also differs, with values <8 for Lake Braças and values >9 for Lake Vela. Both lakes are eutrophic, but only Lake Vela has cyanobacteria blooms and consequent fish deaths. Furthermore, macrophyte vegetation in the two lakes differs. Eulittoral vegetation in Lake Vela is currently dominated by the association *Cladietum marisci* while in Lake Braças the association *Typho angustifoliae-Phragmitetum australis* is more common (Martins 1999). Differences also exist in the present phytoplankton communities (Table 1).

Past development

Certain dissimilarities seem to have persisted since lake formation 2-3 centuries ago. Although lake formation in both basins was relatively synchronous in response to the same background geo-

hydrological and climatic forcings (Danielsen 2008), differences in phytoplankton and plant development remain evident.

In Lake Vela the phytoplankton development went from *Botryococcus* dominance in a shallow, oligotrophic habitat, to a deeper and more eutrophic and alkaline environment dominated by *Scenedesmus* and *Pediastrum angulosum var. angulosum*, and ended with a polluted, cyanobacteria-dominated assemblage with blooms of *Aphanizomenon flos-aquae* and *Microcystis aeruginosa*. The development in Lake Braças since the *Erica erigena* wet heathland phase similarly commenced with a phase of *Botryococcus* dominance, but in contrast to Lake Vela, this was followed by a deeper, oligotrophic phase dominated by *Pediastrum integrum*. In the next phase, *P. duplex var. rugulosum* and *Coelastrum* were the most important algae, suggesting incipient eutrophication, ultimately accompanied by *P. simplex* and *P. boryanum var. cornutum*, indicating a naturally eutrophic water body.

Possible causes of the observed differences

Water quality of a lake depends on the interactions between the water and air, soils, rocks and living organisms in the basin. Throughout its hydrologic cycle, water gains or loses elements because of these interactions. If flow is slow, interactions can be intensified. It was not possible in this investigation to state definitively why the lakes are different or when these differences arose. It seems probable, however, that nutrient inputs from nearby agriculture played a role in the eutrophication process because alterations in the phytoplankton community coincided with an increase in pollen from agricultural plants. Both lakes probably had agriculture nearby, but differences in agricultural practices may have caused the observed discrepancies. The time of reforestation (1924) coincides in Lake Vela with a sharp reduction in *Botryococcus*, suggesting a connection between the two, but nothing was found in the literature relating to measures implemented in the lakes themselves. The decline in *Botryococcus* was more likely a result of the establishment of agricultural fields on the eastern side of Lake Vela, and subsequent eutrophication, contemporary with and facilitated by the stabilization of the sand dunes through reforestation.

The observed discrepancies may also be a consequence of differences in water sources or the speed of groundwater flow. Because this sandy region is characterized by several aquifer layers (Castilho *et al.* 2007b), water sources for the two lakes may be different. Moreover, the aquifer layers are enclosed by more or less impermeable units within the sediment profile. The depth of the impermeable layers differs between lakes, being about 5 m in Lake Vela and 15 m in Lake Braças (Keller 1962, 1967). This

could lead to more rapid groundwater flow in Lake Braças and more stagnant water in Lake Vela, which may explain the differences in water quality and the development of eulittoral vegetation and phytoplankton.

Recent mapping of water fluxes in the region yielded results that may help us understand the differences between the two lakes (Castilho, 2008). In Lake Vela, water flux is E-W, while in Braças it is SSW-NNE. Furthermore, the hydraulic gradient is much higher near Lake Braças. These observations imply that water entering Lake Vela flows through the agricultural fields, while water input to Lake Braças comes from the forested area. In summer, the agricultural fields are fertilized and intensively irrigated. In winter, water flows through the fields where nutrients are dissolved and washed into Lake Vela. Because the gradient is low, water flow is slow and the time of contact between water and soil is long, resulting in a high degree of leaching. The main water flux to Lake Braças is from the pine forest in the south, with nutrient-poor, relatively acid soil. The gradient is higher, resulting in faster water flow and a shorter residence time for water in this lake.

Conclusions

Formation of Lakes Vela and Braças occurred relatively recently. Landward drift of dunes 2-3 centuries ago influenced the drainage patterns of wetlands and formed the lakes at their present locations (Danielsen 2008). Analyses of phytoplankton remains and spores supplemented identification of local pollen, and proved valuable in reconstruction of the palaeo-environment in and around the two lakes. The investigation shows that biotic and abiotic conditions in the two lakes differed since they formed. Lake Vela has been more alkaline and has displayed higher trophic status than Lake Braças. The dissimilarities were probably caused by differences in the velocity and direction of water flow to the two lakes, associated with different land uses.

Fig.2 Diagram; Lake Vela
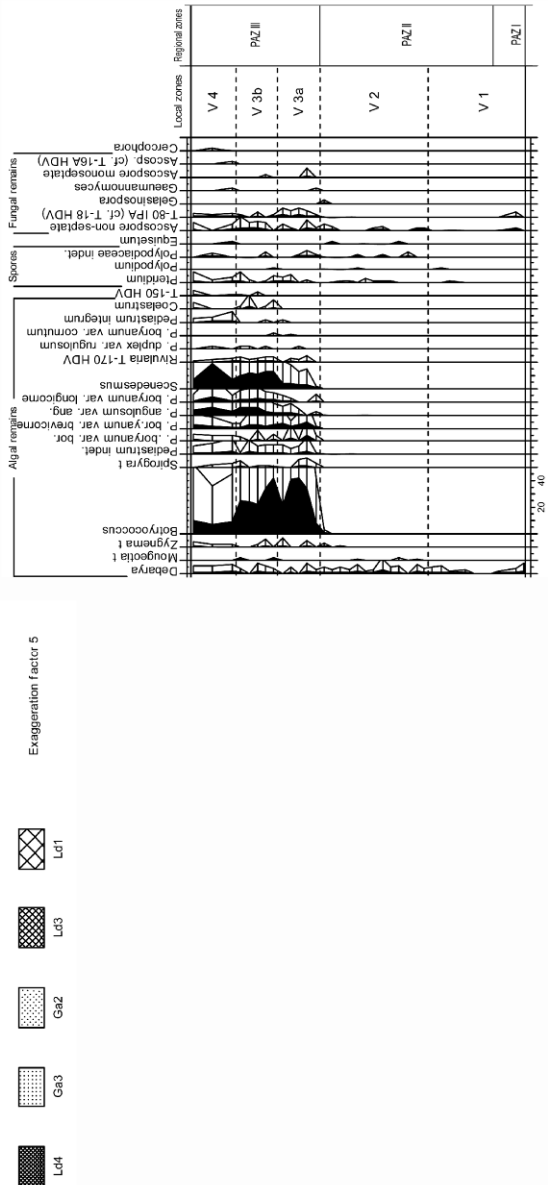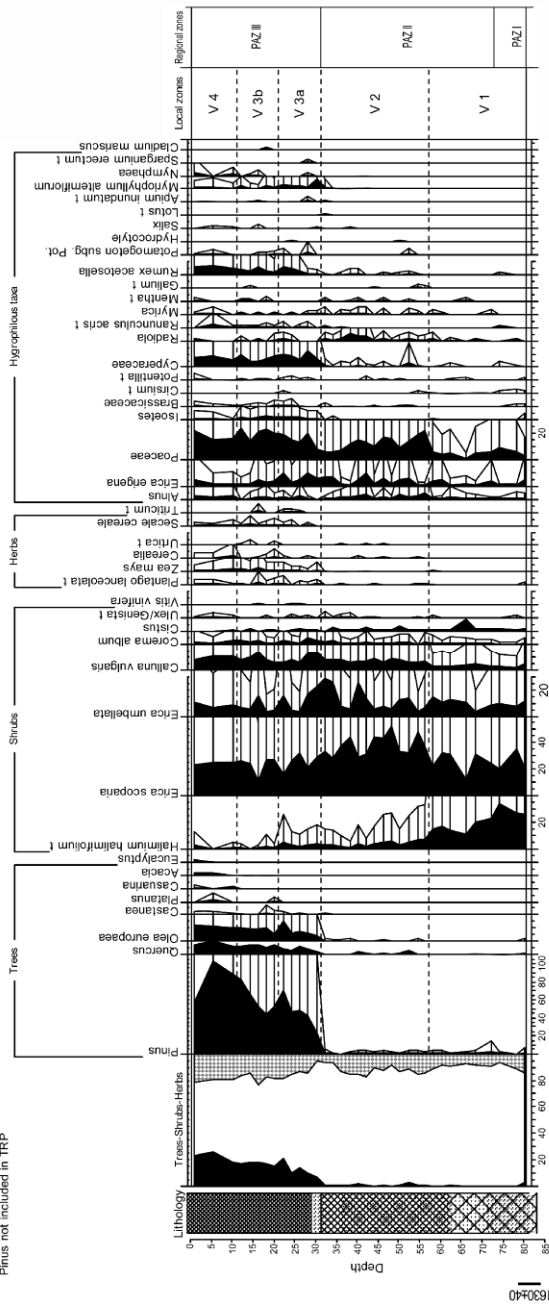
Fig.3 Diagram; Lake Braças
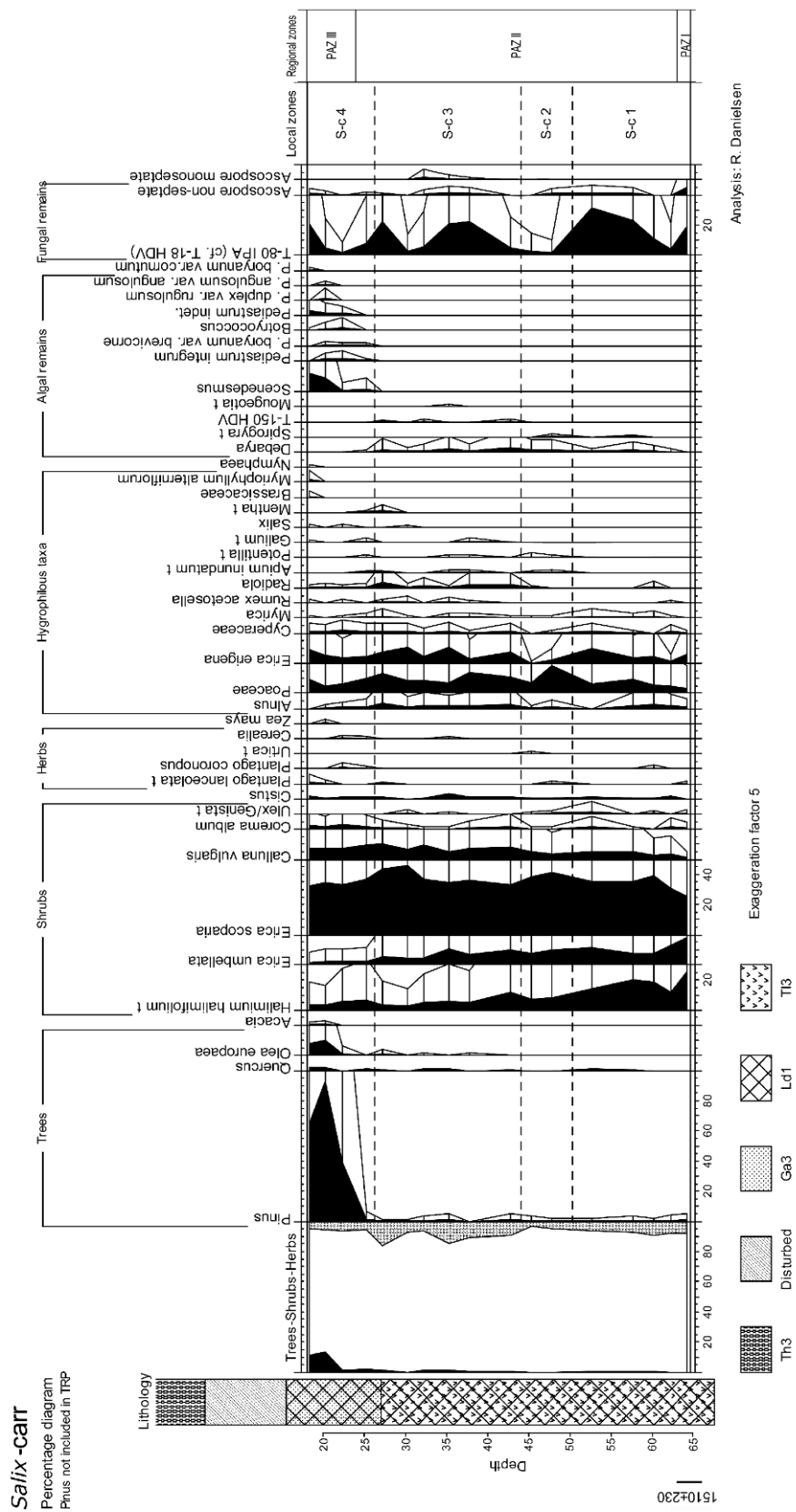
Fig.4 Diagram; *Salix*-carr, Lake Braças

