UNIVERSIDADE DE LISBOA

FACULDADE DE CIÊNCIAS

DEPARTAMENTO DE GEOLOGIA

# DIATOM-BASED CHARACTERIZATION OF IBERIAN COASTAL ENVIRONMENTS AT DIFFERENT TIME SCALES

TÂNIA MARIA DE AZEVEDO FERREIRA

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TÂNIA MARIA DE AZEVEDO FERREIRA

Tese Orientada pela

Professora Doutora Maria da Conceição Pombo de Freitas

e

Professor Doutor Roberto Bao Casal

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To My....

... Once more.

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# Abstract

This thesis presents the mesoscale characterization of the evolution of two lagoon systems, Traba (550 years of sedimentary sequence) and Melides (1745 years of sedimentary sequence), using sedimentological, geochemical and biological, particularly diatoms, indicators. Also, a characterization of 18 present-day transitional environments (coastal lakes and ponds, lagoons and estuaries) of the Western Iberian Atlantic Coast (WIAC) was performed, based on the diatom content of 25 samples of surface sediments and water physico-chemical parameters.

The study of diatom thanatocoenoses in present-day bottom sediments showed that there are distinct assemblages representative of the major types of environments, and that their distribution is mainly governed by gradients in salinity, $PO_4^{3-}$, $NO^{3-}$ and Dissolved Organic Carbon. From this knowledge, a transfer function for salinity was derived which, plus autoecological data on diatoms, sedimentology, geochemical indicators and geochronology, were used to reconstruct the long-term evolution of two contrasting coastal wetlands in the WIAC.

At the considered time scale, the evolution of Traba and Melides was mainly dependent on changes in four natural and anthropogenic factors: sand-barrier breaching (natural and/or human-induced), precipitation, forest cover (natural and/or human-induced), and cultural eutrophication. Sea-level changes played a minor or no role in their recent evolution. The complex interplay among all these factors prompted large ecological regime shifts interpreted in the framework of the Alternative Stable State Hypothesis of Shallow Lakes. Before the systems were impacted by direct human intervention, humid conditions were favourable for the development of turbid phases, generally irrespective of changes in barrier permeability. Whereas this relationship is clear in the Traba record, a higher connection to the ocean in Melides probably gave rise to a much more overlapped signal of the different forcing factors, making more difficult to disentangle the real contribution of climate in its evolution. In recent times cultural eutrophication and artificial barrier breaching accounted for most of the variability in the data, constituting the main drivers of the evolution in the two systems.

In spite of concerns on present-day accelerated sea-level rise, palaeoecological research performed in Melides and Traba shows that the difficult task of good management practice in these systems should first focus in reducing nutrient loads to facilitate their natural recovery.

***Keywords:*** Western Iberian Atlantic Coast; Salinity Transfer function; Holocene palaeoenvironmental evolution; Alternative stable state conditions; Anthropic and climatic forcing factors.

# Resumo

Estuários, lagunas e lagos e charcos costeiros são ambientes de transição em constante evolução, por processos naturais ou atividades antrópicas, enfrentando problemas ambientais como a poluição ou assoreamento provocado por sedimentação de materiais de origem marinha ou continental. Este último, tornou-se mais evidente desde há cerca de 5500-7500 anos cal AP (anos calibrados Antes do Presente), quando a barreira arenosa se tornou uma característica permanente das áreas costeiras da Costa Oeste Ibérica Atlântica (COIA). Torna-se imprescindível reconhecer se os agentes forçadores da evolução destes ambientes são de origem natural, antrópica, ou ambas, sendo as diatomáceas um indicador fundamental (em perspetiva multidisciplinar) no destrinçar dessas mesma origem.

A reconstrução das condições ambientais passadas na COIA, baseada em diatomáceas, tem sido efetuada, até hoje de forma qualitativa, isto é, focada na autoecologia daquelas microalgas. Nesta dissertação pretende-se efetuar uma reconstrução paleoambiental quantitativa. Para tal, duas tipologias de amostragem distintas foram executadas. Um conjunto de amostras representativas das condições ambientais atuais (25 amostras de sedimentos superficiais para avaliação do conteúdo em diatomáceas e parâmetros físico-químicos da coluna de água), de 18 ambientes de transição da COIA (Valdoviño, Doniños, Traba, Louro, Xuño, Muro, Illa de Arousa, Bodeira, Minho, Lima, Vela, Óbidos, Albufeira, Sado, Melides, Santo André, Barbaroxa de Baixo e Mira), e outro, consistindo numa amostragem de alta resolução de duas sequências sedimentares (em Traba, representando os últimos 550 anos e Melides, representando os últimos 1745 anos). Com o primeiro foi possível construir uma função de transferência de salinidade, usada na reconstrução ambiental quantitativa das sequências sedimentares de Traba e Melides.

Os resultados das amostras superficiais mostram que os locais estudados são representativos de ambientes marginais ou de pouca profundidade, podendo ser agrupados em lagos costeiros, lagunas e estuários, de acordo com associações de diatomáceas distintas. O primeiro grupo, constituído por lagos costeiros (Galegos e Portugueses), é caracterizado por diatomáceas ticoplantónicas e epifíticas de água doce/salobra. O segundo grupo, é composto por estuários portugueses e um único lago litoral galego (Doniños), sendo caracterizado principalmente pela presença de diatomáceas epipsâmicas marinhas/salobras. Finalmente, o terceiro grupo é constituído por lagunas portugueses (e o estuário do Sado) onde as diatomáceas epífitas de água doce a salobra são dominantes. As diatomáceas mais comuns e abundantes das amostras superficiais são *Achnanthidium minutissimum*, *Pseudostaurosira trainorii* e *Nitzschia frustulum*, sendo a salinidade, $PO_4^{3-}$, $NO^{3-}$ e Carbono Orgânico Dissolvido, as variáveis que melhor explicam a distribuição das associações de diatomáceas dos ambientes da COIA. De entre estas, a salinidade é a que apresenta maior potencial para a reconstrução quantitativa dos paleoambientes costeiros de Traba e Melides.

As duas espécies de diatomáceas que melhor caracterizam o registo sedimentar de Traba, são a *Pseudostaurosira trainorii* (relacionada principalmente com a instabilidade ambiental associada a alterações na permeabilidade da barreira arenosa) e *Achnanthidium minutissimum*, podendo também ser usadas como indicadoras de mudanças tróficas neste sistema costeiro. Em Melides, são as espécies *Pseudostaurosira trainorii* (também aqui indicadora da instabilidade ambiental associada a alterações na permeabilidade da barreira arenosa), a epipélica *Nitzschia frustulum* e a epifítica *Cocconeis placentula* var. *placentula* (relacionadas com mudanças de estados alternativos estáveis) que predominam. À abundância relativa de taxa de diatomáceas, aliada à reconstrução quantitativa da salinidade adquirida por função de transferência, juntou-se a sedimentologia, a geoquímica e geocronologia, para uma interpretação multidisciplinar da evolução ambiental dos sistemas costeiros de Traba e Melides, mostrando que a sua evolução ecológica, tem como ponto fulcral a teoria dos estados alternativos estáveis para lagos pouco profundos, isto é, os ambientes variam ao longo da sua evolução entre dois estados de equilíbrio, uma condição turva com dominância de biomassa algal e outra transparente, caracterizada por um amplo desenvolvimento de vegetação aquática.

A evolução ao longo de aproximadamente 550 anos a Lagoa de Traba foi controlada pela ação conjunta da variabilidade climática e intervenção humana. Verificou-se que as diatomáceas deste sistema respondem principalmente à abertura da barreira arenosa. Assim, de 1470 a 1875 anos cal EC (anos calibrados da Era Comum), Traba caracterizou-se por um ambiente com ligação ao oceano, de características oligosalinas e com carga significativa de nutrientes (condição turva), potenciada não só pela desflorestação provocada pelo Homem, mas também pelo aumento da precipitação e eventos tempestivos, associados a longos períodos de NAO (North Atlantic Oscilation) negativa durante a Pequena Idade do Gelo (PIG). Entre 1875 e 1990 anos cal EC, o nível de água deste sistema baixa, bem como a carga de nutrientes (condição de transparência). Esta transição não está apenas ligada ao *terminus* da PIG como também à reflorestação feita na bacia hidrográfica desta zona húmida e consequente aprisionamento de nutrientes a montante. A partir de 1992 até 2007 anos cal EC, assiste-se a uma nova mudança, com provável intervenção humana direta nas imediações desta zona húmida, representada por um novo aumento de nutrientes para esta área. Nos últimos anos, o nível de eutrofização diminui, devido à abertura artificial da barreira arenosa.

A Lagoa de Melides, de maiores dimensões que a de Traba, apresenta-se como um sistema de mistura, isto é, mostrando que os múltiplos fatores que influenciam esta zona húmida têm interação complexa e simultânea, tornando a distinção das causas forçadoras dos últimos 1745 anos deste sistema muito difícil. No entanto, verificou-se que as diatomáceas respondem a dois grandes fatores, a instabilidade (potenciada pela abertura da barra, entrada de água da bacia hidrográfica ou precipitação) e mudanças de estados alternativos estáveis do sistema. Assim, de 260 a 530 anos cal EC, Melides era um ambiente restrito, apesar de apresentar condição turva. A partir de 530 até 850 anos cal EC, há um acréscimo de carga de nutrientes no sistema, devido a um aumento da permeabilidade da barreira arenosa. Sugere-se que esta condição de elevada permeabilidade do sistema esteja a mascarar as condições húmidas responsáveis pela entrada de nutrientes via continental, em discordância com as condições

secas bem estabelecidas para o Período das Trevas. Entre 850 e 1700 anos cal EC, a laguna transforma-se num ambiente mais restrito, resultado da baixa conexão com o oceano, embora esta aumente no final este período. Por outro lado, ocorrem duas grandes mudanças nos estados alternativos estáveis. A primeira dá-se entre 850 e 1700 anos cal EC, através de uma mudança gradual de condição turva para transparência, desencadeada não só pelas condições quentes e relativamente áridas da Anomalia Climática Medieval descritas para a Península Ibérica, como também pelas condições de baixa precipitação associadas a fases positivas persistentes da NAO, que diminuíram claramente a carga de nutrientes que chega ao espaço lagunar restrito. Segue-se uma fase de transição, e um novo retorno a um sistema de condição turva adquirida desde 1950 anos cal EC até ao presente. As condições húmidas da PIG que aumentariam a carga de nutrientes, não foram no entanto responsáveis pela transição para uma condição turva, muito devido ao aumento da conexão com oceano, que acontece a partir de 1950. Sugere-se que é a partir desta data que as condições atuais de hipertrofia foram adquiridas, como resultado do aumento de nutrientes potenciado pela carga de fertilizantes chegada por via continental.

Assim, na escala de tempo considerada, a evolução de Traba e Melides dependeu principalmente de alterações em quatro fatores naturais e antrópicos: abertura/fecho da barreira arenosa (natural e/ou induzida pelo Homem), precipitação, cobertura florestal (natural e/ou induzida pelo Homem) e eutrofização cultural. As flutuações do nível médio do mar desempenharam um papel menor ou nulo na evolução recente destes sistemas. A complexa interação entre todos esses fatores conduziu a grandes mudanças de regime ecológico interpretadas segundo a teoria de estados alternativos estáveis para lagos pouco profundos. Estas mudanças em Melides e Traba dependeram em grande parte das Mudanças Climáticas Rápidas ocorridas durante o Holocénico. Antes da intervenção humana direta nos sistemas, as condições húmidas foram favoráveis para o desenvolvimento das fases turvas, e em geral, independentes de alterações na permeabilidade da barreira. Ambos os sistemas experimentaram mudanças a partir de um estado turvo para um de transparência associadas a mudanças de períodos húmidos para secos (o início da Anomalia Climática Medieval em Melides, e o termo da PIG em Traba). Essa relação é clara no registo de Traba, enquanto que uma mais frequente conexão com o oceano em Melides, provavelmente, deu origem a uma sobreposição de sinais dos diferentes fatores que forçam os sistema, tornando mais difícil separar a contribuição real do clima na sua evolução. Nos últimos anos, a eutrofização cultural e a abertura artificial da barreira arenosa, são os responsáveis pela maior parte da variabilidade dos dados, que constituem os principais motores da evolução nos dois sistemas.

Os resultados obtidos mostram-se fundamentais na correta gestão integrada da zona costeira Ibérica. Apesar das preocupações com o atual aumento do nível do mar, a pesquisa paleoecológica realizada em Melides e Traba mostra que as boas práticas de gestão devem primeiro focar-se na redução de cargas de nutrientes para facilitar a sua recuperação natural, e ser acompanhadas por planos de monitorização e investigação científica multidisciplinar.

***Palavras-chave:*** Costa Oeste Ibérica Atlântica; Função de transferência de Salinidade; Evolução paleoambiental Holocénica; Teoria dos estados alternativos estáveis para lagos pouco profundos; Influência forçadora antrópica e climática.

# Preface

This thesis is based on the work carried out as a PhD student at the Departamento de Geologia, Faculdade de Ciências, Universidade de Lisboa, as well as in the Facultade de Ciencias, Universidade da Coruña, between March 2007 and December 2013.

The main objective of this thesis consists on disentangling the natural and anthropogenic factors that drive the evolution of two coastal environments, Traba (Galicia, NW Spain; 550 years of sedimentation) and Melides Lagoon (SW Portugal; 1745 years of sedimentation), using sedimentological, geochemical and biological, particularly diatoms indicators. This thesis is explained in five chapters which can be briefly described as follows:

*Chapter 1*: Introduction – in this introductory chapter the main objectives of this thesis will be discussed as well as its problematic – the issues that can be addressed in the study of the evolution of coastal environments, the identification of diatom communities, its structure and distribution in both present day samples and in core samples, but also questions associated with the sampling strategy and application of transfer functions derived from the present diatoms assemblages to the past (i. e., cores), especially in coastal environments, and also the scientific context of this work;

*Chapter 2*: Study area – in this chapter, the 18 coastal environments with different types of connection to the sea – lakes and ponds, lagoons and estuaries - located in the Western Iberian Atlantic Coast (WIAC) that were studied are presented. Their general features, geological, geomorphological and climatic contexts are also briefly described;

*Chapter 3*: Methods – these 18 environments were subjected to an environmental characterization and identification of the diatom assemblages preserved in their surface sediments. The relationship between the diatom assemblages composition and the environmental variables has been studied, and two coastal wetlands, Traba (Galicia, NW Spain) and Melides (SW Portugal), where selected for coring and reconstructions of past environmental conditions. All the field and laboratory methodologies, as well as the numerical analyses performed on both present day and core data, are explained in this chapter;

*Chapter 4* - Results – the results are presented in three separate paper-like chapters, each one including introduction, results, and discussion and conclusions sections.

*Chapter 4.1*. *Diatom assemblages in present-day bottom sediments of Western Iberian Atlantic coastal environments* - This chapter documents the diatom assemblages present in 18 coastal environments of the *Western Iberian Atlantic* and their relationship with the main hydrochemical variables that characterize them, resulting in a transfer function to be used for the reconstruction of past salinity conditions in the recent history of Traba and Melides coastal wetlands.

*Chapter 4.2. Climatic and anthropogenic impacts in Traba coastal wetland (Galicia, NW Spain) in the last 550 years* – in this chapter the palaeoenvironmental evolution of the Traba wetland in the last 550 years based on diatoms, sedimentology and geochemical proxies is presented. The main forcing factors, both natural and anthropogenic are identified, as well as how they have prompted changes between ecological alternative stable states.

*Chapter 4.3. Natural and human-induced changes in alternative stable states – a 1745 years record of environmental change in the Melides lagoon (Portugal)* – this chapter presents a multiproxy palaeoenvironmental reconstruction of the last 1745 years in the Melides lagoon that includes diatom, sedimentological and geochemical data. The major natural and anthropogenic agents driving this evolution are also identified and, as in the previous chapter, studied as the triggers of changes between ecological alternative stable states.

*Chapter 5*: Discussion and Conclusions - in this chapter a global discussion that integrates all the results found in this thesis, and some general conclusions are presented, as well as some ideas about the future work that could be tackled and self-criticism.

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# 1. Introduction

## 1.1 PROBLEM STATEMENT

Coastal lakes and ponds, lagoons and estuaries are transitional environments in constant evolution, either by natural processes – e. g., climatic changes, sea-level rise - or anthropogenic activities – e. g., afforestation/deforestation, agriculture, water and sediment extraction, urbanization, industry, port constructions. Extremely sensitive, these environments are in the centre of conflict of interests between its use (sometimes abusive), and its preservation, given its great ecological importance, namely in carbon storage, biodiversity conservation, fish production, water purification, and erosion control (Moreno-Mateos et al., 2013). They face not only environmental problems like pollution and silting up, with mainly siltyclastic material, from marine or continental origin, but they are also particularly vulnerable to climate change impacts that include accelerated sea-level rise, increased temperature, changes in rainfall distribution and freshwater inputs, increases in the frequency and intensity of storms, sediment supply, tidal range, land use, and nutrient availability, all operating over a range of temporal and spatial scales (Cooper, 1994; Isla, 1995; Hesp & Short, 1999; Day et al., 2008; Moser et al., 2013; Newton et al., 2013; Williams, 2013). Besides these global agents, direct local human intervention in these systems is a potential major factor that can significantly alter coastal ecosystems (Håkanson & Bryhn, 2008), but the exact pace and ultimate severity of local impacts very much depend on regional climatic changes (Moser et al., 2012).

It is therefore imperative the understanding of these systems and especially their evolution, since most of the world population leaves in the coastal area. Hence, it is important to understand the relative contribution of different modelling agents into shaping these wetlands, including the anthropogenic influence.

Present-day Atlantic transitional systems are frequently in an advanced stage of siltation, due to sediments from ocean and continental origin deposited after the deglaciation and especially in the last 5500 calibrated years Before Present (cal yr BP), when sea-level decelerates (Bao et al., 1999; Freitas et al., 1999; Dias et al., 2000; Freitas et al., 2002a, 2003a; Cearreta et al., 2003; Andrade et al., 2004; Alday et al., 2006; Dinis et al., 2006; Bao et al., 2007; Costas et al., 2009; González Villanueva et al., 2009). It has been suggested that until the end of the first half of the Holocene, global forcing factors control the evolution of the wetlands, whereas in the second half, due to the decrease postglacial marine transgression, mesoscale factors have become progressively more important in explaining that (Devoy et al., 1996; Freitas et al., 2002a; Bao et al., 2007).

Also, global and local forcing factors can induce changes in the equilibrium of ecosystems. For the case of shallow lentic systems, it is known that they can be found in two main types of alternative stable states: a clear state dominated by aquatic vegetation, and a turbid state characterized by high algal biomass (Scheffer et al., 1993; Scheffer, 2004). Major changes in nutrient availability trigger the ecological regime shift from one stable state to another, but this can last long periods of time, making long-term studies imperative for understanding the real nature of this kind of ecosystem transitions (e. g., García Rodríguez et al., 2010; Stutz et al., 2012).

However in most cases environmental monitoring data are not available and, when available, they usually cover less than 15 years, in spite of being essential for knowing, for instance, the effects of climate change in semi enclosed coastal systems (Newton et al., 2013). Palaeoenvironmental records covering decadal to centennial time-scales can substitute the lack of monitoring data for tracking long-term dynamics in aquatic systems whilst smoothing out short-term variability (Sayer et al., 2010). They can not only provide valuable data on reference conditions that can be target for correct restoration plans in disturbed ecosystems, but be used to track the consequences of these plans (Smol, 2008). This is particularly important for the case of wetlands, because they can recover towards alternative states that differ from reference conditions before degradation (Moreno-Mateos et al., 2013).

In order to disentangle anthropogenic from natural forcing factors during the Holocene evolution of coastal areas, multidisciplinary studies have to be done at different time scales, microscale (hundreds of years) to mesoscale (hundreds to thousand years). Conditions prior and after these impacts, can be assessed trough the evaluation of several indicators, namely sedimentological, geochemical or biological, in sediments accumulated in that time period.

The use of microfossils is decisive to the multidisciplinary palaeoenvironmental reconstructions of the coastal area during the Holocene, including the knowledge of the controlling factors on the Holocene evolution of the coast. Recent work about the Holocene sedimentary records of Western Iberian Atlantic Coast (WIAC), limited especially to *Rias* environments and Atlantic continental shelf (e. g., Abrantes, 1991; Bao et al., 1997; Sanchez-Goñi et al., 1999; Abrantes, 2000; Diz et al., 2002; Cobelo-Garcia &Prego, 2003, Desprat et al., 2003; García-García et al., 2005; González-Álvarez et al., 2005; Bartels-Jónsdóttir et al., 2006; Lebreiro et al., 2006, Álvarez-Iglesias et al., 2007; Naughton et al., 2007a; Pérez-Arlucea et al., 2007; Bernardez et al., 2008; Lantzsch et al., 2009; Rodrigues et al., 2009; Mohamed et al., 2010; Evans et al, 2011; Gomes et al., 2012; Martins et al., 2012), have shown the importance of multidisciplinary studies in paleoclimatology, palaeoceanography, sea-level rise or contaminants.

Although there are a good number of works about how the forcing agents (natural or anthropogenic) have control the evolution of transitional coastal environments in the WIAC (e. g., Zazo et al., 1996; Pendon et al., 1998; Ramos et al., 2001; Santos et al., 2001; Henriques et al., 2002; Freitas et al., 2003b; Drago et al., 2004; Santos & Sánchez-Goñi, 2003; Cearreta et al., 2003; Abrantes et al., 2005; Dinis et al., 2005; Cabral et al., 2006; Costa, 2006; Drago et al., 2006; Ferreira et al., 2006; Cearreta et al., 2007; Naughton et al., 2007b; Danielsen, 2008; Costas et al., 2009; Cruces et al., 2009; Arribas et al., 2010; Cruces et al., 2010; Granja et al., 2010; Cruces et al., 2011; De la Rosa et al., 2012; Leorri et al., 2013), and at Mediterranean coast (e. g., Bosky et al., 2002; Andrade et al., 2004; Fletcher et al., 2017; Bosky et al., 2008) most of them are focused on estuaries, whereas lagoons and coastal lakes and ponds studies are still scarse.

There are several palaeoecological indicators suitable to be used in coastal environments evolution. Among them, the analysis of diatoms has proven to be a very effective technique (Anderson & Vos, 1992; Denys & de Wolf, 1999), since they are sensitive to environmental variations and constitute a key element for their detection and control.

Diatoms (Class Bacillariophyceae) are a group of microscopic algae abundant in almost all aquatic habitats. They are constituted by frustules that are composed of hydrated amorphous silica, $SiO_2.nH_2O$. Diatoms are very sensitive indicators regarding the trophic status (Bennion, 1994), sea-level variation and shallow lake alternative states (Gárcia-Rodrigues et al., 2010), sea-level fluctuations and palaeotidal levels (e. g., Zong and Horton, 1999), isolation bowls due to isostasy (e. g., Kjemperud, 1986; Saulnier-Talbot & Pienitz, 2001; Granja et al., 2010), stability of barriers in lagoons (e. g., Bao et al., 1999), changes in hydrological dynamics (e. g., Rovira et al., 2012),"storm surge" events (e. g., Parsons, 1998; Zong and Tooley, 1999) and tsunamigenic activity (e. g., Hemphill-Haley, 1996).

Diatoms have proven to be particularly useful in the WIAC Holocene evolutional studies (Bao et al., 1999; Santos et al., 2001; Cearreta et al., 2003; Ferreira, 2006; Bao et al., 2007; Granja et al., 2010; Santos 2010), but whereas precise quantitative palaeoenvironmental reconstructions could be accomplished elsewhere (e. g., Cooper et al., 2010; Snoeijs & Weckström, 2010), interpretation of the Iberian Atlantic Holocene diatom records have always been qualitative, based on autoecological data from other regions (Vos & de Wolf, 1993). Regarding the study of diatoms in sediments applied to the Holocene evolution of coastal environments and particularly lakes and ponds, lagoons and estuaries, the approach used in the projects PRAXIS/PCNA/C/CTE/12/96 and POCTI/PDCTM/P/MAR/15231/99 allowed, for the first time, its registration in some environments of SW Portugal (Alentejo Coast); these results were integrated in a multi and interdisciplinary perspective, and led to the establishment of a conceptual model of evolution of the coastline in the last thousand years framed with the respective forcing factors, that stand out the variation in means of sea-level, climate change and anthropogenic influence (Bao et al., 1999; Cearreta et al., 2003).

## 1.2 OBJECTIVES

The main objective of this study is to use diatoms as ecological indicators and derive transfer functions to be applied in two cores in order to reconstruct past environmental conditions in the Iberian Atlantic façade.

This general goal will be developed, pointing out, whenever necessary, the various problems associated specially with the sampling and analysis in coastal environments, as detailed in the following items:

1. **To know the present-day diatom associations existing in sediments of lakes and ponds, lagoons and estuaries from western Iberian coastal fringe and relate them to environmental variables, in order to build transfer functions for environmental variables that intervene more decisively in the distribution of the present-day diatom associations (microscale approach);**

   Coastal transitional environments are subjected to a large variety of forcing factors and contributors. It is important to assess what is (are) the main environmental variable(s) responsible for diatom variation. Although relatively low hydraulic energy that usually characterize these environments favour the sediment settling, deposition and preservation, there are a huge amount of geological (i. e., sediment supply, geological settings and isostasy), physical (i. e., oceanographic, atmospheric, fluvial, groundwater processes and sea-level changes), morphological, chemical (i. e., nutrients, pollutants), biological (i. e., intervening flora and fauna) and anthropogenic factors, that play a wide spectra of roles (Perrilo et al., 2009). These leads to different levels of complexity, being the estuaries the environments where these variations and influences are experienced most strongly and the coastal lakes and ponds, the ones that experience the less intensely.

   This complex series of factors are the main cause of diversity and difficulty on the identification of diatoms and for the lack of studies on autoecologies. A thorough and proper compilation of these reasons, especially for estuarine environments, have already been described in Ribeiro (2010); this author points to shortage in specialized literature, namely for brackish waters, considerable morphological variability of widely distributed taxa and also dissolution and fragmentation, due not only to nutrient limitation but also to high hydrodynamism. Actually, according to Ryves et al. (2006), salinity is the most important variable affecting dissolution within each data-set, and Gasse et al. (1995) taphonomic problems related to diatom dissolution are critical in saline waters. Dissolution of diatoms can bias the assemblage by selective dissolution of weakly silicified forms. This process depends on both ionic composition and concentration and thus is site specific (Barker et al., 1994). All these problems can often lead to *aff*. and *cf*. classification forms, which will ultimately result in a less reliable reconstruction.

For the purpose of constructing a transfer function, a set of sediment samples and environmental variables were collected, to evaluate the diatom assemblages in the sediment which responds to the variation of an environmental variable. Transfer functions derive a quantitative relationship between species composition (in these case, diatoms) and water quality parameters. Knowing the optima and tolerances of these diatoms to a given variable, it is possible to transfer that information to the past, and reconstruct quantitatively the given variable along the period of time of the core.

2. **To characterize the existing fossil diatom associations in the sediments of the Traba and Melides coastal wetlands which have been accumulated in the last thousand years (mesoscale approach); to use the transfer functions to reconstruct past environmental conditions and integrate this information in a multi and interdisciplinary perspective in order to refine the existing palaeoenvironmental evolution models;**

   After identification of the diatom assemblage, present in each core and their variation at a high level of resolution, the application of the transfer function can be done.

   In WIAC area, there are few studies devoted to the reconstruction performed of coastal palaeoenvironmental systems based on diatoms and those are essentially concentrated in the continental shelf and the oceanic environments (e. g., Abrantes, 2000; Abrantes et al., 2005). Also, diatoms are usually used to characterize coastal systems and their relationship with the main environmental gradients (Sampayo, 1970; Cabrita e Moita, 1995; Ribeiro et al., 2003; Resende et al., 2005; Gameiro et al., 2007; Brogueira et al., 2007; Resende et al., 2007; Mendes et al., 2009; Ferreira et al., 2010; Gameiro et al., 2010; Ribeiro, 2010, Gomes et al., 2012; Ribeiro et al., 2013). But until present there are no works on a quantitative reconstruction of an environmental variable. With the development of dedicated coastal diatom-water quality transfer functions, it will be possible to estimate some aspects of pre and post-human intervention in water quality in coastal areas, thereby providing a baseline against which it is possible to assess the degree of human impact.

   Transfer functions are powerful tolls that rely on present data to be applied on the past data but as it was shown above, in coastal areas, namely transitional environments, the appliance, although very tempting, must be derived with careful (see discussion in Juggins, 2013). The reasons already pointed out in Objective 1, along with the variability and poor records, are the main reasons for transitional environments being so poorly study, especially in what concerns transfer functions using diatoms.

3. **To get new indicators that allow to understand the forcing factors in coastal areas and to contribute to the characterization of the resilience of the evaluated systems based on behavioural responses, past and present, data of primary importance in the face of global changes and in an Integrated Coastal Zone Management perspective.**

   Intergovernmental Panel on Climate Change – IPCC predicts that coastal areas will undergo rapid and continued changes In the future (IPCC, 2007), thus is important to disentangle if changes in the ecosystem are caused by human pressure and not due to natural variability (Newton et al., 2013).

   Diatoms are sensitive to environmental variations (Anderson & Vos, 1992; Denys & de Wolf, 1999). It is therefore imperative the study of these systems at different scales based on diatoms, which will not only allow assessing the reference situation against which the present-day situation is confronted, but also evaluate the conditions that controlled the evolution of coastal areas. Such studies can provide indicators species that can be used as analogues to the future changes in these coastal systems.

# 2. Study Area

## 2.1 PHYSICAL SETTING

This work focuses in a set of 18 study sites, corresponding to transitional coastal environments spread along the Western Iberian Atlantic Coast (WIAC), particularly coastal lakes and ponds, lagoons and estuaries, extending in latitude from 43 °N to 37 °N (Fig.2.1).

On the WAIC the tide is semi-diurnal which according to Davies (1977), makes this coast to be classified in the mesotidal regime and dominated by swells from the NW (73 %) and from the W (16 %) (Costa, 1994). Mean wave heights vary strongly with season (Vitorino et al., 2002a, b). In summer, typical wave heights are 1–3 m, with periods of 11–13 s. During winter storms often exceed 7 m, typically with periods of 13 s, but they can exceed 18 s (Costa, 1994).

Fig. 2.1- Location of the study sites along the WIAC.

In the following sections a description of the studied lowlands addressed in this study, as well as their geological and climate contexts, is presented.

## 2.2 COASTAL ENVIRONMENTS CHARACTERIZATION

The studied coastal systems have been classified according to the following definitions and references:

- *Coastal lakes* and *ponds* are freshwater coastal bodies located in a depression completely separated from the ocean by any type of barrier.
- *Lagoons* are depressed coastal areas, separated from the ocean by a barrier that allows a permanent or ephemeral communication with the ocean and where river flow is negligible or null (Freitas, 1995).
- *Estuaries* are semi-enclosed coastal water bodies, with connection to the ocean, where seawater is mixed with fresh water from river drainage (Cameron & Prichard, 1963, in Dyer, 1973).

The classification of each coastal environment addressed in this study in the above-cited scheme is evident in the case of estuaries (Minho, Lima, Sado and Mira) and coastal lakes and ponds (Xuño, Bodeira, Illa de Arousa, Vela and Barbaroxa de Baixo). However, the classification of systems with barriers and ephemeral inlets, such as lagoons, is not always so clear (Valdoviño, Doniños, Traba, Louro, Muro, Óbidos, Albufeira, Melides and Santo André).

The classification of Portuguese lagoon systems was based on the existing bibliography (Óbidos - Freitas, 1989; Albufeira - Freitas, 1995; Melides and Santo André – Cruces, 2001). For the Galician environments, the classification was more difficult, since bibliographic information is scarce. An evaluation was therefore made with the available cartographic and photographic data, in order to assess the type and effectiveness of communication with the ocean, the type of inlet (permanent, ephemeral). A set of ancient maps, aerial photographs, Google Earth imagery and ground photographs from different authors offered as shareware in Google Earth Gallery (2013) were used. From these data, it was possible to classify the 18 studied environments in the 3 previously established types.

Table 2.1 summarises the most relevant environmental characteristics of all the studied sites. Figure 2.2.a and b illustrate all studied environments and sample locations.

Table 2.1 – Main environmental characteristics of the studied environments.

| Typ | Environment Name(s) | Orientation | Area (km$^2$) | Max. Depth (m) | Inlet Type | Watershed (km$^2$)/river | Average river inflow m$^3$/s | Observations |
|---|---|---|---|---|---|---|---|---|
| Estuary | Minho | NE-SW | 23 (Ferreira et al., 2005) | 11 (Fidalgo et al., 1994 ) | Permanent | 17081 /Minho (Farinha & Trindade, 1994) | 343.43 (average between 1990-2005, SHIRH data at Foz de Mouro) | Marine influence 35 km upstream the river mouth, in Valencia (Fidalgo et al., 1995, in Bettencourt et al., 2003) |
|  | Lima | ENE-WSW | 5 (Ferreira et al., 2005) | 11 (Costa-Dias et al., 2010) | Permanent | 2446/Lima (Ramos et al., 2006) | 45.36 (average between 1990-2012, SHIRH data at Ponte da Barca) | Saline intrusion 20 km upstream the river mouth (Ramos et al., 2006) |
|  | Sado | NW-SE | 170 (Ferreira et al., 2005) | 10 (Bettencourt et al., 2003) | Permanent | 7672/Sado (Dias, 1999) | 1.89 (average between 1990-2011, SHIRH data at Torrão do Alentejo) | Maximum saline intrusion 70 km upstream (Bettencourt et al., 2003) |
|  | Mira | NE-SW | 3 (Ferreira et al., 2005) | 11 (Loureiro et al., 2009) | Permanent | 1582/Mira (PBH Mira, 2002) | 3 (França et al., 2012) | The limit of tidal propagation is about 40 km upstream the river mouth (Andrade, 1986) |
| Lagoon | Valdoviño (or Frouxeira) | N-S | 0.59 | >2 | Ephemeral | 17.3/Vilar, Foro | - | Separated from the ocean by a 200 m wide beach-dune system (Frouxeira beach); 450 m long inlet with NE-SW orientation |
|  | Traba | NE-SW | 0.06 | 2 | Ephemeral | 0.1/ Traba Vao | - | Separated from the ocean by a 400 m wide beach-dune system (Traba beach); 1 km long inlet with NE-SW orientation (Bao et al., 2007) |
|  | Louro (or Xadas or Xafras) | NW-SE | 0.25 | 1 | Ephemeral | 3.55/Longarelo | - | Separated from the ocean by a 200 m wide beach-dune system (Area Maior beach); 230 m long inlet with ENE-WSW orientation |
|  | Muro (or San Pedro de Muro) | N-S | 0.12 | >0.20 | Ephemeral | 4.3/ Rial | - | Separated from the ocean by the 200 m wide Basoñas and Area Longa beach-dune systems; 930 m long inlet with NNE-SSW orientation |
|  | Óbidos | NW-SE | 6 | 3 | Permanent | 425/Real, Arnóia, Ameal, Cal, Ferrarias (Neves et al., 2009) | 3 (Malhadas et al., 2009) | Connected with the ocean through a tidal inlet artificially opened |
|  | Albufeira | NE-SW | 1.3 | 15 | Ephemeral | 106/Apostiça, Ferraria, Aiana, Sachola (Freitas, 1995) | 0.1 (average between 1987-1990, SHIRH data for Ponte da Apostiça) | Separated from the ocean by a 200 m wide sand barrier which is artificially breached; the inlet remains open from days to several months (Freitas, 1995) |
|  | Melides | NE-SW | 0.4 | 6 (at the main channel) | Ephemeral | 65/Melides (Cruces, 2001) | - | Separated from the ocean by a 120 m wide sand barrier which is artificially breached; the inlet remains open for just a few days (Cruces, 2001) |
|  | Santo André | NW-SE | 2.5 | 3 (at the main channel) | Ephemeral | 145/Cascalheira, Ponte, Forneco, Azinhal, Badoca (Cruces, 2001) | 0.3 (average from Cascalheira and Azinhal rivulets, Matos 1991) | Separated from the ocean by a 200 m wide sand barrier which is artificially breached; the inlet remains open from days to 1-3 months (Cruces, 2001) |
| Coastal Lakes and ponds | Doniños | E-W | 0.25 | 10 | Inexistent | 6.93/- | - | Separated from the ocean by a 320 m wide beach-dune system (Doniños beach) |
|  | Xuño | NW-SE | 0.03 | 1.5 | Inexistent | 0.34/- | - | Separated from the ocean by the 200 m wide Basoñas and Area Longa beach dune-systems |
|  | Espiñeira (or Illa de Arousa) | NW-SE | 0.08 | 1.5 | Inexistent | - | n.a. | Separated from the ocean by a 70 m wide beach-dune system |
|  | Bodeira | NW-SE | 0.02 | 2 | Inexistent | 1/- | - | Separated from the ocean by a 100 m wide beach-dune system |
|  | Vela | NNE-SSW | 0.7 | 2.4 | Inexistent | -/Vala da Veia | - | Separated from the ocean by a 5.8 km m wide beach-dune system  (Mata Nacional da duna de Quiaios) |
|  | Barbaroxa de Baixo | N-S | 0.03 | 1 | Inexistent | n.a. | n.a. | Separated from the ocean by a 230 m wide beach-dune system |
|  | n.a. - not aplicable |  |  |  |  |  |  |  |
|  | - not known |  |  |  |  |  |  |  |

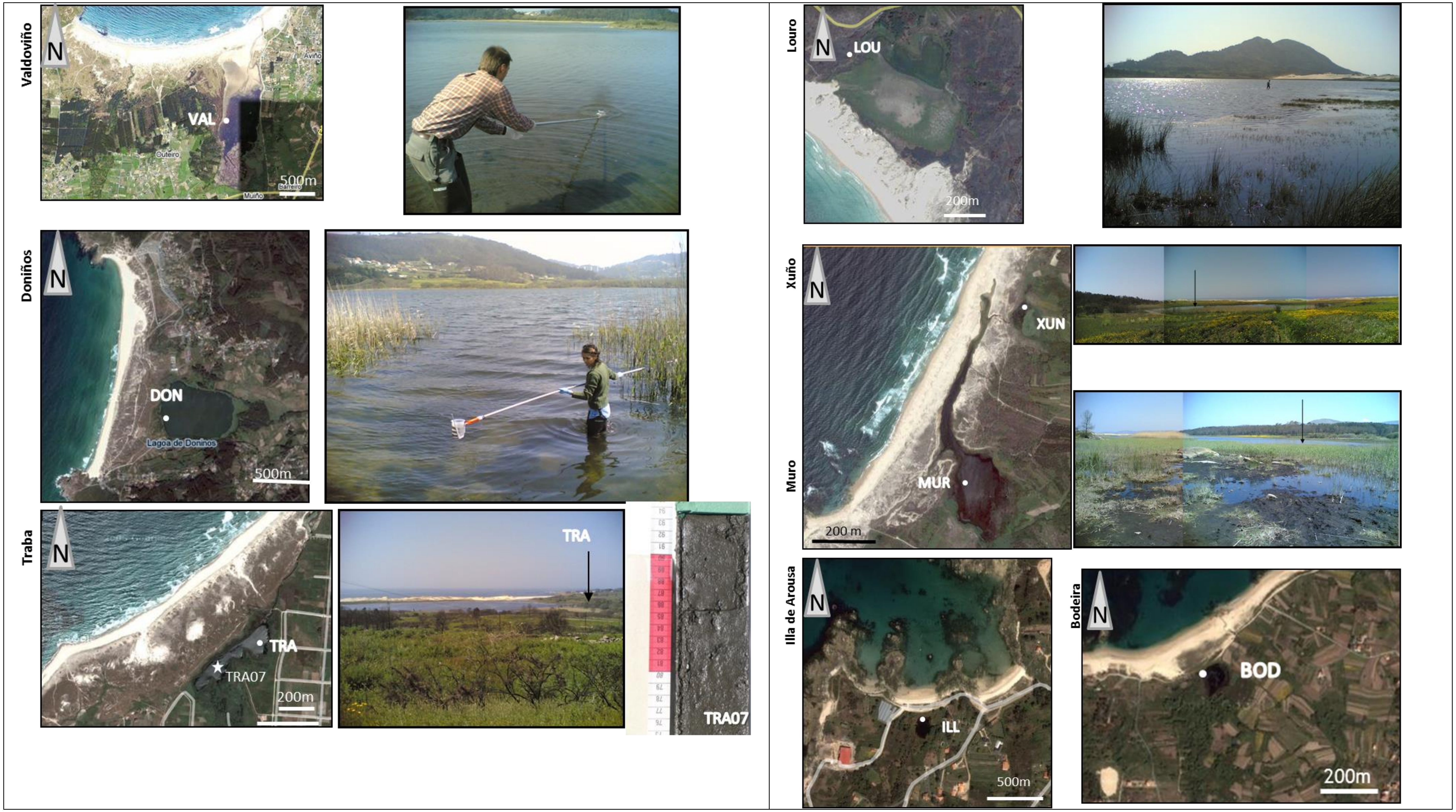

Fig. 2.2a – Sampling locations on the Galician coast (dots – present-day sediments and water sampling sites and code names, star – coring site) (Source of aerial photographs, Google Earth, 2008; field images taken by the author and R. Corbelle).

Fig. 2.2b - Sampling locations in the Portuguese West coast (dots – present-day sediments and water sampling sites and code names, star – coring site) (Source of aerial photographs, Google Earth, 2008; field images taken by the author and C. Freitas, A. Cruces, A. Oliveira, R. Cardoso, and E. Passos).

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Fig. 2.2b (continuation) - Sampling locations in the Portuguese West coast (dots – present-day sediments and water sampling sites and code names, star – coring site) (Source of aerial photographs, Google Earth, 2008; field images and laboratory taken by the author and C. Freitas, A. Cruces, A. Oliveira, R. Cardoso, and E. Passos).

## 2.3 GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The lowlands addressed in this study are distributed throughout the WIAC and are located in the transition between the continent and the ocean (estuaries and lagoons), or just a few hundred metres away from the coastline (in the case of coastal lakes and ponds). In general, they correspond to coastal depressions developed in association with recent coastal features, such as barriers or coastal plains, regardless the age and geology of the regional bedrock. They are located in three fundamental morpho-structural terranes. The Hesperian massif, pre-Mesozoic in age and including a varied suite of metamorphic and magmatic rocks hosts the northern lowlands of Galicia, the Minho and Lima estuaries, as well as the Mira estuary, located further south. The western Mesozoic basin (Lusitanian basin), largely made up by consolidated terrigenous sediments and limestones, deposited in relation with the opening and expansion of the Atlantic Ocean, accommodate the Vela lake and Óbidos lagoon. Finally, the lagoons of Albufeira, Melides, Santo André and Barbaroxa de Baixo pond, as well as the Sado estuary, are located in the Cenozoic basins of the Tagus and Sado rivers (Fig. 2.3).

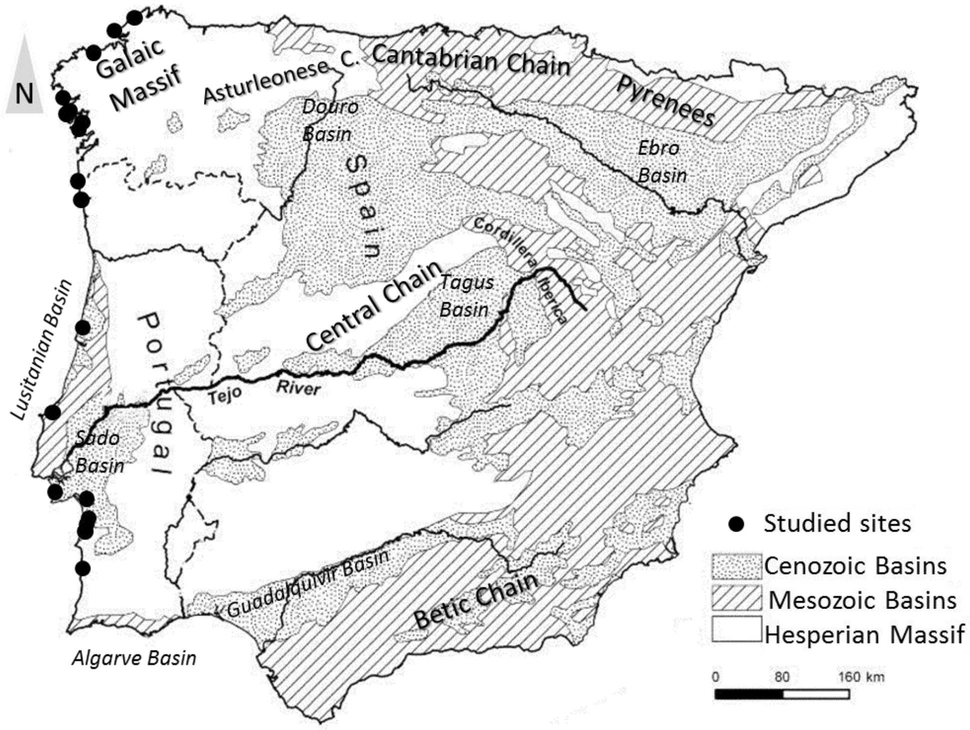

Fig. 2.3 - Plot of the studied environments within the Iberian Peninsula showing the principal morpho-structural units (adapted from Ribeiro et al., 1979).

In general terms, and from a geomorphological point of view, most of the studied sites, extending along the western Iberian Atlantic fringe, are located in littoral plains, carved in Precambrian and Paleozoic terranes that were later covered by detritic deposits (Fig. 2.3). These littoral features confine further inland with mountainous land defined in Mesozoic and essentially pre-Mesozoic terranes. The Cenozoic deposits resting on the substrate are essentially Pleistocene and Holocene in age and include a varied suite of forms and sediments, related with periglacial, lacustrine, fluvial, lagoonal, estuarine, coastal and shallow-marine environments, such as beach and dune ridges (Ribeiro et al., 1979; Ferreira, 1981; Valcarlos & Vidal, 1998) (Fig. 2.3).

## 2.4 CLIMATIC CONTEXT

The previously mentioned geological and structural constraints influence the geomorphology and, consequently, the relief of Iberia. The northern region has in general terms higher altitudes in contrast with the southern one. This contrast translates to some extent in the distribution of the climatic patterns, although a general broad influence from the Atlantic extends along the whole studied region (Ribeiro et al., 1987a, b).

The results from the 1971-2000 climate normals (Iberian Climate Atlas, 2011), can be used to map the spatial distribution of climate types in Iberia according to the Köppen-Geiger classification (which is the latest revision of Köppen, 1936, classification) (Fig. 2.5). The results indicate that most of the Iberian climate is temperate (Type *C);* the littoral façade corresponds to subtype *Cs* (temperate with dry summer) and includes two climate subtypes: the *Csb* subtype (temperate with dry to temperate summer; average temperature in the hottest month below or equal to 22 °C and four months or more with average temperatures above 10 °C), which dominates in the studied area; and the *Csa* subtype (temperate with dry to hot summer, average temperature in the hottest month above 22 °C) applying to the region of the Sado estuary and Albufeira lagoon.

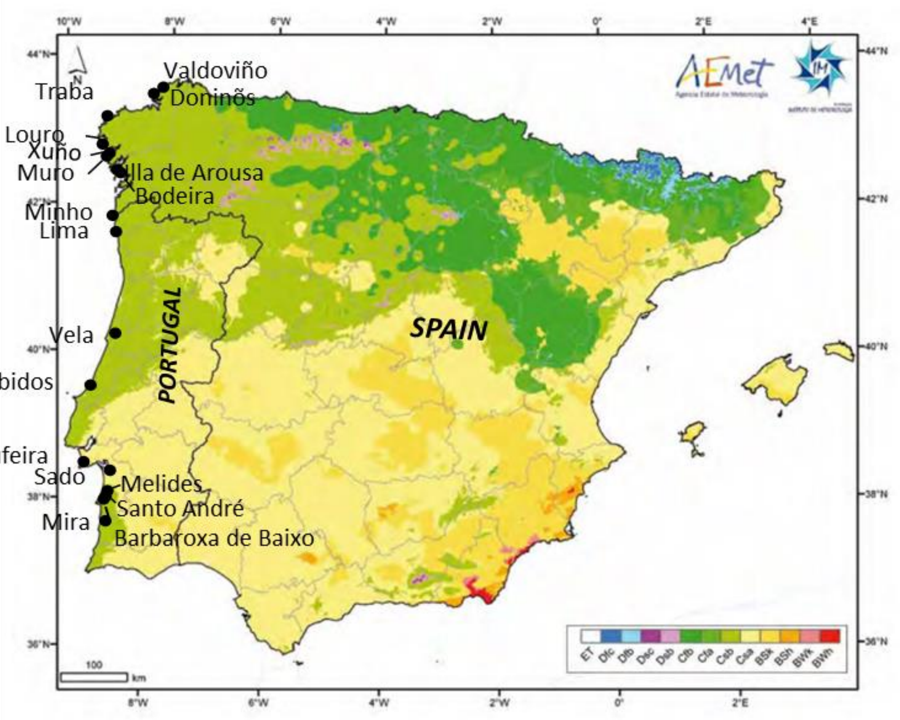

Fig. 2.5- Köppen-Geiger climate classification for the Iberian Peninsula and the Balearic Islands (1971-2000) (adapted from the Iberian Climate Atlas, 2011).

Annual average rainfall in the Iberian Peninsula has a nonuniform distribution throughout the territory. This is mainly due to the orographic distribution (Fig. 2.6). According to Iberian Climate Atlas (2011), highest values are above 2200 mm and are seen in the mountainous areas of north-eastern Continental Portugal (Serra do Gerês), in the northeast of Navarra and in some areas of the southwestern Galicia, close to the “Rias Baixas” in Spain. The lowest values were recorded in the southeast of Spain, in the provinces of Almeria and Murcia, and the south of Alicante, with average annual rainfall below 300 mm. In the areas close to Cabo de Gata (Spain), rainfall is even lower, less than 200 mm.

According to the Iberian Climate Atlas (2011), monthly average rainfall varies between years, with notable seasonality, being stronger in the southern half of the Peninsula, and less notable in the northeast of Spain, with a clear reduction in rainfall in summer. The rainiest month in the Peninsula is December, whereas the driest is July.

The North Atlantic Oscillation (NAO) has been recognised for more than 60 years as one of the major patterns of atmospheric variability in the Northern Hemisphere (Walker 1924; Walker & Bliss 1932). This important circulation mode is clearly identified when time-averaged data (monthly or seasonal) are examined, since time-averaging reduces the "noise" of small-scale and transient meteorological phenomena not related to large-scale climate variability (Hurrel, 2000). In simple terms, the NAO corresponds to a large-scale meridional oscillation between the subtropical anticyclone near the Azores (the Azores High) and the subpolar low pressure system near Iceland (the Icelandic Low) (van Loon & Rogers 1978). The relative strengths and positions of these systems vary from year to year and this variation is known as the NAO.

The negative NAO phase ($NAO^-$) occurs when the Icelandic Low and Açores High are simultaneously weak (e. g., Serreze et al., 1997), favouring the suppression of the westerlies, (Trigo et al., 2002). Negative phases of the NAO induce above-normal precipitation in southern Europe, particularly over the west and southwest sectors of the Iberian Peninsula (Hurrell & van Loon 1997; Trigo et al. 2002). During episodes of strong negative index values, enhanced storminess and precipitation between the Azores archipelago and Iberia occur (Trigo et al., 2004; Vicente- Serrano et al., 2011).

By contrast, the positive NAO phase ($NAO^+$) occurs when the Icelandic Low and Açores High are simultaneously strong (e. g., Serreze et al., 1997), leading to increased westerlies (Trigo et al., 2002). During high NAO index winters, drier conditions occur over much of central and southern Europe, whereas enhanced moisture flux converges from Iceland through Scandinavia (Hurrell, 1995). These circumstances are manifested by an increase in cyclone frequency, enhanced westerlies across the northern North Atlantic and an increase of winter air temperatures (Trigo et al., 2002).

Although NAO exerts a big control on precipitation patterns over the Mediterranean basin, (Trigo et al., 2004), it is also known that the strength of the correlation between the NAO index and local (or regional) climate variables has changed over time (Rodó et al., 1997; Goodess & Jones, 2002).

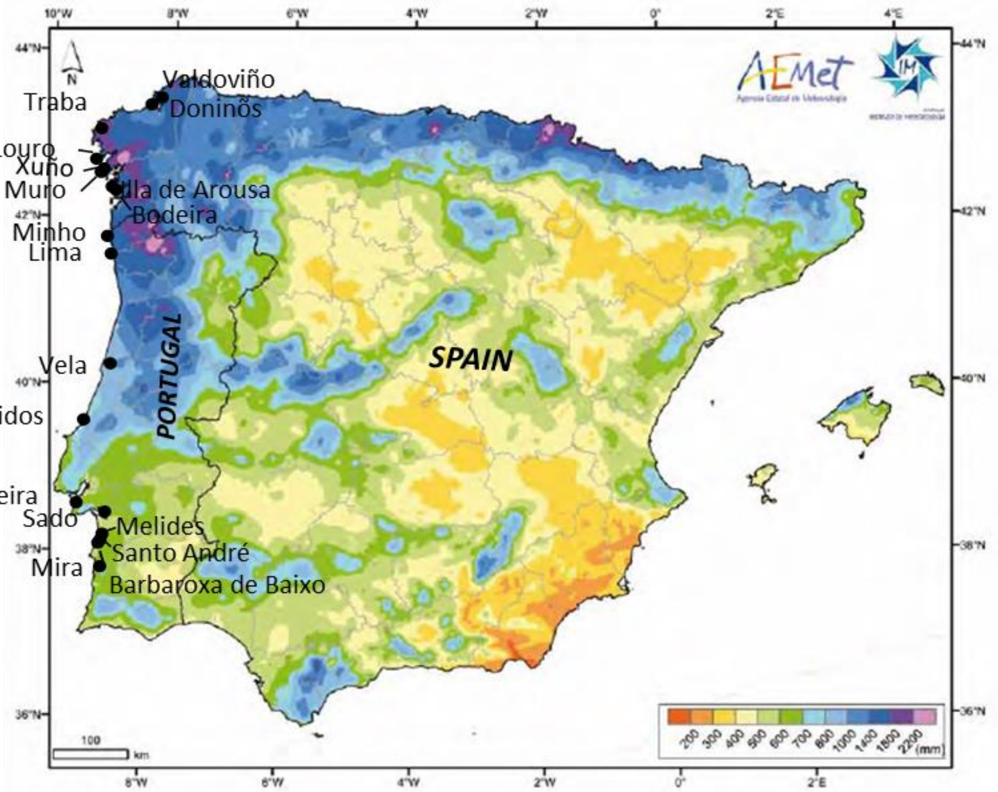

Fig. 2.6- Average total precipitation in the Iberian Peninsula and the Balearic Islands (1971-2000) (adapted from Iberian Climate Atlas, 2011).

# 3. Methods

## 3.1 INTRODUCTION

This study aims at unravelling the main environmental factors governing the present-day composition of diatom assemblages found in bottom sediments of coastal lowlands from the Western Iberian Atlantic Coast (WIAC) and at using this knowledge on the modern analogues for palaeoenvironmental reconstructions.

To achieve these objectives, two groups of samples were studied. A first set of samples consisted of present-day bottom sediments and water samples collected from 18 transitional coastal systems of the WIAC (see Fig. 2.1 and Table 2.1, Chapter 2). It is assumed that bottom sediments in wetlands contain an integrated diatom assemblage that represents the various habitats in the system in the last few months or years of sedimentation (Battarbee et al., 2001). The combination of compositional diatom abundance data from the sediments with physico-chemical data (environmental data) from the water column that describe the key characteristics of the wetland, produces what is called a training data-set (Birks, 2010). Relating the two type of data (diatom abundances in the sediments and environmental data) with statistical analyses, a model called transfer function can be produced allowing the quantitative reconstruction of an environmental variable for a given time of the past (Sachs et al., 1977).

A second set consisted of core samples taken from Lagoa de Traba (ED50: 29T 496302E; 478265N) in Galicia (Fig. 2.2a, Chapter 2), NW Spain, and Lagoa de Melides (ED50: 29S 000165E; 4220501N), in central-west Portugal (Fig. 2.2b, Chapter 2), covering, in both coastal systems, the sedimentation occurred in the very late Holocene. A palaeoenvironmental reconstruction allowing the identification of the main forcing factors driving the recent evolution of the two systems was performed using sedimentological and geochemical data from the cores and, especially, the knowledge of diatom modern analogues from the training data-set.

In the following section, field methods, sample processing techniques and numerical analysis procedures will be described as applied to both the present-day (training set) and core data-sets.

## 3.2 FIELD METHODS

Field surveys for bottom sediment sampling and measurement of physico-chemical variables characterizing the overlying water column were completed between February 2007 and July 2008, on a seasonal basis (Tables 3.1, 3.2 and 3.3, Appendix I).

Table 3.1 – Summary of data collected for the study of present-day samples. Further details in the text.

| Data-Set | Samples | Variables |
|---|---|---|
| **Abiotic (environmental variables)** | Water: in-situ physico-chemical direct measurements | Temperature, pH, Eh, conductivity, salinity, concentration dissolved $O_2$ and % saturation $O_2$ |
| | Water: laboratory analyses | Nutrients ($NO_3^-$, $NO_2^-$, $NH_4^+$, $PO_4^{3-}$, $SiO_4^{4-}$) Anions ($SO_4^{2-}$, $Cl^-$), cations ($Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$ $Si^{4+}$) and Dissolved Organic Carbon (DOC) |
| **Biotic (diatom data-set)** | Bottom sediments | Diatom content |

### 3.2.1 WATER SAMPLING – ENVIRONMENTAL PARAMETERS

Water sampling and in-situ measurements were performed two to four times per year (Table 3.3, Appendix I) to examine the seasonal environmental variability and to compute an annual average. In each sampling station measurements of physico-chemical variables were taken at the surface for shallow water bodies and every 0.5 m along the water column from surface until bottom for deeper water bodies. Temperature, pH, redox potential, conductivity, salinity, dissolved oxygen (concentration and % of saturation) were measured in-situ using calibrated probes (Table 3.2). Water samples were collected with a Van Dorn water sampler for laboratory analyses (surface samples for shallow water bodies and a bottom sample for deeper water bodies); for nutrient ($NO_3^-$, $NO_2^-$, $NH_4^+$, $PO_4^{3-}$, $SiO_4^{4-}$) determination, water was stored in 50 mL bottles and frozen at -20 °C until analysis; water for $SO_4^{2-}$ and $Cl^-$, was stored in 150 mL bottles and kept at 4 °C avoiding direct sunlight; and water for $Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$ and $Si^{4+}$ was collected in 250 mL bottles (pre-acidified with nitric acid) and kept at 4 °C avoiding direct sunlight; water for Dissolved Organic Carbon (DOC) was stored in 1L bottles at 4 °C and avoiding direct sunlight.

Table 3.2 – Instruments and probes used in in-situ water analyses.

| Parameter | Instruments and Probes |
|---|---|
| **pH/ Eh** | WTW pH; electrode SenTix 41 and WTW electrode SenTix ORP probes |
| **Conductivity/ Salinity/ Temperature** | WTW conductivity meter LF 191, WTW Cond 197i ; WTW LA 1/T probe, WTW TetraCon 325 and WTW TetraCon 325 probes |
| **Dissolved Oxygen** | YSI Model 57 oxygen meter and YSI Model 5739; WTW Oxi 197i, CellOx 325 probes |

Table 3.3 – Location, dates and codes of water column and bottom sediments samples collected for the characterization of the studied coastal environments (present-day data-set).

| | | | ED-50 (29) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | code | X | Y | Date | Reference | Date | Reference | Date | Reference | Date | Reference |
| **Galicia, Spain** | Valdoviño | VAL | 29T 568151 | 4828414 | 01.02.07 | VAL0102 | 16.04.07 | VAL1604 | 29.07.07 | VAL2907 | 16.11.07 | VAL1611 |
| | Doniños | DON | 29T 555470 | 4815749 | 01.02.07 | DON0102 | 16.04.07 | DON1604 | 29.07.07 | DON2907 | 16.11.07 | DON1611 |
| | Traba | TRA | 29T 496602 | 4815749 | 01.02.07 | TRA0102 | 17.04.07 | TRA1704 | 31.07.07 | TRA3107 | 19.11.07 | TRA1911 |
| | Louro | LOU | 29T 492298 | 4734128 | - | - | 17.04.07 | LOU1604 | 26.07.07 | LOU2607 | 19.11.07 | LOU1911 |
| | Xuño | XUN | 29T 496971 | 4720279 | - | - | 18.04.07 | XUÑ1804 | 30.07.07 | XUÑ3007 | 20.11.07 | XUÑ2011 |
| | Muro | MUR | 29T 496680 | 4719678 | - | - | 18.04.07 | MUR1804 | 30.07.07 | MUR3007 | 20.11.07 | MUR2011 |
| | Espiñeira | ILL | 29T 510426 | 4710359 | - | - | 15.04.07 | ILL1504 | 27.07.07 | ILL2707 | - | - |
| | Bodeira | BOD | 29T 507839 | 4702728 | - | - | 15.04.07 | BOD1504 | 27.07.07 | BOD2707 | 21.11.07 | BOD2111 |
| | | | | | | | | | | | | |
| **Portugal** | Minho - low salt marsh | MINBS | 29T 0514684 | 4637504 | 17.07.07 | Minho BS 17.07.07 | 18.03.08 | Minho BS 18.03.08 | | | | |
| | Minho tidal flat | MINRM | 29T 0514574 | 4637610 | | Minho RM 17.07.07 | | Minho RM 18.03.08 | | | | |
| | Lima tidal Flat | LIMARM | 29T 0514950 | 4615106 | 18.07.07 | Lima RM 18.07.07 | 19.03.08 | Lima RM 19.03.08 | | | | |
| | Vela | LVB | 29T 0517837 | 4457972 | 10.07.08 | LVB 10.07.08 | 20.02.08 | LVB 20.02.08 | | | | |
| | Obidos | OB1 | 29S 0481233 | 4360867 | 6.07.07 | Ob est1 06.07.07 | 17.03.08 | Ob est1 17.03.08 | | | | |
| | Obidos - Barrosa | OB2 | 29S 0483093 | 4361828 | | Ob est2 06.07.07 | | Ob est2 17.03.08 | | | | |
| | Albufeira - Lagoa Grande 1 | ALB1 | 29S 0485372 | 4263677 | 2.05.07 | Alb est1 02.05.07 | 9.01.08 | Alb est1 09.01.08 | | | | |
| | Albufeira - Lagoa Grande 2 | ALB2 | 29S 0486389 | 4263861 | | Alb est2 02.05.07 | | Alb est2 09.01.08 | | | | |
| | Albufeira - Lagoa Pequena | ALB3 | 29S 0487279 | 4263930 | | Alb est3 02.05.07 | | Alb est3 09.01.08 | | | | |
| | Sado - tidal flat | SADORM | 29S 0521193 | 4252126 | 9.07.08 | SADO RM 9.07.08 | 14.02.08 | Sado 14.02.08 | | | | |
| | Melides | MELB1 | 29S 0518706 | 4220581 | 1.07.08 | MEL B1 01.07.08 | 29.10.07 | MEL 29.10.07 | | | | |
| | Santo André-main channel | SA1 | 29S 0518624 | 4217726 | 11.05.07 | SA est1 11.05.07 | 18.12.07 | SA est1 18.12.07 | | | | |
| | Santo André- Margin | SA2 | 29S 0518221 | 4216946 | | SA est2 11.05.07 | | SA est2 18.12.07 | | | | |
| | Santo André- Alguidares | SA3 | 29S 0517784 | 4217376 | | SA est3 11.05.07 | | SA est3 18.12.07 | | | | |
| | Barbaroxa de Baixo | BB | 29S 0516778 | 4214846 | | BB 11.05.07 | 18.12.07 | BB 18.12.07 | | | | |
| | Mira - low salt marsh | MIRABS | 29S 0520557 | 4175603 | 15.05.07 | Mira BS 15.05.07 | 19.12.07 | Mira BS 19.12.07 | | | | |
| | Mira- tidal flat | MIRARM | 29S 0520478 | 4175680 | | Mira BM 15.05.07 | | Mira RM 19.12.07 | | | | |

### 3.2.2 PRESENT-DAY BOTTOM SEDIMENTS AND CORES

A total of 25 sites from 18 water bodies that make up this study were sampled for the study of modern analogues. Bottom sediments were collected using a van Veen grab sampler. The uppermost 1 cm of sediment was taken and stored in plastic vials at 4 °C.

Short cores were taken in 2003 in Lagoa de Melides (3 replica, cores LM6-1, LM6-2 and LM6-3) and in 2007 in Lagoa de Traba (2 replica, cores TRA07-A1 and TRA07-A2) (Fig. 2.2a and b, Chapter 2; Table 3.4) using a hand-driven gravity corer (Melides) operated from a small boat and a piston corer from Aquatic Research Instruments (based on Fisher et al., 1992) also operated from a small boat (Traba). The cores were kept at 4 °C in the laboratory, described macroscopically, and subsampled at 1 cm intervals. The sedimentological and geochemical characterization of the replicas allowed for detailed correlation between cores of different length and to construct two composite cores, LM6 and TRA07. On Results Chapter (Chapter 4), data and results of analytical procedures, will be refer to the replica core, whereas interpretations and discussion will refer to the composite cores.

Table 3.4 – Summary of analyses performed and core depths from Traba (TRA07) and Melides (LM6).

| Core/replica | Length (m) | Analysis performed |
|---|---|---|
| **TRA07-A1** | 0.45 | Diatoms<br>%TN, %TC, %TS, $\delta^{13}C$, $\delta^{15}N$, $^{210}Pb$ and $^{137}Cs$ |
| **TRA07-A2** | 0.66 | Sedimentology and $^{14}C$ |
| **LM6 - 1** | 0.81 | $^{210}Pb$, $^{137}Cs$ |
| **LM6 - 2** | 0.82 | Sedimentology |
| **LM6 - 3** | 0.88 | Diatoms, %TN, %TC, $\delta^{13}C$, $\delta^{15}N$ and $^{14}C$ |

## 3.3 LABORATORY METHODS

### 3.3.1 WATER ANALYSIS

Nutrients in water ($NO_3^-$, $NO_2^-$, $NH_4^+$, $PO_4^{3-}$, $SiO_4^{4-}$) were analysed in the Instituto de Investigacións Mariñas (Consejo Superior de Investigaciones Científicas - CSIC, Vigo, Spain) using an Integral Futura autoanalyser system (Alliance Instruments), which uses separate analytical lines to determine nitrate ($NO_3^-$), nitrite ($NO_2^-$), phosphate ($PO_4^{3-}$), ammonium ($NH_4^+$), and silicate ($SiO_4^{4-}$), according to standard colorimetric methods (Hansen & Koroleff, 1999). The accuracy of the analytical procedure was assessed by processing certified reference materials: MOOS-1 (seawater nutrients; NRC, Canada), and good agreement has been obtained with the certified values. The precision measured was assessed by relative standard deviation (RSD), always remained less than 5 %. Detection limits, expressed as three times the standard deviation of 10 replicate measurements of reagent blanks, were: 0.14 µM for nitrate, 0.01 µM for ammonium, 0.08 µM for phosphate and 0.14 µM for silicate.

In the Servizos de Apoio á Investigación of the Universidade da Coruña (SAI-UDC), anion content ($Cl^-$, $SO_4^{2-}$) was measured by capillary electrophoresis with a WATERS Capillary Ion analyzer, and cations ($Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$ and $Si^{4+}$) using a High Resolution ICP-MS (Thermo-Scientific Finnigan ELEMENT XR).

Dissolved organic carbon (DOC) was measured with a Total Organic Carbon Analyzer Shimadzu TOC 5000A in the SAI-UDC.

Dissolved inorganic carbon (DIN) results determined from all of the N sources measured, i. e., DIN = $NO_3^- + NO_2^- + NH_4^+$.

### 3.3.2 DIATOMS

Bottom sediment samples taken during the last field survey in each site, were selected for the study of diatom content in order to relate diatom assemblages with water parameters. The collected material (uppermost 1 cm) is assumed to contain representative information of the environmental constrains modulating the depositional system, time-averaged over the last few years or months (Battarbee et al., 2001) (Appendix IIA). Similarly, sediment cores were sampled every 1 cm (Traba, TRA07-A1, Appendix IIB) or every 2 cm (Melides, LM6-3, (Appendix IIC) for diatom analysis.

Both present-day and core sediment samples were prepared following Renberg (1990). Each dry sediment subsample, weighting approximately 0.1 g, was inserted in a 10 mL-capacity centrifuge tube and treated with hot $H_2O_2$ (30 %) and HCl (35 %) to remove organic matter and carbonates, respectively. Following elimination of these components, successive washings with distilled water were made until neutralization of the suspension. After each washing operation, the supernatant was separated by centrifugation at 1200 rpm during 4 minutes.

The suspensions were then successively subjected to dilution or concentration procedures until an appropriate diatom valve concentration in the microscopic slides was achieved for routine identification and counting under the microscope. Finally, 0.5 mL of this suspension was extended on a clean cover glass, dried at room temperature, and mounted on a slide with Naphrax® mounting medium (refractive index = 1.74).

The slides were observed under light microscope for taxonomic identification. This was done at GeoFCUL laboratories (Departamento de Geologia, Faculdade de Ciências da Universidade de Lisboa, Portugal), using an Olympus BX 51 - phase contrast microscope (magnification 1000x), and at the laboratories of the Facultade de Ciencias, Universidade da Coruña (UDC, Spain) using a Nikon Eclipse E600 - differential-interferential contrast Normarsky microscope (magnification 1000x).

In addition to optical methods, Scanning Electron Microscopy (SEM) was used at FCUL and UDC for the identification of problematic taxa in both present-day and core sediment samples. At Centro de Biologia Ambiental (CBA) of FCUL, aliquots of clean material were air dried onto 1 cm-diameter circular pieces of aluminium foil. These stubs were coated with gold using a JEOL JFC-1200 Sputter Coater. A JEOL JSM-5200LV electron microscope operating at 15/25 kV and 20 mm distance was used for the analysis, and digital images were directly captured. At

UDC, aliquots of treated material were air dried onto 2.5 cm-diameter circular pieces of aluminium foil. These stubs were then coated with gold-palladium using a BAL-TEC SCD 004 Sputter Coater. A JEOL JSM 6400 electron microscope operating at 5/30 kV and 20 mm distance was used for SEM analysis and digital images were obtained.

The identification of diatoms was based on the floras of Krammer & Lange-Bertalot (1986-1991), Lange-Bertalot (1993), Snoeijs (1993), Snoeijs & Vilbaste (1994), Lange-Bertalot & Gert (1994), Snoeijs & Potapova (1995), Snoeijs & Kasperovičiené (1996), Krammer (1997a, b), Snoeijs & Balashova (1998), Witkowski et al. (2000), Morales (2001, 2002) and Lange-Bertalot (2000-2003).

A minimum of 400 valves per sample were counted following random transects under the microscope. The categories considered for counting followed Schrader & Gersonde (1978). Raw counts were converted to relative frequencies, that is, the proportion of individual taxa relative to the total diatom count in the sample, and expressed as percentages. In the cases of the cores collected at Melides and Traba, the vertical (downcore) data on diatom abundances were displayed in the form of stratigraphical diagrams constructed using the C2 v.1.5.1 software (Juggins, 2007).

### 3.3.3 SEDIMENTOLOGICAL AND GEOCHEMICAL ANALYSIS

### *3.3.3.1 Core sediments*

#### 3.3.3.1.1 Sedimentology

Cores TRA07-A2 and LM6-2 were sampled every 1 or 2 cm for different types of sediment analysis. Samples from core LM6-2 were analysed for pH, % organic matter, % calcium carbonate and texture. TRA 07-A2 samples were used only for textural analysis.

pH was determined by the electrometric method according to the Portuguese standard E 203 (LNEC, 1967). For the determination of the organic matter content loss on ignition was performed using an oven burning at 500 $^{o}$C for 2 hours. The calcium carbonate content was determined gasometrically using an Eijkelkamp calcimetre. The size separation of the fractions above and below 63 µm was performed by wet sieving using a 4 ϕ sieve. This procedure allowed the textural classification of sediments according to Flemming (2000). Fraction below 63µm was analysed by a Malvern Mastersizer 2000 particle size analyser. All these analyses were performed at GeoFCUL.

In core TRA07-A2, the size separation of the fractions above and below 63µm was performed by wet sieving using a 4 ϕ sieve in UDC. Textural classification of sediments was done following Flemming (2000). Fraction below 63 µm was also analysed at GeoFCUL, using a Malvern Mastersizer 2000 particle size analyser.

#### 3.3.3.1.2 Carbon, Nitrogen and Sulphur Contents

In both cores, the percentages of total carbon (TC) and total nitrogen (TN) were determined by combustion of dry sediment at 1050 °C, using an elemental analyser equipment EuroVector, mod. EuroEA 3000, at GeoFCUL for core LM6-2 and LECO elemental autoanalyzer mod. 1000 for TRA07-A1, at UDC. Total organic carbon (TOC) in core samples of both sites was estimated as the difference between TC and total inorganic carbon (TIC), the latter measured by weight difference before and after incineration of the sample at 450 °C during 4 hours (Cambardella et al., 2001). In this work, TN was considered equal to total organic nitrogen (TON), since in most sedimentary materials the fraction of inorganic nitrogen is negligible (Müller & Mathesius, 1999).

For both cores, TOC, TN, and the ratio of carbon and nitrogen stable isotopes in organic matter ($\delta^{13}C_{org}$ and $\delta^{15}N_{org}$ respectively) were determined using samples taken every 2 cm and pre-treated with HCl at 4 mol $L^{-1}$ to remove inorganic carbon, followed by repeated washing with distilled water until neutrality. Analyses were made in a FlashEA1112 elemental combustion analyser (ThermoFinnigan), coupled with a DELTAplus isotope ratio mass spectrometer (ThermoFinningan) at the SAI-UDC. The results obtained for TOC and TN were converted to the total sample in TRA07. In LM6-3 core, the bulk sample was not weighted prior to analyses. To overcome this drawback, a sensitive analysis was conducted using % $CaCO_3$ data obtained in LM6-1. Results show that for a range of % $CaCO_3$ < 10 %, the converted TOC/TN (referenced as $C_{org}/N_{total}$) values never exceeded 12 (maximum value of unconverted $C_{org}/N_{total}$) and differences to unconverted $C_{org}/N_{total}$ were less than 1 unit. Although absolute TOC values may be different, the interpretations of $C_{org}/N_{total}$ ratios remain unchanged.

In core TRA07-A1 the percentage of total sulphur (TS) was measured by combustion at 1200 °C in a LECO mod. SC 144DR autoanalyzer at the laboratories of the Departamento de Edafoloxía e Química Agrícola from the Universidade de Santiago de Compostela.

#### 3.3.3.1.3 $^{210}$Pb, $^{137}$Cs, and $^{14}$C Radioisotope Dating

LM6-1 and TRA07-A1 cores were dated by measuring the activity profiles of $^{210}$Pb and $^{137}$Cs. The down-core excess of $^{210}$Pb and of $^{137}$Cs activity profiles was measured using gamma spectrometry in 13 samples taken from LM6–1 at the Université de Bordeaux 1 (France), UMR CNRS 5805 Environnements et Paléoenvironnements Océanique et Continentaux (EPOC), using gamma spectroscopy and 11 samples from TRA07-A1 at the University College Dublin School of Physics (Ireland).

Additionally, three samples of organic sediment from LM6-3 (taken at 87.5, 44.5 and 34.5 cm depth) and other three from TRA-07-A2 (taken at 94, 36 and 28 cm depth), were dated by the $^{14}$C method (Björck & Wohlfarth, 2001) using accelerator mass spectrometry (AMS). Analyses were carried out at Beta Analytic Inc. (Florida, USA) for LM6-3 and at the Poznan Radiocarbon Laboratory (Poland) for TRA-07-A2.

## 3.4 NUMERICAL ANALYSIS

The statistical study of the relationship between diatom assemblages in present-day bottom sediments and environmental variables measured in the water column is one of the main goals of this work. The objective is to use this knowledge to make precise quantitative inferences of past hydrochemical conditions from the fossil diatom assemblages found in the cores. To achieve this, different types of multivariate data analyses were performed, as described below.

### 3.4.1 THE PRESENT-DAY DATA-SET

The present-day data-set consists of water column environmental data and abundance data of the main taxa making up diatom assemblages in present-day bottom sediments (Appendix I and IIA). Average values of the water column environmental data were used in the numerical analyses. These values were log (x+1) transformed for regression and calibration (except for pH values). For the case of diatoms, only those taxa with abundance ≥ 2 % and occurring in two or more samples were included in the analyses, to minimize the influence of rare taxa. This reduced the data-set from 386 to 46 taxa, and the abundance values (percentages) were further squared root-transformed for regression and calibration (see section 3.4.1.2.1 below).

#### *3.4.1.1 Environmental data*

##### 3.4.1.1.1 Variance inflation analysis

Some of the variables integrating the environmental data-set may be correlated (for example, salinity and conductivity), thus contributing to undesirable multi-collinearity effects, a statistical property in which two or more predictor variables in a multiple regression model are highly correlated. In order to reduce redundancy introduced by multi-collinearity effects, the environmental data-set was studied for the Variance Inflation Factor (VIF), as implemented in the CANOCO 4.5 computer program (ter Braak & Šmilauer, 2002). VIF measures the proportion by which the variance of a regression coefficient is inflated in the presence of other explanatory variables (Boccard et al., 2011). Higher VIF values indicate existence of more collinear variables in the model and VIF < 10 (the threshold value used in this study) is considered sufficiently low as to avoid collinearity effects.

#### *3.4.1.2 Diatom and Environmental data*

##### 3.4.1.2.1 Diatom-based Palaeoenvironmental reconstructions

One of the goals of this work is to evaluate ecological optima and tolerance of diatom assemblages of the present-day data-set to construct transfer functions that allow palaeoenvironmental conditions to be quantitatively inferred from fossil assemblages data (Birks et al., 1990). Besides these quantitative palaeoenvironmental reconstructions, a qualitative approach based on the known autocologies of the diatom taxa has also been adopted. Autoecological information on life-forms, saline affinities and pH, among others, was mainly obtained from dter Braake Wolf (1982), Kjemperud (1982), Denys (1991a, b), Vos & de Wolf (1993b), Snoeijs (1993), Snoeijs & Vilbaste (1994), Van Dam et al. (1994), Snoeijs & Potapova (1995), Snoeijs & Kasperovičiené (1996) and Snoeijs & Balashova (1998).

Both diatom and environmental data were first analysed using clustering methods in order to recognize similarities that could finally lead to groups for both data-sets. Following this procedure, an evaluation of the ecological optima and tolerance of diatom assemblages from the present data-set was made to construct transfer functions. This procedure involves two steps: (1) the **regression step,** in which the responses of taxa to the contemporary environment are modelled, and (2) a **calibration step,** in which the environmental variable of interest is predicted from the fossil compositional data (Birks, 1995; Birks et al., 2012).

###### *3.4.1.2.1.1 Cluster Analysis*

Cluster analysis was used to examine the whole set of environments addressed in this study according to their affinities with respect to both the diatom assemblages and sample location data. Cluster analysis followed the Ward's method (Ward, 1963) and Gower distance matrix (Gower, 1971), using the functions *hclust* and *vegedist* included in the v*egan* package 1.17-6 (Oksanen et al., 2011) of the R software (R Development Core Team, 2010). A total height cut-off of 20 and 17 was used for diatom and sample grouping, respectively.

###### *3.4.1.2.1.2 Transfer Function*

###### *3.4.1.2.1.2.1 Regression and Calibration*

The mathematical methods for establishing transfer functions are commonly based on linear/monotonic or nonlinear (unimodal) regression techniques (Birks, 2012). Hill & Gauch (1980) defined the length of the gradient of variation in biological data as the range of the sample scores obtained from a Detrended Correspondence Analysis (DCA). If the gradient length is short (2 standard deviation units or less), taxa generally behave monotonically (i. e., they have a linear response) along the gradient (ter Braak & Prentice, 1988; Birks, 1995); otherwise, if the gradient length is larger (2 standard deviation units or more), several taxa will have their optima located within the gradient, and use of unimodal-based models of regression and calibration is more appropriate. In this study, the CANOCO 4.5 computer program (Ter Braak & Šmilauer, 2002) was used to perform the data analyses.

In cases showing a linear response of the diatoms to the environmental gradients, regression and calibration techniques such as classical linear regression, inverse linear regression or partial least (PLS) or redundancy analysis (RDA) can be used (Birks, 1995; Birks et al., 2012). If a unimodal distribution is assumed as more representative of the data-set, then regression and calibration may be achieved using techniques such as weighted averaging (WA, ter Braak, 1987; ter Braak & Van Dam, 1989), correspondence analysis (CA, ter Braak, 1987), canonical correspondence analysis (CCA, ter Braak, 1986) or weighted averaging –partial least squares (WA-PLS, ter Braak & Juggins 1993).

As will be shown later, the diatom responses found in this study agree with a unimodal response model, thus various (unimodal) non-linear regression and calibration methods were used. Canonical Correspondence Analysis regression (CCA) is a multivariate method to elucidate the relationships between biological assemblages (species) and their environment. The method is designed to extract synthetic environmental gradients from ecological data-sets. A good indicator for assessing the viability of an environmental variable selected to construct transfer functions is the ratio of $\lambda 1$ to $\lambda 2$, the first two eigenvalues of partial CCA (ter Braak, 1988; Hall & Smol, 1992). Variables exhibiting high $\lambda 1/\lambda 2$ ratio (> 1) generally produce strong calibration models, but lower ratios can still be of use in the construction of transfer functions provided that care is taken in ecological interpretation (ter Braak, 1987, 1988). The statistical significance of the 1st axis and of all canonical axes was assessed by unrestricted Monte Carlo tests (full model) involving 999 permutations at $p \leq 0.05$.

A series of partial CCAs was then performed. Each run considered one explanatory variable at a time to establish the significance and relative strength of its contribution to the total variance found in diatom data. Variance partitioning was performed by additional partial CCAs where the effects of other variables were removed, or partialled out, by including them as covariables, to establish: (1) the unique contribution of individual chemical gradients, (2) the contribution due to interactions between gradients, and (3) the unexplained variance (Gasse et al., 1995). The amount of variation explained in each case was transformed into percentages by dividing the sum of canonical eigenvalues by the total inertia, according to the procedure described by Borcard et al. (1992). The statistical significance of each explanatory variable was assessed by unrestricted Monte Carlo tests (full model) involving 999 permutations at $p \leq 0.05$. All analyses were performed using the CANOCO 4.5 computer program (ter Braak & Šmilauer, 2002).

After CCA validation, diatom taxon responses (optima and tolerances) were modelled, using WA with C2 v.1.5.1 (Juggins, 2007).

The most popular models of calibration for unimodal distributions used in diatom studies are Weighted Averaging (WA; ter Braak & Van Dam, 1989) and the WA partial least squares (WAPLS; ter Braak & Juggins, 1993), because they perform well in cases considering noisy, species-rich, compositional data, with many zero values and some outliers. Both models were tested using the program C2 v.1.5.1 (Juggins, 2007). In both approaches, the underlying response model is the Gaussian function, that is, each taxon is assumed to follow a bell-shaped distribution along an environmental variable.

For reconstruction purposes, it is essential to estimate the gradient length for the environmental variables(s) of interest. This can be assessed by Detrended Canonical Correspondence Analysis (DCCA, ter Braak, 1986) constrained to that particular environmental variable (Birks, 1995). If the gradient is short (2 standard deviation units or less) taxa generally behave monotonically along the gradient (ter Braak & Prentice, 1988). If the gradient length is larger (more than 2 standard deviation units), several taxa will have their optima located within the gradient, and unimodal-based models of regression and calibration are considered more appropriate. CANOCO 4.5 computer program (ter Braak & Šmilauer, 2002) was used for these tasks.

Validation of the models can be addressed by analysing the different statistical parameters extracted by cross-validation procedures (ter Braak & Juggins, 1993) like jack-knifing (Quenouille, 1949) and/or bootstrapping (Efron, 1979): coefficient of determination ($r^2$), apparent root mean square error (RMSE), root mean square error of prediction (RMSEP), mean and maximum bias. Ideally, the best models should yield high $r^2$ and low RMSEP values when compared to the variable range and low mean and maximum bias values based on cross-validation (ter Braak & Juggins, 1993).

Jack-knifing (also known as 'leave-one-out' measures) is a cross-validation method that provides more reliable measures of the overall predictive ability of the data-set, at least when applied to the modern assemblages (Sejrup et al., 2004). However, it does not provide sample-specific errors for the environmental variable chosen for reconstruction of each core sample (Birks, 1995). Bootstrapping can be used to derive a standard error of prediction (SEpred; Birks et al., 1990), which varies from sample to sample depending upon the composition of the core assemblage and the presence or absence of taxa with a particularly strong signal for the environmental variable of interest (Birks, 1995). Also, the optimal number of components for WA-PLS to include in the transfer functions can be assessed by leave-one-out. In the present case, these validations were undertaken with the C2 v.1.5.1 (Juggins, 2007) software environment.

### 3.4.2 CORE DATA

#### *3.4.2.1 Sedimentology, Geochemistry and Diatoms*

The core data-sets (Traba and Melides) consist of diatom abundance and sedimentological and geochemical data. Sedimentological and diatom abundance data were subject to numerical analyses, aiming to: i) establish contrasting Sedimentological and Diatom Assemblage Zones and ii) use sedimentology data and diatom assemblages to identify the essential underlying palaeoenvironmental changes and/or trends. To minimize the influence of diatom rare taxa, only diatom taxa with abundance ≥ 2 % and occurring in at least one sample were selected for the analyses (Appendix IIB and C).

The concept of Diatom Assemblage Zone (DAZ) is inspired on the concepts of Fossil Assemblage Zone and Fossil Abundance Zone (Murphy & Salvador, 1999). A DAZ may be defined as the body of strata characterized by an assemblage of diatoms in which the abundance of a particular taxon or specified group of taxa is significantly greater than is usual in the adjacent parts of the stratigraphic section. In this study, the definition of the main DAZs in the diatom abundance diagrams was performed using stratigraphically-constrained cluster analysis (Constrained Incremental Sum of Squares Clustering, CONISS, Grimm, 1987), based on squared Euclidian dissimilarity, computed using the packages *vegan* version 1.17-6 (Oksanen et al., 2011) and *Rioja* version 0.5-6 (Juggins, 2009) developed for the R software (R Development Core Team, 2010). Zonation with variances exceeding values generated by a broken-stick model of the distribution of variance was deemed statistically significant (Bennett, 1996). Clustering obtained from cluster analysis was also used for the definition of subzones. Total dispersion cut-offs of 200 and 600, obtained from cluster analyses were used for the definition of subzones in Traba and Melides, respectively. The sedimentological data were also processed using the methodologies described above to obtain a sedimentological/litoestratigraphical zonation and help in the definition of sedimentological units, using a total dispersion cut-offs of 1100 and 155 for the definition of sedimentary subzones in Traba and Melides, respectively.

Ordination analyses were conducted to identify the main environmental gradients explaining the variability in diatom abundance. For both Melides and Traba, data matrices contain few zero values, so classical ordination methods were used. A DCA was first performed to estimate the length of the dominant gradient for the diatom assemblages and thus to evaluate whether the taxa followed a unimodal or linear distribution (Jongman et al., 1987). The CANOCO 4.5 computer program (ter Braak & Šmilauer, 2002) was used for this. As explained above, when the obtained length of gradients was larger than 2 standard deviations, a unimodal distribution was assumed (ter Braak & Prentice, 1988) and a CA was performed. For length gradients of less than 2 standard deviations, the response of the diatoms was considered monotonic/linear, and a Principal Component Analysis (PCA) (Lepš & Šmilauer, 2003), was performed. Both analyses were run using the C2 program, v. 1.5.1 (Juggins, 2007).