74
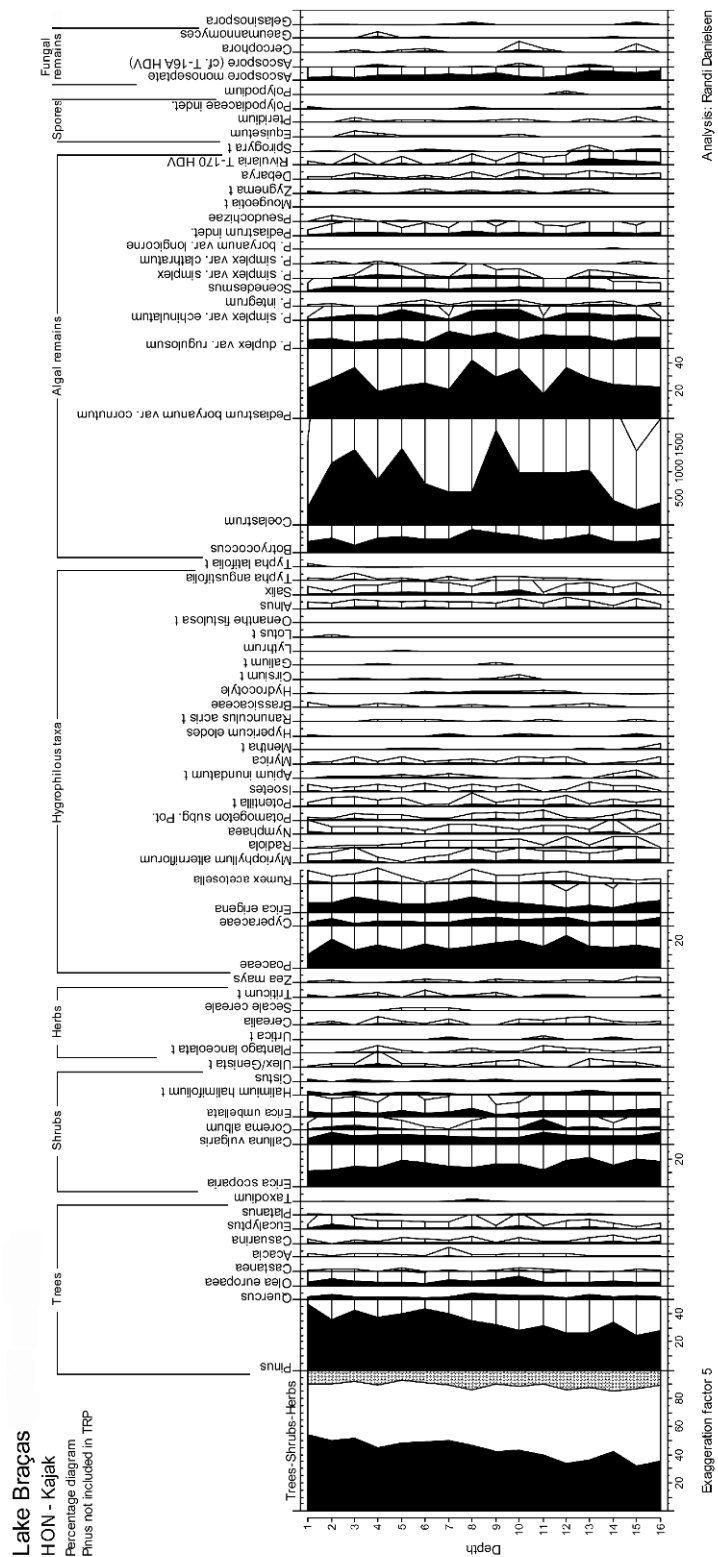
Fig.5 Diagram; Top-sediment samples, Lake Braças

Acknowledgments

References

Abrantes N (2007) Análise de Risco Ecológico na Lagoa da Vela. PhD thesis, Aveiro University, Portugal

Abrantes N, Pereira R, Gonçalves F (2006a) First step for an ecological risk assessment to evaluate the impact of diffuse pollution in Lake Vela (Portugal). Environ Monit Assess 117: 411-431

Abrantes N, Antunes SC, Pereira MJ, Gonçalves F (2006b) Seasonal succession of cladocerans and phytoplankton and their interactions in a shallow eutrophic lake (Lake Vela, Portugal). Acta Oecol 29: 54-64

Antunes SC, Abrantes N, Gonçalves F (2003) Seasonal variation of the abiotic parameters and the cladoceran assemblage of Lake Vela. Ann Limnol 39: 255-264

Appelo CAJ, Postma D (2005) Geochemistry, groundwater and pollution. AA Balkema publishers, Leiden, The Netherlands

Barros P (1994) Implicações ecotoxicológicas de cianobactérias em cladóceras. MSc thesis, Coimbra University, Portugal

Barros P, Silveira S, Ribeiro R, Gonçalves F, Soares AMVM (1993) Estrutura populacional fitoplanctónica nas lagoas das Braças, Vela e Mira (Região Centro-Litoral) Resultados preliminares. Boletim UCA. University of Algarve, UCTRA, 1: 1-8

Bigeard E (1933) Les *Pediastrum* d`Europe. Étude biologique et systématique. Trav Lab Bot Univ Cath Angers 5: 1-192

Bos JAA, Bohncke SJP, Janssen CR (2006) Lake-level fluctuations and small-scale vegetation patterns during the late glacial in The Netherlands. J Paleolimnol 35: 211-238

Calado AJBFM (1993) Algas da lagoa das Braças (Quiaios, Figueira da Foz) ao longo da transição primavera-verão de 1989. (Diatomáceas excluídas). Boletim UCA, University of Algarve, UCTRA 1: 9-23

Castilho AM (2008) Lagoas de Quiaios. Contribuição para o seu conhecimento geológico e hidrogeológico. PhD Thesis. Coimbra University, Portugal

Castilho AM, Danielsen R, Dinis P (2007a) Palaeoenvironmental development of the Quiaios – Tocha dunes based on geological and palynological investigations. Proceedings XXXV IAH Congress-Groundwater and Ecosystems, International Association of Hydrogeologists, Lisbon, Portugal 471: pp. 1-8

Castilho AM, Marques da Silva M, Soares AF, Figueiredo FPO, Senos Matias M, Dinis P (2007b) Preliminary interpretation of geological and hydrogeological data obtained in Quiaios Lagoons. Proceedings XXXV IAH Congress-Groundwater and Ecosystems, International Association of Hydrogeologists, Lisbon, Portugal. 295: 1-7

Danielsen R (2008) Palaeoecological development of the Quiaios–Mira dunes, northern-central littoral Portugal. Rev Palaeobot Palynol 152: 74-99

Dayananda C, Sarada R, Shamala TR, Ravishankar GA (2006) Influence of Nitrogen Sources on Growth, Hydrocarbon and Fatty Acid Production by *Botryococcus braunii.* Asian Journal of Plant Sciences 5: 799-804

Digerfeldt G (1986) Studies on past lake-level fluctuations. In: Berglund, B.E. (ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley & Sons, Ltd. Chichester

Digerfeldt G (1988) Reconstruction and regional correlation of Holocene lake-level fluctuations in Lake Bysjön, south Sweden. Boreas (Oslo) 17: 165-182

Digerfeldt G, de Beaulieu J-L, Guiot J, Mouthon J (1997) Reconstruction and paleoclimatic interpretation of Holocene lake-level changes in Lac de Saint-Léger, Haute-Provence, southeast France. Palaeogeogr Palaeoclimatol Palaeoecol 136: 231-258

de Figueiredo DR, Reboleira ASSP, Antunes SC, Abrantes N, Azeitiero U, Gonçalves F, Pereira MJ (2006) The effect of environmental parameters and cyanobacterial blooms on phytoplankton dynamics of a Portuguese temperate lake. Hydrobiologia 568: 145-157

Fernandes MJS (1999) Modelação e simulação nas Lagoas de Quiaios. PhD thesis, University of Algarve, Portugal

Ferreira AJL (1997) Ictiologia da Lagoa da Vela – Quiaios (Figueira da Foz). M.Sc. thesis. University of Coimbra, Portugal

Figueiredo DALSC (1995) Estudo da dinâmica de um "bloom" de cianofíceas na Lagoa da Vela. Licenciatura thesis. University of Algarve, Portugal

Fægri K, Kaland PE, Krzywinski K (1989) Textbook of Pollen Analysis, 4th edition. John Wiley and Sons, Chichester

Grimm E C (1991-1993**)** *TILIA* and *TILIA GRAPH*. Springfield IL, Illinios State Museum.

Gonçalves F, Ribeiro R, VasconcelosV, Soares AMVM (1996) Anthropogenic influences on seasonal changes of nutrients, physical and chemical factors in three coastal freshwater shallow lakes (Portugal). Limnetica 12, 2: 47-52

Hannon GE, Gaillard M-J (1997) The plant microfossil record of past lake-level changes. J Paleolimnol 18: 15-28

Heide K (1984) Holocene pollen stratigraphy from a lake and a small pond in north-central Wisconsin, U.S.A. Palynology 8: 3-20

Jankovská V, Komárek J (2000) Indicative Value of Pediastrum and other Coccal Green Algae in Palaeoecology. Folia Geobot 35: 59–82

Janssen CR (1973) Local and regional pollen deposition. In: Birks HJB and West RG (Eds.) Quaternary Plant Ecology. Proceedings of the Fourteenth Symposium of the British Ecological Society. Blackwell, New York pp. 31–42

Keller J (1962) Relatório sobre furos de pesquisa e captação de água para abastecimento da Figueira da Foz. Ed. Author, Cascais, Portugal

Keller J (1967) Relatório sobre o trabalho de execução dos furos JK24 a JK28 de abastecimento de água à Figueira da Foz. Ed. Author, Cascais, Portugal

Komárek J, Jankovská V (2001) Review of the Green Algal Genus *Pediastrum*, Implication for Pollen-Analytical Research. J Cremer, Berlin

Martins MJS (1999) Estudo fitossociológico e cartográfico da paisagem vegetal natural e semi-natural do litoral centro de Portugal entre a Praia de Mira e a Figueira da Foz. MSc Thesis, University of Coimbra, Portugal

Mateus JE (1989) Pollen morphology of Portuguese Ericales. Rev Biol (Lisb) 14: 135-208

Mateus JE (1992) Holocene and present-day ecosystems of the Carvalhal region, Southwest Portugal. PhD Thesis, Utrecht University, Netherlands

Medeanic S, Jankovská V, Dillenburg SR (2003) The implication of green algae (Chlorophyta) for palaeoecological reconstruction of the Holocene lagoon system in the Tramandaí Lagoon region, Rio Grande do Sul, Brazil. Acta Palaeobot 43(1), 113-123

Mighall TM, Martínez Cortizas A, Biester H, Turner SE (2006) Proxy climate and vegetation changes during the last five millennia in NW Iberia: Pollen and non-pollen palynomorph data from two ombrotrophic peat bogs in the North Western Iberian Peninsula. Rev Palaeobot Palynol 141: 203–223

Moore PD, Webb JA, Collinson ME (1991) Pollen Analysis, 2nd edition. Blackwell Scientific Publications, London

Nielsen H, Sørensen I (1992) Taxonomy and stratigraphy of lateglacial Pediastrum taxa from Lysmosen, Denmark – a preliminary study. Rev Palaeobot Palynol 74: 55–75

Parra Barrientos OO (1979) Revision der Gattung *Pediastrum* Meyen (Chlorophyta). Bibl Phycol 48

Pereira R (1997) Plano de Ordenamento e Gestão das Lagoas das Braças e da Vela (Centro-Litoral), M.Sc. thesis, University of Coimbra, Portugal

Prentice IC (1985) Pollen representation, source area, and basin size: towards a unified theory of pollen analysis. Quat Res (Orlando) 23: 76– 86

Punt W (Ed.) (1976) Northwest European Pollen Flora, I. Elsevier, Amsterdam

Punt W, Clarke GCS (Eds.) (1980) Northwest European Pollen Flora II, Elsevier, Amsterdam

Punt W, Clarke GSC (Eds.) (1981) Northwest European Pollen Flora III, Elsevier, Amsterdam

Punt W, Clarke GSC (Eds.), 1984. Northwest European Pollen Flora, IV. Elsevier, Amsterdam

Punt W, Blackmore S, Clarke GCS (Eds.) (1988) Northwest European Pollen Flora, V. Elsevier, Amsterdam

Punt W, Blackmore S (Eds.) (1991) Northwest European Pollen Flora, VI. Elsevier, Amsterdam

Queiroz PF (1999) Ecologia Histórica da Paisagem do Noroeste Alentejano. PhD Thesis, University of Lisbon, Portugal

Queiroz PF, van der Burgh J (1989) Wood Anatomy of Iberian Ericales. Rev Biol (Lisb) 14: 95-134

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Bertrand CJH, Blackwell PG, Buck CE, Burr GS, Cutler KB, Damon PE, Edwards RL, Fairbanks RG, Friedrich M, Guilderson TP, Hogg AG, Hughen KA, Kromer B, McCormac G, Manning S, Ramsey CB, Reimer RW, Remmele S, Southon JR, Stuiver M, Tálamo S, Taylor FW, van der Plicht J, Weyhenmeyer CE (2004) IntCal04 Terrestrial Radiocarbon Age Calibration, 0–26 cal kyr BP. Radiocarbon 46 (3): 1029-1058

Renberg I (1991) The HON-Kajak sediment corer. J Paleolimnol 6: 167 – 170

Rhazi M, Grillas P, Charpentier A, Médail F (2004) Experimental management of Mediterranean temporary pools for conservation of the rare quillwort *Isoetes setacea*. Biol Conserv 118: 675-684

Sarmaja-Korjonen K, Seppänen A, Bennike O (2006) *Pediastrum* algae from the classic late glacial Bølling Sø site, Denmark: Response of aquatic biota to climate change. Rev Palaeobot Palynol 138: 95-107

Smittenberg RH, Baas M, Schouten S, Sinninghe Damsté JS (2003) The demise of the alga *Botryococcus braunii* from a Norwegian fjord was due to early eutrophication. The Holocene 15(1): 135-142

Stuiver M, Reimer PJ (1993) A computer program for radiocarbon age calibration. Radiocarbon 35: 215–230

Sugita S (1994) Pollen representation of vegetation in Quaternary sediments: theory and method in patchy vegetation. J Ecol 82 (4): 881–897

Tavares M (1989) O pinhal bravo das dunas do litoral entre Douro e Mondego. Produção lenhosa e crescimento do sistema radical. Dissertação original. Ex-INIA-EFN, Lisboa

Tauber H (1965) Differential pollen dispersion and the interpretation of pollen diagrams. Dan Geol Unders, II. Række 89: 1–69

Troels-Smith J (1955) Karakterisering av løse jordarter. Dan Geol Unders 4, 3 (10)

Vasconcelos VM (1990) Ecotoxicologia de cianobactérias: impacte dos seus "blooms" nas comunidades animais e a sua aplicação na gestão da qualidade da água. Provas de aptidão científica e pedagógica. Faculty of Science, University of Porto, Portugal

Vasconcelos VM, Campos T, Amorim A, Soares AMVM (1993) Toxicidade de estirpes de cianobactérias isoladas a partir das lagoas das Braças, Vela e Mira. Boletim UCA, University of Algarve, UCTRA. 1: 193-201

van Geel B (1976a) A palaeoecological study of Holocene peat bog sections, based on the analysis of pollen, spores and macro and microscopic remains of fungi, algae cormophytes and animals. Academisch proefschrift, Hugo de Vries laboratorium, Amsterdam University, Netherlands

van Geel B (1976b) Fossil spores of Zygnemataceae in ditches of a prehistoric settlement in Hoogkarspel (The Netherlands). Rev Palaeobot Palynol 22: 337-344

van Geel B (1978) A palaeoecological study of Holocene peat bog sections in Germany and the Netherlands. Rev Palaeobot Palynol 25: 1–120

van Geel B, Hallewas DP, Pals JP (1983) A Late Holocene deposit under the Westfriese Zeedijk near Enkhuizen (Prov. of N-Holland, The Netherlands): palaeoecological and archaeological aspects. Rev Palaeobot Palynol 38: 269-335

van Geel B, Coope GR, van der Hammen T (1989) Palaeoecology and stratigraphy of the Lateglacial type section at Usselo (The Netherlands). Rev Palaeobot Palynol 60: 25-129
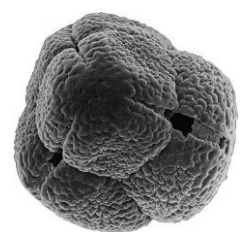
CHAPTER 4

PAPER III

Holocene interplay between a dune field and coastal lakes in the Quiaios – Tocha region, central littoral Portugal.

Randi Danielsen[1], Ana M.Castilho[2], Pedro A. Dinis[3], António C. Almeida [4]

[1]IGESPAR (Laboratório de Paleoecologia e Arqueobotânica)/ University of Minho, Braga,

[2]Centre of Geosciences, Earth Sciences Department, University of Coimbra, [3]Department of Earth Sciences/Institute of Marine Sciences (IMAR-CIC), University of Coimbra, [4]Institute of Geographical studies, Faculty of Letters, University of Coimbra, Portugal

Abstract

Coastal dune fields and dune-body associated lakes were studied through sedimentological and palynological analyses. Deposits in the form of lake sediments and palaeo-soil horizons of more or less organic character, gave new information about phases of aeolian activity and dune building, earlier coast line and sea level, vegetation history and cultural impact during the last 4-5000 years. The region was initially forested with pine and oak. Some time between 4000 and 1600 yr BP the forest was replaced by a semi-natural heathland probably maintained by grazing and cutting. At a later stage the heathland vegetation was partly destroyed allowing dune migration and finally desertification to occur. This process was probably a consequence of a combination of deteriorating climate during LIA and over-grazing. To counteract the degradation, reforestation efforts were initiated in the near vicinity of the investigated region c 300 years ago and locally along the coastal margin as late as 1924 to1940.

Formation of the row of lakes bordering the dune field today was a relatively recent event (c 300 yr BP). An apparently close relation between lake formation and aeolian activity and accumulation of sand dunes at the western banks of the lakes, was found.

Three generations of dunes were identified observed as truncated dunes, parabolic dunes and transverse/oblique dunes and the last generation caused relocation of the lakes.

At the westernmost part of the littoral fringe lagoonal deposits were encountered. These deposits were formed after the Flandrian transgression c 4000 yr BP when sea level rise decelerated and reached a level similar to the present one. The establishment of the lagoon(s) probably resulted from formation of a protective sand barrier along the coast line.

Introduction

An extensive coastal dune field occupies the zone between Quiaios and Tocha in central littoral Portugal. The development of this dune field was episodic and influenced by conditions related to climate, sea level and sediment input, vegetation cover and human activity. Stratigraphy of the dunes records environmental and cultural changes during their evolution. Several sandy aeolian layers from periods of sand drift are interleaved with lake deposits and palaeosols formed under more stable conditions.

Other investigation from the region has indicated that aeolian activity in western Iberia seems to be out of phase with the rest of Europe (Clarke and Rendell, 2006). Sand invasion and dune accretion is linked with storminess and with the North Atlantic Oscillation (NAO). North of Iberia positive NAO winters cause northward displacement of westerly storms and bring wet and windy weather. On the contrary, rainy westerlies over the Iberian Peninsula and the western Mediterranean seem to be caused by negative NAO (Luterbacher *et al.*, 2002; Clarke and Rendell, 2006). Low aeolian activity is hence to be expected in littoral Portugal during periods of high activity in the rest of western Europe.

Episodic sand invasions have caused recurring problems for human activity and agriculture along the Portuguese littoral and stabilization measures to reduce this threat initiated already in the 13th Century when a royal decree ordered the planting of forests of maritime pine (*Pinus pinaster*). The remedy was effective in stabilizing the sand dunes and littoral Portugal nowadays is characterized by planted pine forest. Little is, however, known about past natural vegetation cover and dynamics of vegetation history in the region.

85

The main objective of this investigation is to disclose the evolution of the dune related Holocene deposits of the coastal Quiaios area. Lithofacies, based on the texture, composition and geometry of the sediment bodies is conjugated with fossil content (pollen and molluscs). The palaeoenvironmental conditions and evolution are inferred from these sets of data.

Study site

The area is located north of Serra da Boa Viagem (Fig.1), a coastal mountain with Jurassic carbonate and siliciclastic rocks. At the contact between this relief and the lowland costal margin, there is a north verging thrust (Barbosa *et al.*, 1988).
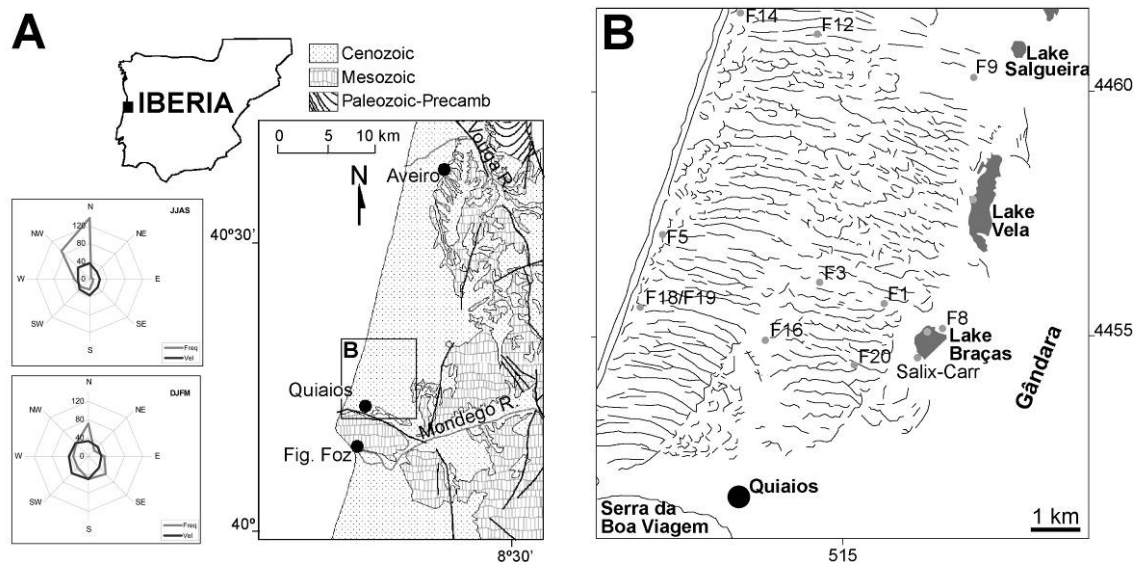
Fig.1 Map of the investigated region. Wind roses of S. Jacinto for the four warmest (JJAS) and coldest (DJFM) months Freq - n° of records. Vel -velocity (km/h, 2x exaggerated) (source: Meteorological Institute, Portugal)

The coastal margin to the north is covered by late Pleistocene and Holocene aeolian deposits. The Holocene dunes extend up to 7 km inland from the coastline. At the border between these dunes and an older and more abraded dune field called the Gândara dunes, a row of shallow lakes is found. The younger dunes` morphology is still preserved in many cases. The foredune is a fairly continuous ridge whose growth is reportedly related to human intervention, through the

setting up and rising of a wooden fence (Almeida, 1995). Inland, behind the foredune, the most common dune forms are elongated dunes classified both as oblique (Almeida, 1995) and transverse (Noivo, 1996; Clarke and Rendell, 2006) dunes. The best defined forms are aligned almost E-W, can reach lengths of more than 1 km and are spaced approximately 200 m apart. These dunes were still active at the beginning of the 20th Century and they were stabilized by reforestation between 1924 and 1940 (Pestana, 1926; Rei, 1940). At present they sustain a pine forest of *Pinus pinaster.* The present day parallel fluvial drainage pattern outlines and is influenced by the orientation of these dune forms. Throughout the dune field several seasonally inundated pools can be found in lower areas between the dune ridges. Furthermore, sectors with parabolic dunes are found scattered in the region (Almeida, 1995; Noivo, 1996; Clarke and Rendall, 2006)*.* The parabolic dunes are more frequent in the proximity of small lakes but are also found immediately north of the village of Quiaios (Barbosa *et al.*, 1988; Almeida, 1996). These dunes show indications of belonging to an earlier dune generation than the oblique/transverse dunes, not only on account of their dune form but moreover due to their further developed and acid soils. This permitted the installation of heathland (*Calluna vulgaris, Erica spp.*) that is practically inexistent in the more recent dunes. In these recent dunes vegetation typical of sand dunes exist with *Corema album* and two species of *Halimium (H. halimifolium* and *H. calycinum*) as the principal ones.

The region is dominated by Mediterranean climatic characteristics envisaged by monthly variations of both precipitation and temperature comprising three hot and dry months (June, July and August). Annual precipitation is around 1000 mm, however, with considerable irregularity from year to year. Relative air humidity is always higher than 74%. The maritime influence causes mild winters and cool summers with mean annual temperature maxima of 19.5°C and minima of 9.2°C. North to northwest winds are most frequent especially in the hottest months (Fig.1). In the colder months winds from the south-western quadrant (SW, S and W) are the strongest and most frequent.

Methods

Fieldwork

Samples were collected from boreholes drilled with the cable tool percussion method (Driscoll, 1986) along selected transects approximately perpendicular to the coastline (Fig. 1). The boreholes were located in interdune sectors. With this method sediments were continuously assessed during the drilling process and it was possible to drill until reaching the bedrock. Selected samples were collected for sedimentological and palynological analysis. Additionally, cores from two lakes (Lake Vela and Lake Braças) were extracted with a 1m long Livingstone piston corer with 6 cm diameter.

Chronology

Standard ^{14}C dating of bulk organic matter of selected samples was performed by Nasjonallaboratoriet, NTNU (Norway), BETA Analytic Inc. (USA) and Instituto Tecnológico e Nuclear, ITN (Portugal). Dates were calibrated with the CALIB 5.0.1 software package (Stuiver and Reimer, 1993) using the INTCAL04 data set (Reimer *et al.*, 2004). For brackish shells the Mixed marine NoHem (Hughen *et al.,* 2004) was used.

Grain-size

A total of 181 samples of sediments of the boreholes were used in the sedimentological analysis. These sediments are organized in a facies framework based on several textural, compositional and geometrical criteria. The grain-size of these sediments was a fundamental aspect on the facies definitions. The grain-size of particles below 2 mm was determined by laser diffraction using a Coulter LS 230 that is able to determine the size of elements between 0.04 μm and 2000 μm. Sediments with more than 5% of particles bigger than 2 mm were also sieved. The bulk grain-size results obtained by both sieving and laser diffraction, were integrated on a conceptual scale with 1/2Ø intervals based on a logarithmic transformation of the particle diameter (D), in mm (Ø=-log$_2$D) (Wentworth, 1922; Krumbein, 1934).

Palynology

Pollen samples were extracted from the muddy units. Samples from the two lake cores were collected with c 2 cm intervals. This accuracy was not possible for the borehole samples. Due to methodological limitations during drilling of the boreholes, each sample contained large amounts of sediment (20-50 cm) and hence a maximum of 2 pollen samples was retrieved from each layer. The pollen samples were subjected to standard laboratory treatment including HF exposure for 48 hours.

The pollen and microfossil data of the samples are presented in percentage pollen diagrams. The minimum sum of regional pollen was 250 whenever possible. In some cases this was unachievable due to low pollen content (in sandy samples). All data were calculated as percentages of total regional pollen (TRP) including pollen of dry-soil taxa with the exception of *Pinus* and taxa occupying the lake margins. Pollen of *Pinus*, local taxa (mainly hygrophilous) and non-pollen palynomorphs (NPP) are expressed as percentages of TRP. The pollen diagrams were constructed using Tilia and Tilia graph (Grimm, 1991-1993).