#### *3.4.2.2 Plot of passive samples in CCA*

Core samples from Melides and Traba were plotted as supplementary passive samples (i. e., not influencing on the ordination) on the biplot of the CCA that relates the present-day diatom assemblages of the WIAC with the main present-day environmental gradients. These plots were used to help in understanding the underlying trajectories of environmental change when interpreting the fossil data (Birks et al., 1990; ter Braak & Šmilauer, 2002). Fossil diatom abundance data were squared root transformed.

#### *3.4.2.3 Transfer functions*

After assessing the best model to use in calibration (section 3.4.1.2.1.2.1), the selected model was applied to the core data. Sample-specific errors of the environmental variable chosen for reconstruction of each core sample were computed by bootstrapping (Birks et al., 1990). Then, a validation of reconstructed environmental values was undertaken. The most powerful validation method is to compare reconstructions with historical records (e. g., Fritz, 1990; Laird et al., 1996; Lotter, 1998), which is limited to the recent past; the second best procedure is to compare reconstructions with independent palaeoenvironmental data (Fritz et al., 1994).

Since the original data-set was processed using a log (x+1) transformation, reconstruction of palaeoenvironmental variables was achieved using an inverse transformation.

#### *3.4.2.4 Geochronology*

Results obtained from the vertical profiles of $^{210}$Pb and $^{137}$Cs activities, as well as from the AMS $^{14}$C dating, allowed to develop an age model by fitting the age–depth data with *linear interpolation between neighbouring levels* using the *clam* code version 2.1 routine (Blaauw, 2010) developed for the software R (R Development Core Team, 2010). This routine calibrates radiocarbon ages using the standard IntCal09 calibration curve (Stuiver et al., 1998; Reimer et al., 2009) and generates Monte Carlo age–depth fits through the calibrated age probability distributions. It then calculates the ‘best-fit’ age-depth curve as the weighted average of 1000 iterations. The confidence intervals are calculated at the 2 σ range centred at the mean value of the iterations.

# 4. Results

*Chapter 4.1. Diatom assemblages in present-day bottom sediments of Western Iberian Atlantic coastal environments*

*Chapter 4.2. Climatic and anthropogenic impacts in Traba coastal wetland (Galicia, NW Spain) in the last 550 years*

*Chapter 4.3. Natural and human-induced changes in alternative stable states – a 1745 years record of environmental change in the Melides coastal lagoon (Portugal)*

# 4.1. Diatom assemblages in present-day bottom sediments of Western Iberian Atlantic coastal environments

### 4.1.1 INTRODUCTION

Most of the estuaries and coastal wetlands of the Western Iberian Atlantic Coast (WIAC) have been originated after c. 5500 cal yr BP (calibrated years before Present) as a result of the late Holocene sea-level rise deceleration (e. g., Bao et al., 1999, 2007; Freitas et al., 1999, 2002a, 2003a; Cearreta et al., 2003; Freitas & Andrade, 2005; Dinis et al., 2006, Costas et al., 2009; González-Villanueva et al., 2009). Since their origin, they have been affected by both global (eustatism, climate) and local (sediment availability and fluvial basin changes, anthropic influence) forcing factors occurring at different time scales. Whereas global drivers of change were mainly responsible for the early evolution of these systems, the relative importance of local factors have increased in more recent times (Freitas et al., 2002a; Dinis et al., 2006; Leorri et al., 2013).

The use of microfossils was decisive in the multidisciplinary palaeoenvironmental reconstructions that lead to the knowledge of the controlling factors on the Holocene evolution of the transitional environments from the WIAC (e. g., Santos et al., 2001; Ramalho, 2003; Santos & Sánchez-Goñi, 2003; Cearreta et al., 2003, 2007; Cabral et al., 2006; Drago et al., 2006; Naughton et al., 2007b; Danielsen, 2008; Gomes et al., 2012; Leorri et al., 2013). Among these, diatoms have proven to be particularly useful (Bao et al., 1999, 2007; Santos et al., 2001; Cearreta et al., 2003; Granja et al., 2010), but whereas precise quantitative palaeoenvironmental reconstructions could be accomplished elsewhere (Cooper et al., 2010; Snoeijs & Weckström, 2010), interpretation of the Ibero Atlantic Holocene diatom records have always been qualitative (e. g., Bao et al., 1999, 2007; Santos et al., 2001; Ferreira, 2006; Santos, 2010), based on autoecological data from other regions (e. g., Vos & de Wolf, 1993a, b).

Understanding the relationship between present-day dead diatom assemblages (thanatocoenoses) and the environmental variables that control their distribution, is a key factor for quantitative palaeoenvironmental reconstruction (Birks, 2012). In spite of the fact that quantitative studies performed on continental aquatic ecosystems are much more common than those carried out on marine or coastal areas (Mackay et al., 2003), some present-day calibration data-sets have been established for different types of coastal systems and geographical areas. Hence, transfer functions have been developed for the reconstruction of changes in salinity and conductivity (e. g., Juggins, 1992; Roberts et al., 2004; Hassan et al., 2009; Wachnicka et al., 2010; Zong et al., 2010; Espinosa et al., 2012), pH (Denys, 2006), nutrients (Clarke et al., 2003; Weckström et al., 2004), tidal and sea-level (Zong & Horton, 1999; Horton et al., 2007), elevation (Sawai et al., 2004), water depth (Campeau et al., 1999; Ng & Sin, 2003) or dissolved inorganic carbon (Denys, 2006). For the case of changes in salinity and conductivity, precise inferences are however hindered by the fact that diatoms adapt to a wide range of conditions in brackish and marine habitats (Denys & de Wolf, 1999).

Few studies have examined the present-day distribution patterns of diatoms in the Ibero Atlantic coastal systems and their relationship with the main environmental gradients (Sampayo, 1970; Gameiro, 2009; Ribeiro, 2010; Ribeiro et al., 2003, 2013; Resende et al., 2005, 2007; Mendes et al., 2009; Ferreira et al., 2010; Gomes et al., 2012), and they have been of limited geographical extent (Lagoa de Albufeira e Santo André), and mainly focussed on the study of estuaries (Aveiro, Tagus, Sado and Guadiana). It has been shown that, at least for the reconstruction of palaeotidal levels, application of regional transfer functions should be preferred rather than those constructed from local training-sets (Wilson & Lamb, 2012). It is therefore necessary to complete our knowledge of the present-day diatom assemblages and their relationship with the physical and chemical environment in a broader geographic extent and arranging a wider set of coastal ecosystems for more precise palaeoenvironmental reconstructions in the future.

This chapter shows how diatom assemblages in present-day bottom sediments of different types of aquatic systems from the Galician and Portuguese coast respond to mg $L^{-1}$ the main environmental gradients. From this knowledge, a transfer function for water salinity in the WIAC has been derived.

### 4.1.2 DATA

The original data-set incorporates data from 25 bottom sediment samples belonging to 18 transitional systems of the WIAC (Fig. 2.1, Table 2.1, Chapter 2). For each bottom sediment sample, diatom abundance and associated environmental data were collected. Only diatom taxa observed in ≥ 2 % abundance and occurring in two or more samples were included in the subsequent data analysis to minimize the influence of rare taxa, reducing the total 398 to 46 taxa. The environmental data consisted on measurements of 21 water variables (Table 4.1.1) taken at the place where the bottom sediments were collected. Raw environmental and diatom abundances data are presented in appendixes I and IIA, respectively, as well as diatom plates in appendix IIIA.

Table 4.1.1 – Summary of the mean values of the environmental variables measured in-situ and in the laboratory.

| Environments | Code | Temp | pH | Eh | Sal. | Cond | D.O. | satD.O. | $NO_3^-$ | $NO_2^-$ | $NH_4^+$ | $PO_4^{3-}$ | $SiO_4^{4-}$ | $SO_4^{2-}$ | $Cl^-$ | $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | $Na^+$ | $Si^{4+}$ | DOC | DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (ºC) | | (mV) | (‰) | (mS cm$^{-1}$) | (mg L$^{-1}$) | (%) | (µM) | (µM) | (µM) | (µM) | (µM) | (µM) | (µM) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (µM) | (µM) |
| **Valdoviño** | VAL | 15.53 | 8.31 | -75.10 | 7.56 | 13.34 | 11.56 | 132.28 | 8.66 | 0.61 | 1.20 | 0.34 | 36.85 | 695.43 | 4979.63 | 123.03 | 314.25 | 90.05 | 2685.75 | 1.81 | 2.10 | 4.99 |
| **Doniños** | DON | 16.12 | 7.01 | 35.75 | 0.13 | 0.23 | 10.89 | 106.03 | 21.88 | 0.60 | 1.06 | 0.30 | 17.41 | 21.59 | 48.79 | 6.07 | 4.90 | 1.82 | 34.00 | 1.24 | 3.49 | 7.72 |
| **Traba** | TRA | 16.78 | 7.33 | 24.50 | 0.92 | 1.75 | 9.95 | 103.78 | 40.45 | 1.18 | 4.39 | 0.23 | 9.93 | 71.84 | 533.93 | 14.86 | 33.05 | 10.82 | 274.88 | 1.02 | 2.67 | 31.09 |
| **Louro** | LOU | 19.38 | 8.01 | 0.50 | 7.62 | 13.66 | 7.94 | 86.37 | 1.53 | 0.90 | 9.37 | 0.46 | 3.06 | 578.17 | 4088.83 | 84.40 | 231.67 | 70.40 | 1931.33 | 0.33 | 8.68 | 11.80 |
| **Xuño** | XUN | 17.93 | 6.54 | 61.53 | 0.16 | 0.33 | 5.17 | 53.83 | 2.08 | 0.77 | 0.87 | 0.34 | 18.84 | 6.69 | 84.24 | 17.83 | 5.33 | 2.69 | 51.30 | 0.76 | 4.91 | 3.72 |
| **Muro** | MUR | 21.70 | 6.97 | 212.30 | 1.92 | 3.72 | 9.71 | 108.40 | 11.13 | 0.77 | 11.99 | 0.32 | 24.58 | 198.16 | 1086.74 | 26.03 | 60.67 | 18.43 | 502.33 | 0.60 | 7.69 | 23.89 |
| **Illa de Arousa** | ILL | 26.00 | 8.30 | 37.70 | 0.19 | 0.39 | 10.15 | 140.00 | 0.06 | 0.55 | 19.37 | 1.54 | 142.42 | 30.53 | 77.58 | 27.40 | 7.55 | 2.95 | 50.15 | 0.36 | 19.03 | 19.98 |
| **Bodeira** | BOD | 18.29 | 6.70 | 81.20 | 0.23 | 0.53 | 4.59 | 49.43 | 41.39 | 0.60 | 100.09 | 1.47 | 39.77 | 162.79 | 56.83 | 63.27 | 16.53 | 6.13 | 43.77 | 1.01 | 15.19 | 142.08 |
| **Minho - low salt marsh** | MINBS | 18.15 | 7.36 | 127.05 | 6.14 | 23.08 | 7.57 | 85.35 | 14.59 | 0.58 | 6.15 | 0.52 | 20.49 | 949.20 | 6645.50 | 165.38 | 494.71 | 137.01 | 4268.19 | 1.09 | 2.99 | 21.32 |
| **Minho - tidal flat** | MINRM | 17.90 | 7.63 | 151.30 | 2.51 | 12.63 | 7.56 | 83.35 | 20.31 | 0.60 | 5.95 | 0.34 | 19.49 | 551.50 | 3908.50 | 86.63 | 258.92 | 72.21 | 2178.32 | 0.63 | 3.30 | 26.86 |
| **Lima - tidal Flat** | LIMARM | 15.45 | 7.53 | 150.20 | 20.96 | 51.90 | 8.32 | 87.15 | 16.14 | 0.66 | 20.19 | 0.34 | 21.71 | 1382.50 | 8751.50 | 252.65 | 703.30 | 414.96 | 6086.28 | 0.98 | 1.92 | 36.98 |
| **Vela** | LVB | 21.25 | 9.32 | 90.10 | 0.36 | 2.72 | 13.17 | 149.05 | 1.08 | 1.18 | 11.22 | 1.47 | 4.16 | 79.95 | 78.05 | 33.95 | 11.92 | 17.50 | 53.37 | 0.10 | 50.85 | 13.47 |
| **Óbidos** | OB1 | 20.05 | 8.40 | 77.60 | 29.81 | 71.43 | 9.31 | 134.78 | 1.55 | 0.67 | 4.09 | 1.40 | 11.96 | 2679.50 | 19746.50 | 349.51 | 1072.97 | 296.71 | 12990.89 | 0.17 | 3.53 | 6.31 |
| **Óbidos - Barrosa** | OB2 | 21.05 | 8.62 | 18.40 | 28.63 | 68.24 | 9.35 | 136.74 | 4.05 | 0.82 | 7.26 | 4.03 | 10.83 | 2186.50 | 15770.50 | 301.89 | 862.75 | 255.20 | 7791.75 | 0.30 | 4.92 | 12.13 |
| **Albufeira-Lagoa Grande 1** | ALB1 | 14.75 | 8.37 | 83.40 | 32.59 | 64.00 | 5.48 | 53.55 | 4.16 | 0.72 | 8.13 | 0.48 | 14.74 | 2491.50 | 15699.50 | 407.80 | 1247.96 | 336.05 | 14811.65 | 0.39 | 5.66 | 13.00 |
| **Albufeira - Lagoa Grande 2** | AlLB2 | 16.35 | 8.69 | 107.80 | 30.23 | 59.47 | 6.10 | 61.25 | 1.19 | 0.74 | 3.67 | 1.24 | 23.48 | 2111.00 | 14617.50 | 396.31 | 1252.56 | 342.35 | 14775.88 | 0.66 | 6.68 | 5.60 |
| **Albufeira - Lagoa Pequena** | ALB3 | 16.20 | 8.62 | 159.30 | 27.76 | 54.91 | 2.91 | 29.66 | 2.34 | 1.40 | 24.45 | 1.51 | 33.48 | 2150.50 | 14444.00 | 343.85 | 1019.46 | 278.29 | 12482.32 | 0.82 | 6.07 | 28.20 |
| **Sado - tidal flat** | SADORM | 16.90 | 7.84 | 109.10 | 32.21 | 63.80 | 6.43 | 70.30 | 0.69 | 0.80 | 3.26 | 0.40 | 22.42 | 2620.00 | 17281.50 | 377.70 | 1156.91 | 313.14 | 14796.21 | 0.69 | 2.92 | 4.75 |
| **Melides** | MELB1 | 22.60 | 8.16 | 96.40 | 9.25 | 24.29 | 6.03 | 68.05 | 5.08 | 1.31 | 23.23 | 0.98 | 75.24 | 564.00 | 3415.50 | 108.11 | 281.76 | 73.74 | 2346.72 | 0.60 | 6.97 | 29.62 |
| **Santo André-main channel** | SA1 | 14.90 | 8.61 | 138.55 | 23.03 | 56.97 | 5.41 | 50.80 | 41.41 | 0.63 | 4.04 | 1.00 | 22.21 | 1583.50 | 11160.50 | 253.79 | 734.63 | 207.84 | 6408.83 | 0.78 | 9.87 | 46.08 |
| **Santo André- Margin** | SA2 | 17.45 | 7.86 | 172.80 | 22.82 | 64.27 | 5.26 | 49.80 | 42.99 | 0.93 | 3.38 | 0.83 | 45.37 | 1291.00 | 8997.50 | 192.52 | 455.58 | 124.77 | 3913.55 | 0.91 | 10.59 | 47.29 |
| **Santo André- Alguidares** | SA3 | 15.55 | 8.18 | 131.75 | 23.48 | 57.79 | 4.91 | 47.45 | 18.75 | 1.40 | 2.94 | 1.12 | 29.59 | 1619.00 | 8923.50 | 186.20 | 538.74 | 150.90 | 4874.52 | 0.56 | 11.39 | 23.08 |
| **Barbaroxa de Baixo** | BB | 12.80 | 6.16 | 190.05 | 0.96 | 4.24 | 2.64 | 23.35 | 6.93 | 2.94 | 3.40 | 0.82 | 94.08 | 38.90 | 241.75 | 4.39 | 14.39 | 7.25 | 160.36 | 0.16 | 83.62 | 13.28 |
| **Mira - low salt marsh** | MIRABS | 18.80 | 8.00 | 146.70 | 34.93 | 81.88 | 4.00 | 42.15 | 5.66 | 0.66 | 10.60 | 0.22 | 12.70 | 2655.50 | 14035.00 | 335.48 | 1002.55 | 284.65 | 9174.07 | 1.30 | 1.69 | 16.92 |
| **Mira- tidal flat** | MIRARM | 16.05 | 8.20 | 168.50 | 34.31 | 81.03 | 4.18 | 41.95 | 43.62 | 0.71 | 4.23 | 0.35 | 13.99 | 2614.50 | 18769.50 | 313.06 | 932.67 | 263.39 | 8317.67 | 0.37 | 2.69 | 48.56 |
| | | | | | | | | | | | | | | | | | | | | | | |
| | **Min** | 12.80 | 6.16 | -75.10 | 0.13 | 0.23 | 2.64 | 23.35 | 0.06 | 0.55 | 0.87 | 0.22 | 3.06 | 6.69 | 48.79 | 4.39 | 4.90 | 1.82 | 34.00 | 0.10 | 1.69 | 3.72 |
| | **Max** | 26.00 | 9.32 | 212.30 | 34.93 | 81.88 | 13.17 | 149.05 | 43.62 | 2.94 | 100.09 | 4.03 | 142.42 | 2679.50 | 19746.50 | 407.80 | 1252.56 | 414.96 | 14811.65 | 1.81 | 83.62 | 142.08 |
| | **Mean** | 17.92 | 7.87 | 99.90 | 15.15 | 35.06 | 7.14 | 79.79 | 14.31 | 0.91 | 11.78 | 0.88 | 30.75 | 1173.35 | 7737.71 | 178.88 | 508.63 | 151.17 | 5240.16 | 0.71 | 11.18 | 25.55 |

### 4.1.3 RESULTS

#### *4.1.3.1 Environmental Variables and Diatom Species Distributional Patterns*

##### 4.1.3.1.1 Environmental data

The study of the 21 water variables (environmental variables) shows that the WIAC environments comprise a large spectrum of characteristics (Table 4.1.1).

The average water temperature ranges from 12.8 °C in Barbaroxa de Baixo to 26.0 °C in Illa de Arousa. Average pH values correspond to water bodies varying from slightly acid to strongly alkaline (6.16 at Barbaroxa de Baixo to 9.32 at Vela). Considering the mean values, all the environments are oxidant (Eh varies between 0.50, at Louro and 212.30 at Muro), with the exception of Valdoviño (Eh= -75.10). Although this is not the only negative value measured between 2007 and 2008, the average values for each sample yielded positive values. In this context, average Eh values must be carefully taken in to account since their values range widely and can therefore bias the average result. The average salinity and conductivity varies from 0.13 ‰ and 0.23 mS cm$^{-1}$ in Doniños (freshwater) to 34.93 ‰ and 81.88 mS cm$^{-1}$ in the low marsh of the Mira estuary (saline water). There is a distinct division between the Galician and Portuguese environments in terms of salinity/conductivity, being the Galician sites predominantly freshwater or slightly brackish (with the exception of Valdoviño an open lagoon, and Louro) and the Portuguese environments, being mainly brackish (with the exception of Barbaroxa de Baixo and Vela, two freshwater coastal pond and lake respectively). Most of the environments constitute, according to dissolved oxygen (D.O.) concentrations, a good to very good support for aquatic life (Andrews et al., 1972). Exceptions are Santo André-Alguidares and Bodeira with D.O. concentration values close to 5 mg L$^{-1}$ (4.59-4.91 mg L$^{-1}$ and 49.43 - 47.45 % of D.O.), the low salt marsh and tidal flat of Mira, with 4-4.18 mg L$^{-1}$ and 41.95-42.15 % of D.O., the innermost part of Albufeira lagoon – Lagoa Pequena and Barbaroxa de Baixo that exhibits the lowest values with 2.91 and 2.64 mg L$^{-1}$ of D.O. and 29.66 and 23.35 % of D.O., respectively.

Nutrients are present in a large spectrum of concentrations. In what concerns N sources, $NO_3^-$ varies from 0.062 µM in Illa de Arousa to 43.62 µM in the tidal flat of Mira, $NO_2^-$ ranges from 0.55 µM in Illa de Arousa to 2.94 µM in Barbaroxa de Baixo and $NH_4^+$ varies from 0.87 µM in Xuño to 100.09 µM in Bodeira. $PO_4^{3-}$ varies from 0.22 µM in the low marsh of Mira to 4.03 µM in station 2 of Óbidos, whereas $SiO_4^{4-}$ varies from 3.06 µM (Louro) to 142.42 µM (Illa de Arousa).

Ionic composition also fluctuates highly. $SO_4^{2-}$ ranges from 6.69 µM (Xuño) to 2679.50 µM (Óbidos). $Cl^-$ varies between 48.79 µM (Doniños) to 19746.50 µM (Óbidos). $Ca^{2+}$ ranges from 4.39 mg L$^{-1}$ (Barbaroxa de Baixo) to 407.80 mg L$^{-1}$ (Albufeira, Lagoa Grande 1), $Mg^{2+}$ varies between 4.90 mg L$^{-1}$ (Doniños) and 1252 mg L$^{-1}$ (Albufeira, Lagoa Grande 2), $K^+$ fluctuates from 1.82 mg L$^{-1}$ in Doniños to 414.96 mg L$^{-1}$ in the tidal flat of Lima, $Na^+$ varies between 34 mg L$^{-1}$ (Doniños) and 14811.65 mg L$^{-1}$ (Albufeira, Lagoa Grande 1) and Si varies from 0.1 mg L$^{-1}$ (Vela) to 1.81 mg L$^{-1}$ in Valdoviño.

DOC ranges from 1.69 µM in the low marsh of Mira to 38.9 µM in Barbaroxa de Baixo and, finally, DIN varies from 3.72 µM in Xuño to 142.08 µM in Bodeira.

Results of the Variance Inflation Factor (VIF) analysis showed that, from the 21 environmental variables previously described, only 9 had VIF values < 10 (Table 4.1.2), thus demonstrating little correlation with each other. These 9 environmental variables will be further used in the numerical analyses to understand the relationship between the diatom assemblages and the environmental variables.

Table 4.1.2 – VIF values for 9 environmental variables showing VIF < 10.

| **Environmental variable** | **VIF values** |
|---|---|
| **pH** | 2.74 |
| **Salinity (‰)** | 3.78 |
| **Dissolved Oxygen Saturation (D.O.) (%)** | 2.06 |
| **$NO_3^-$(µM)** | 1.39 |
| **$NH_4^-$ (µM)** | 1.20 |
| **$PO_4^{3-}$ (µM)** | 2.15 |
| **$SiO_4^{4-}$ (µM)** | 1.45 |
| **$Si^{4+}$ (mg $L^{-1}$)** | 2.44 |
| **DOC (mg $L^{-1}$)** | 3.19 |

#### 4.1.3.1.2 Diatom abundance data

The final diatom data-set consisted of 398 taxa, from which only those with an abundance ≥2 % in at least two samples were considered for study. This resulted in a total of 46 diatom taxa, from which 26 occurred at maximum abundances over 10 %. Most of the diatoms occurring at high relative abundances were epiphytes, such as *Achnanthidium minutissimum* (Kützing) Czarnecki, although the tychoplanktonic *Pseudostaurosira trainorii* Morales, is the taxon displaying the highest relative abundance (72.8 % at Louro). These two species, with *Nitzschia frustulum* (Kützing) Grunow in Cleve & Grunow, are the most common and abundant in the data-set. Frequent, but not so abundant diatoms, are *Cocconeis neodiminuta* Krammer, *Cocconeis placentula* var. *placentula* Ehrenberg, *Cocconeis placentula* var. *lineata* (Ehrenberg) van Heurck and *Synedra tabulata* (Agardh) Kützing. *Staurosirella pinnata* (Ehrenberg) Williams & Round and *Gomphonemopsis obscurum* (Krasske) Lange-Bertalot acquire high percentage values (up to more than 50 %), but are less represented in the data-set than the previous taxa. Euplanktonic diatoms (mainly represented by *Cyclotella comensis* Grunow and *Cyclotella meneghiniana* Kützing) have a very limited importance in the diatom assemblages (mean percentage is 0.99 %).

Hierarchical agglomerative cluster analysis using Gower distance (Gower, 1971) and Ward method (Ward, 1963) was used to classify the diatom species (Fig. 4.1.1), as well as the samples, according to their relative abundance data (Fig. 4.1.2). The analyses produced three main groups of samples (Fig. 4.1.2). Group I is composed by coastal lakes and ponds from both the Galician and Portuguese coast. Tychoplanktonic and epiphytic (Group A) diatoms (e. g., *Pseudostaurosira trainorii*, *Achnanthidium minutissimum* and *Cocconeis placentula* var.

*placentula*) are the main contributors to the diatom assemblages of this group. Group II is composed by estuaries from northern Portugal and a single Galician coastal lake (Doniños). These locations are mainly characterized by epipsammic and epiphytic (Group B) diatoms (e. g., *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova, *Planothidium* aff. e*ngelbrechtii* (Cholnoky) Round & Bukhtiyarova, and *Navicula paul-schulzii* Witkowski et Lange-Bertalot. Finally, all the Portuguese lagoons and Sado estuary are clustered in Group III, where epiphytic (Group C) diatoms are dominant (e. g., *Cocconeis placentula* var. *euglypta* (Ehrenberg) Cleve*, Cocconeis costata* Gregory var. *costata* and *Rhopalodia brebissonii* Krammer), plus the relevant contribution of a tychoplanktonic form (*Staurosirella pinnata*) in Santo André.

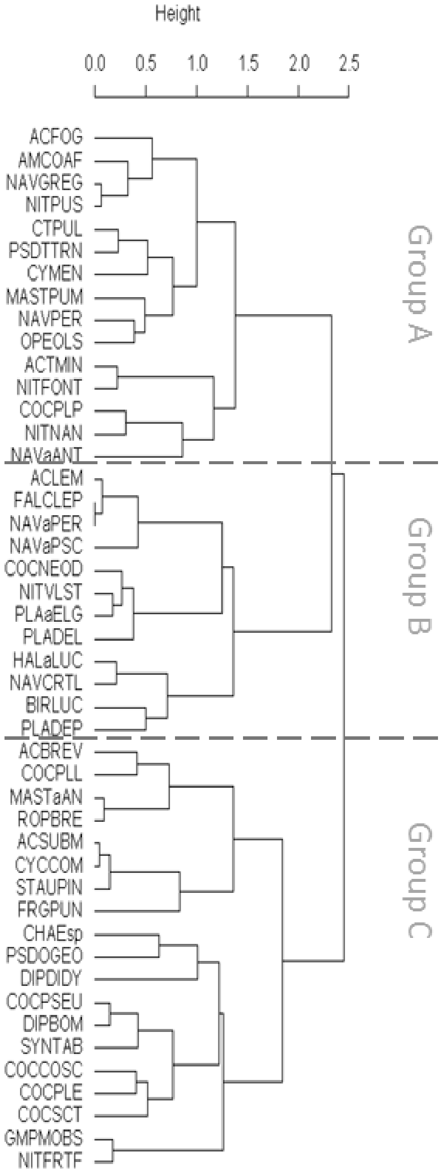

Fig. 4.1.1 – Groups of diatom taxa produced by the cluster analysis. These groups are used for the arrangement of samples in Fig. 4.1.2. See appendix IIA for acronyms of the diatom taxa.

#### *4.1.3.2 Diatom species – Environmental variables Relationships*

##### 4.1.3.2.1 Canonical Correspondence Analysis

A Detrended Correspondence Analysis (DCA) was first performed to estimate the length of the dominant gradient for the diatom assemblages and thus to evaluate whether the taxa followed a unimodal or linear distribution (Birks, 1995). The obtained length of axis 1 was 4.085 standard deviation (SD) units, which suggests a unimodal response of the diatom assemblages to the environmental gradients (Ter Braak & Prentice, 1988; Birks, 1995). According to this result, a Canonical Correspondence Analysis (CCA) was performed to further explore the relationship between the diatom assemblages and the main environmental gradients.

Results of the CCA applied to the 9 explanatory environmental variables and diatom data indicates that axes 1 ($\lambda_1$ = 0.577) and 2 ($\lambda_2$ = 0.472) captured 48.3 % of the variance in taxa composition (Table 4.1.3). The species-environment correlations of CCA axis 1 (0.961) and axis 2 (0.927) are very high. The results of the CCA have also been displayed in the form of a biplot, where these environmental variables are depicted by arrows, and species and locations by dots (Fig. 4.1.3). The relative importance of each variable in explaining the composition of the diatom assemblages is indicated by the length of its arrow, whereas its direction shows the relationship to the two CCA axes (Ter Braak, 1987). According to this ordination diagram, axis 1 is representing the salinity, pH and $PO_4^{3-}$ gradient, and axis 2 the availability in $NO_3^-$ and DOC. The test of significance for axis 1 ($p$ = 0.018) and all canonical ordination axis ($p$ = 0.004) is significant ($p \leq 0.05$).

Table 4.1.3 - Summary statistics for the first two axes of CCA with 9 environmental variables.

| **Axes** | **1** | **2** |
|---|---|---|
| **Eigenvalues (λ)** | 0.577 | 0.472 |
| **Species-environment correlations** | 0.961 | 0.927 |
| **Cumulative percentage variance of species data** | 12.7 | 23 |
| **Cumulative percentage variance of species-environment relation** | 26.6 | 48.3 |
| **Sum of all eigenvalues** | | 4.583 |
| **Sum of all canonical eigenvalues** | | 2.172 |

Salinity ($p$ = 0.001), $PO_4^{3-}$ ($p$ = 0.003), $NO_3^-$ ($p$ = 0.0024) and DOC ($p$ = 0.004) are significant variables according to Monte Carlo permutation tests ($p \leq 0.05$; 999 random permutations), and therefore account for a significant portion of the total variance in the diatom data. The CCA biplot shows that salinity is the environmental variable that account for most of the variability in the data, followed by $PO_4^{3-}$ (axis 1), and DOC and $NO_3^-$ (axis 2).

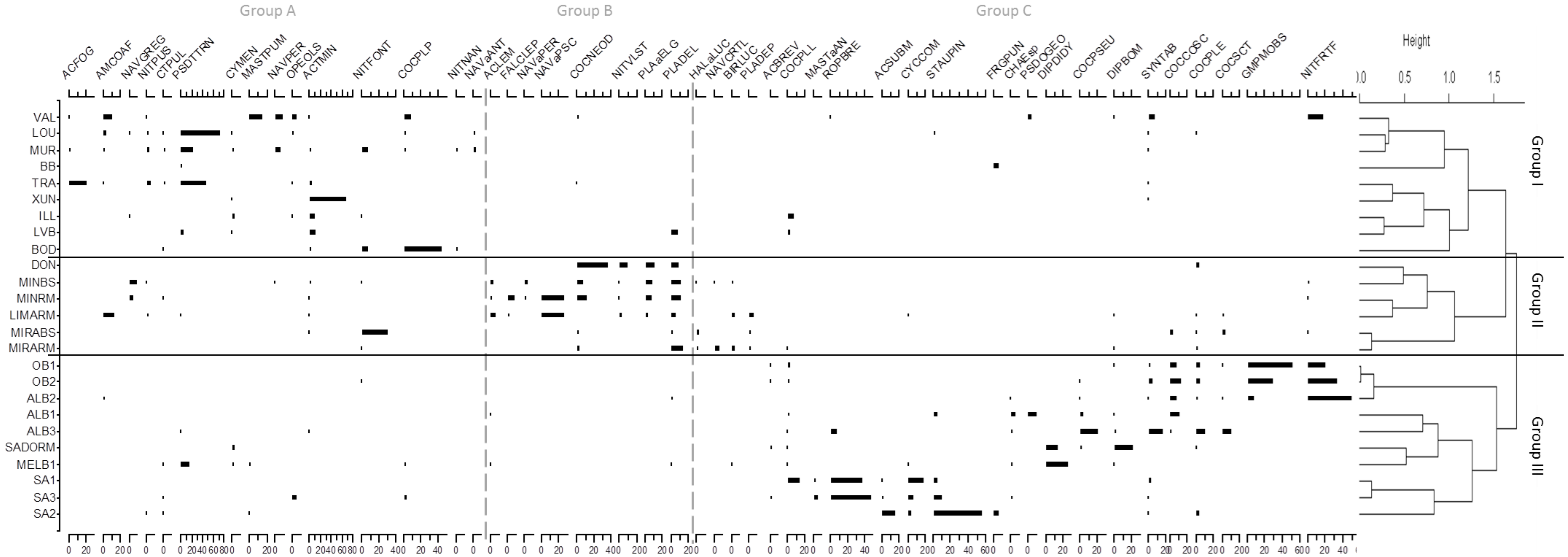

Fig. 4.1.2 – Main diatom assemblages for the 25 present-day surface sediment samples. Only taxa with abundance ≥2 % in at least two samples are shown (46 species). The samples are ordered and grouped (black lines) based on the result of the cluster analysis of the diatom abundance data. Diatoms are ordered according to the results of the cluster analysis shown in Fig. 4.1.1 (grey dashed lines). See appendix IIA for acronyms of the diatom taxa.

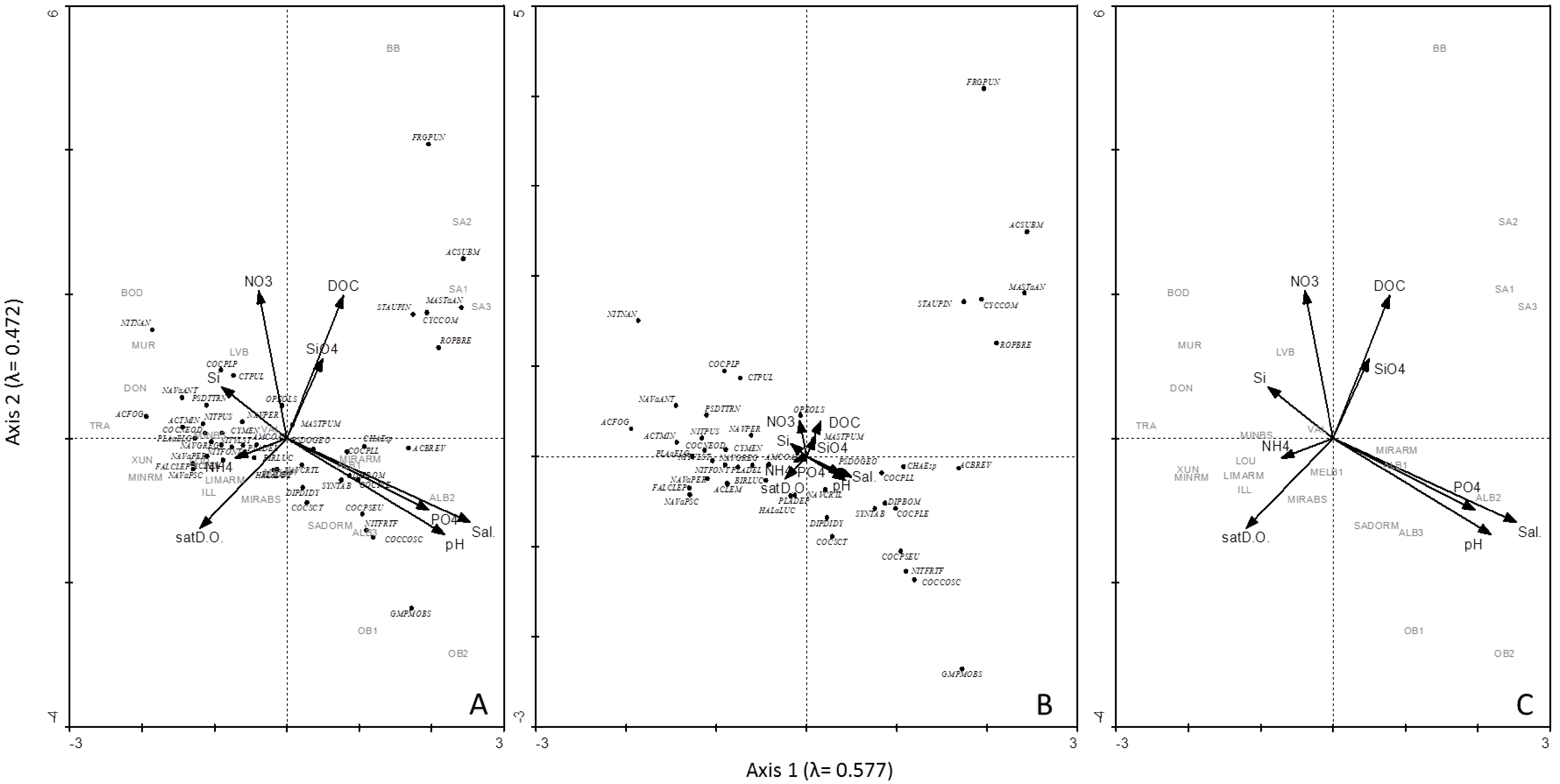

Fig. 4.1.3 – CCA sample and species-environment biplot (A). Arrows represent environmental variables and dots both diatom taxa (B) and samples (C). See appendix IIA for acronyms of the diatom taxa.

#### 4.1.3.2.2 Variance partitioning

Variance partitioning decomposes the total variability into a part that can be explained solely by each variable (% independent variance). Table 4.1.4 shows the contributions of each variable to the total variance in the diatom data, but also the independent variation explained solely by each variable. This is calculated by variation partitioning assessed by partial CCA's, measured with one explanatory variable each time and with co-variables. The 9 environmental variables showed a total explained variance of 56.56 % of the diatom data, where DOC, $PO_4^{3-}$, salinity and $NO_3^-$ contributed with higher independent explained variances. As a result, four major hydrochemical gradients, i. e., salinity, phosphorous ($PO_4^{3-}$) and nitrogen ($NO_3^-$) availability, as well as organic load (DOC) are identified.

Table 4.1.4 - Results of % total explained variance and % of independent explained variance obtained by variation partitioning (Boccard et al., 2006) and λ1/λ2, ratio between the first two eigenvalues of partial CCA (Ter Braak, 1988; Hall & Smol, 1992) for 9 explanatory environmental variables. (*) Significant variables according Monte Carlo permutation test ($p \leq 0.05$; 999 random permutations).

| Explanatory variables | Significant *p*-values | % Total Explained variance | % Independent Explained variance | λ1/λ2 |
|---|---|---|---|---|
| **pH** | | 7.94 | 3.19 | 0.59 |
| **Salinity*** | 0.001 | 10.15 | 4.89 | 0.76 |
| **% O.D.** | | 6.35 | 3.99 | 0.48 |
| **$NO_3^-$*** | 0.002 | 6.55 | 4.80 | 0.46 |
| **$NH_4^-$** | | 3.82 | 4.60 | 0.27 |
| **$PO_4^{3-}$*** | 0.003 | 7.77 | 4.97 | 0.59 |
| **$SiO_4^{4-}$** | | 3.45 | 2.25 | 0.25 |
| **$Si^{4+}$** | | 3.86 | 2.47 | 0.28 |
| **DOC*** | 0.004 | 6.68 | 6.63 | 0.50 |
| **TOTAL** | | **56.56** | **37.79** | |

Once the main environmental gradients that rule the composition of the diatom assemblages are identified, they can be tested for their suitability to produce quantitative inference models for palaeoenvironmental reconstruction. A good indicator for assessing the viability of the environmental variables selected to construct transfer functions is the ratio of λ1 to λ2, the first two eigenvalues of partial CCA (Ter Braak, 1988; Hall & Smol, 1992). Variables with high λ1/λ2 ratios (e. g., >1) generally produce strong calibration models, but variables with lower ratios can still be used in transfer function development if caution is taken in the palaeoecological interpretations (Ter Braak, 1987; Ter Braak, 1988). Table 4.1.4 shows that salinity has the lowest *p* value, the highest total explained variance (after variation partitioning), and the λ1/λ2 ratio closest to 1 among the variables. It is also highly related with axis 1, which is significant, and explains 26.7 % of the relation between variables and species. For these reasons, salinity has been chosen as the variable that would perform better for the construction of quantitative inference models for palaeoenvironmental reconstruction.

#### 4.1.3.2.3 Transfer function for salinity - Regression and Calibration

In order to determine whether a unimodal or linear response model would perform better with the existing training set (i. e., the diatom abundance data from the present-day bottom sediments plus the environmental data from the water column; Birks, 2012), the gradient length of the first canonical axis constrained to salinity was estimated with a Detrended Canonical Correspondence Analysis (DCCA). If the gradient length is greater than 2 SD units, assumption of a unimodal response model is considered the most appropriate for any further data analysis, whereas a linear response model is more suited when gradient length is smaller than 2 SD units (Birks, 1995). The gradient length for the training set was 3.208 SD units, indicating that unimodal calibration models can be used for the reconstruction of salinity in the Western Iberian Atlantic coastal systems. Therefore, the following unimodal calibration models were tested: Two-way Weighted Averaging (WA) and Weighted Averaging-Partial Least Squares Regression (WA-PLS) (Ter Braak & Juggins, 1993).

WA is first used to obtain salinity species optima and tolerances, as well as the number of occurrences of each taxon (N) and Hill's N2 (number of effective occurrences; Hill, 1973) (Table 4.1.5). The latter gives an indication of the number of samples contributing to the calculation of a taxon's WA optima. Optima estimated for taxa with a low number of occurrences or a low N2 should be interpreted with caution (Gasse et al., 1995). Taxa with N > 3 and/or N2 > 2 can be considered more reliable for reconstruction, as it is the case in our data of *Planothidium delicatulum, Ctenophora pulchella* (Ralfs ex Kützing) Williams & Round, *Cyclotella meneghiniana* and *Cocconeis placentula* var. *euglypta* (Table 4.1.5).

According to the estimated salinity optima and tolerances, diatom taxa show in the WIAC a wide saline distribution, from oligohalobous halophobous to polyhalobous (Hustedt, 1953), tolerating salinities ranging from 0.42 to 31.98 ‰. Taxa located at both ends of the diagram showed the narrowest tolerance ranges (Fig. 4.1.4).

Table 4.1.5 - Weighted-averaging salinity optima (WA opt.) and tolerances (WA tol.) of the most abundant diatom taxa, their number of occurrences (N) and effective number of occurrences (Hill's N2). (*) taxa with low values of N and/or N2, that should be considered with caution in palaeoenvironmental reconstruction. See appendix IIA for acronyms of the diatom taxa.

| Code taxa | N | Hill's N2 | WA opt. (‰) | WA tol. (‰) |
|---|---|---|---|---|
| **ACTMIN** | 13 | 2.51 | 0.41 | 0.95 |
| **NITNAN*** | 2 | 1.93 | 1.06 | 0.84 |
| **ACFOG** | 4 | 1.31 | 1.11 | 0.83 |
| **COCPLP** | 7 | 2.20 | 1.36 | 2.78 |
| **COCNEOD** | 9 | 2.97 | 1.74 | 3.00 |
| **CTPUL** | 12 | 6.39 | 1.96 | 1.46 |
| **PLAaELG** | 5 | 3.79 | 2.60 | 2.20 |
| **NITVLST** | 6 | 2.46 | 2.88 | 6.19 |
| **NAVaANT*** | 2 | 1.89 | 3.42 | 1.15 |
| **PSDTTRN** | 10 | 3.54 | 3.45 | 1.42 |
| **CYMEN** | 11 | 7.54 | 3.58 | 2.59 |
| **NITPUS** | 9 | 5.08 | 3.81 | 1.72 |
| **FALCLEP** | 3 | 1.80 | 4.38 | 1.98 |
| **NAVGREG** | 10 | 3.71 | 4.84 | 1.13 |
| **NAVPER** | 6 | 2.89 | 5.36 | 1.14 |
| **PLADEL** | 14 | 7.69 | 5.45 | 3.11 |
| **FRGPUN*** | 2 | 2.00 | 6.03 | 4.85 |
| **NAVaPER** | 3 | 2.58 | 6.27 | 1.23 |
| **NAVaPSC*** | 2 | 2.00 | 7.91 | 2.66 |
| **MASTPUM** | 4 | 1.56 | 8.04 | 0.34 |
| **OPEOLS** | 7 | 3.97 | 9.43 | 1.19 |
| **ACLEM** | 5 | 3.05 | 9.50 | 1.57 |
| **COCPLL** | 12 | 4.53 | 10.00 | 3.84 |
| **NITFONT** | 9 | 2.46 | 11.55 | 5.44 |
| **AMCOAF** | 8 | 3.94 | 11.98 | 1.26 |
| **DIPDIDY** | 2 | 1.86 | 14.73 | 1.30 |
| **BIRLUC** | 5 | 3.54 | 15.58 | 1.49 |
| **SYNTAB** | 15 | 4.26 | 18.70 | 1.12 |
| **COCPLE** | 12 | 6.49 | 19.84 | 1.93 |
| **PSDOGEO*** | 2 | 1.81 | 20.16 | 1.63 |
| **STAUPIN** | 6 | 1.98 | 22.23 | 0.40 |
| **CYCCOM** | 5 | 2.28 | 22.70 | 0.16 |
| **ACSUBM** | 3 | 1.39 | 22.92 | 0.02 |
| **NITFRTF** | 9 | 3.67 | 23.27 | 0.84 |
| **MASTaAN*** | 2 | 1.74 | 23.34 | 0.01 |
| **ROPBRE** | 4 | 2.31 | 23.57 | 0.10 |
| **CHAEsp** | 5 | 3.27 | 24.49 | 0.65 |
| **HALaLUC** | 5 | 2.98 | 24.74 | 1.60 |
| **COCSCT** | 7 | 2.84 | 25.99 | 0.79 |
| **PLADEP** | 4 | 2.98 | 26.85 | 0.34 |
| **ACBREV** | 5 | 3.14 | 27.34 | 0.20 |
| **COCPSEU** | 5 | 1.65 | 28.76 | 0.11 |
| **GMPMOBS** | 3 | 2.18 | 29.44 | 0.03 |
| **DIPBOM** | 10 | 1.67 | 30.22 | 0.33 |
| **COCCOSC** | 8 | 5.38 | 30.69 | 0.07 |
| **NAVCRTL** | 3 | 1.65 | 31.98 | 0.70 |

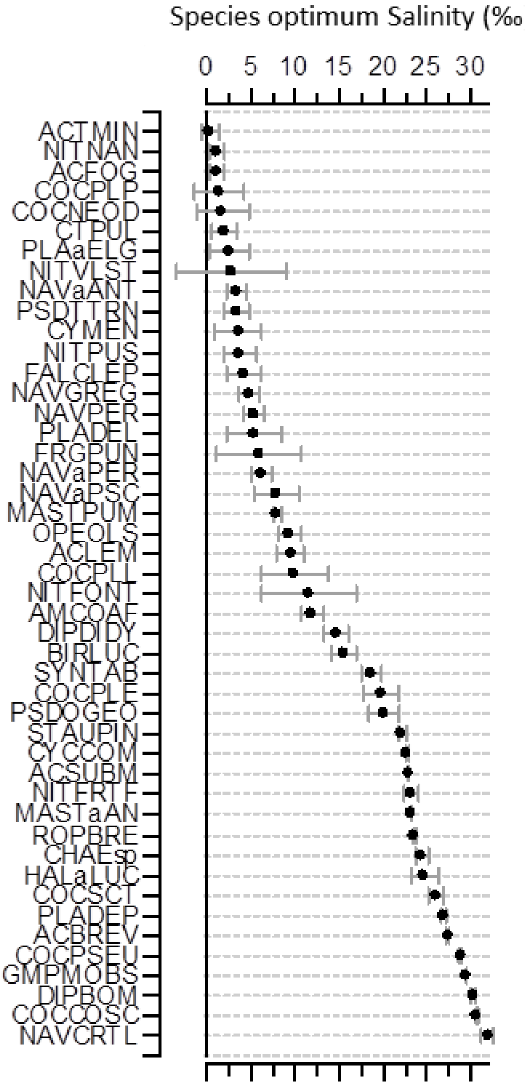

Fig. 4.1.4 - Plot of the WA salinity optima and tolerances of diatom taxa (Table 4.1.5). See appendix IIA for acronyms of the diatom taxa.

According to the performance of the several salinity transfer functions models developed with validation using jack-knifing method Quenouille (1949) (Table 4.1.6), the components 4 and 5 of the WA–PLS model appear to perform better than WA, since they showed the highest $r^2_{aparent}$ (0.99 for both components), the highest $r^2_{jack\text{-}knifed}$ value (0.56 and 0.55, respectively), the lowest root mean square error of prediction (RMSEP) $RMSEP_{jack\text{-}knifed}$ (0.39 and 0.40, respectively) and the lowest maximum deviation (0.47 and 0.48 respectively). Component 4 WA–PLS model was chosen for the final reconstruction of salinity since it presents lower values of $RMSEP_{Jack\text{-}knifed}$ (0.39) than component 5. Bootstrapping (Efron, 1979) cross-validation statistic method was used to derive the standard error of prediction (SEP, Birks et al., 1990) of the reconstructed salinity to be used in core samples. Scatterplots of observed against

Diatom–inferred salinity (DI-salinity) values, and summary performance measures are shown in Fig. 4.1.5.

Table 4.1.6 - Main statistics of the several salinity transfer functions developed for the calibration set. WA – weighted averaging; CLA- classical, INV – Inverse; WA-PLS – weighted averaging-partial least squares; RMSE - root mean square error; $r^2$ - coefficient of determination in regression; RMSEP - root mean square error of prediction. (*) indicates the model selected for the salinity reconstruction.

| **Model** | **Apparent** | | | **Jack-knifing** | | | **Bootstrapping** | | |
|---|---|---|---|---|---|---|---|---|---|
| | RMSE | $r^2$ | Max. bias | $r^2$ | Max. deviation | RMSEP | $r^2$ | Max. bias | RMSEP |
| **WA-INV** | 0.21 | 0.86 | 0.19 | 0.47 | 0.50 | 0.43 | 0.52 | 0.47 | 0.43 |
| **WA-CLA** | 0.23 | 0.86 | 0.23 | 0.48 | 0.47 | 0.44 | 0.53 | 0.45 | 0.44 |
| **WA-PLS -1** | 0.22 | 0.86 | 0.22 | 0.47 | 0.52 | 0.42 | 0.47 | 0.51 | 0.44 |
| **WA-PLS-2** | 0.12 | 0.96 | 0.20 | 0.50 | 0.56 | 0.42 | 0.50 | 0.49 | 0.43 |
| **WA-PLS-3** | 0.10 | 0.97 | 0.13 | 0.54 | 0.48 | 0.40 | 0.53 | 0.48 | 0.43 |
| **WA-PLS-4*** | 0.07 | 0.99 | 0.08 | 0.56 | 0.47 | 0.39 | 0.53 | 0.47 | 0.43 |
| **WA-PLS-5** | 0.05 | 0.99 | 0.05 | 0.55 | 0.48 | 0.40 | 0.53 | 0.47 | 0.43 |

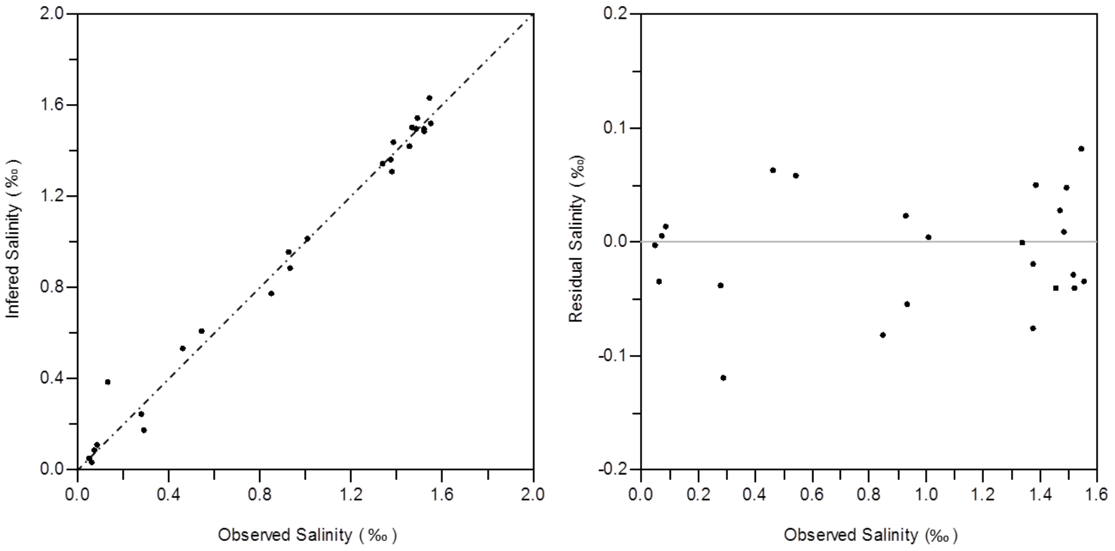

Fig. 4.1.5 - Plots of observed vs inferred salinity and observed vs residual salinity, based on the selected WA-PLS model.

## 4.1.4 DISCUSSION

### *4.1.4.1 Environmental variables and diatom species distribution patterns*

The studied environments of the WIAC are characterized by a large range of physico-chemical conditions. Along this spectrum, diatom assemblages are dominated by benthic and tychoplanktonic diatoms of freshwater to brackish/marine affinities. Many of the taxa found as dead assemblages in this study of bottom sediments have previously been reported in studies of benthic diatom biocoenoses of this coastline (Resende et al., 2005, 2007; Ribeiro, 2010;

Gomes et al., 2012; Ribeiro et al., 2013). This suggests that diatoms of the dead assemblages in bottom sediments are a reliable image of the taxonomic composition of the biocoenoses they come from. The dominance of periphytic taxa and almost absence of euplanktonic forms is certainly related to the predominance of very shallow water bodies throughout the region. Only Albufeira (Portugal) and Doniños (Galicia) surpass a maximum water depth of 5 m. The sampled sites are therefore good representations of the shallow or marginal habitats of the region. As a result, caution should be taken with the use of the modern analogues of these systems for the quantitative or qualitative palaeoenvironmental reconstruction where pelagic environments prevail.

Results of cluster analysis show that freshwater coastal lakes and ponds, and restricted lagoons, environments mainly present in the Galician coast, are characterized by brackish/freshwater to freshwater epiphytic and tychoplanktonic diatoms such as *Achnanthidium minutissimum*, *Cocconeis placentula* and *Pseudostaurosira trainorii* (de Wolf, 1982; Vos & de Wolf, 1993b; Morales, 2001). By contrast, the lagoons of the Portuguese coast, more connected to the ocean, show a more diverse assemblage of dominant diatoms, probably as a result of the less stable conditions in these environments. Consequently, they are characterized by diatoms ranging from freshwater to purely brackish affinities of a mainly epiphytic character such as *Cocconeis placentula* var. *euglypta, Cocconeis costata* var. *costata, Gomphonemopsis obscurum* or *Rhopalodia brebissonii* (de Wolf, 1982; Vos & de Wolf, 1993b; Snoeijs, 1993; Witkowski et al., 2000). An epipelic diatom typical of estuarine conditions, *Nitzschia frustulum*, acts also as a good indicator of these kinds of environments (Rovira et al., 2012). The inclusion of Sado in this group, which is the biggest studied Portuguese estuary, makes sense, since it has been considered more closely related to lagoons and not to estuaries due to its low river discharge (e. g., Ferreira et al., 2005). Finally, true estuaries belonging to the Portuguese coast are mainly characterized by two closely related taxa. *Planothidium delicatulum* is a marine/brackish epipsammic diatom, whereas *Planothidium* aff. *engelbrechtii*, in spite of its still not definite taxonomic identity, can very likely be considered as an epipsammic salt-loving diatom because of its close resemblance to *Planothidium engelbrechtii* (Robinson, 2004). The indicator value of epipsammic diatoms in this group is surely a reflection of the coarser nature of the estuarine sediments in the whole studied area (Ferreira, unpublished data). It is also known that epipsammic diatoms are a common component in the sandflats of the Tagus estuary (Ribeiro et al., 2013). Another species characteristic of this group is *Navicula paul-schulzii*, an epipelic diatom, which has been defined as typical of water bodies characterised by continuous freshwater inputs with high nutrient contents (Trobajo, 2005), a distinct feature of the estuarine ecosystems. Quite surprising is the inclusion of the freshwater coastal lake of Doniños in this group. The site sampled in this system showed a high abundance of not only the typical *Planothidium delicatulum* and *Planothidium* aff. e*ngelbrechtii,* that characterize the group it belongs to, but also of *Cocconeis neodiminuta*, a diatom that is also present in the estuaries of Minho and Lima. This assemblage can however be considered atypical for this system for several reasons. First, the lake has a maximum depth of 11 m and pelagic, instead of periphytic habitats, are more represented in it. Present-day diatom assemblages on the deeper parts are dominated by *Aulacoseira* spp. Thwaites, *Fragilaria crotonensis* Kitton and *Achnanthidium minutissimum* (Carballeira & Leira, pers. comm.). On the other hand, the marginal environments are dominated by species such as *Achnanthidium minutissimum*, *Cocconeis placentula* and *Fragilaria capucina* Desmazière, the latter a freshwater tychoplanktonic diatom (Carballeira & Leira, pers. comm.). A combination of factors might explain the prevalence of the mesohaline epipsammic taxa that were found in Doniños during the sampling for this thesis in 2007. The marginal area where the sampling took place is, at the present, dominated by aeolian sands, probably as a reflection of its exposure to a nearby active dune field. On the other hand, the N-S orientation of the sand barrier, facing the open ocean, which differs from other water bodies with less exposed orientations (e. g., Xuño and Muro), might well explain the dominance of mesohalobous taxa, especially at times of increased barrier permeability such as November, when the sampling was carried out. The existence of well-defined groups of diatoms characteristic of these three major types of environments could be a powerful tool for the reconstruction of past sedimentary environments which do not rely solely on autoecological data from elsewhere (e. g., Vos & de Wolf, 1993) but on the specific knowledge of modern analogues from the WIAC.

The classification of samples in three main groups related to well-defined distinct salinity conditions suggests that salinity plays a major role in the distribution of the diatom assemblages. This is corroborated by the CCA results once highly correlated environmental variables, as demonstrated by VIF analysis, are removed. In the ordination diagram (Fig. 4.1.3) salinity is the most relevant variable in the data-set, showing the largest correlation with the ordination axes, followed by $PO_4^{3-}$ (axis 1), DOC and $NO_3^-$ (axis 2). This relationship between salinity and $PO_4^{3-}$ is not surprising. Ruttenberg (2004) suggests that dissolved phosphate is typically present in water with circumneutral pH and seawater salinity. Phosphorous, and particularly the availability of $PO_4^{3-}$, is well known to limit the productivity in most lakes (Schindler, 1977). The plot of samples of the different water bodies discriminates, in general terms, the low salinity sites, mainly belonging to Galicia on the left, from the more saline Portuguese environments to the right, according to the values of axis 1. Axis 2 seems to be related to a trophic gradient according to its relationship with N sources ($NO_2^-$ and $NO_3^-$) and DOC. This minor source of variation within the present-day data-set could however be demonstrated as potentially more important with the inclusion of new data, since it is known that nutrient gradients play a major role on the distribution of recent dead assemblages in similar coastal environments elsewhere (e. g., Weckström et al., 2004).

#### *4.1.4.2 Modern analogues as tools for coastal palaeoenvironmental reconstruction*

From the results of the partial CCA analysis, 9 environmental variables accounted for 48 % of the explained variance in the diatom data (Table 4.1.4). However, 52 % total variation of the diatom data remains unexplained, which can be related to some overlooked factor not contemplated in this study. This explained percentage is however higher or similar to those found in many other similar biological data-sets in coastal areas, having larger number of samples, that were used to develop conductivity or salinity transfer functions (e. g., Zong & Horton, 1999; Hassan et al., 2009).

Both cluster analysis and CCA results clearly indicate that salinity and nutrient concentrations are the most important environmental variables explaining the diatom distribution in the studied environments. Salinity is often the dominant factor influencing diatom community composition in coastal areas (Denys & Wolf, 1999; Snoeijs & Weckström, 2010), and studies involving the use of diatoms to reconstruct the long-term evolution of coastal systems usually employ salinity reconstructions (Cooper et al., 2010). For these reasons, a salinity transfer function was developed to infer past salinity conditions (DI-salinity) from fossil samples in the water bodies of the WIAC.

The predictive ability of the salinity transfer function ($r^2_{\text{apparent}}$ = 0.99) compares well with those of other coastal regions for salinity or conductivity (e. g., $r^2_{\text{apparent}}$ = 0.86-0.97, Juggins, 1992; Parson et al., 1999; Hassan et al., 2009; Wachnika et al., 2010). The poor performance under jack-knifing ($r^2$ = 0.56) and bootstrapping ($r^2$ = 0.53) reflects the heterogeneous nature of the dataset. Any DI-salinity estimated from this data-set should therefore be used with caution, namely taking into account the presence of certain diatom taxa with low N and N2 values. Although this work represents the first transfer function available for palaeoenvironmental reconstruction in continental aquatic systems of the WIAC, the results clearly show that the calibration data-set can be improved by merging other available data-sets (e. g., Ribeiro et al., 2013; Resende et al., 2005, 2007) or new data. For the case of DI-salinity reconstructions, the data-sets should include a wider range of salt conditions and environments (i. e., the inclusion of deeper water bodies depicting pelagic habitats) to broaden the use of the transfer function to coastal areas with more varied salinities and morphologies. Moreover, the extension of the calibration data-sets to develop regional rather than local transfer functions has recently been recommended for carrying out palaeoenvironmental reconstructions in coastal ecosystems (Wilson & Lamb, 2012; Watcham et al., 2013).

This study also corroborates that it is difficult to achieve precise inferences in coastal habitats because of the adaptation of many taxa to a wide range of ecological conditions (Anderson & Vos, 1992; Vos & de Wolf, 1993; Denys & de Wolf, 1999). Some present-day diatom taxa in the studied data-set showed salinity optima with wide tolerances (namely in the freshwater/brackish salinity ranges). These broad tolerances can hinder their use as modern analogues when compared to fossil taxa for salinity reconstructions. For the case of the four taxa presenting the highest values for N and N2 (Table 4.1.5), the salinity optima derived from this study reflect both similarities and discrepancies with those estimated from other data-sets.

The results derived from the present data-set shows that *Planothidium delicatulum* is a taxon typical of lagoon and estuarine environments of the WIAC with salinity optima of 5.45 ± 3.11 ‰. This optima and the wide tolerance are in agreement with its wide distribution in different types of sandy coastal environments (Witkowski et al., 2000; Ribeiro et al., 2003; Robinson, 2004; Ribeiro, 2010). On the other hand, *Cocconeis placentula* var. *euglypta* resulted to be a taxon typical of lagoon and estuarine environments of the WIAC, with salinity optima of 19.84 ± 1.93 ‰, hence exhibiting the most brackish/marine character compared with other *Cocconeis placentula* varieties. This is in correspondence with the estuarine character of this taxon elsewhere (Snoeijs & Balashova 1998; Cantoral-Uriza & Aboal, 2010). *Cyclotella meneghiniana* is traditionally considered a euplanktonic freshwater or freshwater/brackish diatom in coastal areas (Denys, 1991b). The salinity optima derived from the present day data-set is 3.58 ± 2.59 ‰, which is below the 6 ‰ estimated salinity optima in coastal water bodies from, for instance, north-eastern Argentina (Hassan et al., 2009). *Cyclotella meneghiniana* is a common diatom in an open estuary such as the Tagus (Ribeiro et al., 2003; Ribeiro, 2010; Santos, 2010) which, with the estimated salinity optima obtained for the WIAC, support its affinity for salty environments in this region. This taxon lives in a wide range of habitat types, from oligotrophic lakes to polluted lagoons, and shows a large morphological variation, resulting in one of the most problematic species in the study of diatom ecology (Håkansson & Cherpurnov, 1999). Because of its morphological variability, Ribeiro (2010) points that *Cyclotella meneghiniana* in estuarine waters and sediments can easily be misconfused with several closely related species, especially under light microscope cell counts. Although misidentification of some specimens or ecophenotypic variability cannot be completely ruled out, the salinity optima derived for *Cyclotella meneghiniana* in this study is in line with the euryaline character stated by Håkansson (2002).

The high unexplained variance (52 %) from the CCA result indicates that diatoms respond not only to salinity, $PO_4^{3-}$, $NO_3^-$, and DOC but to other unknown variables as well. Hence, it is advisable to use the constructed transfer function for salinity in a multiproxy approach that also contemplates employment of total organic carbon/total nitrogen ratios ($C_{org}/N_{total}$) and stable isotopes (Lamb et al., 2006) or trace elements such as Br, Cl or S (Freitas et al., 2003) as indicators for inferring salinity changes in coastal sedimentary records.

Future studies in the WIAC should assess not only the role of salinity or nutrient gradients on the composition of diatom dead assemblages in present-day bottom sediments, but also of other environmental variables, such as tidal levels, sediment composition or depth. This would lead to more reliable palaeoenvironmental reconstructions in these systems where the complex interplay between continental and marine influences complicates the interpretation of the sedimentary record.

### 4.1.5 CONCLUSIONS

This work provides an ecological basis for understanding the variability of present-day dead diatom assemblages in the Western Iberian Atlantic coastal environments and the main environmental factors that govern their composition. The similarities found between the dead assemblages and the biocoenoses reported in previous studies suggest a minor taphonomical bias. The sampled sites are also good representations of the shallow or marginal habitats samples of the region. Results of cluster analysis revealed that coastal lakes and ponds, lagoons and estuaries can be characterized by distinct diatom assemblages, being *Achnanthidium minutissimum*, *Pseudostaurosira trainorii* and *Nitzschia frustulum*, the most common and abundant diatoms in the data-set from these environments, and salinity, $PO_4^{3-}$, $NO^{3-}$, and DOC, the water column most significant variables influencing the composition of the dead diatom assemblages in the region.

It is possible to discriminate among three distinct types of coastal environments according to the dominating types of diatoms. A first type is constituted by coastal lakes and ponds from both the Galician and Portuguese coast, and it is characterized by freshwater to brackish/freshwater tychoplanktonic and epiphytic diatoms. The second type comprises estuaries from Portugal and an outlier, a single Galician coastal lake (Doniños), which are mainly characterized by marine/brackish epipsammic diatoms. Finally, the third type consists of Portuguese lagoons (and Sado estuary) where freshwater to brackish epiphytic diatoms are dominant. The comparison of taxa belonging to these three main types of environments with those dominating fossil diatom assemblages can be used for the reconstruction of past sedimentary environments in the WIAC that until now solely rely on autoecological data from elsewhere.

Diatom salinity optima and tolerances, estimated by WA, showed a wide haline distribution, ranging from oligohalobous halophobous to polyhalobous taxa. The results indicate that *Planothidium delicatulum*, *Cyclotella meneghiniana* and *Cocconeis placentula* var. *euglypta*, are the most reliable diatoms for past salinity reconstructions. On the other hand, WA–PLS demonstrated to be the model with the best fit for past salinity reconstruction. The strong and highly significant relationship of the present-day dead assemblages with salinity enabled the construction of a transfer function for this variable with a good predictive power. This transfer function could be used in future studies on the history of the coastal evolution of this area, such as research on long-term sea-level change, or on the history of natural or human-induced permeability of coastal lakes and lagoons. The application of this technique to the sedimentary record will rely on the close correspondence between the taxonomic composition of the present-day data-set and the fossil assemblages. On the other hand, the use of this transfer function should be restricted to the reconstruction of marginal environments in coastal water bodies. Merging of other existing data-sets or new ones is advisable to generate a new transfer function applicable to deeper water environments.

# 4.2. Climatic and anthropogenic impacts in Traba coastal wetland (Galicia, NW Spain) in the last 550 years

### 4.2.1 INTRODUCTION

Wetlands are among the most valuable ecosystems in the world because they provide critical ecosystem goods and services, such as carbon storage, biodiversity conservation, fish production, water purification, and erosion control (Moreno-Mateos et al., 2012). Those wetlands located in the interface of land and ocean, are highly productive and particularly complex because they can include multiple habitats such as sand dunes, mudflats, creeks and channels and associated ecotones such as salt marsh and sea-grass meadows (Newton et al., 2013). However, not only coastal wetlands, but littoral ecosystems in general, are particularly vulnerable to climate change impacts that include accelerated sea-level rise, increased temperature, changes in rainfall distribution and freshwater inputs, and in the frequency and intensity of storms, all operating over a range of temporal and spatial scales (Day et al., 2008). Besides these global agents, direct local human intervention in these systems is a potential major factor that can significantly alter coastal ecosystems (Håkanson & Bryhn, 2008), but the exact pace and ultimate severity of local impacts very much depend on regional climatic changes (Moser et al., 2012). It is therefore essential to know the relative importance that local and regional factors have on the dynamics of these complex ecosystems and how they have operated at different time scales.

Global and local forcing factors can induce changes in the equilibrium of ecosystems. For the case of shallow lentic systems, it is known that they can be found in two main types of alternative stable states: a clear state dominated by aquatic vegetation, and a turbid state characterized by high algal biomass (Scheffer et al., 1993). Major changes in nutrient availability trigger the ecological regime shift from one stable state to another, but this can last long periods of time, making long-term studies imperative for understanding the real nature of this kind of ecosystem transitions. Environmental monitoring data are however not available in most cases and, when available, they usually cover less than 15 years, in spite of being essential for knowing, for instance, the effects of climate change in semienclosed coastal systems (Newton et al., 2013). Palaeoenvironmental records covering decadal to centennial time-scales can substitute the lack of monitoring data for tracking long-term dynamics in aquatic systems whilst smoothing out short-term variability (Sayer et al., 2010). They can not only provide valuable data on reference conditions that can be target for correct restoration plans in disturbed ecosystems, but be used to track the consequences of these plans (Smol, 2008). This is particularly important for the case of wetlands, because they can recover towards alternative states that differ from reference conditions before degradation (Moreno-Mateos et al., 2012).

Coastal wetlands are fairly uncommon and unstudied features in Galicia (NW Spain). As for similar systems in the western Ibero Atlantic coast (WIAC), they originated behind sand-barriers when the rate of sea-level rise was attenuated around 5500 cal yr BP (Bao et al., 2007; Costas et al., 2009; González-Villanueva et al., 2009). Although low-resolution studies have identified eustatism and climate as major controls on the long-term evolution of these systems, local forcing factors such as direct human intervention have increasingly played a more significant role in the last centuries to decades (e. g., Devoy et al., 1996; Santos et al., 2001; Bao et al., 2007; Costas & Alejo, 2007; González-Villanueva et al., 2009; Vázquez-Loureiro, 2011). Disentangling to what extent local vs global drivers prompted changes in the ecological status of these systems in recent times requires high-resolution multiproxy studies that would allow to distinguish when changes in the state of the ecosystem are caused by human pressure and when are due to natural variability (Newton et al., 2013).

The Traba coastal wetland, located in the Galician “Death Coast”, is a Site of Community Importance under the Habitats Directive of the European Union (EU). It can be classified as a coastal freshwater lagoon according to the Ramsar Convention Classification System for Wetland Types (Ramsar-Convention-Secretariat, 2013). Although the major environmental changes that took place in this wetland since it origin at 5700 cal yr BP are well known (Bao et al., 2007) a high temporal resolution study characterizing how climatic and non-climatic stressors could have promoted changes in its ecological state at centennial to decadal time scales is still lacking. There is a strong need for this since it has been addressed that development of observing systems acting at appropriate scales to detect global climate change and its effects on coastal wetlands is essential for the correct management of these complex systems (Day et al., 2008).

In this work a palaeoecological multiproxy approach (sedimentology, fossil diatom assemblages, and geochemistry) is used, to identify ecological regime shifts in the Traba coastal wetland during the last 550 yrears and relate them to the natural and anthropogenic stressors that could have caused them. This work pretends to establish the theoretical basis for implementing correct management policies in this EU’s Site of Community Importance.

### 4.2.2 RESULTS

#### *4.2.2.1 Sedimentology and Stratigraphy*

Sedimentology and the main stratigraphic units were defined in core TRA07-A2 (94 cm long). This core is basically made up by organic slightly sandy muds (% > 63 µm ≤ 25 %) intercalated with muddy sands and sandy mud levels (% > 63 µm > 25 %) (Flemming, 2000; Fig. 4.2.1). The term “sandy” is used here in a strictly dimensional sense. Thus, the sandy levels are not only made up by rounded quartz grains of aeolian origin but also by large organic fibers (Fig. 4.2.1). Two distinct sedimentary units could be defined according to stratigraphically constrained cluster analysis based on squared Euclidian dissimilarity (CONISS, Grimm, 1987):

Unit I (94 - 52 cm): Silts (< 63 µm and > 2 % µm) are the main component of this unit (Fig. 4.2.1). The > 63 µm fraction varies between 9.5 and 41.9 %, being mainly made up by slightly sandy muds with fewer sandy mud sediments (% > 63 µm > 25 %, Fig. 4.2.1). Sands of aeolian origin are scarce.

Unit 2 (52 - 0 cm): The > 63 µm fraction in this unit varies between 14.9 and 60.1 %, corresponding to sediments classified as sandy muds with muddy sand deposits (% > 63 µm > 50 %) (Fig. 4.2.1).

Another parallel core, TRA07-A1, which recovered only Unit II, was taken and correlated with TRA07-A2 (Fig. 4.2.1 and 4.2.2). Results on diatom content and geochemical proxies refer to samples taken in this shorter core.

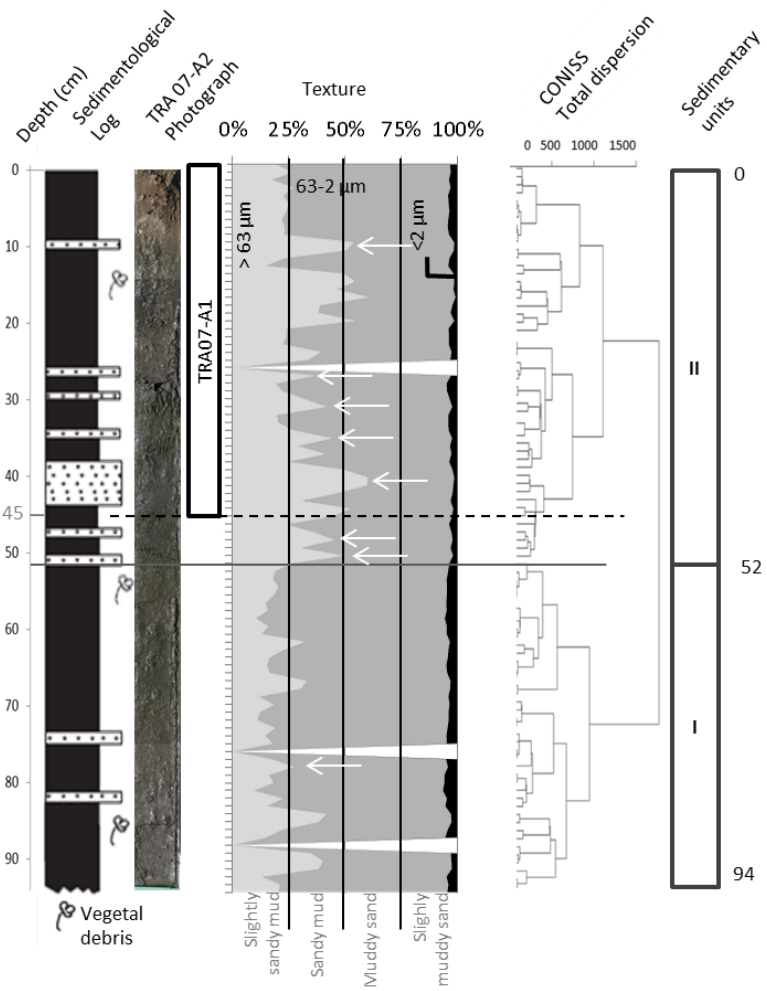

Fig. 4.2.1 – Sedimentology with textural classification according to Flemming (2000) based on the % > 63 µm fraction. Sedimentary units defined by cluster analysis for core TRA07-A2. Position of the correlated core TRA07-A1 where diatom and geochemical analyses were made is shown. Arrows indicate sandy mud and muddy quartz aeolian sand events. White area corresponds to absence of data.

#### *4.2.2.2 Diatom stratigraphy*

The study of diatoms in core TRA07-A1 gave a record consisting of 89 taxa. The relative abundance diagram, once taxa reaching a value < 2 % were removed to minimize the influence of rare diatoms as shown in Figure 4.2.2. This reduced the number of taxa from 89 to 23, which however represent 93 % of the total counted diatoms (Appendix IIB for diatom abundances and appendix IIIB for diatom plates). The diatoms are grouped in the diagram by their apparent salinity and habitat tolerances (Vos & de Wolf, 1993) (Fig. 4.2.2). Diatom assemblage zones (DAZs) were delimited with a broken-stick model of variance distribution (Bennett, 1996). Subzones were defined by stratigraphically constrained cluster analysis based on CONISS method (Grimm 1987) (Fig. 4.2.2). The analyses defined three distinct DAZs (Fig. 4.2.2):

*DAZ TRA07-I (45 - 19 cm)*

This zone is characterized by the dominance of tychoplanktonic diatoms (mainly *Pseudostaurosira trainorii* Morales; ≥ 49 % relative abundance) with the freshwater epiphytic *Achnanthidium minutissimum* (Kützing) Czarnecki as subdominant taxa with values always lower than 10 %. Other taxa represented in low abundances are the also tychoplanktonic *Stauroforma exiguiformis* (Lange-Bertalot) Flower, Jones & Round, the epiphytic *Encyonopsis subminuta* Krammer & Reichardt, the epipelic *Navicula radiosa* Kützing, *Brachysira vitrea* (Grunow) Ross in Hartley or *Nitzschia fonticola* (Grunow) Grunow in Van Heurck and the epipsammic *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova. All these taxa are almost exclusively restricted in the core to this zone. On the basis of these taxa, this zone can be subdivided in two subzones. Whereas in subzone TRA07-Ia (45-33 cm) these taxa are present in abundances ranging from 0 to 6.7 %, in subzone TRA07-Ib (33-19 cm) they diminish, except for *Achnanthidium minutissimum*, in favor of *Pseudostaurosira trainorii*, which records maximum abundances for the whole sequence (Fig. 4.2.2).

*DAZ TRA07-II (19 - 14 cm)*

In this zone, *Pseudostaurosira trainorii* starts to decrease, although it is still the dominant taxon (46 to 65 %). This reduction is followed by an increase in the freshwater epiphytic *Achnanthidium minutissimum*. Taxa in minor abundances that also start to increase are *Ctenophora pulchella* (Ralfs ex Kützing) Williams & Round, *Psammothidium oblongellum* (Oestrup) Van de Vijver, *Cocconeis placentula* var. *placentula* Ehrenberg and *Halamphora veneta* (Kützing) Levkov (Fig. 4.2.2).

*DAZ TRA07-III (14 - 0 cm)*

This zone is characterized by the sharp decrease in the brackish/freshwater tychoplanktonic *Pseudostaurosira trainorii* which is mainly replaced by the now dominant freshwater epiphytic *Achnanthidium minutissimum*. The marine/brackish epiphyte *Ctenophora pulchella*, the freshwater epiphytic *Psammothidium oblongellum*, and the freshwater epipelic *Halamphora veneta* act as codominant or subdominant taxa in this zone. Mainly according to shifts in the abundance of *Achnanthidium minutissimum*, this zone can be divided in two subzones. In subzone TRA07-IIIa (14 to 3 cm) this taxon dominates the assemblage, with the exception of the top samples which are codominated by *Psammothidium oblongellum.* Subzone TRA07-IIIb (3 to 0 cm) shows an increase in *Pseudostaurosira trainorii*, being the assemblage not dominated by a single taxon, but rather codominated by *Pseudostaurosira trainorii*, *Achnanthidium minutissimum*, *Psammothidium oblongellum* and *Halamphora veneta* (Fig. 4.2.2).

Detrended Correspondence Analysis (DCA) was performed on the diatom abundance data to reveal the length of the dominant gradient for the diatom assemblages and to evaluate the unimodal or linear distribution of the data (ter Baak & Prentice, 1988). Because the obtained length of gradient was 1.35 standard deviation units, the response was considered linear and a Principal Components Analysis (PCA) was subsequently performed. 90 % of the total variance of the diatom compositional change is represented by axis 1 of the PCA, whereas axis 2 represents only 0.04 % (Fig. 4.2.3). *Pseudostaurosira trainorii* and *Achnanthidium minutissimum* showed the minimum and maximum scores for axis 1 (Fig. 4.2.3B). *Psammothidium oblongellum* and *Achnanthidium minutissimum* are the two taxa more closely related to axis 2 (Fig. 4.2.3B).

#### 4.2.2.2.1 Ordination of the fossil samples on the main environmental gradients of the WIAC

Data for each of the 45 studied samples in core TRA07-A1 were placed as supplementary passive samples in the ordination space of the Canonical Correspondence Analysis (CCA) that analyzed the relationship between the present-day diatom and dead assemblages in the WIAC and the main environmental variables (Chapter 4.1). Position of these fossil samples on the resulting CCA biplot (Fig. 4.2.4) provides an indication of the main trajectories of environmental change through time with respect to the significant environmental variables ruling the composition of the diatom assemblages (salinity, $PO_4^{3-}$ – axis 1 and $NO_3^-$ and DOC – axis 2; see Chapter 4.1).

The fossil samples show a reduced variation compared to the length of the gradients found in the Ibero Atlantic coast, suggesting that minor environmental changes took place in approximately the last 550 years (Fig. 4.2.4). All the samples are plotted at the side of low salinity and $PO_4^{3-}$ conditions indicating the development of freshwater or slightly brackish waters with low P concentrations at all times. Samples below the 13 cm depth are positioned at the more saline extreme of this reduced gradient for axis 1, pointing to a freshening of this water body in recent times. The extent of variation is greater for axis 2, indicating more significant changes related to $NO_3^-$ and DOC than to salinity or P availability. At approximately 13 cm depth there seems to be a threshold separating the more $NO_3^-$ and DOC enriched samples at the bottom of the core from those at the top.

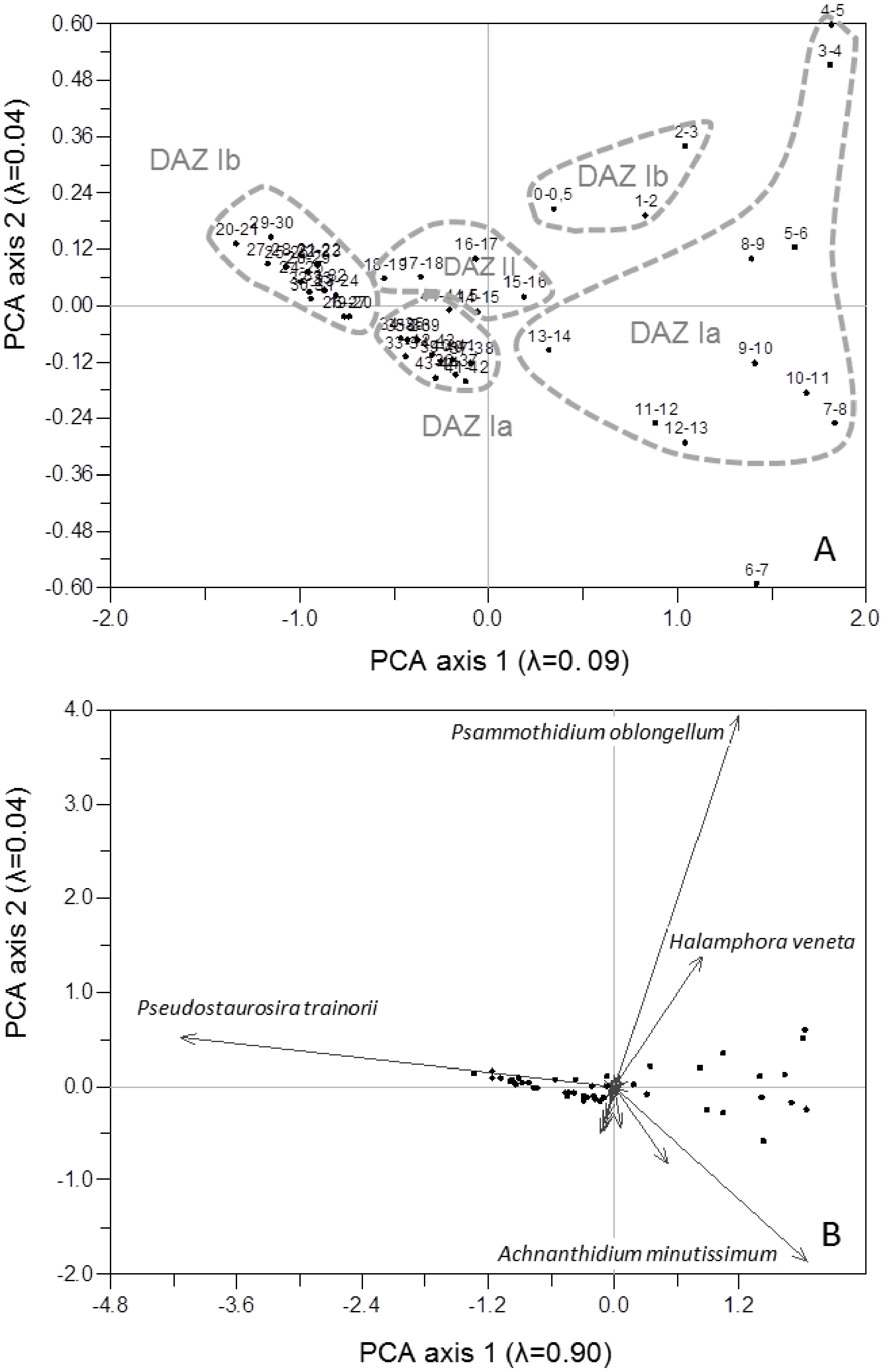

Fig. 4.2.3 – Principal Component Analysis (PCA) ordination biplot of (A) samples and (B) diatom species for core TRA07-A1 core. Only species with high scores are indicated.