Organic facies contained pollen, spores and other microfossils and the assemblages of indicator species suggest seven different palaeoenvironments (Table 1).

Table 1. Pollen assemblages and inferred palaeoenvironments

Palaeoenvironments	Main taxa / families	Others
Forest	*Pinus, Quercus*	*Pteridium*, Polypodiaceae
Heathland/maqui	*Calluna, Erica scoparia, E. arborea,* Cistaceae, *Ulex*	*E. umbellata, E. australis*
Dunes	*Artemisia, Corema, Juniperus*	Caryophyllaceae
Cultural activity	Agriculture: Cerealia, *Secale, Triticum, Castanea, Olea, Juglans*	Pastures: *Urtica, Plantago lanceolata, Cercophora, Gelasinospora*
Others (Taxa and families belonging to more than one environment)	Compositae, Liliaceae	
Wetland	*Erica erigena, Halimium lasianthum, Myrica* cf. *gale, Alnus,* Cyperaceae, Poaceae	*Hypericum elodes, Radiola, Apium inundatum, Isoetes, Mentha, Salix,* Type HDV-18 (fungal spore)
Open water	*Myriophyllum, Potamogeton, Botryococcus, Pediastrum*	*Debarya, Mougeotia t, Rivularia, Spirogyra t, Zygnema t*
Saltmarsh	Chenopodiaceae, *Spiniferites*	*Cymatiosphaera*

Results

Chronology

Nine samples were ^{14}C-dated (Table 2). Four are from lake sediments; two from Lake Vela and two from Lake Braças both pairs from the base of the sediment column and from the level of lake formation. The rest of the datings are from the borehole samples, two are from a brackish lagoon (base and top) and the other three from layers rich in wooden remains.

All dates quoted in this article as yr BP are conventional (non-calibrated) ^{14}C years.

Table 2. [14]C datings

Sample	Code number	Depth (m)	Material	Depositional environment	Dating technique	Conventional radiocarbon age (years BP)	Calibrated age Calib 5.0.1 (1σ ranges)
L. Vela (Base)	Beta - 205149	0.765 - 0.84	Mud	Marsh / wet heathland	AMS	1630±40	383-441 AD [1]
L. Vela (Lake formation)	TUa – 7369A NaOH soluble fraction	0.30	Mud	Lacustrine	AMS	590±35	1312-1359 AD [1]
L. Braças (Lake formation)	Sac- 2154		Wood *Erica erigena*	Lacustrine	Radiometric	180±35	1733-1785 AD [1]
Lake Braças (*Salix*-carr) (Base)	Sac - 2138	0.63 – 0.66	Mud	Marsh	Radiometric	1510±230	310-720 AD [1]
F18, A9 (Top)	TUa - 7366	7.4 – 7.7	Shell	Lagoonal	AMS	4045±35	2192-2046 BC [2]
F18, A12 (Base)	TUa - 7365	8.3 - 9	Shell	Lagoonal	AMS	4145±35	2332-2202 BC [2]
F19	TUa - 7364	14.5	Wood *Fraxinus*	Riparian?	AMS	4375±40	3023-2919 BC [1]
F5, A2	TUa - 7367	4	Wood	Beach	AMS	3215±40	1515-1440 BC [1]
F16, A7	TUa – 7368	9.5	Wood	Terrestric	AMS	5590±45	4455-4368 BC [1]

[1] INTCAL04 (Reimer *et al.*, 2004), [2] Mixed marine NoHem (Hughen, *et al.*, 2004)

90

Sedimentology

The studied sediments have 7 different facies defined by multiple criteria (Table 3). The grain-size distributions and fossil content are the fundamental attributes for the facies definition.

Table 3. Sedimentary facies description

Facies	Lithology	Biological remains	Interpretation
FA	Light colour (10YR8/2 to 10YR8/4), well sorted, fine to medium, unimodal sands	Shell fragments (littoral), wood, plant remains	Aeolian dune
FB	Brown, well sorted, fine to medium sands	Pollen, wood, plant remains	Podzolized aeolian dune
FC	Grey to dark grey (10YR5/1 to 10YR 3/1) fine to medium bi- or polimodal sands; significant proportion of silt-clay fraction	Pollen, wood, charcoal, plant remains	Interdune flat
FD	Light grey, very pale brown or yellow (10YR7/2 to 10YR6/4, or 5Y8/2), well sorted, fine to medium sands; coarse sand or granule particles	Pollen, plant remains, charcoal	Water lain reworked aeolian deposits or aeolian accumulation under extreme wind conditions
FE	Dark grey to very dark greyish brown (10YR4/1 to 10YR3/2) with high organic content sediments; Polymodal, with fine sand and silt-clay populations	Pollen, freshwater algae, plant remains	Lake
FF	Grey to olive grey (5YR6/1 to 5YR4/1 or 10YR 4/1), fine grained sediments with frequent shell fragments; Mixtures of sand and silt-clay populations	Pollen, dinoflagellates, brackish molluscs, wood, plant remains	Lagoon
FG	White to very pale brown (2.5Y8/1 to 10YR8/3), moderately to well-sorted, medium to coarse sands; frequent shell fragments	Infralittoral mollusc (disarticulated and abraded), spores, wood	Foreshore and shoreface

<u>Facies FA-FD</u>

The most frequent facies (FA, FB, FC and FD) are characterized by well or very well sorted sand dominated sediments with limited amounts of gravel, silt and clay and usually unimodal grain-size distributions. The modal size and mean is always in fine to medium sand grain-size classes (0.15-0.5mm). Facies FA consists of light grey (in particular close to the topographic surface) or very pale brown (in lower stratigraphic levels) sands. They are found widespread along the studied coastal margin, constituting the most common sediment. In some locations the entire quaternary record shows this facies. However they are frequently intercalated with facies FB, FC and FD.

Darker, brown or greyish brown, podzolized sands of facies FB are found at depths greater than 2 m. These sediments show just slight grain-size distribution differences from facies FA, such as higher proportion of silt-clay-size fraction, and finer mean. The podzols are usually incipient and these sediments still tend to be friable. Up to two levels of facies FB are observed in the eastern sectors. These sediments may be fairly rich in pollen.

Facies FC is distinguished by the presence of significant proportion of a silt-clay size fraction (up to 6%) and its darker greyish colour. They are relatively thin (a few cm) and frequently associated with podzolized levels (FB).

Facies FD contain higher amounts of coarse sand and gravel-size particles (up to 18.7%, but usually below 2%), sometimes assuming a bimodal or polymodal grain-size distribution. Facies FD occasionally have dark organic nodules with a few centimetres long axis. Facies FD is particularly common at the bottom of the aeolian succession.

Facies FA to FD are primarily related to aeolian deposition. The higher proportion of fine particles in sediments of facies FB and FC is explained by the development of pedogenetic processes in interdune areas or during periods of relatively low aeolian activity, respectively. The coarser-grained character of facies FD and the presence of organic nodules suggest that they are related to water lain reworking of previous aeolian deposits. Alternatively, they may be associated with earlier phases of dune accumulation under extreme wind conditions.

<u>Facies FE</u>

Facies FE are exclusive of the eastern locations in the proximity to present day shallow lakes. It is distinguished by its polymodal character, with modes of very fine to medium sand and silt-size, and the significant proportion of silt-clay grain-size fraction (up to 27.6%). Internally its grain-

size distribution is highly variable. They define beds of diverse thickness (a few centimetres to 1 m). These sediments are very rich in organic material, including pollen and algal remains, which is responsible for their dark colour.

The polymodal grain-size distribution, with relatively high proportion of silt-clay particles in a mixture with a sand fraction and the high organic content, are indicative of palustrine or shallow lacustrine environments located in the dune field. The presence of pollen of aquatic plants and algal remains equally confirm a freshwater lake-swamp environment.

Facies FF

In western locations in a fringe 800 to 1000 m from the present day coastline, there are muddy sand sediments with bivalve and gastropod shells. They define facies FF. The grain-size distribution of these sediments is quite heterogeneous, with silt-clay fraction of the bulk sample varying between 1 and 83%. However, the relation silt/clay is relatively constant (around 8). The fraction coarser than 2 mm is composed mainly of fragments of shell. The grain-size distribution curve is polymodal, including modes of fine to medium sand, medium to coarse silt and fine to very fine silt. The sand population is very similar to facies FA. They constitute sediment beds up to 2 m thick. The pollen and mollusc content is relatively rich, with several elements characteristic of brackish environments (Danielsen *et al.*, 2008).

The mollusc association point to a brackish lagoon environment with sandy mud substrate and algal mats. This association was adapted to low-energy, rather restricted, ecological conditions, but always with significant influx of sea-water. This fact seems to be confirmed by the absence of freshwater or low salinity mollusc species, as well as by the presence of debris of stenotypic echinoids (Danielsen *et al.*, 2008*).

Facies FG

Facies FG is also restricted to the western fringe and is always found below facies FF. It is made of medium to coarse sands of light colours with abundant shell fragments. The silt-clay fraction is limited (<1.3%). The total thickness of these sediments could not be measured because the boreholes never reached the lower sediments, but in places it can be around 9 m. No samples for pollen analysis were collected in these sediments. Just wooden remains were found later determined to *Fraxinus.* The shell fragments are frequently disarticulated and abraded and are typical of marine and brackish environments (Danielsen *et al.,* 2008).

93

The textural features and the mollusc association indicate that these sediments were deposited in coastal, beach to shoreface environment. They record a Holocene evolutionary phase when the coastline was located further inland than at present.

Facies distribution

Three sectors, with different facies and facies sequences, may be recognized along an east-west transect (Fig.2). The western sector extends eastwards from the coastline for about 0.8-1 km inland. The transitional sector extends eastward to around 3 km from the coastline and the eastern sector continues eastwards. As expected, only the western sector shows a marine influenced succession. Here the Holocene sequence comprises, from base to top, beach sediments (facies FG), brackish lagoon sediments (facies FF) and aeolian sands (facies FA). Its eastern limit coincides with the eastern limit of the lagoon and beach facies.

In the transitional sector aeolian dune sands (facies FA) dominate the record. The podzolized aeolian sands and interdune facies are poorly represented in the investigated part of the succession. In some boreholes facies FA is found until a depth of around 10 m.

In the eastern sector there are aeolian dune sands (facies FA), wetland and freshwater lake deposits (facies FE) and it is possible to identify one or more levels of podzol (facies FB) and interdune sediments (facies FC). The most developed podzol level is fairly continuous and may be found all along the eastern sector. Facies FE with abundant and variable species of algae and aquatic plants are found at depths of around 5 m in western part of the eastern sector and between 1-2 m further east in the proximity of the present day lakes. The coarser grained facies FD are found in lower stratigraphic levels where the boreholes reached the pre-Holocene succession.
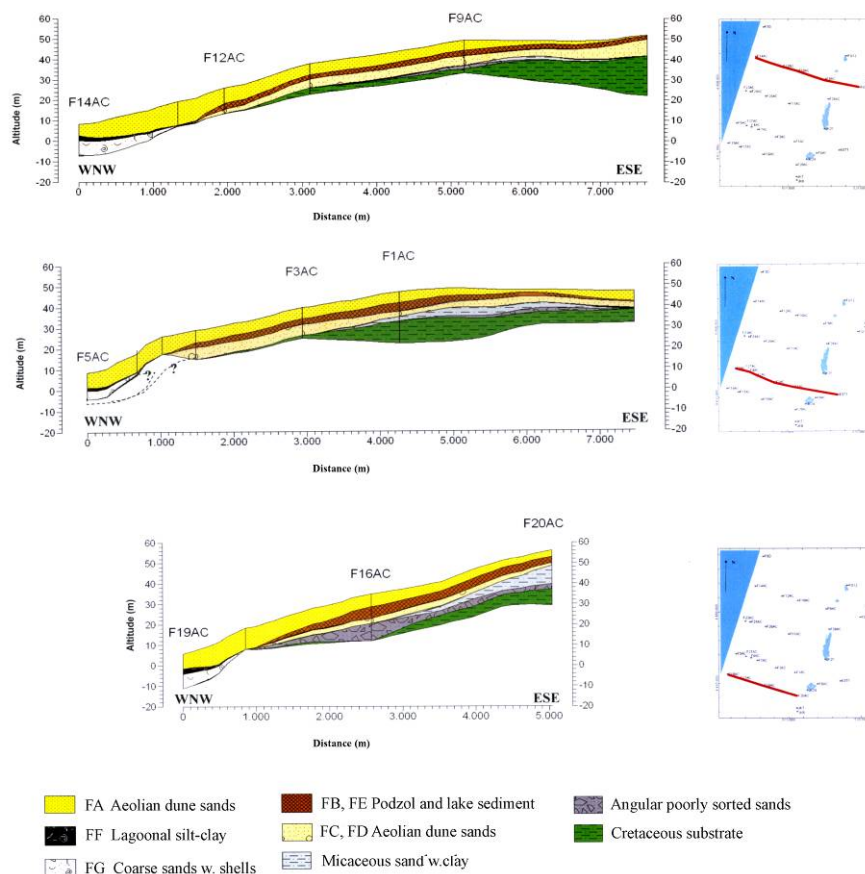
Fig.2 Stratigraphy of the Quiaios - Tocha dune field (Castilho 2008)

Palynology

Lake cores

The pollen assemblages found in the lake cores (Figs.3 and 4) could be divided into three pollen assemblage zones (PAZ) recording the regional vegetation through time. Local vegetation changes in hygrophilous taxa and algae were divided into local zones. A more explicit analysis of the lake cores are presented respectively in the two articles Danielsen, (2008) and Danielsen, (*in press.*). A summarized version of the vegetation development, as deduced from the lake samples, is offered here.

PAZ I

Sediment accumulation at the lake location started around 1630 yr BP. This initial zone is characterized by low values of arboreal pollen (< 5%) and high values of heathland and wetland plants. The upland vegetation registered in this zone is interpreted as treeless open heathland vegetation with *Erica scoparia* and *E. umbellata*. Wetland vegetation with *Halimium lasianthum* and *Erica erigena* dominated locally representing a terrestrial hydroseral stage.

PAZ II

In this zone a continuous low representation of forest vegetation prevailed concomitant with the dominance of pollen of heathland species such as *Erica scoparia*. Pollen of *Olea,* Cerealia and *Zea mays* appear in this zone suggesting agricultural activity. Indicators of grazing also increased from this zone onwards. The local dominance of *Halimium lasianthum* was gradually substituted by *E. erigena* and Poaceae possibly due to higher humidity or water-level of the soil.

PAZ III

Reforestation of the region is recognized in this zone. Pollen of *Pinus* was most important but pollen of *Quercus* also increased. Lakes developed at the onset this phase (c 2-300 years ago) as seen by the large increase in quantity and variety of algal remains. Indicators of agriculture and grazing attained high values. The local reforestation (1924-1940) is identified in the upper part of the zone by the emergence of pollen of exotic taxa (*Eucalyptus, Acacia, Platanus* and *Casuarina).*

Borehole samples (Facies FB, FC, FD, FE and FF)

Only the western and eastern sectors have organic deposits that contain pollen and other microfossils (Fig.5).

Western sector:

The boreholes from the western sector penetrated a 1-2 m thick deposit of clay, rich in mollusc fragments and plant remains including pollen. All depths given for boreholes are in metres below surface.

F5 (7.5-8.8 m) & F18 (7.7 m and 7.4 m) (Facies FF)

The three samples from F5 and F18 contain relatively high values of arboreal pollen (>40%). *Pinus* and *Quercus* are the main taxa, but also *Alnus* have a relatively high representation. Pollen of Chenopodiaceae are frequent. Cysts of the dinoflagellate *Spiniferites* and remains of the green algae *Cymatiosphaera* are present. The upper sample from F18 (7.4 m) has an increasing content of pollen of heathland species (*Erica scoparia* and *E. arborea)* and possible indicators of agriculture (Cerealia).

Pollen content of both F5 and F18 register salt marsh vegetation. It is always difficult to interpret regional and extra-local palaeovegetation structure in salt-marsh deposits subject to tidal influence. The dominance of pollen from pine and oak may indicate the proximity of a presumable mixed forest formation of these taxa. Pollen of Chenopodiaceae suggest a salt marsh environment as do the presence of the dinoflagellate *Spiniferites.* Also the green algal genus *Cymatiosphaera* is considered an indicator of marine influence (Bakker and van Smeerdijk, 1982; Mateus, 1992)*.* A humid *Alnus* carr with grass and sedges seem to have fringed the lagoon inland.

The younger part of the lagoonal deposit (F18, 7.4 m) shows continuing presence of the mixed oak/pine forest, although heathland plants appear to have been gaining territory. The occurrence of large pollen of Poaceae (possibly Cerealia) may indicate agriculture and human presence in the near vicinity of the lagoon in this more recent deposit although we cannot discard the inflection of Cerealia type produced by saltmarsh/dune Gramineae (Mateus, 1992).

F14 (c 6.3 m) (Facies FC/FF)

This pollen sample was extracted from inside a mud nodule in a layer containing wooden remains in a transitional facies above the lagoonal deposit. It had too few pollen to construct a diagram, the only ones represented being of *Quercus, Pinus, Alnus, Erica arborea, Daphne, Mercurialis* and Poaceae. Large amounts of spores of the Polypodiaceae were found.

The pollen and spore content, although scarce and inadequate as a representation of the existing vegetation, depict a forest environment similar to the one found in the lagoonal deposits.

F12 is found at the western limit of the eastern sector. The rest of the boreholes are well within the area of podzolized sands used in the delimitation between the transitional and eastern sector.

F12 (c 7.5 m) (Facies FC)

Sample F12 is dominated by pollen of *Erica scoparia* and other Ericaceae. *Halimium halimifolium* type pollen (including *H. lasianthum*), Cyperaceae and Poaceae are frequent. Arboreal pollen values are low (c 3%). Remains of *Debarya* are frequent, indicating a shallow, seasonally inundated pool (van Geel *et al.*, 1989).

The environment revealed implies a regional heathland with *E. scoparia.* Local vegetation suggests a dune slack or a lake edge with grass and sedges and with *H. lasianthum* and *E. erigena* in slightly less humid habitats. High values of *Debarya* and lack of pollen of aquatic plants and other algae, point to seasonal soil water-logging and pools rather than a lake at the site. The relatively high values of fungal spores of *Gelasinospora* may suggest human impact. The fungus is reported to grow on dung (Lundqvist, 1972) and may thus indicate local pastures. Later research has shown a connection between the spores and periods of fire (van Geel, 1976) as the fungus also grows on burned wood.

F3 (c 5.3 m) (Facies FE)

The sample from F3 contains 74% pollen of heathland plants, with *Erica scoparia* and *Calluna vulgaris* as the most abundant but with high values for *Erica erigena* as well. *Halimium halimifolium* type pollen is common as are pollen of grasses and sedges. Arboreal pollen values are low (c 2%).

The palaeosol at F3 has a pollen content that indicates a regional vegetation of heathland type. Pollen of hygrophilous plants like *E. erigena, H. lasianthum* and Cyperaceae suggest that the local environment included humid dune slacks.

F9 (c 7 m) (Facies FB)

The sample contains 69% pollen of heathland plants, mainly *Erica scoparia* and *E. umbellata,* but with high pollen values of *Calluna vulgaris* and *Corema album* as well*.* Arboreal pollen percentages are low (c 2%).

The pollen content records an open, unforested heathland mosaic including relatively dry dunes with *C. album* and areas with more developed soil conditions favouring *Erica* species and *C. vulgaris*.

F1 (7.0-7.2 m and 5.3-5.4 m) (Facies FC and FE)

Two samples were collected from F1; a lower deposit found in podzolized sand (facies FC) and an upper organic deposit (facies FE).

The lower deposit is predominated by pollen of *Erica scoparia, E. arborea* and *Calluna vulgaris* with high pollen values for *E. erigena* and *Halimium halimifolium* from the local vegetation. Arboreal pollen values are low (c 3%).

The upper deposit maintains relatively low arboreal pollen values (c 9%) and dominance of pollen of species of the Ericaceae. The major constituents of local pollen are *E. erigena, H. lasianthum, Myrica cf. gale, Myriophyllum alterniflorum, Potamogeton* and Poaceae. Algal remains from *Botryococcus* and various taxa of *Pediastrum* (*P. boryanum, P. integrum, P. angulosum*) are frequent. Pollen of *Olea, Triticum, Secale cereale, Castanea* and *Juglans* are common.

Heathland dominated by Ericales characterized the vegetation during the formation of both deposits. Arboreal pollen have very low percentages so eventual trees must have been scattered or distant.

In the lower sample, the local element of the pollen content in this muddy unit was deposited in a wetland area or at the edge of a lake, possibly seasonally inundated.

The upper muddy layer, however, was deposited in a lake environment at a time when the water table was higher and lake conditions persisted throughout the year. The abundance of various species of algae and aquatic plants confirm this fresh water lake environment. This muddy unit shows high percentages for wetland plants presumably from the near surroundings of the lake. Open heathland with various species of Ericales seems to have predominated in the region surrounding the lake at that time. Anthropogenic activities in the vicinity are demonstrated by the presence of pollen of agricultural plants.

F20 (4 m and 5 m) (Facies FB and FB/FC)

Both samples have around 6-7% arboreal pollen mainly represented by *Pinus* and *Quercus*. They have high pollen values of *Erica scoparia, E. arborea, E. umbellata* and *Calluna vulgaris*.

The lower sample has a higher content of pollen of *E. erigena* and *H. halimifolium* type. The upper sample has a larger amount of pollen of Cyperaceae and Poaceae and contains algae of the Zygnemataceae.

Both samples suggest a regional vegetation of open heathland with varying degree of local soil humidity. The lower sample was probably a wet heathland while the upper sample suggests even higher soil water content in a grass/sedge marsh. Both habitats were possibly located at the margin of a lake or in a dune slack.

F8 (5.3-5.8 m) (Facies FD)

Mud nodules from borehole F8 contain relatively high values of arboreal pollen (c 50%) with *Pinus* as the main contributor of pollen. Pollen of wetland vegetation like Cyperaceae, Poaceae, *Ranunculus acris* type and *Potentilla* type dominate. *Plantago coronopus* and *P. lanceolata* have high pollen values. Pollen of large Poaceae, possibly Cerealia, are present.

The mud nodules from borehole F8 contain a pollen association suggesting a pine forest probably from a period prior to the above mentioned heathland phase. Pollen of agricultural plants (cf. Cerealia) and high pollen values of *Plantago lanceolata* as well as spores of coprophilous fungi like *Cercophora* indicate cultural activity (van Geel *et al.,* 1981; 1983; Wiel, 1983).

Further, towards the surface between c 1 and 1.8 m, a limnic mud is found. This deposit is presumably the same as is found in the nearby Lake Braças and described above. In F8 it is covered by aeolian sand.

Discussion

Vegetation history and cultural influence

<u>Forest phase</u>

The oldest ^{14}C datings were obtained from boreholes F16 and F19. As the samples were collected with the help of water during drilling, no pollen containing sediments were retrieved. In borehole F16 at 9.5 m depth, the layer was characterized by large quantities of wooden remains and gave an age of 5590±45 yr BP. In F19 at 14.5 m many fragments of *Fraxinus* were found in

beach to shoreface sediments and a fragment was dated to 4375±40 yr BP at a time when the coastline reached around 1 km more landward than today. *Fraxinus* is common in freshwater zones and not in beach environments, but the fragments probably originated from over-washed habitats near the coast or were transported from riverbanks to the sea.

Borehole F5 and F18 (and possibly F8) intercepted the apparently oldest pollen containing deposits found during this investigation. Pollen content of the lagoonal deposits in F5 and F18 record a mixed oak/pine forest with some *Alnus* bordering the lagoon. The upper and more recent sample in borehole F18 shows continuing high frequency of arboreal pollen, although heathland plants seem to have been gaining territory.

In the inland borehole F8 the lower organic palaeo-horizon has a pollen content characteristic of a pine forest influenced by grazing and cultural activity. The age of the deposit is not yet known, except that it is older than the above-lying limnic deposit dated in a nearby site to around 1510 yr BP.

Pollen and macrofossil remains depict a forest of *Pinus* and *Quercus* possibly with *Alnus* in coastal marshes and *Fraxinus* in freshwater areas before and around 4000 yr BP. Deforestation of the region happened some time between 4000 yr BP and c 1600 yr BP. The latter date is based on the fact that at the time of the initial sediment accumulation at the lake sites (PAZ I) there was no trace of forest in the diagrams (Danielsen, 2008).

Heathland phase

Forests were replaced by heathland vegetation during this phase. This vegetation type existed along the whole European coast (Haaland, 2002) and was preserved by anthropogenic action (grazing, cutting and burning) and hence is considered semi-natural.

Both lake cores and also boreholes F3, F1, F9, F12 and F20 record this next vegetation phase. During the heathland phase, a vegetation mosaic of dry heathland and wetland zones characterized the region. The heathland was dominated by the tall heather *Erica scoparia* together with other Ericales like *E. umbellata*, *E. australis* and *Calluna vulgaris* and with species of the Cistaceae. Dune slacks were characterized by *Halimium lasianthum* and *E. erigena* and by algal remains of the Zygnemataceae (*Debarya*, *Zygnema* type and *Mougeotia* type) indicative of seasonally inundated pools. This semi-natural vegetation phase seem to have prevailed for a long period due to use of the region for pastures.

The cause of deforestation is not known but may have been related to cultural activity like cutting, burning and grazing, or by climatic change. It is possible that forests disappeared as a result of a combination of negative impact from climate and human activity surpassing threshold values for the existence of such forests.

Indicators of grazing and agriculture are found in both the lake and borehole samples during the heathland phase. The amount of settlements from Iron Age and Roman times registered in the hills nearby (Santos Rocha, 1888-1900; 1908; Mesquita de Figueiredo, 1943; Guerra and Ferreira, 1971; 1974) suggest that human activity is a plausible cause of the deforestation process.

Deforestation and heathland development has been reported from palynological investigations of other parts of Portugal; northwest Alentejo (Mateus, 1989; Mateus, 1992; Queiroz, 1989; Queiroz, 1999; Queiroz and Mateus, 1994), the Tagus valley, about 75 km NE of Lisbon (van Leeuwaarden and Janssen, 1985), Nazaré (Gomes, 2007), Furadouro-Esposende region (Gómes-Orellana *et al.*, 2001), Serra da Estrela (van der Knaap and van Leeuwen, 1995) and Viseu (López Sáez *et al.,* 2001).

Reforestation phase

Replanting of forests took place in many parts of Portugal either as a measure of protection against advancing sand dunes or to replenish scarcity of wood. In the lake samples this regional reforestation is registered as a large and rapid increase in arboreal pollen values, particularly in values of *Pinus* pollen. Initial reforestation is detected in the pollen diagrams from around 300 yr BP (Danielsen, 2008).

Local planting in the Quiaios dunes themselves was carried out between 1924 and 1940 and is recorded in the diagrams as a large increase in *Pinus* pollen values and appearance of pollen of exotic species such as *Acacia, Eucalyptus, Platanus* and *Casuarina* also planted in the region (Almeida, 1995).