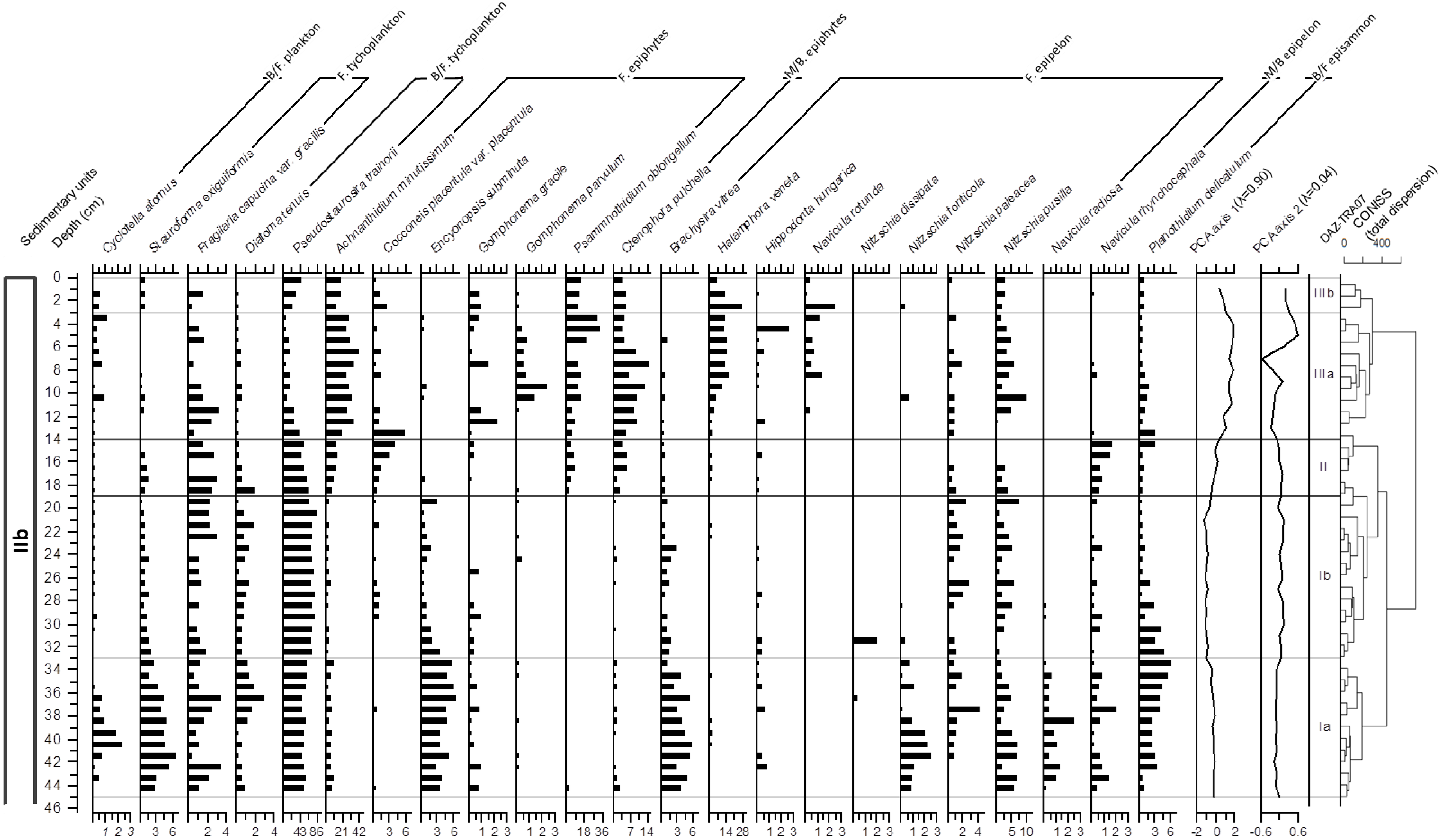

Fig. 4.2.2 - Diatom percentage diagram for selected taxa (≥ 2 % abundance in at least one sample) from TRA07-A1, with Diatom Assemblage Zones (DAZs), CONISS clustering, and loadings for PCA axes PC1 and PC2. Ecological groups according to Vos & De Wolf (1993): F - Freshwater; B/F – Brackish/Freshwater; M/B - Marine/Brackish.

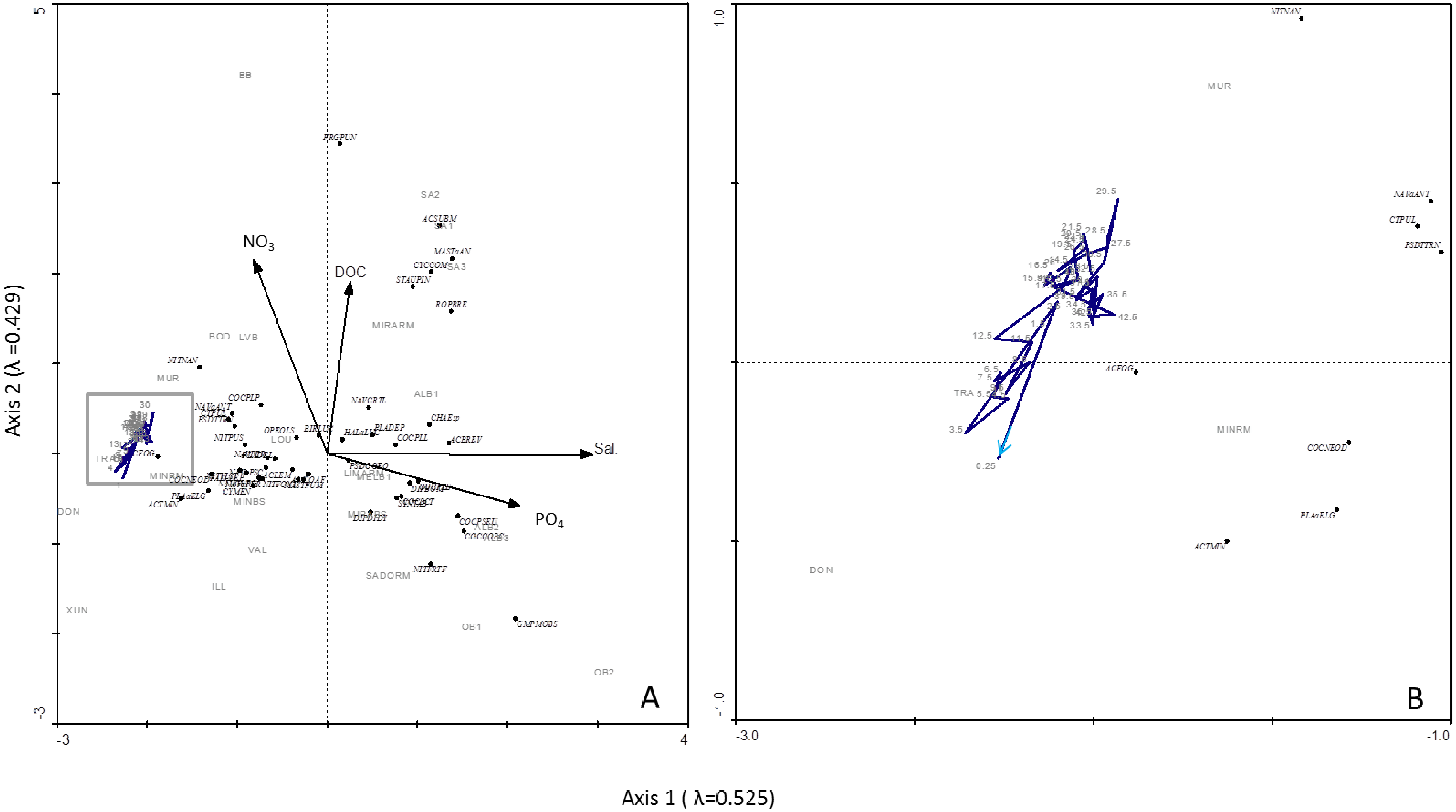

Fig. 4.2.4 - A - Samples from core TRA07-A1 plotted as passive samples within the ordination space of the CCA of diatom and environmental variables data from the surface sediment data-set of the WIAC (Chapter 4.1). B – Enlarged biplot corresponding to samples from core TRA07-A1 (box in A). Light blue arrow indicates the direction of the environmental change. See Table 3.3 (Chapter 3) for site code names and appendix IIA and B for acronyms of the diatom taxa.

#### 4.2.2.2.2 Quantitative Salinity Reconstruction

The salinity transfer function developed for the water bodies of the WIAC (Chapter 4.1) was used for inferring salinity changes in Traba during approximately the last 550 years. Component 4 of the Weighted Averaging Partial Least Squares Regression model (WA-PLS, ter Braak & Juggins, 1993) was used for this task. The resultant diatom-inferred salinity (DI-salinity) profile (Fig. 4.2.5) shows minor changes in salinity, as predicted by the position of the downcore samples in the ordination space of the CCA performed with surface sediment data from the region (Fig. 4.2.4).

DAZ TRA07-I shows very constant salinity values around 3.6 ± 0.2 ‰ to 5.7 ± 0.3 ‰, all in the freshwater to slightly brackish water range. Highest salinity values for this zone are recorded in subzone TRA07-Ib. There is a net shift towards more freshwater conditions along DAZ TRA07-II, with inferred salinities ranging from 2.2 ± 0.2 ‰ to 4.1 ± 0.2 ‰. The freshwater character is accentuated during DAZ TRA07-III which records minimum salinity conditions ranging from -0.1 ± 0.2 ‰ to 1.9 ± 0.2 ‰ in subzone TRA07-IIIa. Subzone TRA07-IIIb salinity recover to values very similar as those recorded in zone II (2.2 ± 0.2 ‰ to 4.1 ± 0.2 ‰). Reconstructed salinities for subzone TRA07-IIIa should however be taken with caution, as indicated by some estimated salinities that, according to the model, yielded negative values.

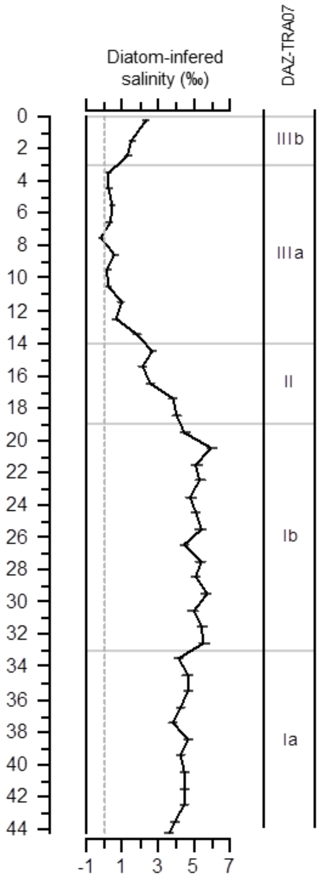

Fig. 4.2.5 – Downcore DI-salinities for TRA07-A1 estimated from the salinity transfer function for the Western Iberian Atlantic coastal water bodies (Chapter 4.1).

### *4.2.2.3 Elemental and stable-isotope geochemistry*

The different DAZs were characterized by their total carbon (TC), total organic carbon (TOC), total nitrogen (TN) and total sulphur (TS) contents as well as by their $C_{org}/N_{total}$ ratios and $\delta^{13}C_{org}$ ($\delta^{13}C$) and $\delta^{15}N_{org}$ ($\delta^{15}N$) signatures (Table 4.2.1, Fig. 4.2.6) from core TRA07-A1.

Table 4.2.1 - Ranges of elemental and stable isotope values recorded for each diatom assemblage zone (DAZ) in TRA07-A1.

| **DAZ TRA07** | **Depth (cm)** | **TC(%)** | **TOC(%)** | **TN(%)** | **TS(%)** | **$C_{org}/N_{total}$ (weight)** | **$\delta^{13}C_{org}$** | **$\delta^{15}N_{org}$** |
|---|---|---|---|---|---|---|---|---|
| **IIIb** | 0-3 | 6.71-10.34 | 3.52-6.68 | 0.85-1.31 | 1.92-2.42 | 12.54-12.87 | -26.70 to -25.95 | 5.19 -5.44 |
| **IIIa** | 3-14 | 4.63-8.27 | 2.91-5.70 | 0.50-0.91 | 1.37-2.07 | 12.67-13.92 | -26.96 to -25.89 | 4.27-5.52 |
| **II** | 14-19 | 6.30-7.75 | 3.66-4.60 | 0.60-0.76 | 1.70-4.43 | 13.68-14.15 | -26.76 to -26.51 | 4.23-4.41 |
| **Ib** | 19-33 | 2.86-7.21 | 1.51-5.02 | 0.27-0.69 | 0.82-1.79 | 12.47-15.18 | -27.42 to -26.07 | 3.07-4.43 |
| **Ia** | 33-45 | 7.14-9.32 | 2.98-5.42 | 0.69-0.90 | 1.55-2.14 | 13.45-15.20 | -27.47 to -26.63 | 2.78-3.92 |

*DAZ TRA07-I (45 - 19 cm)*

TC shows high values at the base of this zone (with a maximum of 9.32 %), experiencing a decreasing trend similar to that of TN. This trend is followed by TOC only in subzone TRA07-Ia, being reversed in subzone TRA07-Ib. As a result, the $C_{org}/N_{total}$ ratio shows a net decreasing trend throughout the zone with values ranging from 12.47 to 15.20 (Table 4.2.1). In spite of this decrease, subzone TRA07-Ia records the maximum value for the whole sequence. $\delta^{13}C$ and $\delta^{15}N$ show minimum values for the entire core, with a net increasing trend towards the top of the zone. TS content is relatively constant in this zone, showing a subtle upwards decreasing trend (Fig. 4.2.6).

*DAZ TRA07-II (19 - 14 cm)*

TC and TN experience a sharp shift at the base of this zone, whereas TOC continues the slight increasing trend started in the previous subzone. As a consequence, the $C_{org}/N_{total}$ ratio increases to values around 14. $\delta^{15}N$ maintain its previous slight increasing trend, whereas $\delta^{13}C$ shows a minor negative excursion. TS increases, with a sharp peak at 15 cm that represents its maximum abundance in the whole sequence (Fig. 4.2.6).

*DAZ TRA07-III (14 - 0 cm)*

Whereas TC, TOC and TN show net increases throughout the zone, the $C_{org}/N_{total}$ ratio experiences a decreasing trend, showing values as low as 12.54. By contrast, $\delta^{15}N$ prolongs its increasing trend, whereas $\delta^{13}C$ starts the zone with an increase, diminishing afterwards. TS returns to values around 2 % after the previous peak, but also starts a slight increasing trend towards the top of the sequence (Fig. 4.2.6).

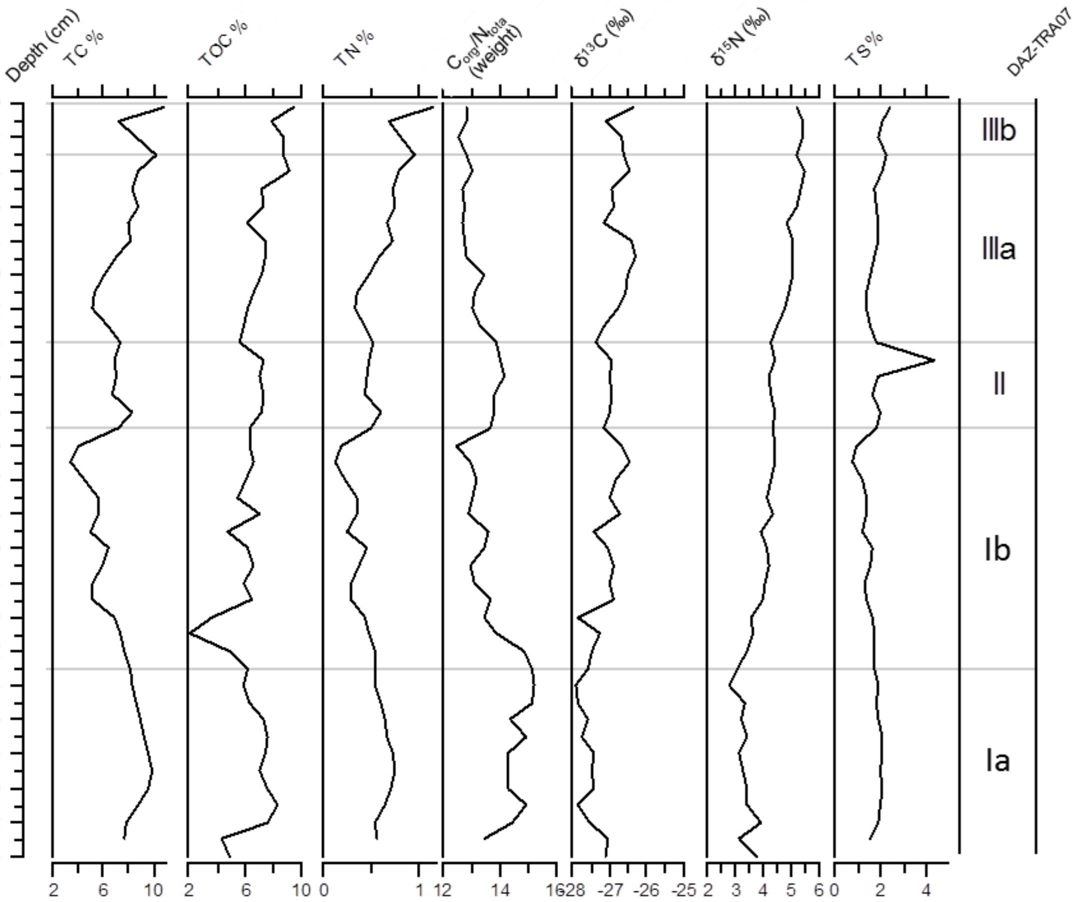

Fig. 4.2.6 – Downcore profiles of geochemical proxies including total carbon (TC), total organic carbon (TOC), total nitrogen (TN), $C_{org}/N_{total}$ ratio, $\delta^{13}C$ and $\delta^{15}N$, and total sulphur (TS) cotents and DAZ.

### *4.2.2.4 Geochronology*

The $^{210}Pb$ activity signal recorded in eleven samples from TRA07-A1 is small (-45 to 48 Bq $kg^{-1}$) and indistinguishable within the uncertainties of the measurement (67 to 111 Bq $kg^{-1}$), thus preventing being unable to provide a chronology using $^{210}Pb$. In spite of this, the record of $^{137}Cs$ activity shows a start at 15.5 cm, with a peak at 11.5 cm (Fig. 4.2.7). Whereas the start of the $^{137}Cs$ activity can be ascribed to 1954, the peak can be interpreted as belonging to the 1963 maximum deposition rate of $^{137}Cs$ before the Nuclear Test Ban Treaty, with no evidence of the 1986 Chernobyl event in this core (León Vintró, pers. comm.). The radiocarbon dating was performed in 3 samples (at 28, 36 and 94 cm depths in TRA07-A2). The topmost sample accused post-modern carbon (Table 4.2.2).

CLAM 2.1 (Blaauw, 2010) produces an age-model for the sedimentary sequence using both radiocarbon and non-radiocarbon $^{137}Cs$ ages (Table 4.2.3). CLAM calibrates the $^{14}C$ ages using calibration curves from IntCal09 (Reimer et al., 2009), creating a model constructed in cal BP ages (calibrated ages). Linear interpolation was chosen to create the models in Fig. 4.2.7, considering no outliers (model A) and an outlier Poz-43729 (model B). The model generates interpolated ages for each centimeter associated with a 95 % confidence, based on the 'best' age- depth model.

Table 4.2.2 - Radiocarbon and calibrated ages for core TR07-A2; pMC – post-modern Carbon; cal yr BP – calibrated years Before Present; cal yr CE - calibrated years of Common Era.

| Lab. code | Sample (cm) | Age $^{14}C$ | Age cal yr BP (2σ) | Age cal yr CE (2σ) |
|---|---|---|---|---|
| **Poz-43729** | 28 | 103.15 ± 0.33 pMC | 0 | 0 |
| **Poz-41704** | 36 | 415 ± 30 | 332-356 432-521 | 1429-1518<br>1594-1618 |
| **Poz-36880** | 94 | 485 ± 30 | 500- 543 | 1407-1450 |

Table 4.2.3 - Radiocarbon and non-radiocarbon ages used for age-model construction for TRA07; cal yr BP –calibrated years Before Present.

| Core | Lab code | Mean depth (cm) | $^{14}C$ Age | Age $^{14}C$ error | Non $^{14}C$ age cal yr BP | Non $^{14}C$ age error |
|---|---|---|---|---|---|---|
| **TRA07-A1 & A2** | - | 0 | - | - | -57 (2007) | 1 |
| **TRA07-A1** | $^{137}$Cs-11.5 | 11.5 | - | - | -13 (1963) | 1 |
| **TRA07-A1** | $^{137}$Cs-15.5 | 15.5 | - | - | -6 (1954) | 1 |
| **TRA07-A2** | Poz-43729 | 28 | - | - | 0 | 1 |
| **TRA07-A2** | Poz-41704 | 36 | 415 | 30 | - | - |
| **TRA07-A2** | Poz-36880 | 94 | 485 | 30 | - | - |

Sedimentation rates (SRs) were estimated for the composite sequence using the two constructed models. The downmost sedimentation rates of 11.4 and 12.6 mm yr$^{-1}$ estimated with models A and B, respectively, were extended to the 33 cm level according to the gentle and continuous trends in both the composition of the diatom assemblages and geochemical indicators (Figs. 4.2.2 and 4.2.6). The major difference between the two models rely on the estimated SRs between 33 and 15.5 cm. Model A considers two different SRs (0.2 and 17.9 mm yr$^{-1}$) whereas in model B there is a unique estimated SR of 0.4 mm yr$^{-1}$. Model B was chosen based on its simpler assumptions. Model A would assume a major erosive or sedimentation hiatus (294 years) taking place between 33 and 28 cm, i. e., between 1656 and 1950 cal yr CE - calibrated years of Common Era. There is no evidence either in the diatom assemblages or the geochemical proxies of any abrupt shift indicating a major change in the sedimentary environment. Hence, interpolated ages are from here on based on the 'best' age-depth model from the CLAM age-depth model B.

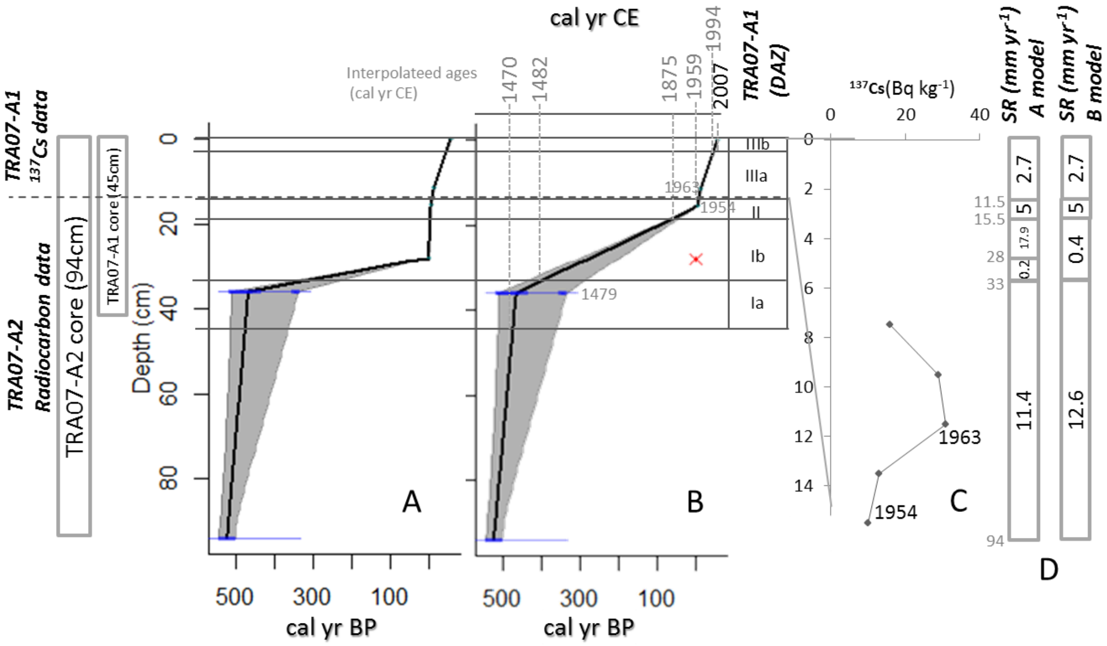

Fig. 4.2.7 - Two age-depth plots constructed with CLAM 2.1 (Blaauw, 2010). **Model A CLAM settings**: linear interpolation; 1000 iterations weighted by calibrated probabilities at 95 % confidence ranges and resolution 1 year steps; 35 models with age reversals were removed. CLAM output statistics: 0-94 cm; -log goodness –of-the-fit = 9.92; 95 % confidence range from 3 to 175 years, average 70 years. **Model B CLAM settings**: linear interpolation; 1000 iterations weighted by calibrated probabilities at 95 % confidence ranges and resolution 1 year steps; assumed outlier (Poz-43729, marked with a red cross); 27 models with age reversals were removed. CLAM output statistics: 0 - 94 cm; -log goodness –of-the-fit = 23.52; 95 % confidence range from 3 to 177 years, average 81 years. C - $^{137}$Cs measured radiometric activity. D – Sedimentation rates presented are interpolated using age-models A and B.

Application of the model yielded four SRs: (1) 12.6 mm yr$^{-1}$ (94 to 33 cm), (2) 0.4 mm yr$^{-1}$ (33 to 15.5 cm), (3) 5 mm yr$^{-1}$ (15.5 to 11.5 cm), and (4) 2.7 mm yr$^{-1}$ (Fig. 4.2.6). The first SR, 12.6 mm yr$^{-1}$ (94 to 33 cm), is certainly enlarged by the presence of centimetric aeolian sand layers (Fig. 4.2.1). Removal of the 8 cm of sand layers, presumably deposited during short episodic events, would yield a more reasonable SR of 9.8 mm yr$^{-1}$.

### 4.2.3 DISCUSSION

#### *4.2.3.1 Meaning of the diatom assemblages and isotopic signatures*

The results of the PCA, combined with the study of the behavior of the fossil samples in the ordination space defined by the CCA on present-day samples of the WIAC (Chapter 4.1), provide the main basis for the palaeoecological interpretation of the diatom assemblages found in core TRA07. Variance explained by the first two components of the PCA (90 % for PC1 and 0.04 % for PC2) shows that almost all the variation can be reduced to what the PC1 means. This first component mainly reflects variations in the abundance of *Pseudostaurosira trainorii* and *Achnanthidium minutissimum*. Both species constitute two of the main taxa characterizing the cluster of freshwater coastal lakes and ponds and restricted lagoons of the WIAC (Chapter 4.1). *Pseudostaurosira trainorii*, which belongs to the *Fragilaria* s. l. group, is an opportunistic brackish/freshwater tychoplanktonic small diatom found elsewhere in small water bodies with neutral pH and low to high concentrations of phosphorous (Morales, 2001). *Achnanthidium minutissimum* is a widespread and abundant species, constituting one of the most frequently occurring diatoms in freshwater benthic samples (Patrick & Reimer, 1966; Krammer & Lange-Bertalot 1991). The dominance of these two taxa throughout the core suggests that during the studied period Traba behaved as a coastal lake or pond with minor connection to the ocean (Vos & de Wolf, 1993), as it occurred during the 5700 cal yr BP of its history (Bao et al., 2007). However, the clear alternate dominance of the two species before and after c. 1875 cal yr CE points to an underlying environmental change that significantly altered the composition of the diatom assemblages. *Fragilaria* s. l.-dominated assemblages are typical of shallow-water littoral zones of a wide variety of water bodies under conditions of environmental instability (Reed, 1999). Under these circumstances they often bloom in coastal environments (Denys, 1990), having been considered typical before and during the process of water body isolation from the ocean (Stabell, 1985). Growth of this taxon is also favored by alkalinizing base cations released from the catchment (Axford et al., 2009). For the mentioned reasons, and the brackish/freshwater affinity of *Pseudostaurosira trainorii*, its dominance before c. 1875 cal yr CE point to the existence of instable environmental conditions associated to a more frequent and/or intense connection to the ocean. As the rest of the *Fragilaria* s. l. species, it would also indicate the predominance of shallow but open waters (Fan et al., 1996). On the other hand, *Achnanthidium minutissimum* is common in well-oxygenated lakes and streams with low or moderate concentrations of nutrients and organic pollution (Kelly, 2000). It is not only an epiphytic species indicative of extensive macrophytic development (Vos & de Wolf, 1993), but also an indicator of increased infilling in wetlands behind a sand barrier (Earle & Duthie, 1986). In the long-term evolution of Traba, *Achnanthidium minutissimum* was the dominant species during the transition from a lacustrine to palustrine environment, at c. 3100 cal yr BP in the innermost position of the present-day wetland (Bao et al., 2007). According to the ecologies of these two dominant taxa in core TRA07, shifts in the PC1 scores throughout the record (Fig. 4.2.2) can be used as rough indicators of changes in the confinement of the system. Low values of this axis would be indicative of more frequent and/or intense connection to the ocean, whereas high values would be characteristic of a less permeable sand barrier that gave rise to a more confined environment.

Besides changes in sand-barrier permeability, nutrients exert also a control on the composition of the diatom assemblages, as shown by the plot of fossil samples in the CCA (Fig. 4.3.4). Top samples dominated by *Achnanthidium minutissimum* fall at the side of low P and N sources compared to those dominated by *Pseudostaurosira trainorii*. This result suggests that these two species can be used to trace changes in the eutrophy of the system.

Shifts in carbon isotope ratios in lake sediments have mainly been attributed to changes in productivity, metabolic pathways for carbon fixation, source of organic matter and diagenesis, among others (Meyers & Teranes, 2001; Cohen, 2003; Lamb et al., 2006). For the particular case of coastal environments, variations in the fluvial vs. marine inputs of organic matter play a major role on C fractionation (Lamb et al., 2006). Although the net increase in $\delta^{13}C$ values would be coherent with the diatom-inferred salinity reconstruction for the first part of the record (DAZs I and II, Figs. 4.2.5 and 4.2.6), the pattern is reversed in the most recent history of the wetland (DAZ-I). Other factors should therefore be taken into account for the observed change in the carbon isotope ratio. It is known that the delivery of light dissolved inorganic carbon from land runoff can result in isotopically light algal organic matter (Meyers & Teranes, 2001; Lamb et al., 2006). Variations in $\delta^{13}C$ values found in Traba are in general terms inverse to those in the $C_{org}/N_{total}$ ratio, suggesting that changes in the incorporation of terrestrial vs. aquatic organic matter can be the main responsible for shifts in the carbon isotope ratios. The observed net increase in $\delta^{13}C$ would therefore be indicative of a reduction in the catchment runoff. This explanation is likely applicable to the observed pattern of $\delta^{15}N$. Inorganic nitrogen reservoirs available to land plants and aquatic plants differ in their isotopic contents so land-derived organic matter yields a lighter N signature than aquatic organic matter (Meyers & Ishiwatari, 1995). For the particular case of Traba, the reduced size of the catchment probably magnified the effects of land-derived vs aquatic organic matter inputs over other factors on both the C and N isotope signatures, explaining the net increase through time of both proxies.

#### *4.2.3.2 Palaeoenvironmental reconstruction*

Diatom assemblage data indicate that Traba was always a wetland with no tidal influence according to the classification of Vos & de Wolf (1993) throughout the studied period, but have responded to changes in water level and sand barrier permeability as well as to nutrient concentration. Based on the sedimentology, changes in the diatom assemblages, $C_{org}/N_{total}$ ratios, isotopic signatures in organic matter ($\delta^{13}C$ and $\delta^{15}N$) and DI-salinity, three main stages in the evolution of the system can be identified (Fig. 4.2.8).

#### Stage A (interpolated age c. 1470-1875 cal yr CE)

As stated before, dominance of brackish/freshwater tychoplanktonic diatoms suggests the development of shallow but open oligohaline waters during this stage. $C_{org}/N_{total}$ ratios point to a mix of aquatic and terrestrial organic carbon sources which progressively become more aquatic, after 1600 cal yr CE (Meyers & Ishiwatari, 1995). Sedimentation rates experience a drastic decline from 9.8 to 0.4 mm $yr^{-1}$ (Fig. 4.2.8). At the same time, there is an increase in the abundance of tychoplanktonic taxa, indicating that depth and/or extension of open waters was at its peak for the whole studied period. Both diatom and $C_{org}/N_{total}$ ratio data suggest that the progressive expansion of open waters is paralleled, as expected, by a relative increase in the contribution of algae to primary productivity. Flood simulations in Traba have shown that extreme water elevations would imply extensive inundation of the sand-barrier (González-Villanueva et al., 2013) (Fig. 4.2.8). This would have facilitated exchange with the ocean, and thus the dominance of pioneering diatoms typical of instable environments such as *Fragilaria* s. l. (Stabell, 1985; Denys, 1990) to which the genus *Pseudostaurosira* belongs to. Diatoms of this group are also reported as being benefited from alkalinizing base cations released from the catchment (Axford et al., 2009; Reed et al., 1999). The dominance of these diatoms during this stage could indicate enhanced runoff and increased cation input to lake waters.

Allochthonous inputs are not only limited to byproducts of weathering, but also to sands of aeolian origin, as shown by the maximum number of sand layers in the record at this time (Fig. 4.2.8).

A correlation between the core TRA07 (this hapter) and the marginal TR1 (Bao et al., 2007) shows that at this latter position infilling already had started, as indicated by its diatom community dominated by freshwater epiphytes. Besides this, a minor peak in oligohalobous halophilous taxa confirms that some kind of marine influence affected even this inner position at this time.

**Stage B (interpolated age c. 1875-1990 cal yr CE)**

During this stage a progressive transition from an open wetland with reduced but more or less constant ocean influence to a more confined freshwater environment takes place, as indicated by the DI-salinity reduction (Fig. 4.2.8). The change is accompanied by a probable decrease in aeolian activity, shown by the reduction in the deposited sand layers (Fig. 4.2.8). However, major changes affected the trophic status and composition of biological communities in the lake itself.

The stage starts with an increase in the $C_{org}/N_{total}$ values (in the range of 13.7 to 14.2) indicating enhanced contribution of land-derived organic matter. This increase is coincident with the decline in tychoplanktonic diatoms, which are progressively replaced mainly by freshwater epiphytes. Debris of macrophytes associated to epiphytic diatoms might explain the cellulose-rich organic matter that would increase the $C_{org}/N_{total}$ values (Meyers & Teranes, 2001), as well as a higher sedimentation rate. A similar correspondence between an increase in epiphytic diatoms and $C_{org}/N_{total}$ is found in the previous Stage A (DAZ-Ia, Fig. 4.2.8). However, after the peak in $C_{org}/N_{total}$ recorded at the start of this Stage B there is a progressive decrease in the values of the ratio, starting at c. 1960 cal yr CE, in spite of the epiphytic diatoms net rise. At this time both diatom data and aerial photograph surveys indicate extensive growth of areas colonized by emerged macrophytes at the expense of the water body (González-Villanueva et al., 2013). This would be in conflict with the decline shown by the $C_{org}/N_{total}$ profile. A probable explanation would lie on the relative importance of emerged vs. submerged vegetation on the recent palludification of the whole system (Bao et al., 2007). The marginal areas of the lake are currently colonized by reeds (*Phragmites australis*), whereas the bottom is covered during spring and summer by a mat of the algae *Aegagropila linnaei* and a submerged macrophyte community dominated by *Ruppia maritima*, with other plants, such as *Ceratophyllum demersum*, being subdominant (Carballeira & Leira, pers. comm.). Analyses of samples of *Phragmites australis* in the coastal lake of Doniños, northern Galicia, yielded average values of $C_{org}/N_{total}$ = 27.2 and $\delta^{13}C$= -31.0 ‰ (Bao et al., unpublished data) not in the range of those observed in the sediments of Traba during this stage. Although we lack isotopic and $C_{org}/N_{total}$ data from the dominant *Aegagropila linnaei* and *Ruppia maritima*, it is very likely, especially for the former, that their values are very close to those of the subdominant *Ceratophyllum demersum,* which in Doniños yielded figures of $C_{org}/N_{total}$ = 8.4 and $\delta^{13}C$= -19.5 ‰ (Bao et al., unpublished data), clearly in the range of freshwater to marine algae (Lamb et al., 2006). The low values in the sediment's $C_{org}/N_{total}$ ratio during this stage would therefore not be associated to the known expansion of emerged macrophytes in the marginal areas of the lake (González-Villanueva et al., 2013). On the contrary, they seem to be related to the development of extensive beds of submerged plants that would support the epiphytic diatom communities showing a peak in the sedimentary record during this stage. The positive excursion of $\delta^{13}C$ could very probably be related to the expansion of submerged plants, these also with heavier carbon.

The reduction in connection with the ocean is probably a consequence of a less extended water table, according to the available simulations (González-Villanueva et al., 2013), and/or a more consolidated and thus less permeable sand barrier (Fig. 4.2.8). A big event of barrier breaching or overwash is however suggested by the peak in TS recorded at c. 1960 cal yr CE. This has no correspondence with a similar rise in TOC, so the S peak is not due to a correspondent increase in organic matter. The high S content, reflected in a TOC/TS value of 14, suggests a very short-term episode of salinization accompanied by strong reducing conditions in the lake (Berner et al., 1979). This episode had a limited effect on the biological communities, as shown by the slight modification in the DI-salinity profile (Fig. 4.2.8), confirming the very short-lived condition of the event.

The shift from an assemblage dominated by *Pseudostaurosira trainorii* (Stage A) to *Achnanthidium minutissimum* in 1875 cal yr CE, points to a modification of the eutrophic status of the lake. According to the plot of the fossil samples from core TRA07 on the CCA of the present-day diatom dead assemblages and environmental variables (Fig. 4.3.4), this shift would be related to a reduction in the N and P sources. The coincidence of these conditions with the development of macrophytes rises as a probable explanation for a change of equilibrium in the system, due to a reduction in nutrient levels. According to the alternative stable states hypothesis, shallow lakes can have two opposite alternative states: a high nutrient turbid state with few submerged plants, or a clear state with abundant submerged macrophytes (Scheffer et al., 1993; Scheffer & van Nes, 2007). This model has successfully been used to interpret the long-term evolution of coastal lake systems that became separated from the ocean (e. g., García-Rodríguez et al., 2010). Conforming to this model, Traba experienced a transition (DAZ-II, c. 1875 to 1960 cal yr CE) from a turbid state characterized by higher nutrient levels and low macrophytic development (Stage A) to a clear state (Stage B) with lower nutrient load and abundant submerged plants. As stated above, the latter would be the responsible for the apparently counterintuitive observed low $C_{org}/N_{total}$ ratios.

**Stage C (interpolated age c. 1990-2007 cal yr CE)**

This stage is characterized by the absence of aeolian sandy events and by a minor but steady salinity increase to 4.1 ± 0.2 ‰. Both this shift and the also subtle decline in PC1 is a reflection of the change from a diatom assemblage dominated by *Achnanthidium minutissimum* (Stage B) to one codominated by this taxon and the formerly dominant (Stage A) *Pseudostaurosira trainorii*. A reversal of the trend might have taken place, but the subtle changes involved in the rest of the proxies do not allow confirming this hypothesis. $C_{org}/N_{total}$ ratio remains in low values that represent mixed sources of organic matter (aquatic and land-derived, Lamb et al., 2006), whereas $\delta^{13}C$ and $\delta^{15}N$ show a net zero change during this stage. The reduction in freshwater epiphytic diatoms in favor of brackish/freshwater tychoplanktonic forms suggest however a system that is now more permeable to ocean influence and thus subject to increased environmental instability (Fig. 4.2.8). The absence of clear consistent trends in $C_{org}/N_{total}$, $\delta^{13}C$ and $\delta^{15}N$ values for this short period, limits interpretations based on the alternative stable states hypothesis of shallow lakes.

#### *4.2.3.3 Climatic and non-climatic forcings in the recent ecological evolution of the wetland*

Comparison of the Traba wetland based on this multiproxy approach, with the already available local and regional palaeoenvironmental data, allows us to elucidate the main factors responsible for the evolution of this site. It can also serve for the purpose of contributing to a better understanding of the palaeoclimatic variability of Galicia in the approximately last 550 years.

For more than 500 years Traba behaved as a coastal freshwater to slightly brackish wetland with a varying extension of open waters and communication with the ocean. As a result of this dynamism, the lake experienced at least two different ecological states according to the alternative stable states hypothesis (Scheffer et al., 1993; Scheffer & van Nes, 2007). From c. 1470 to 1875 cal yr CE, the system experienced a more intense nutrient load that led to a turbid state according to Scheffer & van Nes, (2007). After this time, and for approximately 85 years (c. 1875 to 1960 cal yr CE), the lake transformed to a clear state until c. 1990 cal yr CE, when a sound shift in the diatom assemblages suggests the possibility of a new state change that would last until present. Both regional (climate change) and local (sand barrier permeability, in-lake processes, and anthropogenic influence) factors account for the observed changes in the state of this lake system.

##### 4.2.3.3.1 The turbid state

For approximately 400 years (c. 1470 to 1875 cal yr CE) an opportunistic diatom flora flourished in Traba, indicating a high water table that facilitated some kind of connection with the ocean (according to simulation models of González-Villanueva et al., 2013). This period falls quite accurately in the Little Ice Age (LIA), a climate anomaly that extends from c. 1350 to 1850 cal yr CE and had a worldwide imprint (Soon & Baliunas, 2003; Wanner et al., 2008; Desprat et al., 2003, Fig. 5.1A, Chapter 5), lowering 1 to 2 °C air temperature in Galicia (Martínez-Cortizas et al., 1999). Analyses of marine records have suggested a dry LIA for Galician latitudes. Both the rías of Muros and Vigo reflect a reduction in runoff at the onset of the LIA (Lebreiro et al., 2006; Pena et al., 2010; Andrade et al., 2011). Disentangling the relative importance among marine factors (upwelling of deep waters and productivity) and land factors (changes in river input) in these records, has however been proven difficult (Cacho et al., 2010). This mixture of two primary signals could explain why using different proxies a more humid LIA was also suggested for the Ría de Vigo (Bernárdez et al., 2008). By contrast, several continental records of the Iberian Peninsula characterize the LIA as a period of increased water availability associated with predominant negative values of the North Atlantic Oscillation (NAO) index (Benito et al., 2003; Moreno et al., 2008). For instance, an abnormal high frequency of large floods in the Atlantic sector of the Iberian Peninsula seems to be well documented (Benito et al., 2008) matching with evidences of an intensified fluvial geomorphic activity in Europe (Rumsby & Macklin, 1996; Grove, 2001; Macklin & Lewin, 2003). This scenario of large water availability fits with a well developed water table in Traba, and is also in close agreement with the wet period dating 1430–1865 cal yr CE identified from organic matter chemistry in a Galician peat (Schellekens et al., 2011), as well as with palaeolimnological records of the Iberian Peninsula (Roberts et al., 2012).

Climate forcing on the environmental features of the wetland at this time is not restricted to precipitation variability. The LIA has been considered a period of enhanced storminess over the North Atlantic coastlines (Dawson et al., 2003, 2007; Clarke & Rendell, 2009; Trouet et al., 2012). This increased storminess coincided with numerous episodes of sand drift and dune building along the western European coast as documented by historical records (Clarke & Rendell, 2009). Both stormy conditions and intense aeolian activity are compatible with the palaeoenvironmental reconstruction of Traba for the LIA. DI-salinity reveals that it was during this period that the highest saline conditions were acquired in the system. These could have been the product not only of an easier connection to the ocean due to an elevated water table, but also to the phenomena of storm-induced barrier breaching. On the other hand, high aeolian activity in Traba is manifested in the water body by the highest frequency of deposited aeolian sand layers for the last c. 550 years. This intensification of sand movements has also been recorded in northwest Portugal for the LIA (Granja et al., 2008). The Traba record adds new information on the conflicting views of the relationship between NAO and storminess variabilities in the North Atlantic (Trouet et al., 2012). It has been suggested that the increase in storminess during the LIA is linked to a pervasive NAO positive state (Dawson et al., 2003, 2007), a view that conflicts with the hypothesis of a negative NAO condition suggested by other authors (Trouet et al., 2009; Mann et al., 2009). The high water table and cation enrichment recorded in Traba during the LIA suggest enhanced precipitation conditions that are in agreement with a dominant weakened NAO state. This supports the hypothesis of Trouet et al. (2012) of increased storminess not associated to more frequent storms, as a pervasive strengthened NAO would suggest (Dawson et al., 2007), but to more intense storms compatible with a NAO negative state scenario. The Traba record also gives an additional evidence that the intensification of aeolian activity coincident with increased storminess and prolonged negative phases of NAO extended well into SW Europe during the LIA (as pointed by Costas et al., 2012) (Fig. 5.1A, Chapter 5).