Saltmarsh, wetland and lake development

<u>Saltmarsh</u>

Sediment accumulation in the brackish lagoon(s) started after the Flandrian transgression when sea level rise decelerated and reached approximately the level of today. ^{14}C datings of shells from the lagoonal deposits in F18 at 8.3–9 m and 7.4-7.7 m below surface gave respectively 4145±35 yr BP and 4045±35 yr BP. This corresponds well with the sea level curve for Portugal (Dias *et al.,* 1997; 2000) which shows that between 3000 and 5000 yr BP sea level reached a position similar to the present one. At this time sand barriers developed in several parts of the Portuguese coast (Mateus, 1992; Bernardes *et al.,* 2001; Henriques and Neto, 2002; Callapez *et al.,* 2005 a, b) presumably resulting in the formation of lagoons behind the barrier. A comparable event is reported from the Galician coast resulting from the same attenuation of sea level rise after the Flandrian transgression (Bao *et al.,* 2007).

The lagoon(s) recorded by facies FF presumably owed its existence to similar formation of a sand barrier on the Quiaios –Tocha coast.

<u>Wetlands and lakes</u>

At the freshwater lake sites organic sediment accumulation started around 1600 yr BP initially through a wetland phase. The facies FE (and possibly some of the facies FB and FC) in boreholes F1, F12, F20 and zones PAZ I and II of the lake samples, register wetland or dune slack habitats at times when groundwater was high and seasonal inundations occurred. The dominant local vegetation was *Halimium lasianthum, Erica erigena* and various Cyperaceae and Poaceae species, characteristic species in wet heathland and dune slack vegetation at present.

In F1 the upper layer of facies FF registers a lake environment characterized by the presence of algal remains from the genus *Pediastrum* and of aquatic plants like *Myriophyllum alterniflorum* and *Potamogeton.* The surrounding vegetation was still a heathland and content of arboreal pollen was low. This indicates that a lake existed at the site during the heathland phase, and hence at a time prior to the formation of the lakes at Vela and Braças sites. At both these latter sites, lakes formed contemporaneously with the onset of a regional reforestation around 300 years ago (Danielsen, 2008).

The existence of a lake in F1 during the heathland phase, later covered by aeolian sand, suggest an eastward movement of lakes. Sand drift from the west possibly enhanced by deteriorating climatic conditions during LIA, probably led to an infilling of existing lakes and wetland areas and impeded drainage of wetland zones more inland. The consequence was an eastward shift of lakes ultimately reaching their current location (Castilho *et al.*, 2007). Similar drainage impediment by sand drift and resulting lake development has been reported from a palaeo-lake in the Netherlands (Bos *et al.,* 2006). This eastward displacement of lakes and marshes and flooding of cultural fields caused by dune migration was reported from the region in 1904 (Andrade, 1904).

Aeolian activity and sand dune formation

Three dune generations have been proposed for the region (Almeida, 1995; Noivo, 1996) and similar geomorphology of the dunes has been ascribed to synchronous aeolian intensification. The dune generations are related to the previously described evolution of vegetation cover and wetlands.

Comparable dune fields exist in south-western France, the Landes dunes, in the Aquitaine region. The French dunes have been compared to the Portuguese dunes in various publications (Carvalho, 1954; Paskoff, 2001) and analogies between them in what concern dune generations have been described especially regarding the first generation of presumably Pleistocene origin. Palaeosol layers inter-bedded in the Landes dune sands have been dated and three periods of dune development determined (Tastet and Pontee, 1998; Clarke *et al.*, 2002). Chronologically the generations do not coincide with the Portuguese but as the Aquitaine region lies in the southern limit of the positive NAO influence (Clarke and Rendell, 2006), it is to be expected that the dune development there is out of phase with the Portuguese dunes.

1ˢᵗ dune generation

The truncated dunes east of the lakes (in the Gândara plain) are thought to be the oldest and may be of Pleistocene origin (Carvalho, 1964). A distinction of these dunes was made on the criterion that they have a pedological palaeo-horizon, an ironpan ("sorraipa") (Carvalho 1954; Carvalho, 1964), and they were assigned to the Würm (Weichselian) glaciation because the dunes were associated with wind-worn pebbles and Palaeolithic artefacts, as well as periglacial

deposits. More recently the dunes are placed in a wider time frame ranging from the Weichselian to the Holocene (Granja and Carvalho, 1992). Although the precise period of this phase of dune formation in the Quiaios-Tocha region is still unclear, we may conclude that the former forest that existed around 4-5000 yr BP, may have contributed to the development of the podzol horizons that characterize these deposits.

2nd dune generation

The parabolic dunes are remnants of a dune generation of earlier origin than the WNW-ESE oriented oblique/transverse dunes. Parabolic dunes are always associated with vegetation – grasses, shrubs or trees, which anchor their "arms". They are preserved in areas where vegetation cover was adequate to protect them against subsequent sand invasions. Parabolic dunes are found in the triangular pine forest ("Pinhal do Povo") planted prior to 1773 (Serra *et al.*, 1773) to protect the village of Quiaios against invading sand. They also exist in an area south of Lake Braças and near the coast (Fig.1). The coastal ones have probably developed from blowouts behind the foredune and consequently are of a younger generation than the others. The great majority of the parabolic dunes point towards southeast and east indicating the existence of dominant north-westerly winds during the time of formation.

The parabolic dunes have not been dated but it is likely that they were formed during the heathland phase when vegetation cover still was sufficiently uninterrupted to function as anchors and still scarce enough for aeolian activity to occur. Parabolic dunes probably formed throughout the dune field but were later covered or deflated by the third dune generation. They were only preserved in areas with forest cover or in wetland zones where they are consequently found today.

3rd dune generation

The oblique/transverse dunes belong to the most recent dune generation and their formation according to other investigations (Noivo, 1996; Clarke and Rendell, 2006; Danielsen, 2008) probably dates back to around 3-400 years ago. The cold and windy climate in the region during the Little Ice Age (LIA), further enhanced by limited vegetation cover, is thought to have resulted in dune instability and sand invasion.

These linear dunes are mainly oblique as their crests are uniformly sloping on both sides indicating that they were formed by winds of two opposite quadrants. In fact, the present-day

wind roses (Fig.2) show that in spite of the general dominance of winds from north and northwest, the southwest winds are stronger and more efficient for sand transport in the humid months. The transverse dunes, with a steeper inclination on the leeward side of the dune crest, are exclusively found in a limited area in the south-eastern part of the investigated region. These dunes formed by the action of winds from north to northwest as they were protected by the winds from the south because of the existence of the above mentioned "Pinhal do Povo".

With the exception of planted patches of forests (Quiaios) where sand ridges of 15-20 m were built up, the Quiaios-Tocha region lacked forest cover and the sand consequently could move freely towards the east, forming oblique/transverse dunes of many kilometres length.

The magnitude of sand migration during LIA may be illustrated by the dimension of dunes in an area c 50 km to the south, where the dunes accumulated near the western edge of a large pine forest (Pinhal do Rei) planted on the order of king Dom Dinis (1261-1325). The outline of a dune ridge that reaches an elevation of 70 m follows the ancient forest edge (André, 1996; André and Cordeiro, 1998; Almeida *et al.* 1998). At this site, a fossil pine trunk found *in situ* at the base of a 40 m dune ridge gave 370±40 yr BP (cal. 1540±85 AD) demonstrating the quantity of sand deposited there in a relatively short period of time (André, 1996).

Conclusions

The investigation gives insight into vegetation and landscape development of the Quiaios – Tocha dunes during the last 4-5000 years (Fig.6). The region passed through three major vegetational phases during this period. In the beginning a mixed oak/pine forest seems to have existed in the western sector. This was the condition at the time when sea level reached its current position around 4000 yr BP. The forest persisted for a long time but was eventually replaced by heathland at some stage before 1600 yr BP. During this forest phase the existing dunes were vegetated and some podzol horizons were formed.

The second vegetational phase was characterized by a semi-natural heathland with scattered occurrences of trees. During this phase wetland environments developed and water table seems to have been high. Cultural activity including forest clearance, pastures and agriculture may have caused the deforestation and contributed to the maintenance of the open heathland. After deforestation the landscape was especially vulnerable to climate and cultural activity and two periods of major sand mobilization can be detected. The dunes from the first of these periods are

106

exclusively preserved in the proximity of former forests and wetland habitats, where deflation was more difficult. During a following period of sand mobilization, oblique/transverse dunes formed in unvegetated and barren parts of the coastal plain.

The third vegetational phase was a time of sand invasion and the counteractive reforestation of the last centuries. Deteriorating climatic conditions may have intensified sand drift from the west. Dunes invaded existing lakes and wetlands, disrupting the drainage patterns in the coastal plain and eventually relocated the lakes eastwards to their present location.
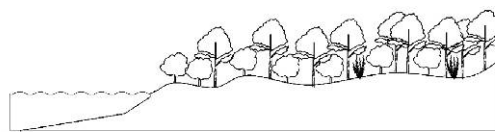

Maximum Flandrian transgression around 4300 yr BP (cal. 3000 BC). Coastline c. 1 km inland compared to the present situation. Vegetation is a mixed pine/oak forest.
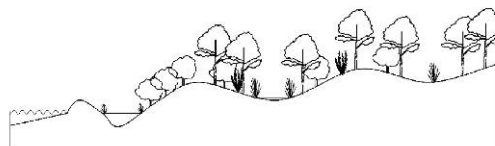
Development of a sand barrier and brackish water lagoon(s) along the coastline around 4000-4100 yr BP (cal. 2300-2100 BC). Vegetation is a mixed pine/oak forest with increasing amounts of scrub.
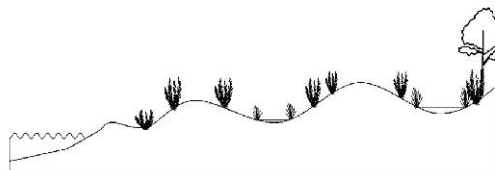
Infilling of the brackish lagoon(s). Deforestation and development of heathland vegetation. Increased aeolian activity, deflation and accumulation areas.
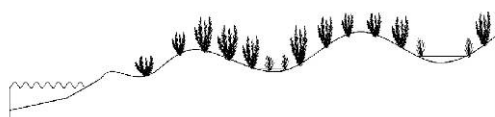
Heathland vegetation with periods of aeolian activity. Formation of wetlands at Vela/Braças sites around 1600 yr BP (cal. 400 AD).
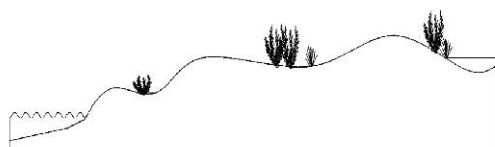
Degraded heathland vegetation and strong aeolian activity with formation of transverse/oblique dunes. Eastward shift of lakes due to infilling of sand and impeded drainage patterns around 300 years ago. Lake formation at Vela/Braças sites.
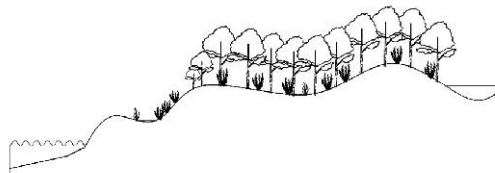
Complete reforestation between 1924 and 1940. Stabilization of sand dunes.

Fig.6 Evolution phases of the Quiaios –Tocha littoral dune fields since the Flandrian transgression

Fig.3 Diagram; Lake Vela

108

Fig.4 Diagram; Lake Braças

Fig.5 Diagram; Boreholes

110

Acknowledgments

References

Almeida, A.C., 1995. Dunas de Quiaios, Gândara e Serra da Boa Viagem. Uma abordagem ecológica da paisagem. PhD Thesis, University of Coimbra, Portugal.

Almeida, A.C., André, J.N., Cunha, P.P., 1998. Visita de estudo à zona costeira entre Cabo Mondego e S. Pedro de Moel. EUROCOAST-PORTUGAL. Porto, 24 p.

Andrade, E.M., 1904. Dunas. F. França Amado, Coimbra, Portugal.

André, J.N. (1996) - Morfologia dunar da área entre o Cabo Mondego e S. Pedro de Moel. MSc thesis, Coimbra University, Portugal.

André, J.N., Cordeiro, M.F.N., 1998. The importance of "Pinhal do Rei" in the Settlement of the Aeolic Sands. EUROCOAST-PORTUGAL. pp. 3-27.

André, J.N., Cordeiro, M.F.N., 1999. Percurso ambiental-geobotanico da Lagoa da Ervedeira a S. Pedro de Moel. Ramalho & Vieira Lda, Leiria, Portugal.

André, J.N., Rebelo, F. & Cunha, P.P., 2001. Morfologia dunar e movimentação de areias entre a lagoa da Ervedeira e o limite sul da Mata Nacional de Leiria. Territorium, Revista de Geografia Física aplicada no ordenamento do território e gestão de riscos naturais, Editora Minerva, Coimbra, Portugal. nº 8, pp. 51-68.

Bakker, M., van Smeerdijk, D.G., 1982. Palaeoecological study of a Late Holocene section from "Het Ilperveld", Western Netherlands. Review of Palaeobotany and Palynology 36, 95-163.

Barbosa, B.P., Soares, A.F., Rocha, R.B., Manuppella, G., Henriques, M.H., 1988. Carta Geológica de Portugal. Notícia Explicativa da Folha 19-A. Cantanhede. Lisboa: Serviços Geológicos de Portugal.