The climatic conditions of the LIA had not only an impact on the precipitation and storm regime of the area, but probably also on the forest cover of the basin. The combined effects of increased water availability and a reduced forest cover very probably explain the intensified cation release from the basin that is suggested by the dominance of *Pseudostaurosira*. It is known from historical sources and pollen data that a process of intense deforestation followed the Roman Warm Period (250 cal yr BCE – calibrated years Before Common Era, to 450 cal yr CE, Desprat et al., 2003) and that it did not stop in Galicia until the mid 1800's, when an open landscape dominated by shrubs prevailed (Guitián Rivera, 2001; Kaal et al., 2011). For the specific case of coastal areas, pollen data also indicate that locations such as the surroundings of the Ría de Vigo were almost completely deforested during the LIA (Muñoz-Sobrino et al., 2012). However, both climatic deterioration and human activities participated in the process of deforestation that led to increased erosion, making difficult to disentangle the relative contribution of the two sources in the environmental degradation that took place at the time (Kaal et al., 2011).

#### 4.2.3.3.2 The clear state

By the end of the LIA, almost all proxies show some kind of inflection, indicating a gradual transformation during approximately 85 years (c. 1875 to 1960 cal yr CE) that underwent in a change of state.

A reduction of nutrient availability was probably the main cause involved in this shift of state, as indicated by the trajectories of change of the passive fossil samples in the CCA biplot that relates diatom composition with the environmental variables (Fig. 4.3.4). External nutrient load was very probably reduced by a gradual transformation from a shrub to a forest-dominated landscape in the surroundings (Guitián Rivera, 2001). The expansion of *Pinus* in Galicia started at c. 1650 cal yr CE, but it was only in the begining of the last century that large afforestation, especially in coastal areas, took place (Ramil-Rego et al., 2001; Desprat et al., 2003). From the mid century onwards, this was accompanied by the also massive afforestation with *Eucalyptus globulus*. Both should have contributed to a reduced export of nutrients from the catchment to the wetland, facilitating gradual transition from a turbid to a clear state (Schallenberg & Sorrell, 2009). Besides this, aerial surveys show a net increase in the extension of the area occupied by emergent macrophytes in the shores since, at least, 1945 (González-Villanueva et al., 2013). The progression of the marginal marsh could have also benefited the reduction in the nutrient loads (Jacobs & Gilliam, 1985; Gasiorowski, 2008). In any case, the nutrient decrease was however gradual, not only because of the progressive transformation of the landascape, but also because it is necessary a strong nutrient reduction to enable recolonization by plants from a previous turbid state (Scheffer et al., 1993).

Besides the reduction in the catchment nutrient flux to the wetland, other factors could have contributed to the shift of alternative states. First, there are indications that changes in the water level affecting the performance of submerged macrophytes may have been an important trigger of the switches in shallow lakes (Scheffer et al., 1993; O'Farrell et al., 2011). Submerged macrophyte dominance is positively related to the occurrence of lake level drops, and negatively to lake surface area (van Geest et al., 2007). The low water period in Traba that extended from 1875 to 1990 cal yr CE very probably had its influence in the transition from a turbid to a clear state. Second, heavy storms can sometimes be implicated in the change between alternative stable states (van Nes et al., 2007). Enhanced storminess during the 1950's (González-Villanueva et al., 2013), is documented in the sedimentary record of Traba by a short-lived episode of barrier breaching indicated by the notable TS peak. As indicated above, this episode had a quite limited effect on the biological communities, and probably might have had a little contribution to the change from a turbid to a clear state, but some kind of influence cannot be completely ruled out.

Although sedimentation rate increases during this phase to be reduced afterwards, there is not a consistent pattern during this or the previous phase between changes in sedimentation rates and in ecological conditions. This observation agrees with the fact that the sedimentation rate does not depend on the ecological status but rather on depth, lake area and hydrological conditions (Gasiorowski, 2008).

### 4.2.3.3.3 A transition to a new stable state?

The sedimentary record reflects a change in the abundance trends of epiphytic vs. tychoplanktonic diatoms, as well as an increase in salinity from 1992 to 2007 cal yr CE. These changes might be indicative of the start of a new change from a clear to a turbid state, but the behavior of the remaining sedimentary record proxies do not allow to confirm this hypothesis. Some other data suggest however that this might be the case.

Birdwatchers monitoring waterfowl populations in the wetland for the last 35 years witnessed dramatic changes in land use that took place in the inmediate catchment from the start of the 1990’s onwards (J. L. Rabuñal, pers. comm.). This involved channelization of the small tributaries that feed the system, transformation of the higrophilous grasslands mainly made up by *Juncus* spp. and *Eleocharis palustris* into pastures, intensive use of manure as fertilizer, and intermittent artificial opening of the drainage channel that allows sea water entrance. Large development of emergent macrophytes at the shores also occurred.

The increase in arable land and the use of fertilizers could have implicated an intensification of nutrient loads (Schallenberg & Sorrell, 2009), likely triggering a transition of the system to a new turbid state that could be taking place nowadays. TN concentrations recorded at present in the water column range from 1.4 to 3.1 mg $L^{-1}$ when the inlet is not artificially opened (Carballeira & Leira, pers. comm.). On the other hand, in spite of cultural eutrophication, average nitrate (0.61 mg $L^{-1}$) concentrations occuring in the water body at present makes it fall in the category of a mesotrophic system (Håkanson & Bryhn, 2008). These data would put Traba in an intermediate rather than pure turbid state according to the classification of Ibelings et al. (2007). Both the buffering effect (Gasiorowski, 2008) of the marginal marsh mainly made up by *Phragmites australis* and *Typha latifolia*, and the artificial barrier breaching to prevent the flooding of the adjacent artifical pastures very probably counteracted to avoid pure eutrophic conditions in the wetland. Nitrate concentration in the lake can be reduced as much as 300 times when breaching takes place, until the normal concentrations that range from approximately 1.0 to 3.0 mg $L^{-1}$ are reached some weeks later, when natural closure of the channel occurs (Carballeira & Leira, pers. comm.). Although this type of manipulation can have a temporary impact on nutrient concentrations, it is not sure that it can provide a return to the previous clear state (Hobbs et al., 2012).

The additive effect of natural eutrophication in a hypothetic change of state can also not be disregarded. Shallow lakes can cyclically switch from vegetation dominated clear water phase and a contrasting turbid phase as a result of slow internal eutrophication (van Nes et al., 2007). This “time bomb effect” occurs when during the clear phase P is sequestered from the water column by the macrophytes and accumulated in the sediments. The accumulation of organic matter results in increased oxygen demand that causes anaerobic conditions, boosting a P release from the sediments that can provoke a shift to a clear state. At least 7 years of macrophyte dominance has been observed as the lapse time needed for these regular cycles (van Nes et al., 2007). Traba showed at least 35 years of dominance of a clear state, making plausible that the “time bomb effect” exerted some influence on a change of state.

Another line of evidence supporting a plausible change of state comes from birdwatching monitoring data that shows in Traba a drastic reduction in wintering and breeding populations of rails and waterfowl from approximately 1992-2003 to present (J. L. Rabuñal, pers. comm.). At least for the case of waterfowl, lower numbers are known to occurr at times with low macrophyte cover and turbid water, compared to times when submersed macrophytes flourish and the water is clear (Hansson et al., 2010). Although there is a time lag between the first historical and sedimentary evidences for change and the response of waterfowl populations (mainly Mallard *Anas platyrhynchos*, J. L. Rabuñal, pers. comm.) a probable close relationship cannot be dismissed.

Validation of the hypothesis of a change to a new turbid state in Traba requires ecological monitoring data that started to be gathered in 2007, at the time when the studied core was retrieved from the wetland. It will not be until a long-term ecological database is completed that a final conclusion could be drawn about the ecological present day status and fate of this freshwater coastal environment.

### 4.2.4 CONCLUSIONS

The multiproxy palaeoenvironmental reconstruction of Traba demonstrates that the evolution of this coastal wetland in the last approximatley 550 years was dependent on the complex interplay between a variety of factors that acted simultaneously. Climatic variability and direct or indirect human intervention gave rise to at least two different ecological states in its history that can be understood in the framework of the shallow lakes alternative stable state hypothesis. During the period extending from 1470 to 1875 cal yr CE Traba was characterized by a turbid state fed by significant nutrient loads facilitated by a deforested catchment. Deforestation was not only the product of human impact after the Roman Warm Period until the 1800’s but also of the deteriorated climatic conditions associated to the LIA. A pervasive NAO negative phase brought intensified precitation to the region during this climatic anomaly, increasing external nutrient inputs and a rise in the water table. Under this climatic scenario, the system was also subject to increased storminess that facilitated some exchange with the ocean through the sand barrier, raising its salinity. The Traba record gives additional support to a scenario of intensification of aeolian activity coincident with increased storminess and prolonged negative phases of NAO during the LIA in the Atlantic European coast.

From 1875 to 1990 cal yr CE the lake experienced a gradual transition to a clear phase, that last approximately 85 years. Reduced nutrient loads to the lake, as well as a lake level drop, facilitated the transition to a submerged macrophyte dominated state. The start of this transition is not only coincident with the termination of the LIA, but also with the afforestation of the catchment that hindered nutrient export to the wetland. The inertia of the system and the gradual afforestation of the catchment made the transition from the turbid to the clear state a long process.

The record shows a recent hypothetical new change of state that probably started at 1992 cal yr CE with the direct human intervention in the inmediate surroundings of the lake. Transformation of the hygrophilous grassland shore communities to pastures, and the intensive use of manure as fertilizer, contributed to enhanced nutrient inputs to the lake. Episodic artificial breaching of the sand barrier performed to avoid flooding of pastures, and the buffering effect of the marginal marsh have however probably alleviated eutrophication in the lake in the last years.

Regime shifts between alternative stable states in the recent history of this small shallow water body are coincident with known human intervention, both indirectly affecting the catchment (i. e., via deforestation/afforestation) or directly on the inmediate surroundings (i. e., via land reclamation, fertilization, and sand barrier breaching). However, climatic variability has also played a major role as a forcing agent on its evolution (cold conditions associated to the LIA, NAO, and storminess variability). The story of Traba reflects the difficulties to unravel the relative importance that the two main groups of forcing agents, climatic and human-induced, have in the recent evolution of these systems.

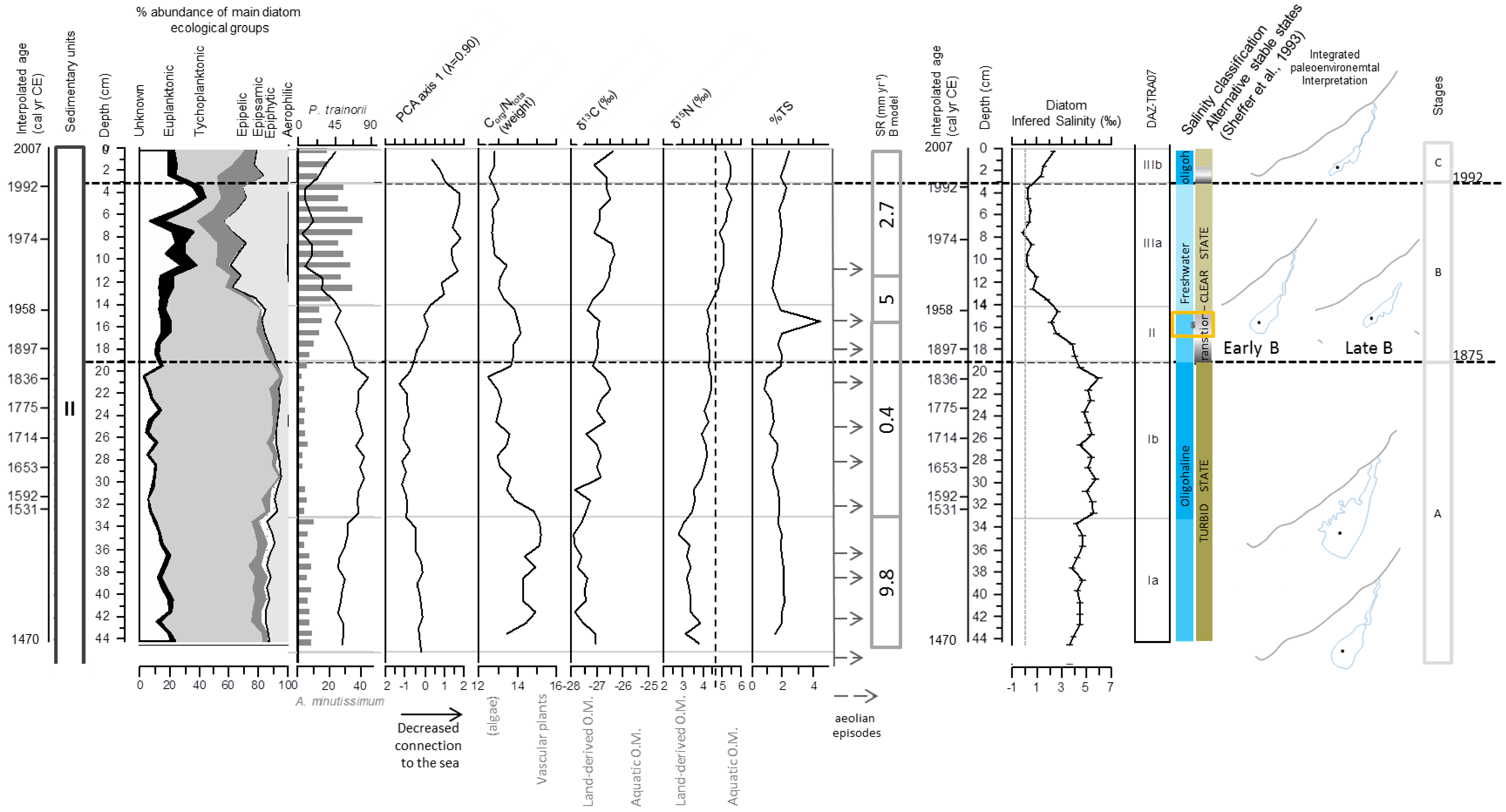

Fig 4.2.8 –Summary of main diatom a geochemical proxies from core TRA07 with indication of the main palaeoenvironmental stages in the evolution of the system and tentative reconstruction of the extension of the water table, adapted from simulations in González-Villanueva et al. (2013).

# 4.3. Natural and human-induced changes in alternative stable states – a 1745 years record of environmental change in the Melides lagoon (Portugal)

### 4.3.1 INTRODUCTION

The reduction in the rate of postglacial sea-level rise that took place since the mid-Holocene (Lambeck et al., 2002) facilitated the formation of sand-barriers and associated back-barrier wetlands in the Western Iberian Atlantic coast (WIAC) around 5500 cal yr BP (Bao et al., 1999, 2007; Freitas et al., 1999, 2002a, 2003a; Cearreta et al., 2003; Freitas & Andrade, 2005; Costas et al., 2009; González-Villanueva et al., 2009). The evolution of these coastal systems in the world is forced by global or regional factors, such as changes in sea-level, climate and tectonic stability, and by local factors such as changes in sediment supply, tidal range, land use, and nutrient availability (Cooper, 1994; Isla, 1995; Hesp & Short, 1999; Day et al., 2008; Moser et al., 2012; Newton et al., 2013; Williams, 2013). Although the deceleration of the Holocene postglacial marine transgression seem to have induced local factors to become progressively more important (e. g., Devoy et al., 1996), the current context of accelerated sea-level rise induced by global warming (Nicholls & Cazenave, 2010) may reactivate the relevance of global stressors on coastal wetlands. Disentangling the relative importance of local vs global forcing factors driving the recent evolution of these systems and how they have operated at different time scales is essential for their correct management (Newton et al., 2013). This is particularly relevant when long-term changes in ecological status involving different stable states (Scheffer et al., 1993) take place (e. g., García Rodríguez et al., 2010; Stutz et al., 2012).

The Melides lagoon lies in the southern half of the Tróia-Sines coastal ribbon 80 km south of Lisbon (Portugal). As other similar features located nearby, it was originated after the establishment of a sand barrier which isolated the previous marine setting from the open sea around 5500 cal yr BP (Cearreta et al., 2007). In the last decades Melides was studied under contrasting spatial and temporal scales. At a microscale the physico-chemical characteristics of the lagoon have been described for its water and bottom sediments (Cruces, 2001; Cruces in prep.), and detailed studies on the calcareous nanoplankton (Ramalho, 2003) and benthic foraminifera (Alday, 2004) assemblages in surface sediments have also been carried out. Meso- to macroscale multiproxy studies involved sedimentological (Freitas et al., 2002a, b), geochemical (Cruces, in prep.), and palaeoecological analyses of the sedimentary record, the latter focussed on the downcore analyses of nanoplankton (Freitas et al., 2002a; Ramalho, 2003; M. J. Ramalho unpublished data in Cruces, in prep.), ostracoda (Cabral et al., 2006), benthic foraminifera (Cearreta et al., 2007; Alday, 2004; M. Alday unpublished data in Cruces in prep.) and pollen (Queiroz & Mateus 2004; Santos, 2010) assemblages.

These studies have identified global eustatic sea-level rise as the main factor responsible for coastal development in the area during the postglacial interval and first part of the Holocene (Cearreta et al, 2007). Sea-level was of secondary importance after the sand-barrier formation, being the dynamics of the barrier what played the most significant role in the evolution of the lagoon (Cabral et al., 2006). On the one hand, barrier breaching promotes drainage of freshwater lowering the lagoon depth and reducing the wet surface. Conversely, barrier closure promotes accumulation of freshwater, increases depth and expands the wet surface. This sand-barrier dynamism acted differently through time. First, from 5500 to 500 cal yr BP, it were natural variations in the stability and effectiveness of the barrier in excluding marine water over time the primary control of the physico-chemical and biological features of the lagoon. Second, human intervention in the system since 500 cal yr BP through artificial opening of the inlet to prevent eutrophication largely replaced natural variability as the main reason for change (Cearreta et al., 2007). Besides artificial opening of the inlet, agricultural activities and timber production/consumption on the catchment goes back to 3250-3950 cal yr BP (Mateus, 1999), both activities contributing to disturb the natural sedimentary budget of the lagoon. In the last decade, and especially since 2003 (Freitas et al., 2009), the Melides lagoon has faced many environmental problems including significant deterioration of water quality in the shallower sections of the lowland and, in some cases, death of aquatic life.

The morphological and sedimentological evolution and stability of the semi-enclosed coastal environments of the World, such as Melides, is not well understood, and the main driving processes in their evolution urgently need to be described and interpreted (Newton et al 2013). Distinguishing the relative effects of global and local stressors is essential, because although many coastal wetlands could adjust to the predicted climate change, human impacts, in combination with climate change, can significantly affect these ecosystems (Day et al., 2008).

There is therefore the need to conduct high temporal resolution studies of the environmental changes that occurred in coastal wetlands in the last centuries, and the likely causes for any shift in ecological regimes that could have taken place, a study that is still missing in the Melides lagoon.

In this work we examine the main ecological changes in the Melides history since the 3rd century by means of the multiproxy study of its sedimentary record. Using sedimentological, geochemical and, especially, the analysis of the diatom assemblages making up its recent fossil record, we identify the main changes in alternative stable states sensu Scheffer (2004) and dilucidate the natural, such as the periods of Rapid Climate Change (Mayewski et al., 2004), and/or anthropogenic determinants behind them. We also explore whether its most recent history is more influenced by local forcing factors or by global phenomena such as the present day accelerated sea-level rise caused by climate change.

### 4.3.2 RESULTS

#### *4.3.2.1 Sedimentology and Stratigraphy*

Core LM6-2 reached a depth of 82 cm below surface, and the sediment was found to be relatively uniform in terms of texture, though with different contributions of calcium carbonate ($CaCO_3$) and organic matter (OM). Sedimentological analysis (Fig. 4.3.1), revealed the presence of three different lithological units, defined by stratigraphically constrained cluster analysis based on CONISS method (Grimm, 1987). The basal Unit I consisted essentially of organic muds low in calcium carbonate. Unit II is mainly made up by muddy sediments with higher $CaCO_3$ content. Unit III is similar to Unit I, but richer in $CaCO_3$ and OM.

A detailed description of these three units, according to the clay (< 2 µm) fraction, pH of sediment and % OM and $CaCO_3$ is given below:

Unit I (82 – 45cm): Consists of a sub-alcaline organic mud with nil to low (% < 1.5) content in $CaCO_3$. The % of coarse-sized particles (> 63 µm) consists mainly of plant fibres. The proportion of clay is higher in both the basal (from the base of the core to 64 cm - 14.5 to 19.3 %) and upper sections (55 to 45 cm - 15.8 - 18.2 %), with a middle section (64 to 55 cm) showing lower values (9.8 to 13.9 %). OM varies mainly between 6.8 and 12 %, being consistently higher than 10% from 60 to 45 cm (Fig. 4.3.1).

Unit II (45 – 11 cm): The sediments are very similar in pH to the previous unit (sub-alcaline), but the % of coarse-sized (> 63 µm) particles (consisting of plant fibres and minerogenic sand) is the lowest found in the whole core (0.7 %). The $CaCO_3$ content is slightly higher than in Unit I, with several peaks mainly corresponding to bioclasts fragments reaching 3.8 % (mainly in the < 63 µm fraction). The values decrease towards the top of the unit, where carbonates are completely absent. The % of clay varies between 13.2 and 21.1 %, this unit exhibiting the higher values of clay in the whole core. OM decreases from around 9 % to 6 % between 45 and 19 cm and increases from 7 to 9 % between 19 and 10 cm (Fig. 4.3.1).

Unit III (11 – 0cm): The pH in this unit is homogeneous, but lower than in the lower sections, whereas OM reveals the higher values of the whole core. The base of Unit III (represented by four samples collected between 7 and 11 cm) records a single event, with higher values of % > 63 µm, OM and $CaCO_3$ (13.4 %, 13.8 % and 9.3 % respectively). This corresponds to a sub-alcaline to neutral slightly sandy mud very rich in OM (7 - 13.8 %) and with also high bioclastic $CaCO_3$ content. The top 7 cm consist of neutral organic muds free of $CaCO_3$ (Fig. 4.3.1).

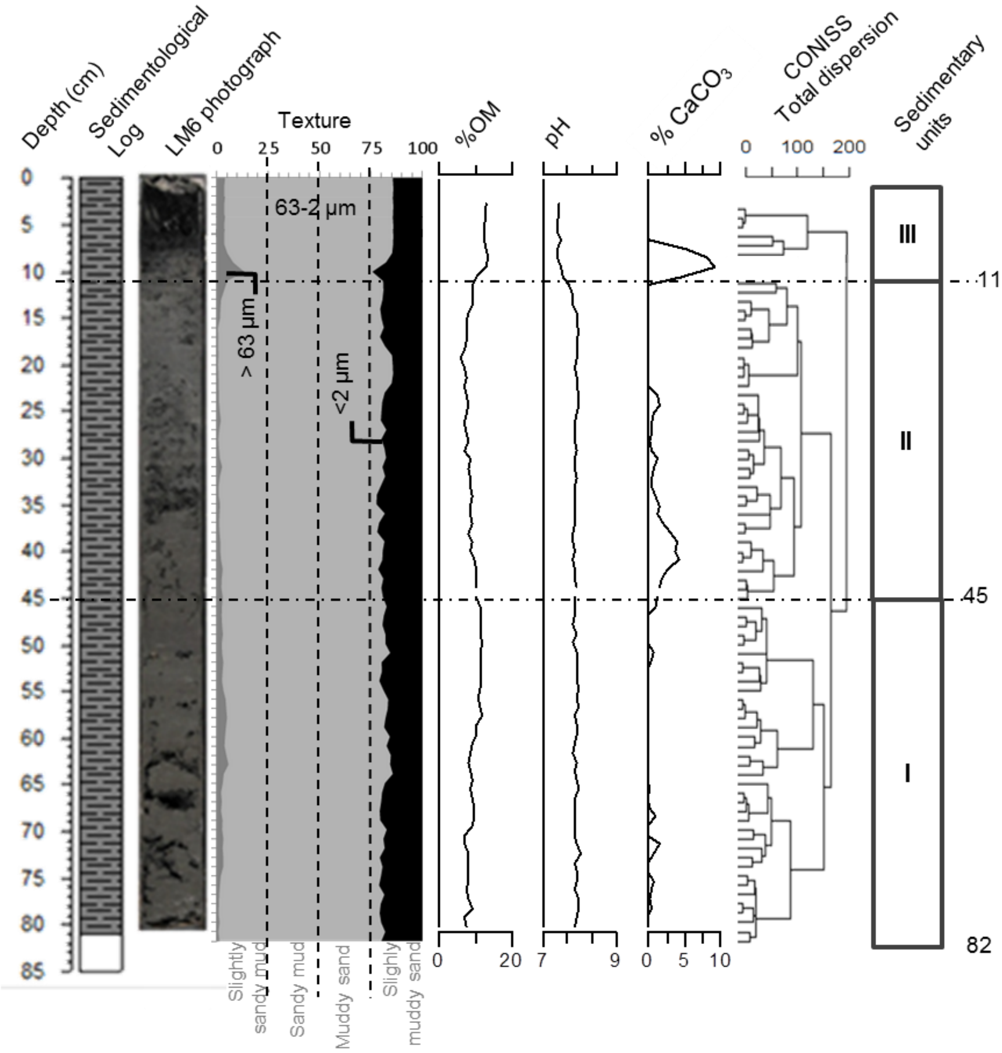

Fig. 4.3.1- Sedimentology with textural classification according to Flemming (2000) based on the % > 63 µm fraction, % OM, pH and % CaCO$_3$. Sedimentary units defined by cluster analysis for core LM6-2.

#### *4.3.2.2 Diatom stratigraphy*

Core LM6-3 was studied for diatom content, giving a record consisting of 138 taxa. Many valves showed strong evidence of dissolution or were broken, and this prevented in some cases identification to the species level of some forms of *Navicula* and *Amphora* s. l.. The number of taxa considered for further statistical analyses was reduced to 39, as only those reaching a frequency of ≥ 2 % were considered for quantitative studies (Appendix IIC for diatom abundances and appendix IIIC for diatom plates). The resulting diatom abundance diagram, with taxa grouped according to their apparent salinity and habitat tolerances (Vos & de Wolf, 1993) is shown in Fig. 4.3.2. Diatom Assemblage Zones (DAZs) were delimited with a broken-stick model of variance distribution (Bennett, 1996). Subzones were defined by stratigraphically constrained cluster analysis based on CONISS method (Grimm 1987). The analyses defined three distinct DAZs (Fig. 4.3.2):

*DAZ I (88 - 35cm)*

This zone is mainly characterized by the presence of brackish/freshwater to marine/brackish epipelic diatoms, although the epiphytic *Cocconeis placentula* var. *placentula* Ehrenberg is the most abundant species. *Nitzschia frustulum* (Kützing) Grunow in Cleve & Grunow is almost exclusive of this zone. In spite of being classified as a brackish/freshwater epipelic diatom in the Vos & de Wolf (1993) system, this species is common in estuarine euryaline environments (Trobajo et al., 2004; Rovira et al., 2012).

*DAZ II (35 - 13 cm)*

The main feature of this zone is the almost disappearance of *Nitzschia frustulum*. This zone was subdivided in two subzones. Subzone DAZIIa (35 - 21cm) is dominated by the freshwater/brackish epiphyte *Cocconeis placentula*, although with some variations in the abundance of its different varieties. The subzone is also characterized by moderate abundances of the marine/brackish epiphytic *Achnanthes brevipes* C. Agardh and a subtle increase in the brackish/freshwater *Pseudostaurosira trainorii* Morales. Subzone DAZ IIb (21 - 13 cm) exhibits a decrease in the abundance of *Cocconeis placentula* in favour of *Pseudostaurosira trainorii*. *Cymbella* aff. *affiniformis* Krammer*, Synedra tabulata* (C. Agardh) Kützing, *Staurophora salina* (Smith) Mereschkowsk and *Rhopalodia acuminata* Krammer show higher abundances in this sub-zone, whereas taxa like *Diploneis smithii* (Brébisson) Cleve and *Opephora guenter-grassii* (Witkowski & Lange-Bertalot) Sabbe & Vyverman*,* decrease in percentage. Sub-zone DAZ IIb reveals an increase in marine epipelon and marine/ brackish epiphytes as well as of tychoplanktonic taxa and *Chaetoceros* spp. resting pores (although with abundance < 2 %).

*DAZ III (13 - 0 cm)*

The diatom assemblage in this zone is characterized by the dominance of the brackish/freshwater tychoplanktonic *Pseudostaurosira trainorii,* being sub-dominated by the brackish/freshwater epiphyte *Cocconeis placentula* (mainly *Cocconeis placentula* var*. lineata* (Ehrenberg) van Heurck).

Detrended Correspondence Analysis (DCA) was performed on the diatom abundance data to reveal the length of the dominant gradient for the diatom assemblages and to evaluate the unimodal or linear distribution of the data (ter Braak & Prentice, 1988). The obtained length of gradient of the first axis (1.713 standard deviation units) was less than 3.0 standard deviation units and so, diatom response was assumed to follow a linear distribution. As a result, a PCA was subsequently performed to explore the diatom assemblages' composition under the main environmental gradients. Most of the variability is summarized in the first two principal components (Fig. 4.3.3). PCA axis 1 and 2 explain 49 % and 19 % of the total variance, respectively. Cocconeis placentula var. placentula and *Pseudostaurosira trainorii* show minimum and maximum scores for axis 1, whereas *Nitzschia frustulum* and *Cocconeis placentula* var. *placentula* are the two species more positively and negatively related to axis 2. Plot of sample scores throughout the core (Fig. 4.3.2), show minimum, moderate, and maximum values of PC1 for DAZs I, II and III respectively. PC2 shows a net increase from DAZ I to II, declining afterwards in DAZ III.

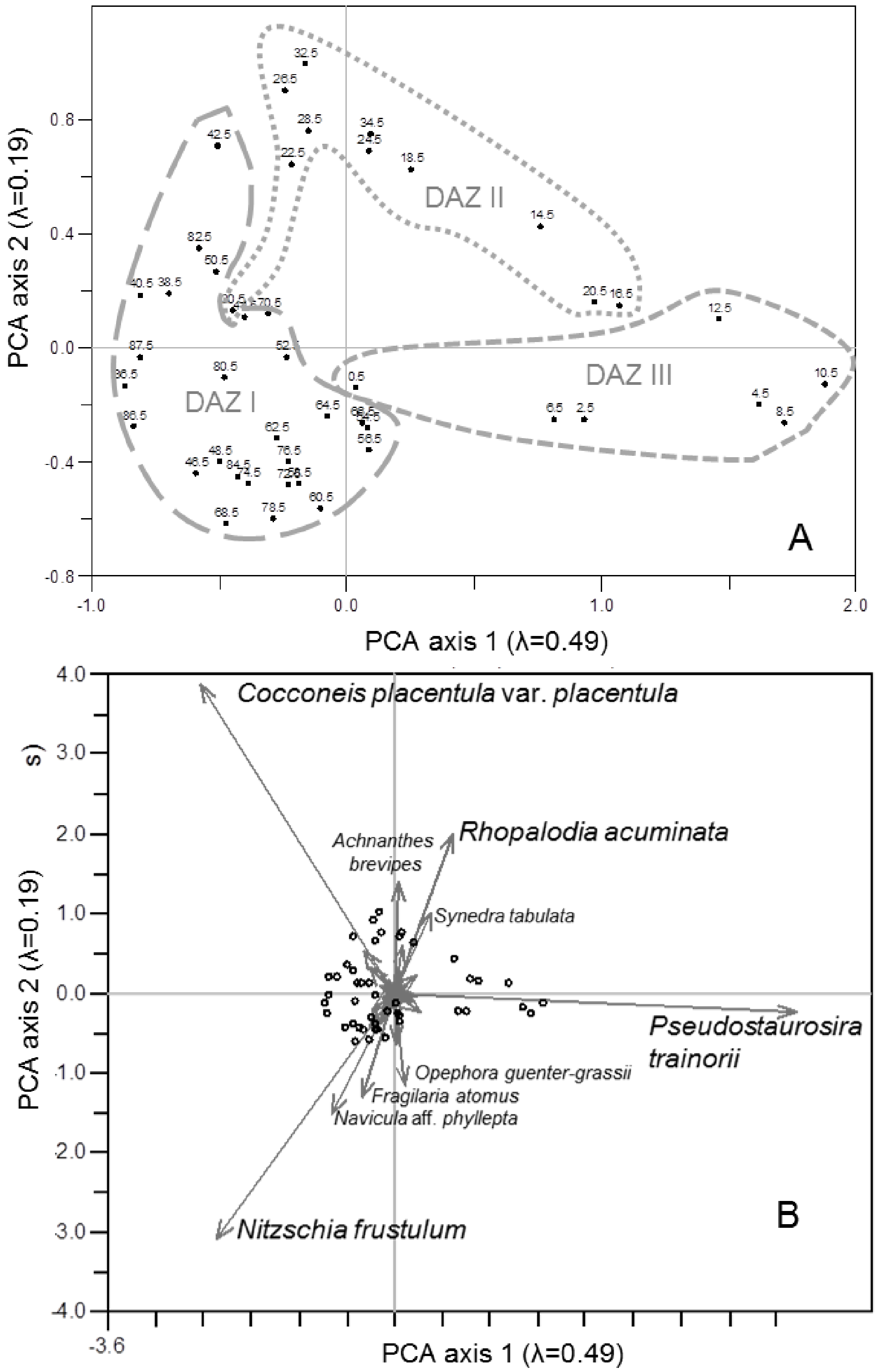

Fig. 4.3.3 - Principal Component Analysis (PCA) ordination biplot of (A) samples and (B) diatom species for core LM6-3. Only species with higher scores are indicated.

#### 4.3.2.2.1 Ordination of the fossil samples on the main environmental gradients of the WIAC

Samples from core LM6-3 were used as supplementary passive samples of the Canonical Correspondence Analysis (CCA) that analyses the relationship between the present-day species data-set of the WIAC and 4 statistically significant environmental variables (Salinity and $PO_4^{3-}$ – axis 1 and $NO_3^-$ and DOC – axis 2) (Chapter 4.1). The plot of the fossil samples on the space defined by the first two CCA axes (Fig. 4.3.4) shows a limited amount of variation that indicates minor environmental long-term changes in the Melides lagoon compared to the present-day spatial variability throughout the WIAC. The exhibited trajectories also show that the main source of variation is related to the trophic status of the system, mainly associated to $NO_3$ and DOC concentrations (axis 1), although variations in salinity and, secondarily, $PO_4$ levels (axis 2) also play a significant role.

#### 4.3.2.2.2 Quantitative Salinity Reconstruction

Salinity changes in the Melides lagoon throughout its recent history were reconstructed calculating the diatom-inferred salinity (DI-salinity) from the transfer function developed for the water bodies of the WIAC (Chapter 4.1) (Fig. 4.3.5). The component 4 of the Weighted Averaging Partial Least Squares Regression (WA-PLS, ter Braak & Juggins, 1993) model was used. The resultant DI-salinity values range from 1.51 to 5.7 ‰, (errors ranging from ± 0.29 to 0.83 ‰), indicating fresh to slightly brackish waters.

DAZ I, shows the major range of variation, with both the lowest and highest salinity values of 1.51 ± 0.63 and 5.71 ± 0.30 ‰. DAZ II, shows a gradual increase from low (DAZ IIa, 1.51 ± 0.60 to 2.96 ±0.47 ‰), to higher DI-salinity values (DAZ IIb, 2.97 ± 0.57 to 3.87 ± 0.58 ‰). DAZ III, shows a smaller range of variation (2.94 ± 0.73 and 4.35 ± 0.78 ‰).

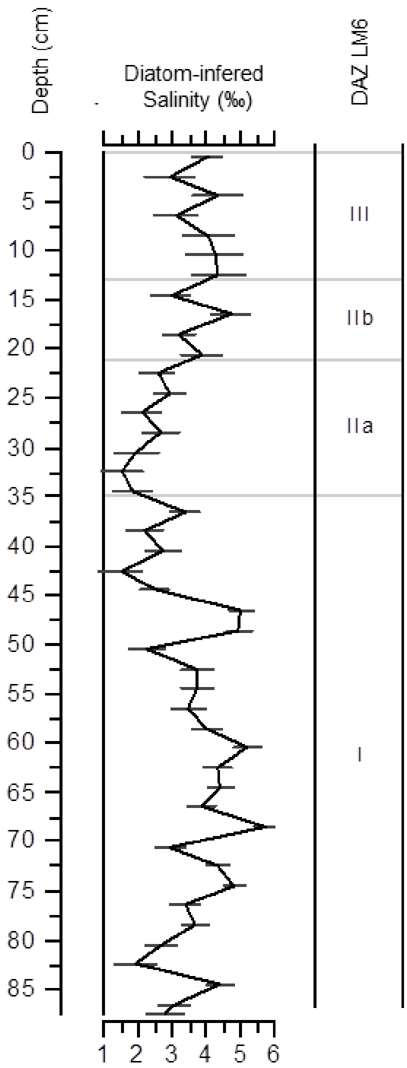

Fig. 4.3.5 – Downcore DI-salinities for LM6-3 estimated from the salinity transfer function for the Western Iberian Atlantic coastal water bodies (Chapter 4.1).

### *4.3.2.3 Elemental and stable-isotope geochemistry*

Core LM6-3 was characterized for total carbon (TC), total organic carbon (TOC), total nitrogen (TN) contents, as well as by their $C_{org}/N_{total}$ ratios and $\delta^{13}C_{org}$ ($\delta^{13}C$) and $\delta^{15}N_{org}$ ($\delta^{15}N$) signatures (Table 4.3.1, Fig. 4.3.6).

TC varies between 0.21 and 7.01 %, with a peak at 40.5 cm, probably related to the presence of carbonates (Fig. 4.3.1). High TC values are also recorded in the topmost section of the core (DAZ III). The lowest values were found at DAZ II. %TOC ranges from 6.78 to 13.76 %. A rising trend in %TOC is detected from the base of the core to approximately 50 cm depth, declining afterwards until approximately 20 cm depth, when a new rising trend starts. Maximum values for the whole core are recorded at DAZ III. %TN shows the same trend as TOC, exhibiting higher values at DAZ I and III (Fig. 4.3.6, Table 4.3.1). The $\delta^{13}C$ values range from -21.8 ‰ to -25.3‰ and $C_{org}/N_{total}$ ratios from 6.16 to 12 (Table 4.3.1, Fig. 4.3.6).

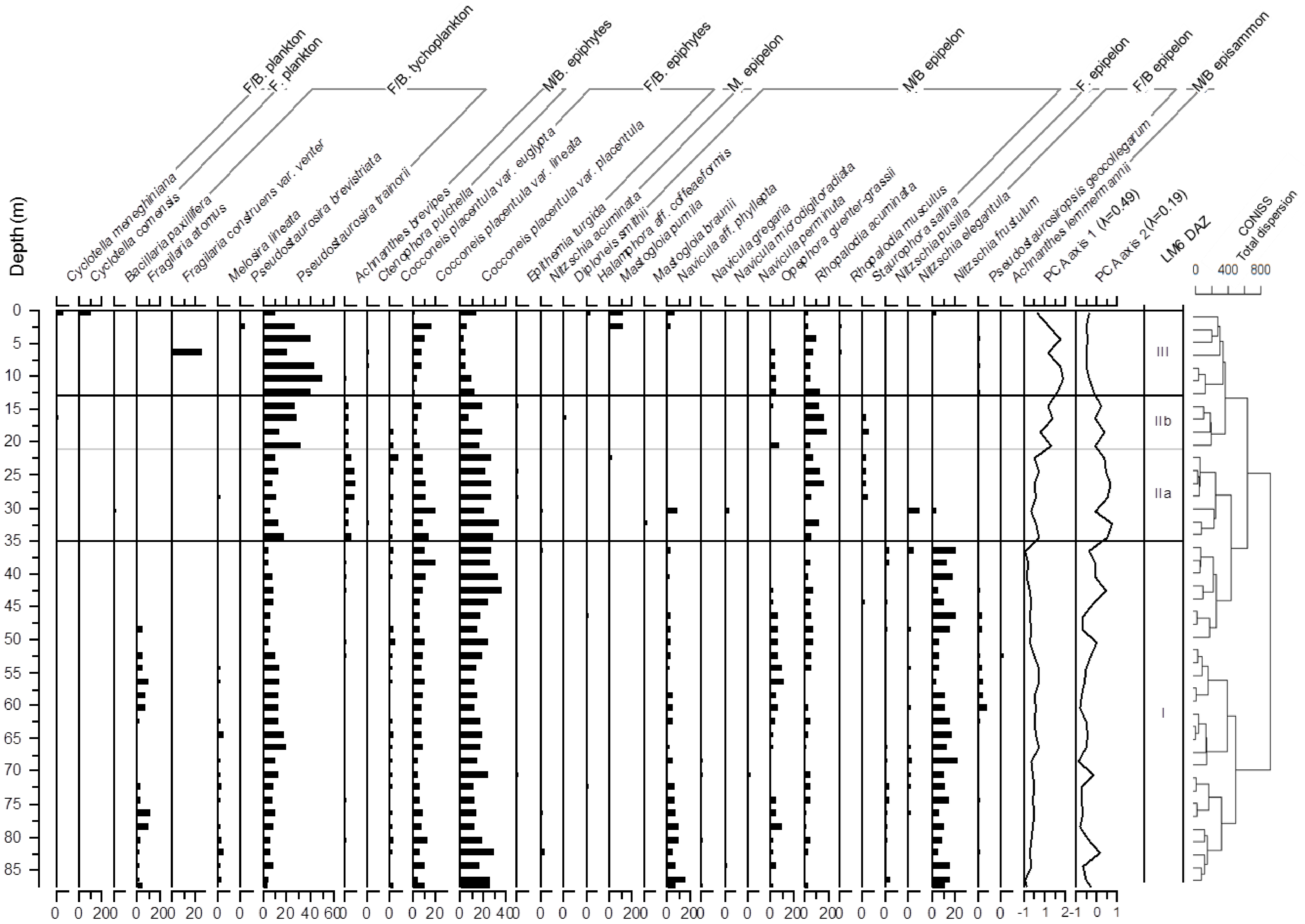

Fig 4.2.8 –Summary of main diatom a geochemical proxies from core TRA07 with indication of the main palaeoenvironmental stages in the evolution of the system and tentative reconstruction of the extension of the water table, adapted from simulations in González-Villanueva et al. (2013).

Lower $\delta^{13}C$ values and high values of $C_{org}/N_{total}$ were identified in DAZ I at 67-62 cm, DAZ IIb at 20-21cm and DAZ III at its surface (0 - 1 cm). $\delta^{15}N$ varied between 2.99 ‰ and 5.59 ‰ (Table 4.3.1,

Fig. 4.3.6) and values higher than 4.9 ‰ stand out at depths of 76.5, 66.5 and 42.5cm in DAZ I, 28.5 cm in DAZ II and 6.5 cm in DAZ III (Fig. 4.3.6).