Bao, R., Alonso, A., Delgado, C., Pagés, J.L., 2007. Identification of the main driving mechanisms in the evolution of a small coastal wetland (Traba, Galicia, NW Spain) since its origin 5700 cal yr BP. Palaeogeography, Palaeoclimatology, Palaeoecology 247, 296–312.

Bernardes, C.M., Noivo, L.M., Corrochano, A., 2001. Evolution of Holocenic Coastal Dunes at Leirosa, South of Cape Mondego, Portugal. Thalassas 17(2), 47-56.

Bos, J.A.A., Bohncke, S.J.P., Janssen, C.R., 2006. Lake-level fluctuations and small- scale vegetation patterns during the late glacial in The Netherlands. Journal of Paleolimnology 35, 211-238.

Callapez, P.M., Paredes, R., Dinis, P., Danielsen, R., Soares, A.F., & Carvalho, M., 2005a. Biofacies from the Holocene paleolagoon of Leirosa (Figueira da Foz, West Central Portugal). Coastal Hope Conference 2005, Lisbon, Portugal. pp. 24-29.

Callapez, P.M., Paredes, R., Carvalho, M., Danielsen, R., Soares, A.F. & Dinis, P., 2005b. The paleolagoon of Leirosa (Figueira da Foz) and the Holocene brackish malacofauna of West Portugal. Portugala-Noticiario Malacológico –Congresso Português de Malacologia, Albufeira, Portugal. pp.16-17.

Carvalho, G.S., 1954. A Gândara (Portugal) e as Landes da Gasconha (Franca). Memórias e Notícias, Museu Mineralógico e Geológico da Universidade de Coimbra 37, 21-36.

Carvalho, G.S., 1964. Areias da Gãndara (Portugal). Uma formação eólica Quaternária. Publicações do Museo Mineralógico e Geológico da Faculdade de Ciências da Universidade do Porto 81 (4), 3-32.

Castilho, A.M. 2008. Lagoas de Quiaios. Contribuição para o seu conhecimento geológico e hidrogeológico. PhD Thesis. Coimbra University, Portugal

Castilho, A., Danielsen, R., Dinis, P., 2007. Palaeoenvironmental development of the Quiaios — Tocha dunes based on geological and palynological investigations. Proceedings XXXV IAH Congress-Groundwater and Ecosystems, 471. International Association of Hydrogeologists, Lisbon, Portugal. pp. 1–8.

Clarke, M.L., Rendell, H.M., Tastet, J.-P., Clave, B. and Masse, L. 2002. Late-Holocene sand invasion and North Atlantic storminess along the Aquitaine Coast, southwest France. The Holocene 12, 231-238

Clarke, M.L., Rendell, H.M., 2006. Effects of storminess, sand supply and the North Atlantic Oscillation on sand invasion and coastal dune accretion in western Portugal. The Holocene 16(3), 341-355.

Danielsen, R., 2008. Palaeoecological development of the Quiaios–Mira dunes, northern-central littoral Portugal. Review of Palaeobotany and Palynology 152, 74-99.

Danielsen, R., in press. History of two littoral lakes in central Portugal; dissimilarities elucidated through local-scale evolution of the environment. Submitted to Journal of Paleolimnology Jan. 2009.

Danielsen, R., Castilho, A.M., Dinis, P., Callapez, P.M., 2008. Evolução da paisagem a Norte do Cabo Mondego durante os últimos milhares de anos. Lopez, F.C. & Callapez, P.M. (Eds.). Por Terras da Figueira, Tipografia Cruz & Cardoso Lda., Figueira da Foz. pp. 45-53.

Dias, J.M.A., Rodrigues, A., Magalhães, F., 1997. Evolução da linha de costa, em Portugal, desde o Último Máximo Glaciário até à actualidade: Síntese dos conhecimentos. Estudos do Quaternário 1, APEQ, Lisboa, pp. 53-66.

Dias, J.M.A., Boski, T., Rodrigues, A., Magalhães, F., 2000. Coast line evolution in Portugal since the Last Glacial Maximum until present - a synthesis. Marine Geology 170, 177-186.

Driscoll, F. G. (1986). Groundwater and Wells. 2nd ed. Johnson Division, Minnesota.

Gomes, S.D., 2007. A palinologia da Lagoa do Saloio (Nazaré, Portugal) e a evolução holocénica da região da Mata Nacional do Valado. MSc Thesis, Polytechnic institute of Tomar and University of Trás-os-Montes and Alto Douro, Portugal.

Gomez-Orellana, L., Ramil-Rego, P., Martínez Sánchez, S., 2001. Modificaciones del paisaje durante el Pleistoceno Superior – Holoceno en los territorios litorales Atlánticos del NW Ibérico. Estudos do Quaternário 4, APEQ. Lisboa. pp. 79-96.

Granja, H.M., Carvalho, G.S., 1992. Dunes and Holocene deposits of the coastal zone of Portugal, north Mondego Cape. Carter, R.W.G., Curtis, T.G.F. and Sheehy-Skeffington, M.J. (Eds.) Coastal Dunes: geomorphology, ecology and management for conservation. Proceedings of the Third European Dune Congress, Galway, Ireland. pp. 43-50.

Grimm, E. C., 1991-1993. TILIA and TILIA GRAPH. Springfield IL, Illinios State Museum.

Guerra, V.A., Ferreira, O.V., 1971. Inventário das Estações da Idade do Ferro nos Arredores da Figueira da Foz. Actas do congresso Nacional de Arqueologia, vol. I, Coimbra, Portugal. pp. 297-303.

Guerra, V.A., Ferreira, O.V., 1974. Inventário dos monumentos megalíticos dos arredores da Figueira da Foz. Escola Gráfica Figueirense, Figueira da Foz, Portugal.

Haaland, S., 2002. Fem tusen år med flammer Det europeiske lyngheilandskapet. Vigmostad /Bjørke, Bergen, Norway. p. 160.

Henriques, M.V., Neto, C., 2002. Caracterização geo-ecológica dos sistemas de cordões dunares da Estremadura (Nazaré, S. Martinho do Porto e Peniche – Baleal). Finisterra XXXVII 74, 5-31.

Hughen, K.A., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C., Blackwell, P.G., Buck, C.E., Burr, G., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, F.G., Manning, S., Bronk Ramsey, C., Reimer P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Tálamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. Radiocarbon 46, 1059-1086.

Krumbein, W.C., 1934. Size frequency distributions of sediments. Journal of Sedimentary Petrology 4, 65-77.

López-Sáez, J.A., López García, P., Cruz, D.J., Canha, A.J., 2001. Palaeovegetation and human impact in the Upper Paiva region: Palynology of the Late Bronze Age settlement of Canedotes (Vila Nova de Paiva, Viseu, Portugal). Journal of Iberian Archaeology 3, 47-72.

Lunqvist, N., 1972. Nordic Sordariaceae s. lat. Symb. Bot. Ups. 20 (1), 1-374.

Luterbacher, J., Xoplaki, E., Dietrich, D., Jones, P.D., Davies, T.D., Portis, D., Gonzalez-Rouco, J.F., von Storch, H., Gyalistras, D., Casty, C. and Wanner, H., 2002. Extending North Atlantic Oscillation reconstructions back to 1500. Atmospheric Science Letters 2, 114-124.

Mateus, J.E., 1989. Lagoa Travessa: A Holocene pollen diagram from the south-west coast of Portugal. Revista de Biologia 14, 17-93.

Mateus, J.E., 1992. Holocene and present-day ecosystems of the Carvalhal region, Southwest Portugal. PhD Thesis, Utrecht University, Netherlands.

Mesquita de Figueiredo, A., 1943. A Pré-história do concelho da Figueira, foz do Mondego. Novos descobrimentos feitos nos Arquivos. Imprensa Portuguesa, Porto.

Noivo, L.M., 1996. Morfologia e dinâmica sedimentar das dunas de Quiaios, Portugal. MSc Thesis, University of Aveiro, Portugal.

Paskoff, R., 2001. Analogies entre les Dunes Littorales du Nord-Ouest du Portugal et celles du Sud-Ouest de la France. Homenagem ao Professor Doutor Gaspar Soares de Carvalho.

Albergaria Moreira M. E., Casal Moura A., Granja H. M., Noronha F., (Eds.), Braga. pp. 301-306.

Pestana, G.C.N., 1926. Relatório dos Serviços realizados nos perímetros encorporados na 5ª Regência Florestal. Relatório final do curso de engenheiro silvicultor. Tipografia Popular, Figueira da Foz, Portugal.

Queiroz, P.F., 1989. A preliminary palaeoecological study at Estacada (Lagoa de Albufeira). Revista de Biologia 14, 3-15.

Queiroz, P.F., 1999. Ecologia Histórica da Paisagem do Noroeste Alentejano. PhD Thesis, University of Lisbon, Portugal.

Queiroz, P.F., Mateus, J.E., 1994. Preliminary palynological investigation on the Holocene deposits of Lagoa de Albufeira and Lagoa de Melides, Alentejo (Portugal). Revista de Biologia 15, 15-28.

Rei, M.A., 1940. Arborização — Alguns artigos de propaganda regionalista. Tipografia e Papelaria Costa, Figueira da Foz, Portugal.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Tálamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 Terrestrial Radiocarbon Age Calibration, 0–26 cal kyr BP. Radiocarbon 46 (3), 1029-1059.

Santos Rocha, A., 1888-1900. Antiguidades Pré-históricas do Concelho da Figueira. Coimbra, Imprensa da Universidade, Coimbra, Portugal.

Santos Rocha, A., 1908. Estações Pré-Romanas da Idade do Ferro nas vizinhanças da Figueira. Imprensa Portugueza, Porto, Portugal.

Serra, E.G., Silva, R.F.A., Marques, T.P., 1773. Borrão de campo e planta thopografica do sitio da mina do carvão de pedra no promontório do Mondego. Instituto geográfico Português (IGP), Lisbon, Portugal.

Stuiver, M., Reimer, P.J., 1993. A computer program for radiocarbon age calibration. Radiocarbon 35, 215–230.

Tastet, J.-P., Pontee, N.I., 1998. Morpho-chronology of coastal dunes in Médoc. A new interpretation of Holocene dunes in Southwestern France. Geomorphology 25, 93-109.

115

van der Knaap, W.O., van Leeuwen, J.F.N., 1995. Holocene vegetation succession and degradation as responses to climatic change and human activity in the Serra de Estrela, Portugal. Review of Palaeobotany and Palynology 89, 153-211.

van der Wiel, A.M., 1983. A palaeoecological study of a section from the foot of the hazendonk (Zuid-Holland, The Netherlands) and its significance as a palaeo-environmental indicator. Acta Bot. Neerl. 32 (5/6), 431-436.

van Geel, B., 1976. A palaeoecological study of Holocene peat bog sections, based on the analysis of pollen, spores and macro and microscopic remains of fungi, algae cormophytes and animals. Academisch proefschrift, Hugo de Vries laboratorium, Amsterdam University, Netherlands.

van Geel, B., Bohncke, S.J.P., Dee, H., 1981. A palaeoecological study of an upper Late Glacial and Holocene sequence from "De Borchert", The Netherlands. Review of Palaeobotany and Palynology 31, 367-448.

van Geel, B., Hallewas, D.P., Pals, J.P., 1983. A Late Holocene deposit under the Westfriese Zeedijk near Enkhuizen (Prov. of N-Holland, The Netherlands): palaeoecological and archaeological aspects. Review of Palaeobotany and Palynology 38, 269–335.

van Geel, B., Coope, G.R., van der Hammen, T.,1989. Paleoecology and stratigraphy of the Lateglacial type section at Usselo (The Netherlands). Review of Palaeobotany and Palynology 60, 25–129.

van Leeuwaarden, W., Janssen, C.R., 1985. Preliminary palynological study of peat deposits near an oppidum in the lower Tagus valley, Portugal. Actas da I Reunião do Quaternário Ibérico, 2, pp. 225-236.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. Journal of Geology 30, 377-392.
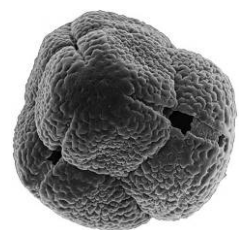
CHAPTER 5

FINAL DISCUSSION

Palynological analysis has proved to be a useful tool in the interpretation of vegetation development of the investigated region and for depicting environmental changes. Vegetational changes recorded in the lake samples and in the organic palaeo-horizons, shed light on a variety of processes and dynamics of past habitats. In addition to giving an overview of the vegetation history of the region, it also contributed with decisive information about disputable themes like past natural vegetation, the coast line at the end of the Flandrian transgression, the age of the lakes, phases of aeolian activity and man's role in the building of a cultural landscape. Furthermore, differences between the distinct water-bodies, such as the two investigated lakes (Lake Vela and Lake Braças), were elucidated.

The investigation covers a period of around 4-5000 years during which man seems to have had an increasing impact on the vegetation and landscape. Human influence, together with climate and sea level change shaped and reshaped the landscape several times until the present. Because anthropogenic activity partially masks the climate signal from the palynological data especially in the later phases, it is not possible by this investigation alone to discriminate in quantitative terms the degree of influence made by man compared to the part caused by climate changes, sea level alterations and other natural processes. More investigation is necessary locally but also engaging a larger region if we aim for a more detailed comprehension of the various events and processes.

The region passed through three major vegetational phases during the period covered by the investigation (Chapter 2; Chapter 4). In the initial phase it was forested with a mixed pine/oak (*Pinus/Quercus*) forest. The *Quercus* pollen encountered during this phase consisted of approximately equal amounts of the two types *Q. coccifera* and *Q.* deciduous. Regarding *Pinus* it has not been possible to distinguish whether it was *P. pinaster* or *P. pinea* (or both) on account of bad preservation and crumpling of the grains in the lagoonal deposit, the only deposit with sufficient statistical amount of pollen of the genus for such an analysis.