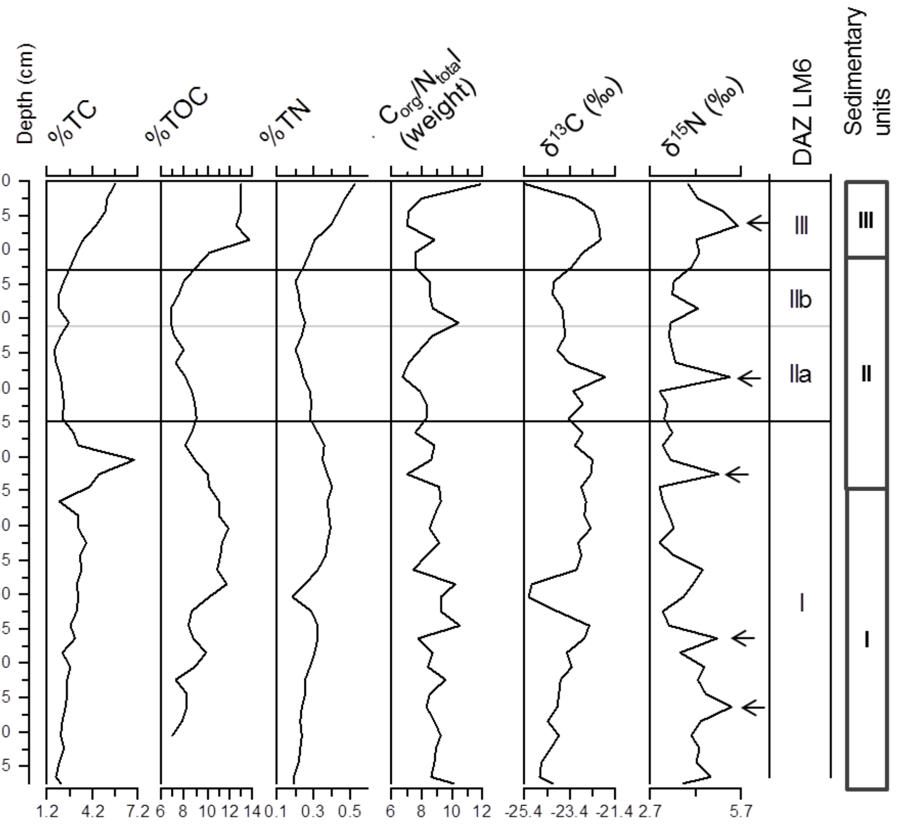

Fig. 4.3.6 - Downcore profiles of geochemical proxies including total carbon (TC), total organic carbon (TOC), total nitrogen (TN), $C_{org}/N_{total}$ ratio, $\delta^{13}C$ and $\delta^{15}N$ contents in core LM6-3, diatom assemblage zone (DAZ) and Sedimentary units. Arrows represent $\delta^{15}N$ values higher than 4.9 ‰.

Table 4.3.1 - Ranges of elemental and stable isotope values recorded for each diatom assemblage zone (DAZ) in LM6-3 core; $C_{org}/N_{total}$ not recalculated to total sample.

| DAZ LM6 | Depth (cm) | TC(%) | TOC(%) | TN(%) | $C_{org}/N_{total}$ (weight) | $\delta^{13}C_{org}$ | $\delta^{15}N_{org}$ |
|---|---|---|---|---|---|---|---|
| **III** | 0-13 | 2.82-5.71 | 9.02-13.76 | 0.2-0.53 | 7.04-11.92 | -25.32 to -22.01 | 3.98-5.59 |
| **IIb** | 13-21 | 0.21-0.25 | 6.78-8.03 | 0.21– 0.25 | 8.52-10.42 | -24.10 to -23.67 | 3.40-4.26 |
| **IIa** | 21-35 | 0.21-0.29 | 7.18-8.17 | 0.21-0.25 | 6.16 – 8.73 | -23.90 to -21.82 | 2.99-5.33 |
| **I** | 35-88 | 7.01 – 1.87 | 7.00 -11.86 | 0.19-0.41 | 7.08 - 10.5 | -25.18 to -22.35 | 3.00-5.39 |

#### *4.3.2.4 Geochronology*

For the estimation of sedimentation rates in core LM6-1, $^{210}$Pb and $^{137}$Cs were analysed (Fig. 4.3.7 C). A sedimentation rate of 2.4 mm yr$^{-1}$ was inferred from $^{210}$Pb activity considering only the topmost 5 samples. Below 13.75 cm, the activity profile of $^{210}$Pb was disregarded, since the data strongly suggest incorporation of younger material at this depth and also further downcore (Fig. 4.3.7 C), as shown by an increase in $^{210}$Pb activity (probably by bioturbation). $^{137}$Cs exhibits a single shallow peak, at 8.75 cm, interpreted as the signature of maximum atmospheric fallout from 1963 (Appleby, 2001). This interpretation leads to an inferred sedimentation rate of 2.2 mm yr$^{-1}$ that is in agreement with the estimates derived from $^{210}$Pb.

Linear extrapolation of this sedimentation rate further downcore would indicate 11.3 cm as the depth of the earliest $^{137}$Cs activity in the core, in correspondence with 1954, the time-boundary of commencement of nuclear testing. In fact, detectable amounts of $^{137}$Cs are found below that depth, within a core section that is contaminated by more recent materials, as indicated by the $^{210}$Pb activity record. Given that the results of $^{137}$Cs and $^{210}$Pb are mutually consistent above 13.75 cm, and taking into account the imprecision introduced by the thickness of the samples analysed in terms of depth values, 13.75 cm was assumed as the more likely depth for the first appearance of $^{137}$Cs.

A number of studies of recent past sediments (e. g., Barker & Bouisset 2001) reported the existence of a double-peak profile in $^{137}$Cs that includes a peak in activity that is attributed to the Chernobyl nuclear power plant accident in 1986. However, not all European locations received fall-out from Chernobyl, and at some, the Chernobyl contribution overprints the earlier weapon signature, so the two peaks become blurred (Appleby, 2001; Roux & Marshall, 2011). Records showing both peaks have not been yet found in the SW Portuguese lowlands. Single-peak profiles in $^{137}$Cs are the common pattern in the nearby lagoons (e. g., Santo André - LSA11 core, Ramos, 2005) and undoubtedly interpreted as corresponding to 1963.

Radiocarbon $^{14}$C ages were obtained from three samples throughout the core LM6-3 (Table 4.3.2). Results show that the lowest sample corresponds to the older one but an age reversal exists between samples taken at 34.5 and 44.5cm. This was considered in the two age-models (A and B) shown in Fig. 4.3.7, where each of these two samples were considered as outliers. Model A excludes sample Beta – 327816 (44.5 cm), whereas model B excludes sample Beta – 333509 (34.5 cm).

Table 4.3.2 - Radiocarbon and calibrated calendar ages for core LM6-3; pMC – post-modern Carbon; cal yr BP – calibrated years Before Present; cal yr CE - calibrated years of Common Era.

| Lab. Code | Sample (cm) | Age $^{14}$C | Age cal yr BP (2σ) | Age cal yr CE (2σ) |
|---|---|---|---|---|
| **Beta 333509** | 34.5 | 1360±30 | 1310-1270 | 640 -680 |
| **Beta 327816** | 44.5 | 1170±30 | 1170-1050 | 780- 900 |
| | | | 1030-980 | 920-970 |
| **Beta 324220** | 87.5 | 1770±30 | 1770-1760 | 180-190 |
| | | | 1740-1610 | 210-340 |

The combination of ages obtained from radiocarbon dating and inferred from $^{137}$Cs activity (here reported as "radiocarbon ages" and "non-radiocarbon ages" in Table 4.3.3) were used to construct two age-models using the CLAM version 2.1 (Blaauw, 2010), for the software R (R Development Core Team, 2010). This code calibrates the $^{14}$C ages using the IntCal09 calibration curve (Reimer et al., 2009) and yields results in cal yr BP. Linear interpolation was chosen to create the models A and B in Fig. 4.3.7. The model generates interpolated ages for each core centimetre associated with a 95 % confidence level, based on the 'best' age- depth model.

Table 4.3.3 - Radiocarbon and non-radiocarbon ages for age-model construction for LM6; cal yr BP –calibrated years Before Present.

| Core | Lab code | Mean depth (cm) | $^{14}$C Age | Age $^{14}$C error | Non $^{14}$C age cal yr BP | Non $^{14}$C age error |
|---|---|---|---|---|---|---|
| **LM6-1 &3** | - | 0 | | | -53 | 1 |
| **LM6-1** | | 8.75 | | | -13 | 1 |
| | | 13.75 | | | -4 | 1 |
| **LM6-3** | Beta 333509 | 34.5 | 1360 | 30 | | |
| | Beta 327816 | 44.5 | 1170 | 30 | | |
| | Beta 324220 | 87.5 | 1770 | 30 | | |

Model B was chosen based on its simpler assumptions. Considering the Model A, the 44.5 cm sample would correspond to an incorporation of recent carbon by bioturbation. It would imply that the diatom record at 44.5 cm (DAZ I, Fig. 4.3.2) would be more similar to the DAZ IIa. Since this condition is not verified (Fig. 4.3.2), plus the fact that there is a strong continuity in diatom record until 35cm (DAZ I) and in unit I from the sedimentary record (until 45cm, Fig. 4.3.1), it is reasonable to assume that there is no bioturbation, and the sample 44.5 cm is an outlier. Hence interpolated ages are from here on based on the 'best' age-depth model from the CLAM age-depth model B.

SRs were estimated for the composite sequence using the constructed model B, yielding four SRs (Fig. 4.3.7 D): (1) 0.7 mm yr$^{-1}$ (88 to 44.5 cm) (2) 0.3 mm yr$^{-1}$ (44.5 to 13.8 cm); (3) 5.6 mm yr$^{-1}$ (13.8 to 8.75 cm) and (4) 2.2 mm yr$^{-1}$ (8.75 to 0 cm).

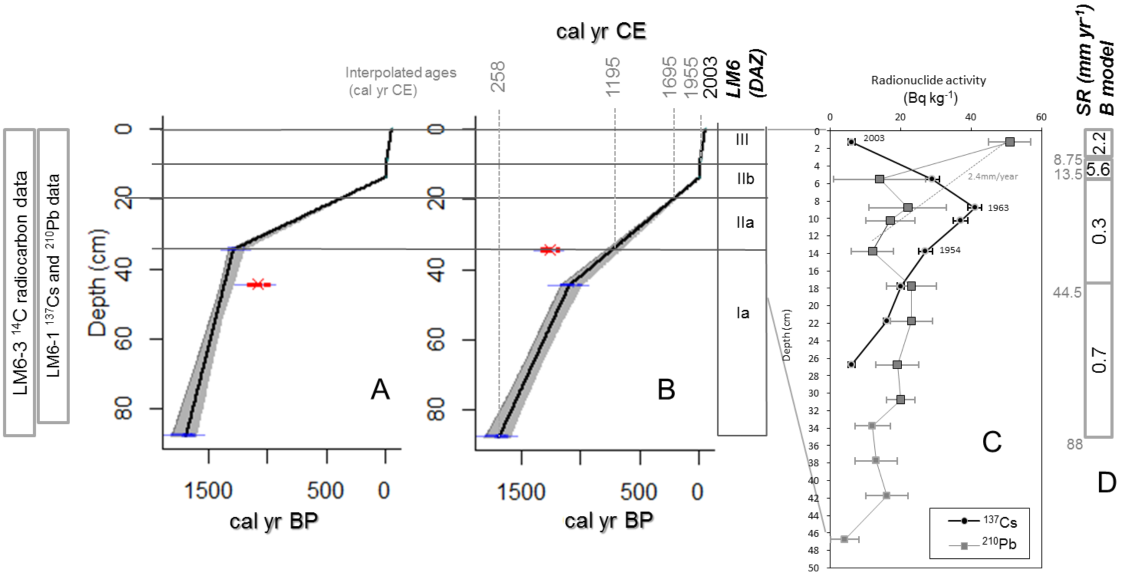

Fig. 4.3.7 - Two age-depth plots constructed with CLAM 2.1 (Blaauw, 2010). **Model A CLAM settings**: linear interpolation; 1000 iterations weighted by calibrated probabilities at 95 % confidence ranges and resolution 1 year steps; assumed outlier (Beta – 327816, marked with a red cross). CLAM output statistics: 0 - 88 cm; -log goodness–of-the-fit = 6.97; 95 % confidence range from 2 to 207 years, average 99 years. **Model B CLAM settings**: linear interpolation; 1000 iterations weighted by calibrated probabilities at 95% confidence ranges and resolution 1 year steps; assumed outlier (Beta - 333509, marked with a red cross). CLAM output statistics: 0-88 cm; -log goodness –of-the-fit = 3.23; 95 % confidence range from 3 to 218 years, average 112 years. C - $^{137}$Cs and $^{210}$Pb measured radiometric activity. D – Sedimentation rates (SR) for age-model B.

## 4.3.3 DISCUSSION

### *4.3.3.1 Meaning of the diatom assemblages and Geochemical Proxies*

The dominance of benthic taxa throughout the core somewhat hinders ecological explanations for the meaning of the diatom assemblages, since ecology of benthic diatoms is in general less known than that of planktonic diatoms (Round et al., 1990). Results of PCA indicate however two major sources of variation in the diatom assemblages. PC1 (49 % explained variance) is strongly related to the abundance of *Pseudostaurosira trainorii* in the sediments. Autoecology of this taxon is not fully known yet, but it has been found in a wide range of phosphorous concentration and conductivity conditions (Morales, 2001). Its eurioic character is surely a reflection of the opportunistic behaviour of the *Fragilaria* s. l. group to which it belongs. This genus has traditionally been considered as characteristic of shallow-water periphytic habitats under conditions of environmental instability (Reed et al., 1999). For the particular case of coastal environments, they occur in high percentages before, during, and after the contact of a continental water body with the ocean (Stabell, 1985; Denys, 1990). Interpretation of PC1 in the Lagoa de Melides can therefore be related to instable environmental conditions associated to events of both connection and isolation from the ocean (i. e., barrier breaching/closing).

Changes in barrier permeability are at present the main forcing factor on the perturbation of the lagoon characteristics (Freitas et al., 2011).

PC2 (19 % explained variance) relates, on the one hand, epipelic (minimum score for *Nitzschia frustulum*) and, on the other hand, epiphytic diatom taxa (maximum score for *Cocconeis placentula* var. *placentula*) that need macrophytes to live. It is known that epipelon is more abundant in unvegetated areas than in those containing abundant macrophytes, probably as a consequence of reduced irradiance at the sediment surface or because macrophytes outcompete epipelon for nutrients (Goldsborough & Robinson, 1996). PC2 can tentatively be interpreted in terms of the alternative stable state hypothesis of shallow lakes (Scheffer et al., 1993; Scheffer & van Nes, 2007). According to this model, shallow lake systems can have two opposite alternative states with regard to the development of macrophytes: a macrophyte-dominated equilibrium at low nutrient and turbidity conditions (clear state), and a turbid unvegetated situation favoured by high nutrient concentrations (turbid state). Changes in PC2 scores define three distinct phases in the evolution of the lagoon that roughly coincide with the main DAZs (Fig. 4.3.2): a clear state corresponding to the top of DAZ-I and the whole DAZ-II, and two turbid states represented by the bottom and half of DAZ-I, and the whole DAZ-III. The close correspondence between shifts in PC2 and TOC from the top of DAZ-I to the top of the entire sequence supports this interpretation.

Results of PCA indicate that both changes in environmental stability, mainly associated to barrier breaching variability (Fig. 4.3.2), and in nutrient state, are responsible for most of the variation in the diatom assemblages, as the projection of passive fossil samples on the CCA of present-day samples from the WIAC (Chapter 4.1) also reflects (Fig. 4. 3. 4). Also, the three main species confirming the diatom assemblages, from bottom to top, *Nitzschia frustulum*, *Cocconeis placentula*, and *Pseudostaurosira trainorii*, constitute part of the most relevant taxa discriminating the different major coastal environments of the WIAC according to results of the cluster analyses (Chapter 4.1). DAZ-I would therefore be characterized by a more open lagoon type (dominance of *Nitzschia frustulum*, an euryaline species typical of estuaries according to Rovira et al., 2012) compared to the more restricted conditions represented by DAZs II and III (dominance of *Cocconeis placentula* and *Pseudostaurosira trainorii*).

The lack of a close resemblance between the DI-salinity and the $\delta^{13}$C suggests that changes in fluvial vs. marine inputs of organic matter on the system play a minor role on C fractionation in Melides. By contrast, $\delta^{13}$C major trends follow variations in TOC, with the exception of a short interval in DAZ-IB and the topmost part of the core. Although other factors such as source of organic matter (pelagic vs. land-derived, fluvial vs. marine), diagenesis, dominant vegetation within the watershed or changes in metabolic pathways for C fixation can have contributed to the fractionation of C (Meyers & Teranes, 2001; Cohen, 2003; Lamb et al., 2006), the parallelism between the two curves suggests that changes in productivity have played the most significant role in Melides.

The interpretation of the $\delta^{15}N$ record is more difficult, not only because of the complexity of processes that intervene in N fractionation (Talbot, 2001), but to the lack of a clear match with other independent proxies in the Melides record. In lagoonal systems light values of $\delta^{15}N$ are characteristic of increased contribution of organic matter from land, whereas rises in $\delta^{15}N$ are interpreted as the product of the increased contribution of the autochthonous organic matter fraction (Müller & Voss, 1999). However the large extent of biogeochemical processes taking part in N fractionation in lagoons (ammonification, nitrification, denitrification, nitrate dissimilatory reduction and nutrient assimilation) make difficult interpretation of $\delta^{15}N$ sedimentary records in terms of provenance of organic matter (Müller & Voss, 1999). The lack of a correspondence between the $C_{org}/N_{total}$ and $\delta^{15}N$ curves of Melides suggests that other factors intervene more directly on N fractionation in this system than the origin of organic matter.

Finally, most of the organic matter sedimentation in the lagoon had a pelagic or slightly mixed source, as indicated by values of the $C_{org}/N_{total}$ ratio ranging from 6.2 to 12.0 (Meyers & Teranes, 2001).

#### *4.3.3.2*

#### *4.3.3.3 Palaeoenvironmental reconstruction*

According to the available multiproxy data, Melides was always a lagoon system with small tidal influence in the last 1745 years, but subject to changes in its connection with the ocean and trophic conditions. Up to six distinct stages can be distinguished in its evolution (Fig. 4.3.8).

**Stage A (interpolated age c. 1692 – 1417 cal yr BP; 260-530 cal yr CE)**

The history of the lagoon starts with a codominance of epipelic (mainly made up by *Nitzschia frustulum*) and epiphytic diatom communities (mainly *Cocconeis placentula*) of primarily brackish/freshwater character typical of lagoons of small tidal influence (Vos & de Wolf, 1993). Throughout this stage the increase in $\delta^{13}C$, which is paralleled by OM and TOC, indicates an increase in productivity (Teranes & Bernasconi, 2005), as the low values of PC2 also suggest. This interpretation is supported by the high abundances of *Nitzschia frustulum*, a species tolerant to high organic matter and nutrient concentrations (Denys, 1991a,b; van Dam, 1994; Trobajo et al., 2004) and by the present-day observation that this species is typical of two eutrophic lagoons in the Portuguese coast, Óbidos and Albufeira (Chapter 4.1). Most of the productivity relied on algae at this stage, as indicated by the $C_{org}/N_{total}$ ratios (Lamb et al., 2006). Although there is a small difference between net and peak values of $\delta^{15}N$ (approximately 2 ‰), its peak, together with a drop on $C_{org}/N_{total}$ and a rise of $\delta^{13}C$, may indicate stratification or eutrophication conditions (Bratton et al., 2003) leading to an anoxic or suboxic environment at the bottom. This would result in bacterial denitrification and, consequently, heavier N in the sediments (Cohen, 2003; Meyers & Teranes, 2001) (Fig. 4.3.8). All the evidences indicate that, in the spectrum of eutrophic conditions, the system would fall close to a turbid phase in the alternative stable states hypothesis (Scheffer et al., 1993).

### Stage B (interpolated age c. 1417-1101 cal BP; 530 – 850 cal CE)

This stage is characterized by minor fluctuations in the OM content of the sediments that however show a net increase (Fig. 4.3.8). It starts with a $\delta^{15}N$ peak that might indicate the persistence of anoxic or suboxic conditions at the bottom. The ecological stability of the system is reduced, as evidenced by the increase in *Pseudostaurosira trainorii* (higher values for PC1) (Fig. 4.3.8). Barrier breaching, with associated short-term changes that favoured the development of opportunistic taxa and an increase in salinity (Fig. 4.3.8), could account for more instable conditions. As a result, the bottom probably became more oxygenated, and this might be the reason for the drop in $\delta^{15}N$ values. Evidence of a less restricted environment, more connected to the ocean, is also provided by the presence of calcareous nannoplankton at this time interval (M. J. Ramalho unpublished data in Cruces, in prep., Fig. 4.3.8). In spite of the existence of more renewed waters, the lagoon did not relax its trophic condition, as indicated by the TOC and $\delta^{13}C$ net increases. At the start of this stage, values of the $C_{org}/N_{total}$ ratio rise, indicating enhanced allochthonous organic loads. These are also suggested by the negative excursion in $\delta^{13}C$ that, during this particular event, seems to be more related to inputs of organic matter of continental origin than to productivity (Lamb et al., 2006). At the end of this stage DI-salinity shows a peak that coincides with a peak in calcareous nannoplankton (M. J. Ramalho unpublished data in Cruces, in prep., Fig. 4.3.8). The gradual decline in the PC1 values however suggest that the rise in salinity might likely be the result of punctual episodes of barrier breaching not significantly affecting the stability of the biological communities in the mid-term.

### Stage C (interpolated age c. 1101-755 cal yr BP; 850-1200 cal yr CE)

A gradual major transition that involves a change in sedimentary units, among others, takes place during this stage. A decline in DI-salinity is accompanied by a more stable environment, as indicated by low values of PC1 (Fig. 4.3.8). These observations point to a more restricted communication with the ocean. In spite of the development of a less permeable lagoon, there are no clear evidences of a significant water level rise. Quite the contrary, the $C_{org}/N_{total}$ ratio decreases, indicating reduced organic matter inputs and therefore likely reduced precipitation in the region. Oligohaline conditions would however be maintained by reduced connection with the ocean. In turn, productivity decreases, as indicated by the TOC content in the sediments (Fig. 4.3.8), and the system gradually experiences a change to a clear phase (Scheffer et al., 1993). This is corroborated by the partial replacement of epipelic by epiphytic diatoms (increase in PC2), that suggests significant macrophytic development. In spite of the difficulties in interpreting $\delta^{15}N$ records (Talbot, 2001), it might be the case, as in previous stages, that the $\delta^{15}N$ peak at the start of this stage might be related to an anoxic or suboxic bottom of the lagoon due to a more restricted environment.

### Stage D (interpolated age c. 755 -255 cal yr BP; 1200-1700 cal yr CE)

An increase in DI-salinity points to more intense and/or frequent barrier breaching during this stage. Intensified connection to the ocean is also suggested by the presence of calcareous nannoplankton (M. J. Ramalho unpublished data in Cruces in prep., Fig. 4.3.8) and *Chaetoceros* spp. resting pores, the latter, a predominantly marine diatom taxon, that may be indicative of entrances of marine water conveyed either through the inlet or barrier overwash. Values of PC1 indicate increased environmental instability that is very likely explained by frequent shifts in the water column characteristics of the lagoon associated to barrier breaching. Consequences of a more persistent opening of the inlet were twofold. On the one hand, renewed waters probably favoured a relaxation of the trophic state of the system, as suggested by the decreasing trends in the TOC and $\delta^{13}C$ profiles (Fig. 4.3.8). On the other hand, a second probable implication of barrier breaching was the lagoon shallowing, which favoured the development of macrophytes, as suggested by the increased abundance of epiphytic diatoms, many of marine/brackish affinity. The diatom community codominated by epipelic and epiphytic diatoms of the previous stages is replaced by an epiphytic-dominated community (Fig. 4.3.8). Submerged macrophytes would be benefited by the lower nutrient and turbidity conditions that the TOC and $\delta^{13}C$ records suggest, so the shift from a turbid to a clear phase, initiated during the previous stage, is consolidated at this time. This shift to a clear state, in the sense of Scheffer et al. (1993), was however never close to the equilibrium line proposed by these authors, since algal productivity was still dominant, as reflected by the $C_{org}/N_{total}$ signal in the sediments (Fig. 4.3.8).

### Stage E (interpolated age c. 255 to -5 cal yr BP; 1700- 1950 cal yr CE)

During this stage the trend in salinity increase persists, as shown by the DI-salinity record, and instable environmental conditions seem to be reinforced looking at the PC1 profile (Fig. 4.3.8). Connection of the system with the ocean was at least as common as in the previous stage. Low TOC and $\delta^{13}C$ values suggest that productivity conditions were also similar, in spite TOC showing a slight increase at the top. In spite of these similarities with the previous stage, epiphytic diatoms show a sharp decline, suggesting a transitional phase with less macrophytic cover and the likely start of a new gradual change towards a turbid state, as the modest TOC increase would support. Entrance of organic matter of continental origin, as indicated by the increase in the $C_{org}/N_{total}$ ratio, could be, among other factors, behind this still modest change in the trophism of the system.

### Stage F (interpolated age c. -5 to -53 cal yr BP; 1950-2003 cal yr CE)

The previous transitional stage is followed by a situation where the highest TOC content and minimum abundances of epiphytic diatoms of the whole record occur. This circumstance points to a shift toward one the end terms in the alternative states model, when a critical turbidity threshold is surpassed and macrophytes can even disappear (Scheffer et al., 1993). It can be hypothesized that present-day hypertrophic conditions (Freitas et al., 2011) started to be acquired at this time.

To disentangle the main underlying reason for the productivity increase, the 10-year moving average precipitation from the close meteorological station of Grândola for the period 1932 to 1999 was plotted contiguous to the $C_{org}/N_{total}$ ratio curve (Fig. 4.3.8). Peak precipitation coincides with the increase in TOC, suggesting a possible link between productivity and the arrival of nutrients from the catchment. Yet, even at times of reduced precipitation, the TOC increasing trend is maintained, pointing to an uncoupling between external nutrient loads and productivity in the system. The high organic matter and nutrient concentration condition is accompanied by the maximum peak in the $\delta^{15}$N record, probably indicating common anoxic or suboxic conditions at the bottom of the lagoon. Accumulation of organic matter at the bottom under low oxygen concentration might result in P release (van Nes et al., 2007), so internal nutrient recycling could have prompted high productivity conditions irrespective of nutrient allochthonous entrances in the system.

Moderate barrier permeability seems to be maintained at this time, as the still high values of DI-salinity and persistence of instable conditions as the PC1 record indicate. In the more recent times of this stage, significant openings of the barrier occurred, as evidenced by the calcareous nannoplankton and foraminifera records (M. J. Ramalho and M. Alday unpublished data in Cruces in prep., Fig. 4.3.8). These however were probably episodic, as no significant increase in the DI-salinity is recorded, nor a change to more instable conditions, as shown by the PC1 record, occurs. In spite of the regular connection with the ocean, this seems to have had no effect on the relaxation of the trophic condition of the system, at least on the long-term.

#### ***4.3.3.4 Main forcing in the evolution of the lagoon***

Long-term evolution of lagoon systems is the result of the complex interplay among different processes taking place at regional and local scales (Bird, 1994). The multiproxy record of the evolution of the Melides lagoon allows us to identify changes in marine influence and continental supply as the main agents provoking the major environmental changes detected in this short time-span, 1745 years. Results of the plot of passive samples in the CCA of diatom and environmental variables from the surface sediment data-set of the WIAC (Chapter 4.1) indicates that the main source of variation in the diatom assemblages is related to changes in the salinity and in trophic status (Fig. 4.3.4). Whereas significant changes in trophic status are also supported by results of PCA (axis PC2) and independent geochemical proxy data (mainly variations in TOC and $\delta^{13}$C), variations in salinity triggered by changes in barrier permeability are confirmed by the detected shifts in DI-salinity and results of the PCA (axis PC1) (Fig. 4.3.8). As a result of these variations, the lagoon experienced one major change in relation to marine connection (from an open to a more restricted lagoon that lasted from around 850 to 1700 cal yr CE) and two major changes in the trophic status that can be interpreted in terms of the alternative stable state hypothesis of shallow lakes (Scheffer & van Nes, 2007). A change from a turbid to a clear phase occurred between 850 and 1700 cal yr CE, followed by a transitional phase, and a return to a turbid state from 1950 cal yr CE to present-day. Whether there are causal climatic reasons for these changes or more local factors intervene behind them is however ambiguous on the light of the data. The LM6 sequence encompasses 1745 years of coastal environmental evolution that cover some global periods of Rapid Climate Change (Mayewski et al., 2004) such as the Roman Warm Period (RWP, 250 cal yr BCE – 450 cal yr CE; Desprat et al., 2003), the Dark Ages (DA, 450-950 cal yr CE; Desprat et al., 2003; Álvarez et al., 2005), the Medieval Climatic Anomaly (MCA, 950-1250 cal yr CE; Mann et al., 2009), the Little Ice Age (LIA, 1350-1850 cal yr CE; Wanner et al., 2008) and the Recent Period (Fig. 5.1B, Chapter 5). Previous evidences in this lagoon and in the close interdune coastal peat dune slack of Barbaroxa and Sancha, located 7 km south, point to episodes of terrestrialization and inundation likely driven by climatic shifts (Cruces et al., 2011). It is therefore relevant to study the relationship between the main stages in the recent evolution of the lagoon and the known late Holocene periods of Rapid Climate Change (Fig. 5.1B, Chapter 5).

The bottom of the Melides record covers approximately the last half of the RWP (Stage A). This period has specifically been characterized for the Iberian Peninsula and referred to as the Iberian–Roman Humid Period (IRHP, 550 cal yr BCE to 350 cal yr CE), the most humid phase of the last 4000 years in southern Spain (Martín-Puertas et al., 2008, 2009). Humidity conditions during this interval were however not homogeneous. Stage A of the Melides record falls during the decline of the Roman Empire, when humid conditions were reactivated after an arid event (Martín-Puertas et al., 2009). Although values of the $C_{org}/N_{total}$ ratio suggest a mixture of autochthonous and land-derived organic matter, the most significant increase in the inputs of continental organic material do not occur during this phase but latter (Stage B), during the DA. This period has been identified as a cold and dry phase from northern Iberian records (Desprat et al., 2003; Andrade et al., 2011; Martín-Chivelet et al., 2011). Even taking into consideration a more restricted chronology for this period (approximately 400-650 cal yr CE, e. g., Abrantes et al., 2005; Gil et al., 2006; Lebreiro et al., 2006), the DA appear in the Melides record as a period of increased continental loads and productivity. The strong consistency of the data that indicate less humid conditions for the DA in the Iberian Peninsula (including lower lake levels in southern Spain, Martín-Puertas et al., 2008), suggest that the climatic signal can be masked in the Melides record, as for the IRHP and for this time interval. Both periods concur with the development of an open lagoon with less restricted ocean influence, as indicated mainly by the composition of the diatom assemblages, the DI-salinity, and the presence of calcareous nannopankton in the sediments. It can be hypothesized that either increased marine influence, with associated environmental instability (PC1), acted to obscure the true climatic signal associated to the IHRP and DA in the Melides record or, less probably, that a real trend of enhanced precipitation throughout those periods took place.

The most significant change in the Melides lagoon took place, however, when the system transformed from an open to a more restricted lagoon, also coinciding with a gradual modification of its trophic status from a turbid to a clear phase (Stage C). The start of this change roughly coincides with the onset of the MCA that involved warm and relatively arid conditions in the Mediterranean Iberia (Moreno et al., 2012). Palaeoenvironmental data from the Melides lagoon is compatible with a warm and dry regime in the area. Reduced allochthonous nutrient inputs to the lagoon associated to low precipitation by a pervasive positive state of the NAO (Trouet et al., 2009; Mann et al., 2009) might be the natural cause for a change of state from a turbid to a clear phase that would have facilitated extensive macrophytic coverage in the lagoon. On the other hand, persistence of a NAO positive phase in the SW European Atlantic coast seem to have favoured reduced storminess activity compared to the subsequent LIA (Trouet et al., 2012). The Melides record shows that during the MCA connection with the ocean was reduced to a minimum, suggesting that attenuated storminess could have played a significant role on the reduction of barrier permeability at this time. Afterwards, from 1200 to 1700 cal yr CE, Melides experienced a gradual salinization (Stage D) that could likely be related to the climatic MCA/LIA transition that involved more intense storms (Costas et al. 2012; Trouet et al., 2012), promoting increased permeability of the sand barrier. Whereas the MCA/LIA transition could have been responsible for a return to a more open condition of the lagoon, it seems however not to have acted on the change to a new trophic state. The clear phase in the lagoon persisted from the MCA to the end of the LIA, when productivity started to recover (Stage E). The scenario of more humid conditions in Iberia during the LIA, relatively to the MCA (e. g., Abrantes et al., 2005; Moreno et al., 2012), is consistent with the observed increase in the $C_{org}/N_{total}$ ratio in Melides at this time. It also coincides with the start of the so called terrestrialization phase of Queiroz & Mateus (2004) and the progradation of the fluvial system into the lagoon (Cabral et al., 2006; Cearreta et al., 2007). Enhanced continental loads however did not promote an increase in productivity as in previous phases (Stage B). Rather than caused by low temperatures associated to the LIA (minimum productivity, as indicated by the TOC levels, is coincident with the Maunder Minimum of 1675-1715 cal yr CE, Luterbacher et al., 2000), a local driving factor, intensified interchange of water between the ocean and the lagoon, and could have maintained low productivity levels in the system. Present-day evidences demonstrate that phosphorous concentrations can be reduced up to 100 times in Melides when the inlet is artificially opened (Freitas et al., 2011). It is therefore very probably a matter of balance between intensity and frequency of barrier breaching and degree of continental nutrient loads what makes the lagoon to naturally be more (Stage B) or less (Stages D and E) productive, and therefore to shift between different alternative states.

The recent evolution of the lagoon is mostly a reflection of human activities in the system. Historical records indicate that artificial barrier breaching of Melides began at least in 1839 CE (Cruces, 2001), being intensified in more recent times. Human intervention on the system not only includes the opening of the inlet, but also several activities performed in the catchment area, such as inert extraction (increasing solid suspension), intense rice production (delivering nutrients and pesticides), livestock farming activities (not only increasing organic matter and nutrient levels, but also bringing pathogens to the system), and discharges from two wastewater treatment plants (Freitas et al., 2009). These impacts are evidenced in the Melides sedimentary record since 1950 cal yr CE (Stage F), triggering a change from a clear to a turbid state, as indicated by the highest TOC levels and minimum abundances of epiphytic diatoms. The shift of state agrees with the present day hypertrophic condition of the lagoon, where phosphorous concentrations > 5000 $\mu g\ L^{-1}$ can be reached (Freitas et al., 2011). Although the short lived periods of sand barrier breaching can induce a significant lowering of nutrient levels, the fast recovery of pre-opening concentrations is however a common feature in lagoon systems (Suzuki et al., 1998). It is also known that once a system has switched to a turbid state, a strong nutrient reduction is necessary for a reversion to a clear phase (Scheffer et al., 1993). The evolution recorded during Stage F indicates that artificial breaching of the barrier had just a limited short-term impact on the trophic status of the lagoon that maintains its turbid condition since at least 1950 cal yr CE. However, the use of biodegradable fertilizers since 2004 under the Integrated Protected System Management Policy (Freitas et al., 2009) brings the possibility of a relaxation of the hypertrophic status of the lagoon in the mid-term.

Another human-induced factor, accelerated sea-level rise associated to global warming, seem to have however played a secondary role on the recent evolution of the lagoon. The record shows increased environmental instability from the most recent parts of Stage E to the lower half of Stage F, coetaneous to the 1905-1945 cal yr CE time period, when modern rates of accelerated sea-level rise started (Gehrels & Woodworth, 2013). Yet, this trend is reversed in the last decades, which also do not show any consistent pattern of increase in salinity. The recent record, therefore, shows no indication of any sea drowning prompted by the present-day accelerated sea-level rise, suggesting that the response of the lagoon is largely more dependent on local conditions (Williams, 2013). The Melides lagoon would thus confirm the increased control on the dynamics of the Portuguese barrier-lagoonal system by local driving agents instead of climatic variability or present accelerated sea-level rise in their more recent history (Bao et al., 1999; Freitas et al., 2005; Dinis et al., 2006).

### 4.3.4 CONCLUSION

The sedimentary record of the Melides lagoon shows that the evolution of this system in the last 1745 years experienced changes in its ecological condition forced by regional, mainly climatic, and local, mainly man-induced, factors. All these agents acted simultaneously, producing an overlapped signal that cannot be easily disentangled. Whereas anthropogenic influence produced a quite clear signal in the sedimentary record, the effects of the Late Holocene periods of Rapid Climate Change on the evolution of the system are at some time intervals ambiguous on the light of the data.

Changes in barrier permeability and trophic status were the main components of environmental change at decadal to centennial scales in this system. These can be understood in the framework of the shallow lakes alternative stable state hypothesis.

From the period 260-850 cal yr CE the lagoon exhibited its more open condition, which however kept the water body in a turbid phase and always within the range of oligohaline to slightly mesohaline waters. During the 530-850 cal yr CE interval the recorded intensification of organic matter loads of continental origin are not in agreement with the well-established dry conditions for the DA in the Iberian Peninsula. It is therefore hypothesized that the climatic signature in the sedimentary record is masked by the environmental noise introduced by the frequent and/or intense breaching of the barrier rather than reflecting increased precipitation at these times.

From around 850 to 1700 cal yr CE the lagoon transformed into a more restricted environment as a result of reduced connection to the ocean through a less permeable sand barrier, although there is an increase in the barrier permeability towards the end of this period. On the other hand, two major shifts in its trophic status occurred when the system changed very gradually its turbid equilibrium state to a clear phase in the period from 850 to 1700 cal yr CE, followed by a transitional phase, and a return to a new turbid state acquired from 1950 cal yr CE to present-day, when hypertrophic conditions are recorded.

As the lagoon experienced reduced barrier permeability, being converted in a more restricted environment, there is a closer correspondence between the known palaeoclimatic events in the Iberian Peninsula and environmental changes taking place in the lagoon. The gradual transformation from the turbid to the clear state (850-1700 cal yr CE) starts with the onset of the warm and relatively arid MCA. Reduced precipitation associated to a pervasive positive phase of the NAO could have been the natural trigger for the ecological transformation of the lagoon into a clear state, diminishing external nutrient loads. These were again accentuated during the LIA, when humid conditions in the Iberian Peninsula prevailed. Humidity did not however prompt a rapid transformation to a new turbid phase, probably because renewed connection to the ocean counteracted avoiding increased nutrient concentrations in the system. The gradual change to a new equilibrium phase lasted from 1700 to 1950 cal yr CE. It is at this latter date when the lagoon probably acquired its present turbid condition as a result of intensified intervention in the system that introduced high loads of fertilizers from the catchment. In spite of being anthropogenic influence the main forcing agent in the evolution of the lagoon since 1950 cal yr CE, there are no evidences of drowning induced by the present-day accelerated sea-level rise.

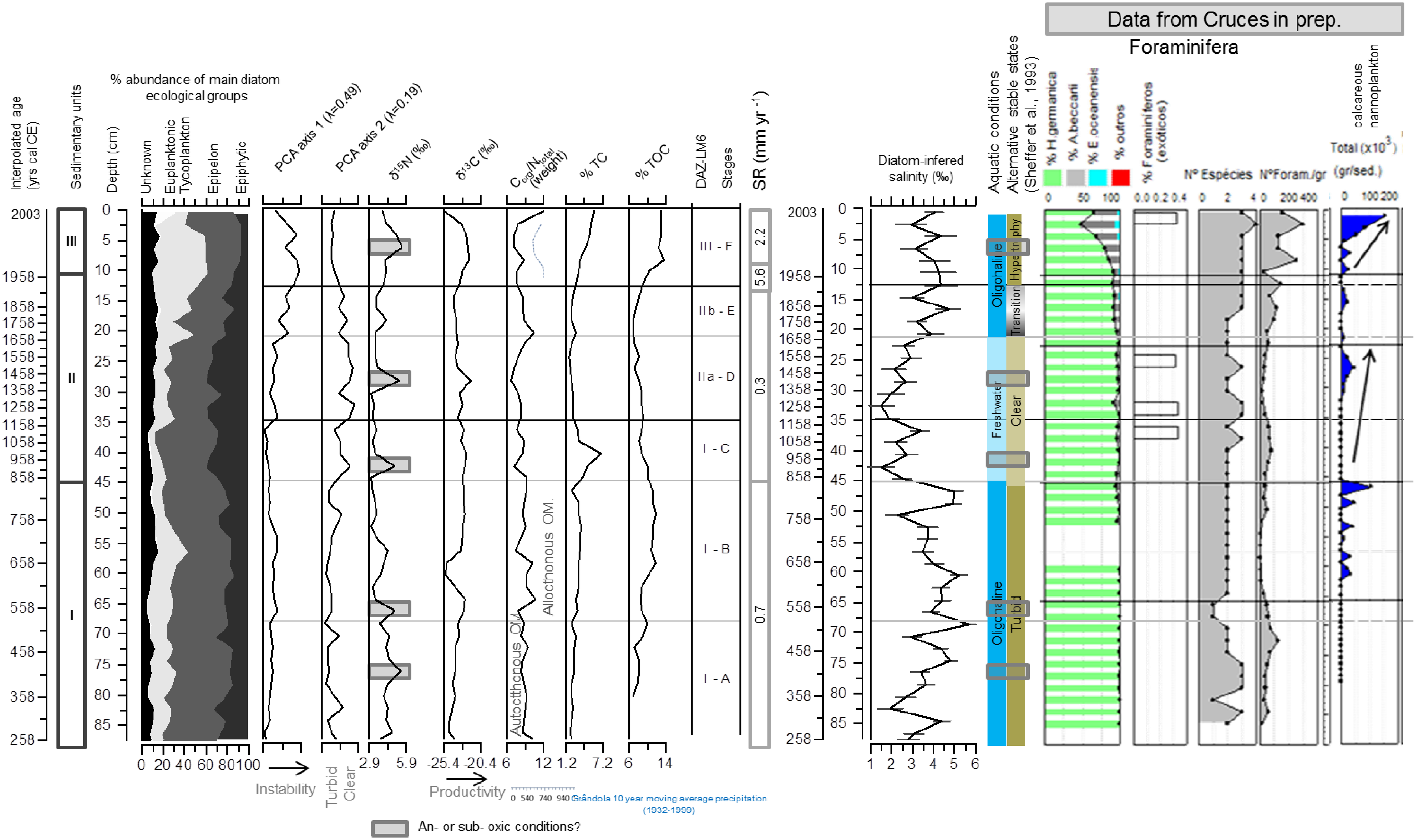

Fig. 4.3.8 - Summary of main diatom and geochemical proxies from core LM6 with indication of the main palaeoenvironmental stages in the evolution of the system. Data on calcareous nannoplankton and benthic foraminifera (M. J. Ramalho and M. Alday unpublished data respectively in Cruces in prep. are also included).

# 5. Thesis discussion and conclusions

## 5.2 PRESENT-DAY DIATOM DEAD ASSEMBLAGES IN THE WIAC AND THEIR RELATIONSHIP WITH THE MAIN ENVIRONMENTAL GRADIENTS

The studied lowlands of the Western Iberian Atlantic Coast (WIAC) – Valdoviño, Doniños, Traba, Louro, Xuño, Muro, Illa de Arousa, Bodeira, Minho, Lima, Vela, Óbidos, Albufeira, Sado, Melides, Santo André, Barbaroxa de Baixo and Mira - are characterized by a large range of environmental conditions. It is this large environmental gradient what makes possible the construction of quantitative inference models for physico-chemical variables from the past as an aid to reconstruct the long term history of these systems (e. g., Birks, 2010). Before trying to know the main environmental changes that occurred in two case studies of the WIAC (Melides and Traba) in the last centuries, a study relating the distribution of dead diatom assemblages throughout the WIAC and the main environmental gradients ruling them was performed.

Diatom-based palaeoenvironmental reconstructions, whether qualitative or quantitative, rely on the fidelity of fossil diatom assemblages to the diatom biocenoses they come from (Birks & Birks, 1980). However, in the taphonomic pathway from the biocoenoses to the death assemblage or thanatocoenoses preserved in the sediments information is inevitably lost. The lack of correspondence between fossil data and their contemporary environment has profound implications on palaeoenvironmental inferences (Battarbee et al., 2005; Ryves et al., 2009). Coastal environments are highly dynamic systems where taphonomical biases can be particularly accentuated by removal of species by breakage or dissolution, or by the transport of allochthonous taxa by tidal currents among other processes (e. g., Beyens & Denys, 1982; Vos & de Wolf, 1988; Sherrod et al., 1989; Sherrod, 1999; Sawai, 2001; Hassan et al., 2008). Although it was beyond the scope of this thesis to precisely quantify the linkage between present-day diatom distribution in bottom sediments and the live assemblages they come from, the comparison with the available data on benthic diatom biocoenoses of the Portuguese coast (Resende et al., 2005, 2007; Ribeiro, 2010; Gomes et al., 2012; Ribeiro et al., 2013) show very close similarities between diatom biocenoses and thanatocoenoses in present-day bottom sediments. Because almost all the studied water bodies correspond to very shallow environments, this conclusion should not be extrapolated to the few water bodies of the WIAC with average water depths > 3 m.