Some time before 1600 years BP the forest disappeared probably as a result of combined pressure from human activity of cutting and burning and from climatic change. The forest was replaced by a semi-natural heathland dominated by the tall scrub *Erica scoparia* but with a variety of other species from the Ericaeae and the Cistaceae. Wetter zones with hygrophilous vegetation existed in dune slacks characterized by *E. erigena* and *Halimium lasianthum*. Around

1600 years BP the zone, where the present lakes are situated, was wetland depressions of interdunal character and sediment accumulation started at the site. The onset of this paludification is still difficult to incorporate in the context of forcing factors (climate, geodynamics, human activity). It was possibly also directly associated with the deforestation itself due to the reduced uptake of water from vegetation.

Heathland vegetation depends on grazing, cutting and/or burning in order to be maintained and not develop into a forest. However, excessive grazing pressure together with the climatic deterioration during the Little Ice Age (LIA) must have partly destroyed this vegetation cover, leaving the region defencelessly exposed to aeolian sand flight. This is recorded in the sediment columns as lenses of sand of varying thickness; in Lake Vela of only around three centimetres and in Terra da Areia of more than half a metre. The more or less continuous heathland vegetation was subsequently replaced by new forest through reforestation measures executed to counteract sand invasion of agricultural fields as dunes advanced from the west. This happened in the outskirts of the investigated area c 2-300 years ago. The local reforestation of the dune field in the west happened as late as in the 20th century in a desert like habitat where vegetation cover was virtually inexistent.

Genesis of Lake Vela and Lake Braças as open water-bodies was approximately synchronous with the initial regional replanting 2-300 years ago. Their formation from a wetland zone passed through an unusual and partly reversed hydroseral development from a semiterrestric-telmatic stage to a limnic stage (Chapter3). The investigation indicates that there was a direct relation between lake formation and dune advance. Dunes seem to have invaded existing lakes and wetlands, disrupting the drainage and water reservoir patterns of these habitats and eventually "pushing" the lakes eastwards to their present location (Castilho *et al.,* 2007; Chapter 2; Chapter 4). The discovery of lake sediments from a phase prior to reforestation in sites west of the present lakes, indicates this process. Another source confirming similar relocation is the observations of Andrade (1904, p.19); "*As aguas das lagoas e pântanos existentes no litoral, sob a pressão das areias, caminham cada vez mais para o interior, inundando as terras visinhas, que, além de inutilizadas para a cultura, se transformam, devido ao reprezamento das aguas, em pântanos, paúes e brejos, constituindo um grave perigo para a população visinha.*"

The investigation also showed that biotic and abiotic parameters in Lake Vela and Lake Braças differed since lake formation (Chapter 3). The inclusion of algae in the analysis was very useful in this

respect. Algae are good indicators of environmental conditions, because aquatic organisms with rapid dispersal rates and short life cycles respond quickly to changes in lake parameters like nutrient availability, temperature, pH and water-level variations. Many taxa have well-defined environmental optima and tolerances to important limnological variables. *Pediastrum* is a genus of green algae (Chlorophyceae) that was found in large amounts in the lake samples. The genus has proved useful in the reconstruction of past environments (Nielsen and Sørensen 1992; Jankovská and Komárek 2000; Komárek and Jankovská 2001; Sarmaja-Korjonen *et al.* 2006). Both lakes were initially relatively oligotrophic to mesotrophic. Lake Vela seems to have always been more alkalic than Lake Braças and it suffered a stronger eutrophication. Recent mapping of the water fluxes in the region (Castilho, 2008) may partly explain this phenomenon. It showed that the water in Lake Vela has a lower flux due to a much lower hydraulic gradient than Lake Braças. Additionally the directions of the fluxes are different. In Lake Vela the flux is E-W while in Braças it is SSW-NNE implying that the water in Lake Vela flows through the fertilized agricultural fields in the east, while it in Lake Braças passes through the forested area. The hydrogeologically unfavourable location of Lake Vela, causing little renewal of water due to low hydraulic gradient and high input of nutrients due to flow direction from the agricultural fields, has resulted in the presently observed contamination (Abrantes *et al.,* 2006; Abrantes, 2007) and Cyanobacterial bloom causing fish death. In addition the recreational value of the lake is very low as it is a direct health hazard to humans (Abrantes, 2007).

Sea level studies from Portugal have been systematized by Dias (Dias *et al.*, 1997; 2000). Sea level increased rapidly from around -120 m c 18 000 years BP until it decelerated to the present level around 4-5000 years BP (Fig. 1).
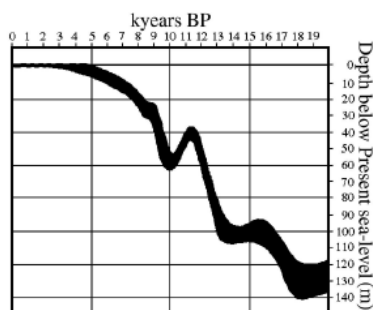

Fig.1. Sea level rise curve for the northern part of the Portuguese shelf (Dias *et al.*, 2000).

The eustatic sea-level rise was the major factor influencing the shape of the coastline until mid-Holocene and the contour of the shore line at the maximal of the Flandrian ingression and transgression, was completely different from the present one. Subsequent erosion of cliffs and terrigenous sediments transported by the rivers, led to formation of sand barriers, spits and lagoons in several regions of Portugal (Mateus, 1992; Bernardes *et al.*, 2001; Freitas *et al.,* 2002; Henriques and Neto, 2002; Callapez *et al.,* 2005 a, b).

The identified brackish palaeolagoon(s) in the investigated region (Chapter 4) was probably formed by the same processes owing its (their) existence to a protective sand barrier. The formation date back to around 4000-4100 years BP (Danielsen *et al.*, 2008; Chapter 4). This corresponds well with the sea level curve for northern Portugal (Fig.1). The attempt to date the barrier breaching by dating the top of the lagoonal deposit (4045±35 years BP) was not successful. The result was very similar to the date of the base of the lagoon (4145±35 years BP) giving the lagoon an age of only c 100 years. The reason may be that the top sediment contained older eroded sediment that washed in as a result of the barrier breaching. The lagoonal deposits reach around 1 km inland, but it is not known how far they stretch into the ocean floor.

Lamellibranch shells appear in large numbers at the surface of interdune depressions along the whole coast from Quaios and northwards. Dating of shell samples from the Tocha - Torreira zone (Granja *et al.*, 1996) gave ages between 3750 ±120 years BP and 1460±110 years BP (corrected for reservoir effect). It is possible that the background for this phenomenon was erosion of palaeolagoonal deposits from the ocean floor during extreme weather or tsunami incidents.

The coast line in the investigated region was c 1 km further inland in comparison to the present one sometime before the installation of the littoral lagoons because the substrate directly under the lagoonal deposits is from a beach/foreshore facies (Chapter 4). Such deposits are not identified further to the east and they record the maximal ingression of the coastline around 5000 years ago before the subsequent progradation of the coast possibly caused by the formation of a sand barrier. This is at variance with the hypothesis of the coast line for the region that according to various authors (Abecassis, 1961; Figueiredo, 1987; Noivo, 1996; Dias *et al.*, 1997; Reigota, 2000) supposedly went 6-7 km further inland and hence passed near the row of lakes existing there at present. Other evidence that rules out the hypothesis of a coast line near the lakes is the height above sea level of sediments of pre-Holocene and even pre-Quaternary origin (Chapter 4, Fig.2). The implicit tectonic uplift of the terrain necessary for such a landward

coastline is completely unrealistic. Planned analysis of the region with the help of georadar may give more concise data in this discussion and it is therefore not elaborated at this stage. Further investigation may in addition disclose whether the brackish deposit originated from one long lagoon (similar to Ria de Aveiro) or many smaller ones.

A geographical expansion of this investigation to the north until Mira and to the dune field south of the Mondego River would benefit the comprehension of the processes involved. The two regions on the opposite sides of the river are similar regarding the existence of dune fields and sand-buried lagoonal deposits near the coast but the southern region was forested earlier on the order of Dom Dinis (1261-1325) and therefore suffered less from aeolian activity and deflation processes. This may have resulted in the preservation of organic horizons containing information from periods poorly preserved in the Quiaios –Tocha region.

The extraction of complete cores suitable for pollen analysis in sandy sediments is difficult. The borehole samples from the organic layers beneath the sand dunes (Chapter 4) were collected during sampling for a hydrogeological project, and the method was consequently not ideal for palynological research but the only one available. For future work the employment of new equipment like georadar and vibracorer may respectively assist in the identification of organic layers of interest and facilitate the extraction of continuous core samples from these layers.

References

Abecassis, C.K., 1961. As formações lagunares e os seus problemas de engenharia litoral. Contribuição para um estudo sistemático. Lisboa, 39–46.

Abrantes, N., 2007. Análise de Risco Ecológico na Lagoa da Vela. PhD thesis, Aveiro University, Portugal. 190 p.

Abrantes, N., Pereira, R., Gonçalves, F., 2006. First step for an ecological risk assessment to evaluate the impact of diffuse pollution in Lake Vela (Portugal). Environmental Monitoring and Assessment 117, 411-431.

Andrade, E.M., 1904. Dunas. F. França Amado, Coimbra, Portugal. 58 p.

Bernardes, C.M., Noivo, L.M., Corrochano, A., 2001. Evolution of Holocenic Coastal Dunes at Leirosa, South of Cape Mondego, Portugal. Thalassas 17 (2), 47–56.

Callapez, P.M., Paredes, R., Dinis, P., Danielsen, R., Soares, A.F., & Carvalho, M., 2005a. Biofacies from the Holocene paleolagoon of Leirosa (Figueira da Foz, West Central Portugal). Paper presented at Coastal Hope 2005. Lisbon, Portugal. 24-29.

Callapez, P.M., Paredes, R., Carvalho, M., Danielsen, R., Soares, A.F. & Dinis, P., 2005b. The paleolagoon of Leirosa (Figueira da Foz) and the Holocene brackish malacofauna of West Portugal. Portugala-Noticiario Malacológico – Paper presented at Congresso Português de Malacologia. Albufeira, Portugal. 16-17.

Castilho, A.M., 2008. Lagoas de Quiaios. Contribuição para o seu conhecimento geológico e hidrogeológico. PhD Thesis. Coimbra University, Portugal.

Castilho, A.M., Danielsen, R., Dinis, P., 2007. Palaeoenvironmental development of the Quiaios – Tocha dunes based on geological and palynological investigations. Proceedings XXXV IAH Congress-Groundwater and Ecosystems, International Association of Hydrogeologists, Lisbon, Portugal, 471; 1-8.

Danielsen, R., Castilho, A.M., Dinis, P., Callapez, P.M., 2008. Evolução da paisagem a Norte do Cabo Mondego durante os últimos milhares de anos. Por Terras da Figueira. Lopez, F.C. & Callapez, P.M. (Eds.). 45-53.

Dias, J.M.A., Rodrigues, A., Magalhães, F., 1997. Evolução da linha de costa, em Portugal, desde o Último Máximo Glaciário até à actualidade: Síntese dos conhecimentos. Estudos do Quaternário, APEQ, Lisboa, 1, pp. 53–66.

Dias, J.M.A., Boski, T., Rodrigues, A., Magalhães, F., 2000. Coast line evolution in Portugal since the Last Glacial Maximum until present — a synthesis. Marine Geology 170, 177–186.

Figueiredo, M.M., 1987. Degradação paisagística da faixa costeira: uma reflexão. Locus, Revista da Associação de Investigação do Território, 2/3, pp. 29–47.

Freitas, M.C., Andrade, C., Cruces, A., 2002. The geological record of environmental changes in southwestern Portuguese coastal lagoons since the Lateglacial. Quaternary International 93–94, 161–170.

Granja, H.M., Carvalho, G.S., de Groot, T., Soares, A.M., Parish, R., 1996. Geochronology and the recent geomorphological evolution of the northwest coastal zone of Portugal. In: Taussik, J., Mitchell (Eds.), Partnership in Coastal Zone Management (Proceeding 3rd International Symposium EUROCOAST, Littoral 96, Portsmouth, U.K.). Samara Publishing Limited, Cardigan, pp. 297–308.

Henriques, M.V., Neto, C., 2002. Caracterização geo-ecológica dos sistemas de cordões dunares da Estremadura (Nazaré, S. Martinho do Porto e Peniche – Baleal). Finisterra, XXXVII, 74, 5-31.

Jankovská, V., Komárek, J., 2000. Indicative Value of Pediastrum and other Coccal Green Algae in Palaeoecology. Folia Geobot 35, 59–82.

Komárek, J., Jankovská, V., 2001. Review of the Green Algal Genus *Pediastrum*; Implication for Pollen-Analytical Research. J Cremer, Berlin.

Nielsen, H., Sørensen, I., 1992. Taxonomy and stratigraphy of lateglacial Pediastrum taxa from Lysmosen, Denmark – a preliminary study. Review of Palaeobotany and Palynology 74, 55–75.

Noivo, L.M., 1996. Morfologia e dinâmica sedimentar das dunas de Quiaios, Portugal. MSc Thesis, University of Aveiro, Portugal. 169 p.

Reigota, J., 2000. A Gândara Antiga. CEMAR, Portugal. 474 p.

Sarmaja-Korjonen, K., Seppänen, A., Bennike, O., 2006. *Pediastrum* algae from the classic late glacial Bølling Sø site, Denmark: Response of aquatic biota to climate change. Review of Palaeobotany and Palynology 138, 95-107.