The three major types of environments sampled in this study, i. e., coastal lakes and ponds, lagoons and estuaries, showed clearly distinct diatom assemblages in their present-day bottom sediments that can be used to differentiate sedimentary environments by means of facies analysis in long-term records. The statistical multivariate analyses of the data also showed that changes in salinity, $PO_4^{3-}$, $NO^{3-}$ and DOC are the drivers that make diatom thanatocoenoses in present-day bottom sediments to be distinct in the major types of environments. In spite of the likely influence of other environmental variables (no taken into account in this study), such as water depth, sediment composition or tidal levels, this result agrees with the well-known major roles that salinity and nutrient concentration gradients play on the diatom thanatocoenoses in present-day bottom sediments of coastal environments elsewhere (e. g., Weckström et al., 2004; Snoeijs & Weckström, 2010). It is not surprising either that these variables are the main factor ruling the composition of the diatom assemblages in the wetlands of the WIAC, since they are strongly affected by changes in barrier permeability. This, either natural or artificial, have major effects on the present-day nature of the back-barrier wetlands in this region (Freitas et al., 2011; Carballeira & Leira, in prep.).

In spite of the difficulties of constructing precise diatom-based quantitative inference models for past environmental variables in coastal habitats (Anderson & Vos, 1992), a salinity transfer function with a good predictive power was developed for shallow water bodies of the WIAC. Quantitative DI-salinities, diatom autoecological data on habitat preferences, and qualitative inferences for past nutrient concentrations (i. e., those based on the behaviour of passive fossil samples on the space defined by the multivariate analysis of present-day environmental and diatom data) were used to reconstruct the main long-term environmental changes in two contrasting wetlands of the WIAC, Melides and Traba. Diatom-inferred palaeoenvironmental reconstructions were supported by independent multiproxy geochemical and sedimentological data. The results showed that the dynamics of both systems in the last centuries was significantly subject to four main natural and anthropogenic factors: sand-barrier breaching (natural and/or human-induced), precipitation, forest cover (natural and/or human-induced), and cultural eutrophication. A fifth factor, sea-level change, exerted a minor or no control at the time scales considered. The complex interplay among these factors prompted large ecological regime shifts interpreted in the framework of the Alternative Stable State Hypothesis of Shallow Lakes (e. g., Scheffer et al., 1993; Scheffer, 2004). Both water bodies experienced phases of equilibrium with reduced nutrient concentrations and low turbidity conditions that favoured submerged macrophytic development (clear state), and others, were high nutrient concentrations provoked high turbidity and, therefore few submerged plants (turbid state). The long-term evolution of these systems show that the mentioned forcing factors played different roles through time, as explained below.

## 5.3 LONG-TERM MAIN DRIVING AGENTS IN THE EVOLUTION OF TWO WETLANDS IN THE WIAC

### 5.3.1 CHANGES IN BARRIER PERMEABILITY

Previous palaeoecological research on the WIAC has identified barrier breaching as one of the most significant forcing factors in the evolution of back-barrier lagoon systems (Bao et al., 1999, 2007; Cearreta et al., 2003; Freitas et al., 2002a,b, 2003; Andrade et al., 2004). The effects of barrier permeability are mainly manifested as salinity, water level, and nutrient concentration changes in the water body which could have significant consequences on its ecological status. Melides and Traba represent two systems with ephemeral inlets which however show relevant differences in terms of connection to the ocean. In the most recent times Melides experienced natural and man-induced inlet breaching since the 19th century (Cruces, 2001). By contrast, the first known large human intervention in the outlet of Traba dates 1992. The two systems also showed contrasting barrier permeability regimes for the time period that they share in common. Since approximately 1470 cal yr CE, Melides showed increased connection to the ocean that is maintained in moderate levels from approximately 1800 cal yr CE to present, as indicated mainly by values of the DI-salinity (Fig. 5.1) and the scores of PC1, an indicator of ecological instability. Traba shows an almost inverse pattern, being almost isolated from the ocean since approximately 1875 cal yr CE to the decade of the 1990s when the outlet began to be artificially opened. Also, Melides had a previous history of natural more open lagoon like conditions from 260 to 850 cal yr CE. It is at this latter date when the system began a gradual change towards more restricted conditions, roughly coincident with the start of the Medieval Climatic Anomaly (MCA).

Turbid states are recorded in Melides and Traba at times of increased permeability of the sand barriers, and clear phases when the systems reduced their connection to the ocean. Present-day empirical evidence demonstrates that nutrient levels can strongly be reduced at times of barrier breaching in these and other lagoon systems, to be afterwards recovered very fast (Suzuki et al., 1998; Freitas et al., 2011; Carballeira & Leira, in prep.). It can be hypothesized, however, that in the long-term, more permanent connection to the ocean would bring these systems to lower nutrient level conditions that would keep them apart of turbid phases (Roselli et al., 2013), which seems not to be the case in Melides and Traba. Other factors, such as the precipitation regime, should have counteracted to avoid this.

### 5.3.2 PRECIPITATION VARIABILITY

Terrestrial inputs constitute a key source of nutrients in lakes at different environmental contexts (Richey & Wissmar, 1979; Wetzel, 2000), so differences in precipitation need to be taken into consideration in the absence of a meaningful explanation between the degree of barrier permeability and trophic status in Melides and Traba.

The sedimentary records of Melides and Traba span some of the periods of Rapid Climate Change of the Holocene (RCC) (Mayewski et al., 2004), namely the Roman Warm Period (RWP), Dark Ages (DA), and the Medieval Climatic Anomaly (MCA) for the case of Melides, and the Little Ice Age (LIA) and the Recent Period for both records (Fig. 5.1). Similar coastal systems elsewhere record ecological changes of state with climatic ameliorations (warmer/humid periods) being related to turbid regimes, and climatic deteriorations (colder/drier periods) with clear phases (Bracco et al., 2005; Inda et al., 2006; García-Rodríguez et al., 2010). Similar univocal relationships can be established for Traba, but not so easily for Melides. The long-term turbid state that characterized Traba from 1470 to 1875 cal yr CE fit into the LIA, a period of increased water availability, as evidenced by most continental records in the Iberian Peninsula (e. g., Benito et al., 2003; Moreno et al., 2008; Roberts et al., 2012) and, particularly, Galicia (Schellekens et al., 2010) (Fig. 5.1). Besides the elevated water table at this time, diatom data also indicate that there was intensified release of alkalinizing base cations derived from the catchment, both evidences of high water availability in the area. It has been suggested that a pervasive negative phase of the NAO seems to be not only behind this wet period in the region (Moreno et al., 2008), but related to increased storminess as well (Trouet et al., 2012). This is manifested in the Traba record by the intense aeolian activity that brought sands from the sand-barrier to the water body and, probably, by the increase in DI-salinity values. The palaeoenvironmental reconstruction suggests the hypothesis that, in spite of more intense and/or frequent barrier breaching, the turbid state in Traba could be naturally induced by enhanced nutrient inputs from the catchment under an intensified precipitation regime associated to a dominant negative NAO state. This hypothesis is supported by the gradual change to a clear state that follows the termination of the LIA, a period of global drier conditions (Dai et al., 1997; Hulme et al., 1998; Rowel, 2005) that is also manifested in the Iberian Peninsula (Desprat et al., 2013). Changes in allochthonous nutrient flux to the water body mediated by precipitation variability, likely associated to the NAO, could therefore account for naturally-induced changes in ecological regime shifts in Traba.

The extent of climate forcing as a major driver in changes in alternative stable states is however largely obscured in the Melides sedimentary record. Diatom, sedimentological and geochemical data show that for about 600 years (260-850 cal yr CE) dominant ecological conditions in Melides could be ascribed to those of a turbid state (Fig. 5.1). Yet, two contrasting events of RCC developed throughout this time interval. The transition from one humid (RWP) to one dry (DA) period had however no apparent effects on the trophic status of the system. Contrary to expected, cold and dry conditions in the peninsula associated to the DA (Desprat et al., 2003) are coincident in the sedimentary record with an apparent increase in the delivery of land-derived organic matter compared to the previous humid RWP (Martín-Puertas et al., 2008). DI-salinity shows that during these two periods a more permeable sand barrier gave rise to a less confined water body with instable ecological conditions. By contrast, the start of the dry MCA (Moreno et al., 2012) matches a gradual change in equilibrium towards a clear state. But whereas reduced nutrient inputs from the basin could be the likely cause triggering the regime shift, it is not until the period 1200-1700 cal yr CE when the system acquired the lowest productivity levels and maximum macrophytic development. Because this phase is again related to the enhanced humid conditions associated to the LIA, it can be hypothesized that in this case enhanced barrier permeability counteracted to avoid an increase in nutrients in the system (Fig. 5.1).

A common climatic forcing pattern that could explain shifts between different alternative states in Melides and Traba before direct human intervention is therefore lacking. The Melides record shows a high degree of different and sometimes contradictory overlapping signals that probably mask the extent to which climate changes have affected the evolution of the lagoon. Times of enhanced connection to the ocean, amplified for the case of Melides because of its more open condition throughout its history, probably acted to blur the climatic signal in the sedimentary record. A delicate balance between intensity and frequency of barrier breaching on one hand, and land-derived nutrient flux probably controlled shifts between different alternative states in Melides. By contrast, the levels of much more reduced connection to the ocean until human intervention (Bao et al., 2007), facilitated in Traba to validate the causal links between climate variability and the type of ecological equilibrium state, i. e., turbid or clear.

### 5.3.3 CHANGES IN FOREST COVER IN THE CATCHMENT

In spite of the likely role that the precipitation-mediated nutrient influx from the catchment played in ecological regime changes in Traba before direct human intervention on the system, indirect anthropogenic influence on the catchment cannot completely be ruled out from 1470 to 1950 cal yr CE. An open deforested landscape dominated by shrubs prevailed in the Galician coast during the LIA (Muñoz-Sobrino et al., 2012). A large part of this deforestation was not only due to climate deterioration associated to the LIA, but also human-induced (Guitián Rivera, 2001; Kaal et al., 2011). A clear landscape would have facilitated increased rates of erosion and therefore, the entrance of nutrients in the Traba water body. The climatic signal of the more humid LIA could therefore be amplified in the sedimentary record by the effects of human intervention in the catchment, being difficult to disentangle the relative contributions of each sources of variability (Fig. 5.1).

### 5.3.4 CULTURAL EUTROPHICATION

Human-induced accelerated rates of nutrient inputs to aquatic ecosystems are considered one of the most significant drivers of ecological change (Smol, 2008). Multiproxy data indicate that increased runoff of fertilizers from agriculture constitutes a major control in the ecological status starting no later than 1950 cal yr CE in Melides and 1990 cal yr CE in Traba (Fig. 5.1). The problem of cultural eutrophication is related in Melides to intensive rice production, livestock farming activities, and discharges by two Wastewater Treatment Plants, being aggravated by inert extraction in the basin that increase solids in suspension (Freitas et al., 2009). All these factors contributed to its present hypertrophic condition. On the other hand, Traba also experienced dramatic changes in the immediate catchment that involved channelization of the small tributaries that feed the system, and transformation of the hygrophilous grasslands into pastures. Because these changes prompted large development of emergent macrophytes at the shores, there was a buffering effect that still maintains Traba in a mesotrophic condition. Thus, whereas in Melides a new turbid state has been clearly achieved, Traba seems to be still in a transitional phase towards turbid conditions. During very short-term episodes, both systems relax their trophic status when artificial barrier breaching occurs, but man-induced eutrophication seems to be the primary driver in the evolution of the lagoon for the last decades (Fig. 5.1).

### 5.3.5 SEA-LEVEL FLUCTUATIONS

Current concerns regarding the potential eustatic sea-level rise associated to anthropogenic warming of the atmosphere and oceans, and its impacts on coastal resources have resulted in increased interest in former relative sea-level (RSL) fluctuations (IPCC, 2007). One of the main physical impacts of present-day accelerated RSL rise is the increased flooding of coastal wetlands, unless they have sufficient sediment supply (Nichols & Cazenave, 2010). It is therefore vital to have precise estimates of regional rates of sea-level rise and of sedimentation rates for the main coastal wetland areas. This knowledge allows ascertaining whether RSL changes constitute a significant factor in the evolution of these systems at different temporal time scales.

Historical instrumental data provide a global sea-level rise (GSLR) rate of 1.8 mm $yr^{-1}$ (IPCC, 2007), but regional tidal gauges records are essential to understand the regional variability. Unfortunately, these tide gauges are limited in terms of temporal coverage and cannot provide GSLR rates for times before 20th century. The rate of RSL rise estimated for the northern Iberian coast from tide gauge records yielded values of 1.49 to 2.51 ± 0.09 $mmyr^{-1}$ for the period 1943-2001 (Tel & García, 2001; Marcos et al., 2005; Alonso & Pagés, 2010). To put these figures in context, they need to be compared with estimates extending back to the time when lagoons were originated. Rate of sea-level rise derived from salt marsh records of northern Spain yielded a value of 0.7 mm $yr^{-1}$ for the period c. 6700 to 3000 cal yr BP (Leorri & Cearreta, 2009a; Cearreta, 2010). This was followed by a deceleration of -0.2 mm $yr^{-1}$, from 3000 cal yr BP until the 20th century (Cearreta, 2010), and a new increase yielding a value of 1.9 mm $yr^{-1}$ for the 20th century (Leorri & Cearreta, 2009b). This last figure is in very good agreement with instrumental data for the region, especially with estimates of 2.01 ± 0.85 mm $yr^{-1}$ corrected for vertical land movements using GPS records (Marcos et al., 2007) (Fig. 5.1).

For the southern Iberian Atlantic coast, local instrumental records in Cascais extending from 1882 to 2010 (Ferreira et al., 2008; Antunes et al., 2010) allowed estimates of sea-level rise of 0.5 mm $yr^{-1}$ for the period 1882 to 1920 (Ferreira et al., 2008), 1.6 mm $yr^{-1}$ for the period 1920 to 2000 (Antunes & Taborda, 2009), and 2.9 mm $yr^{-1}$ for 1990 to 2010 (Antunes et al., 2010). Most of the estimates of the rate of RSL rise based on sedimentary records focused on the sea-level deceleration that occurred c. 5000 cal yr BP (e. g., Dias, 1987; Psuty & Moreira, 2000; Boski et al., 2002; Teixeira et al, 2005; Vis, 2009), with fewer data on the Late Holocene. Rough estimates for the Mediterranean during the period 7500 cal yr BP until present yielded values of 3 to 5 mm $yr^{-1}$ (Boski et al., 2002; Teixeira et al, 2005), whereas for the period 2600 cal yr BP until present a value of 0.43 mm $yr^{-1}$ was obtained (Psuty & Moreira, 2000) (Fig. 5.1).

Accelerated rates of RSL rise for the northern and southern Iberian Atlantic coasts during the 20th century do not match with DI-salinity records of the two studied coastal wetlands. This is particularly evident for Traba, where a clear decrease in salinity took place during the whole 20th century. The only exception corresponds to the increase of the last decade, which with all certainty is related to the start of artificial breaching of the barrier. Comparison of the rate of

SLR for the northern Atlantic Iberian coast during the 20th century (2.01 mm $yr^{-1}$) with the estimated sedimentation rates for recent times in Traba (2.7 mm $yr^{-1}$) shows that the system would qualify as a “surplus lagoon”, where sediment infill outpaces sea-level rise (Nichols, 1989; Nichols & Boon, 1994). By contrast, recent sedimentation rate (2.2 mm $yr^{-1}$) and recent RSL rise rate (2.9 mm $yr^{-1}$) for the southern Iberian Atlantic coast do not keep pace in Melides making it to be classified as a “deficit lagoon” (Fig. 5.1). In spite of this, no significant trend towards more saline conditions throughout the 20th century is found in this lagoon either, according to the DI-salinities, indicating that salt water intrusions associated to the accelerated RSL rise have not had still any significant effects on the water bodies. Whether this is indicating a high resilience of the system (Elliott et al., 2007) or not is open to question.

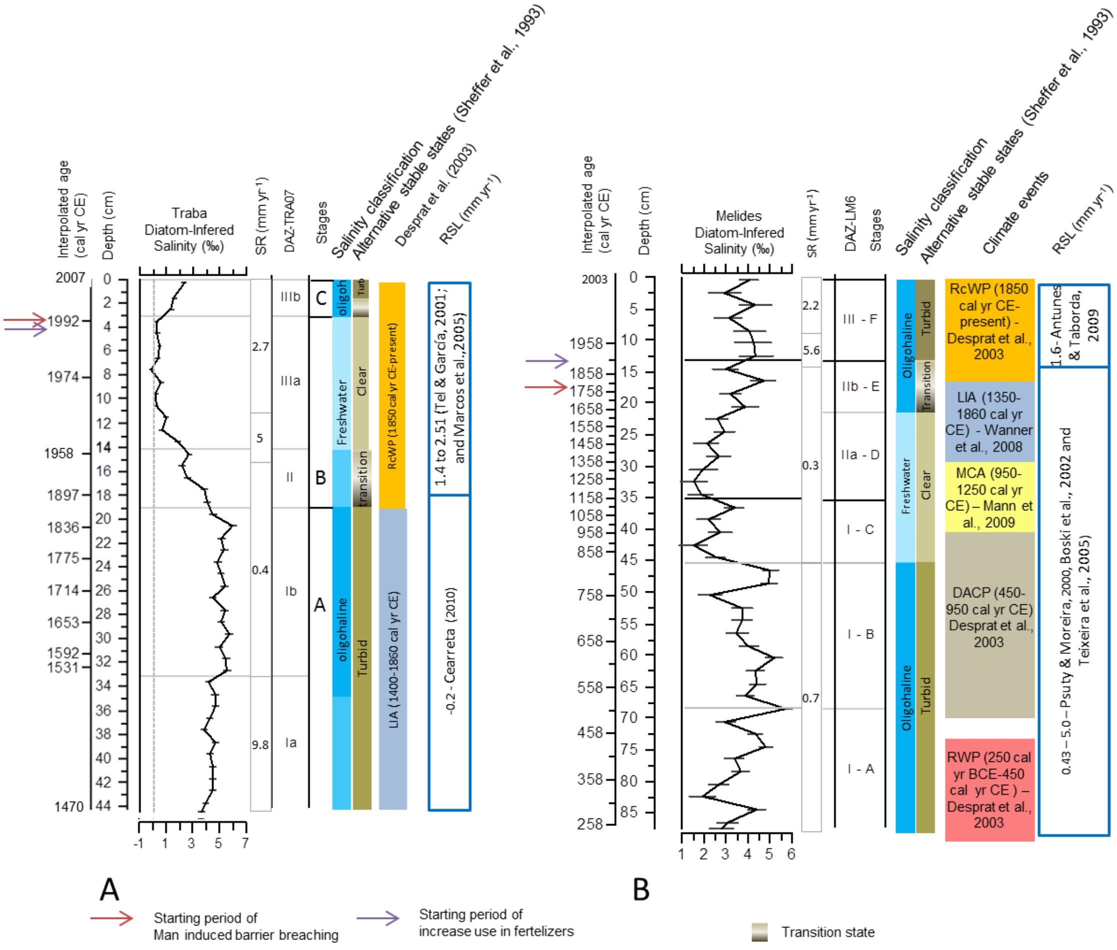

Fig. 5.1 - Summary scheme of periods and stages described in Traba (A) and Melides (B) sedimentary sequences and their relationship with the main historical climatic events (RWP – Roman warm period; DACP – Dark ages cold period; MCA – Medieval Climate Anomaly; LIA – Little Ice Age; RcWP – Recent Warm Period; RSL – Relative sea-Level).

## 5.4 MANAGEMENT PERSPECTIVES

Growing human pressures constitute a challenge for correct decision making in the World's coastal areas (Moser et al., 2012). For the particular case of coastal wetlands, dramatic ecosystem changes have been observed, and actions undertaken to alleviate or even return these systems to their original conditions have failed many times (Newton et al., 2013). Much emphasis has been put on the effects of accelerated sea-level rise associated to Global Warming, but historical loss of coastal wetlands has been dominated by the direct human modification on these systems (Kirwan & Megonigal, 2013). In spite of this, the non-climate drivers in the evolution of coastal environments received much less attention than climate components, because they are considered a local issue (Nicholls et al., 2008; Nicholls & Cazenave 2010). The long-term evolution of Melides and Traba shows that local stressors played a much more significant role on recent environmental deterioration than global scale effects.

For any good management practice in coastal wetlands it is necessary to distinguish when changes in the state of the ecosystem are caused by human pressure and not due to natural variability (Newton et al., 2013). Palaeoecological research developed in Melides and Traba has been decisive for this, demonstrating that both natural and human-induced causes intervened in major long-term environmental shifts that drove the two systems to different ecological states.

The trophic status of Melides and Traba was largely dependent on natural causes linked to Rapid Climate Changes during the Holocene (Mayewski et al., 2004). Both systems experienced shifts from a turbid to a clear phase associated to changes from humid to dry periods (the onset of the MCA in Melides, and the termination of the LIA in Traba). Under these high runoff conditions, even at periods with higher connection to the sea, the systems did not increase the buffer capacity against nutrient enrichment, as should be expected (Roselli et al., 2013). But this natural control on the nutrient concentration status of the water bodies (modulated, at least in the case of Traba, by human-induced changes in forest cover of the catchment), has been replaced by the anthropogenic effects on nutrient levels in the last decades. Cultural eutrophication is one of the major stresses that these systems are facing, and one of the main management strategies should be to reduce nutrient loads and improve water quality. This is particularly important for Melides, where hypertrophic conditions are recorded. The use of biodegradable fertilizers since 2004, under the Integrated Protected System Management Policy (Freitas et al., 2009), brings some hope to foresee a reduction in nutrient levels in this lagoon in the mid-term. By contrast, no active decision making has been put into practice in Traba, where palaeoecological data suggest that it is facing a transition from a clear to a turbid phase probably only mitigated by very short-term episodes of episodic artificial breaching of the barrier and, more permanently, by the large development of emerged macrophytes at the shoreline.

Artificial breaching is known to provoke high reductions in nutrient levels in Melides (Freitas et al., 2011) and Traba (Carballeira & Leira, in prep.). Although it would be tempting to intervene in the inlets to induce more frequent and/or intense connection to the sea, in dynamic coastal systems natural recovery is seen as the most appropriate and most likely mechanism to restore the ecosystem goods and services (Elliott et al., 2007). In the case of Traba, a strict application of the Nitrate Directive (EU, 1991) could have a significant impact on nutrient levels in the wetland. Environmental monitoring should be implemented to follow this and any other remediation plans, both here and in Melides, since there is a strong link among the different forcing factors driving their evolution. Susceptibility to eutrophication in coastal wetlands is not only a simple function of nutrient loadings, but also depends on sedimentary processes that are mainly controlled by a suite of sedimentological and geochemical variables (Moser et al., 2012). For instance, minimisation of sediment loads and vegetation clearance at the margins were suggested as palliative measures that would help functional life prolongation in Traba (Bao et al., 2007). Although this would benefit the extension of the dramatically reduced open waters, it would also limit the buffering effect of the marginal marsh against nutrient enrichment (Gasiorowski, 2008). On the other hand, under the Global Warming scenario, it is expected an increase of precipitation that would enhance the delivery of nutrients to coastal wetlands (Moser et al., 2012). This would make the alleviation of the effects of eutrophication even more challenging in systems like Melides and Traba, where increased precipitation regimes naturally contributed to keep them in turbid states in the past. To complicate things further, the direction of change of eutrophication in coastal wetlands can be site specific (Kirwan & Megonigal, 2013), so general rules on remediation should not be applied.

The given examples of a very complex interplay among the different forcing factors driving the evolution of Melides and Traba shows that successful restoration in coastal environments is not only a matter of engineering, but requires good science and hypothesis testing (Elliott et al., 2007). Management policy in coastal wetlands must therefore recognize the multiple scales of impacting agents and responses (Day et al., 2008). To know this, palaeoecological research is therefore imperative, contributing to develop realistic and well informed management, conservation, and restoration strategies (Smol, 2008, Saunders et al., 2008).

## 5.1 SELF-CRITICISM AND FUTURE WORK

This work has focused on two main approaches, the microscale, addressing the present-day data, and the mesoscale, based on the study of two cores retrieved from the Traba and Melides wetlands. Apart from the fact that every research work can be improved with more data or re-interpreted based on a deeper discussion, it is important to express and, if possible, to justify some aspects in which this work has been based, but also how these apprehensions can constitute future work.

1. In what microscale approach is concerned, although two samples (spring-summer and autumn-winter conditions) of the diatom assemblages have been collected, only the last sample collected was studied due to time restrictions. Nevertheless, it corresponds to a first complete study on diatoms of such a number of Iberian transitional coastal environments. However, it remains unknown how the diatom community responds to seasonal changes, namely in coastal environments with large areas that exhibit heterogenic sediments and diverse water levels and quality according to river discharge and sea connection. Some coastal water bodies are relatively well studied (such as the lagoons of Albufeira, Melides and Santo André), but most part of the Iberian coastal transitional environments are not, enhancing the importance of an exhaustive diatom assemblages study with a complete evaluation of environmental variables.

2. Moreover, few studies have been done relating diatoms with sedimentological and geochemical characteristics in the sediment, such as organic matter, stable isotopes and metals, from the water body itself but also from the adjacent fluvial areas, on a seasonal basis. Future studies in the WIAC should assess not only the role of salinity or nutrient gradients on the composition of diatom dead assemblages in present-day bottom sediments, but also of other environmental variables, such as tidal levels, sediment composition or depth. This would lead to more reliable palaeoenvironmental reconstructions in these systems were the complex interplay between continental and marine influences complicate the interpretation of the sedimentary record.

3. The calibration data-set could be improved merging other available data-sets (e. g., Ribeiro, 2013; Resende et al., 2005, 2007) or new data. For the case of DI-salinity reconstructions, the data-sets should include a wider range of salt conditions and environments (i. e., the inclusion of deeper water bodies depicting pelagic habitats).

4. If detailed knowledge could be achieved, quantitative inferred conditions could be more precise and a more reliable palaeoenvironmental reconstruction could be accomplished, specially focusing on the accuracy of these reconstructions, to provide information about optima and tolerances of diatom taxa in local and regional environments. Also, for a correct regional knowledge, efforts towards intercalibration of probes and methodologies between laboratories of different countries and regions must be imperative, with the prejudice of losing valid samples. Nonetheless, the samples and variables shown in this work represent the first characterization on the Iberian Atlantic façade.

5. It has become clear that to study past conditions in the coastal fringe, the choice should fall on a lake or lagoon with small dimensions. This choice leads to better samples toward a more reliable interpretation. However, the consequence of this choice would lead to an even greater lack of knowledge of coastal areas subject to multi- biotic and abiotic variables, which in the most part of the cases are the environments more subject to anthropic pressures.

6. Although the available meteorological data was used for evolution interpretation of both Traba and Melides, it would be important to install or to re-activate meteorological stations nearby coastal areas, were precipitation and temperature data could be measured and further related with the ecological responses.

7. It is important to expand these multi-proxy studies at high resolution level to other coastal environments, since in most part of the cases, they are centred in higher time-spans (the Holocene or a time interval encompassing the Last Glacial Maximum and the Holocene), focusing mainly on the global factors and addressed at a low resolution level, with little or no information about the local factors forcing the last centuries, especially related with human impacts.

8. Finally, it is essential to improve the chronology, since dates are crucial to frame palaeoenvironmental interpretations.

The development of these approaches depends on research projects and all the related funding, not only at Universities, but also on entities and institutes with social, scientific and technological accountabilities toward a responsible and informed decision-making.

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# Appendix

**APPENDIX I – RAW ENVIRONMENTAL DATA**
(WESTERN IBERIAN ATLANTIC COASTAL ENVIRONMENTS - PRESENT-DAY DATA-SET)

**APPENDIX II - DIATOM DATA**

II A –DIATOM ABUNDANCE DATA FROM PRESENT-DAY DATA SET (WESTERN IBERIAN ATLANTIC COASTAL ENVIRONMENTS)
(≥2% AT LEAST IN TWO SAMPLES)

II B – DIATOM ABUNDANCE DATA FROM TRA07 CORE (TRABA, GALICIA, SPAIN)
(≥2% AT LEAST IN ONE SAMPLE)

II C – DIATOM ABUNDANCE DATA FROM LM6 CORE (MELIDES, PORTUGAL)
(≥2% AT LEAST IN ONE SAMPLE)

**APPENDIX III - DIATOM PLATES**

III A – WESTERN IBERIAN ATLANTIC COASTAL ENVIRONMENTS - PRESENT-DAY DATA-SET

III B– DIATOMS FROM TRABA CORE – TRA07

III C – DIATOMS FROM MELIDES CORE - LM6

# Appendix I - *RAW ENVIRONMENTAL DATA*

## *(WESTERN IBERIAN ATLANTIC COASTAL ENVIRONMENTS - PRESENT-DAY DATA-SET)*

| System | Reference | Depth | Temperature | pH | Eh | Salinity | Conductivity | D.O | satD.O. | $NO_3^-$ | $NO_2^-$ | $NH_4^+$ | $PO_4^{3-}$ | $SiO_4^{4-}$ | $SO_4^{2-}$ | $Cl^-$ | $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | $Na^+$ | $Si^{4+}$ | DOC | DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | (m) | (ºC) |  | (mV) | (‰) | (mS cm$^{-1}$) | (mg L$^{-1}$) | (%) | (µM) | (µM) | (µM) | (µM) | (µM) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (µM) |
| Valdoviño | VAL0102 | - | 9.00 | 6.30 | - | 5.50 | 10.40 | 19.60 | 239.00 | 20.81 | <5 | 0.00 | <1 | - | 452.95 | 3234.90 | 64.50 | 175.00 | 50.60 | 1556.00 | 4.60 | 1.22 | - |
|  | VAL1604 | - | 15.50 | 8.79 | - | 17.93 | 30.10 | 9.20 | 95.00 | - | - | - | - | - | 1837.00 | 13166.00 | 285.00 | 817.00 | 235.00 | 7019.00 | 1.55 | 1.24 | - |
|  | VAL2907 | - | 24.50 | 9.10 | -29.20 | 4.17 | 7.80 | 6.60 | 95.00 | 0.79 | 0.42 | 3.46 | 0.38 | 39.88 | 379.05 | 2628.20 | 83.60 | 172.00 | 50.00 | 1404.00 | 0.74 | 2.79 | 4.66 |
|  | VAL1611 | - | 13.13 | 9.05 | -121.00 | 2.63 | 5.04 | 10.85 | 100.10 | 4.37 | 0.80 | 0.16 | 0.29 | 33.81 | 112.70 | 889.43 | 59.00 | 93.00 | 24.60 | 764.00 | 0.33 | 3.13 | 5.33 |
| Doniños | DON0102 | - | 9.60 | 7.02 | - | 0.11 | 0.23 | 17.30 | 133.00 | 53.55 | <0,10 | <0,021 | <0,1 | - | 21.68 | 50.43 | 5.10 | 3.90 | 1.77 | 27.10 | 3.70 | 3.22 | - |
|  | DON1604 | - | 17.50 | 7.20 | - | 0.11 | 0.23 | 9.80 | 105.00 | 12.11 | 0.41 | 1.96 | 0.32 | 10.83 | 24.10 | 49.11 | 6.74 | 5.00 | 1.90 | 37.60 | 0.46 | 2.99 | 14.47 |
|  | DON2907 | - | 23.70 | 6.67 | 84.50 | 0.18 | 0.22 | 6.48 | 91.00 | 0.00 | 0.80 | 0.16 | 0.29 | 24.00 | 22.96 | 50.44 | 6.22 | 5.40 | 1.50 | 36.30 | 0.31 | 4.05 | 0.96 |
|  | DON1611 | - | 13.66 | 7.16 | -13.00 | 0.11 | 0.24 | 9.96 | 95.10 | - | - | - | - | - | 17.63 | 45.16 | 6.20 | 5.30 | 2.10 | 35.00 | 0.49 | 3.70 | - |
| Traba | TRA0102 | - | 11.70 | 7.16 | - | 0.08 | 0.17 | 12.50 | 120.00 | 70.32 | <0,10 | <0,021 | <0,1 | - | 6.42 | 36.18 | 3.50 | 2.30 | 1.98 | 18.90 | 2.40 | 1.59 | - |
|  | TRA1704 | - | 20.00 | 8.28 | - | 0.08 | 0.18 | 10.60 | 119.00 | - | - | - | - | - | 7.44 | 46.39 | 4.39 | 3.50 | 2.40 | 33.40 | 0.60 | 2.27 | - |
|  | TRA3107 | - | 23.50 | 6.44 | 76.00 | 0.09 | 0.19 | 7.20 | 87.60 | 14.55 | 1.18 | 3.64 | 0.23 | 8.71 | 0.80 | 6.06 | 4.56 | 3.40 | 2.50 | 31.20 | 0.71 | 1.79 | 19.38 |
|  | TRA1911 | - | 11.90 | 7.42 | -27.00 | 3.41 | 6.47 | 9.50 | 88.50 | 36.48 | 1.18 | 5.14 | 0.23 | 11.16 | 272.70 | 2047.10 | 47.00 | 123.00 | 36.40 | 1016.00 | 0.36 | 5.03 | 42.80 |
| Louro | LOU1604 | - | 17.90 | 8.49 | - | 11.09 | 19.53 | 8.70 | 90.00 | - | - | - | - | - | 692.00 | 5056.00 | 116.00 | 312.00 | 98.00 | 2684.00 | 0.35 | 10.72 | - |
|  | LOU2607 | - | 27.70 | 7.64 | 56.00 | 2.89 | 5.52 | 4.89 | 73.80 | 0.96 | 0.70 | 7.47 | 0.44 | 3.51 | 204.00 | 1791.00 | 43.20 | 131.00 | 44.00 | 1162.00 | 0.32 | 7.65 | 9.13 |
|  | LOU1911 | - | 12.53 | 7.91 | -55.00 | 8.89 | 15.92 | 10.23 | 95.30 | 2.11 | 1.11 | 11.26 | 0.48 | 2.61 | 838.50 | 5419.50 | 94.00 | 252.00 | 69.20 | 1948.00 | 0.31 | 7.68 | 14.47 |
| Xuño | XUÑ1804 | - | 20.60 | 6.41 | 83.80 | 0.15 | 0.31 | 7.40 | 85.00 | - | - | - | - | - | 4.61 | 72.95 | 12.40 | 5.80 | 0.78 | 44.80 | 0.63 | 3.89 | - |
|  | XUÑ3007 | - | 22.70 | 6.35 | 89.80 | 0.17 | 0.36 | 1.52 | 18.00 | 0.00 | 0.63 | 0.26 | 0.27 | 15.61 | 8.61 | 79.05 | 27.40 | 4.60 | 1.00 | 51.10 | 1.12 | 5.62 | 0.89 |
|  | XUÑ2011 | - | 10.50 | 6.85 | 11.00 | 0.16 | 0.34 | 6.60 | 58.50 | 4.15 | 0.90 | 1.49 | 0.40 | 22.06 | 6.84 | 100.73 | 13.70 | 5.60 | 6.30 | 58.00 | 0.54 | 5.21 | 6.54 |
| Muro | MUR1804 | - | 21.00 | 6.90 | 566.00 | 2.57 | 4.90 | 9.40 | 108.00 | - | - | - | - | - | 223.00 | 1614.00 | 28.00 | 69.00 | 22.10 | 605.00 | 0.45 | 6.83 | - |
|  | MUR3007 | - | 32.80 | 8.71 | -22.10 | 1.58 | 3.08 | 10.10 | 130.00 | 0.00 | 0.97 | 0.73 | 0.41 | 43.94 | 91.38 | 905.10 | 22.10 | 56.00 | 17.00 | 493.00 | 0.94 | 11.76 | 1.70 |
|  | MUR2011 | - | 11.30 | 5.30 | 93.00 | 1.62 | 3.17 | 9.62 | 87.20 | 22.26 | 0.57 | 23.25 | 0.22 | 5.22 | 280.10 | 741.13 | 28.00 | 57.00 | 16.20 | 409.00 | 0.40 | 4.49 | 46.07 |
| A Illa de Arousa | ILL1504 | - | 24.30 | 8.90 | - | 0.14 | 0.29 | 8.60 | 105.00 | - | - | - | - | - | 8.10 | 49.99 | 19.20 | 4.70 | 4.10 | 33.80 | 0.26 | 12.14 | - |
|  | ILL2707 | - | 27.70 | 7.69 | 37.70 | 0.24 | 0.50 | 11.70 | 175.00 | 0.06 | 0.55 | 19.37 | 1.54 | 142.42 | 52.95 | 105.17 | 35.60 | 10.40 | 1.80 | 66.50 | 0.46 | 25.92 | 19.98 |
| Bodeira | BOD1504 | - | 17.00 | 8.70 | 32.60 | 0.14 | 0.30 | 3.91 | 41.00 | - | - | - | - | - | 7.75 | 47.30 | 21.30 | 5.80 | 4.60 | 32.30 | 0.39 | 15.11 | - |
|  | BOD2707 | - | 23.70 | 6.56 | 92.00 | 0.02 | 0.22 | 2.42 | 35.00 | 0.00 | 0.56 | 28.55 | 1.46 | 74.26 | 6.73 | 51.86 | 22.50 | 6.30 | 1.20 | 40.00 | 0.55 | 18.10 | 29.11 |
|  | BOD2111 | - | 14.16 | 4.85 | 119.00 | 0.53 | 1.08 | 7.45 | 72.30 | 82.78 | 0.64 | 171.63 | 1.48 | 5.28 | 473.90 | 71.33 | 146.00 | 37.50 | 12.60 | 59.00 | 2.08 | 12.35 | 255.05 |
| Minho - low salt marsh | MIN BS 17.07.07 | - | 21.80 | 6.52 | 129.40 | 6.26 | 17.83 | 7.11 | 87.70 | 24.19 | 0.27 | 6.81 | 0.37 | 32.66 | 384.40 | 2434.00 | 70.40 | 197.00 | 59.20 | 1779.00 | 1.08 | 1.72 | 31.27 |
| Minho - tidal flat | MIN RM 17.07.07 | - | 22.20 | 7.09 | 167.20 | 2.29 | 8.12 | 7.41 | 85.40 | 26.06 | 0.32 | 7.68 | 0.35 | 29.18 | 180.00 | 1264.00 | 30.10 | 74.00 | 21.70 | 609.00 | 0.66 | 2.13 | 34.06 |
| Minho - low salt marsh | MIN BS 18.03.08 | - | 14.50 | 8.19 | 124.70 | 6.02 | 28.33 | 8.03 | 83.00 | 4.98 | 0.90 | 5.49 | 0.67 | 8.33 | 1514.00 | 10857.00 | 260.36 | 792.42 | 214.82 | 6757.38 | 1.10 | 4.26 | 11.36 |
| Minho - tidal flat | MIN RM 18.03.08 | - | 13.60 | 8.16 | 135.40 | 2.73 | 17.15 | 7.70 | 81.30 | 14.55 | 0.89 | 4.22 | 0.34 | 9.80 | 923.00 | 6553.00 | 143.16 | 443.84 | 122.73 | 3747.65 | 0.61 | 4.47 | 19.66 |
| Lima - tidal Flat | LIMA RM 18.07.07 | - | 19.90 | 7.17 | 84.40 | 25.67 | 61.71 | 9.60 | 104.30 | 13.10 | 0.21 | 2.94 | 0.16 | 26.12 | 1225.00 | 8919.00 | 217.00 | 627.00 | 627.00 | 5779.00 | 0.52 | 2.24 | 16.25 |
|  | LIMA RM 19.03.08 | - | 11.00 | 7.89 | 216.00 | 16.26 | 42.08 | 7.04 | 70.00 | 19.17 | 1.10 | 37.45 | 0.51 | 17.30 | 1540.00 | 8584.00 | 288.29 | 779.61 | 202.91 | 6393.55 | 1.44 | 1.60 | 57.72 |
| Vela | LVB 20.02.08 | 0 | 14.60 | 9.11 | 153.00 | 0.41 | 2.94 | 12.20 | 120.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 14.60 | 9.11 | - | 0.41 | 2.94 | 12.28 | 120.30 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1 | 14.50 | 9.04 | 142.20 | 0.41 | 2.94 | 11.84 | 116.10 | 2.16 | 1.20 | 9.61 | 1.66 | 3.50 | 73.40 | 71.60 | 34.85 | 10.46 | 15.70 | 46.84 | 0.07 | 44.40 | 12.97 |
|  | LVB 10.07.08 | 0 | 28.10 | 9.60 | 78.50 | 0.32 | 2.46 | 14.95 | 184.20 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  | 0.3 | 28.00 | 9.60 | 38.00 | 0.32 | 2.49 | 14.50 | 182.00 | 0.00 | 1.15 | 12.83 | 1.28 | 4.82 | 86.50 | 84.50 | 33.04 | 13.38 | 19.30 | 59.89 | 0.13 | 57.30 | 13.98 |
| Óbidos | OB est.1 06.07.07 | 0 | 23.30 | 8.16 | -15.00 | 33.78 | 77.95 | 7.00 | 128.54 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 23.40 | 8.25 | - | 33.88 | 78.10 | 7.00 | 128.86 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.8 | 23.40 | 8.26 | -35.00 | 33.88 | 78.10 | 7.00 | 128.86 | 1.68 | 0.13 | 5.20 | 2.01 | 14.09 | 2777.00 | 20757.00 | 244.00 | 751.00 | 213.00 | 6632.00 | 0.18 | 1.76 | 7.02 |
| Óbidos - Barrosa | OB est.2 06.07.07 | 0-0,40 | 24.80 | 8.60 | -40.00 | 32.22 | 74.60 | 7.70 | 141.98 | 6.03 | 0.39 | 5.01 | 3.69 | 7.22 | 2521.00 | 19434.00 | 287.00 | 789.00 | 248.00 | 7257.00 | 0.35 | 4.91 | 11.43 |
| Óbidos | OB est.1 17.03.08 | 0 | 16.70 | 8.55 | 56.80 | 26.54 | 64.75 | 12.57 | 152.30 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 16.70 | 8.66 | - | 26.04 | 64.75 | 12.20 | 152.50 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.7 | 16.70 | 8.53 | 77.60 | 25.74 | 64.75 | 11.61 | 140.70 | 1.41 | 1.21 | 2.98 | 0.78 | 9.82 | 2582.00 | 18736.00 | 455.02 | 1394.94 | 380.41 | 19349.77 | 0.15 | 5.29 | 5.60 |
| Óbidos - Barrosa | OB est.2 17.03.08 | 0-0,25 | 17.30 | 8.64 | 76.80 | 25.03 | 61.88 | 10.99 | 131.50 | 2.07 | 1.26 | 9.50 | 4.37 | 14.44 | 1852.00 | 12107.00 | 316.78 | 936.50 | 262.41 | 8326.50 | 0.25 | 4.92 | 12.83 |

| System | Reference | Depth | Temperature | pH | Eh | Salinity | Conductivity | D.O | satD.O. | $NO_3^-$ | $NO_2^-$ | $NH_4^+$ | $PO_4^{3-}$ | $SiO_4^{4-}$ | $SO_4^{2-}$ | $Cl^-$ | $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | $Na^+$ | $Si^{4+}$ | DOC | DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | (m) | (ºC) |  | (mV) | (‰) | (mS cm$^{-1}$) | (mg L$^{-1}$) | (%) | (µM) | (µM) | (µM) | (µM) | (µM) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (µM) |
| Albufeira Lagoa Grande 1 | ALB est.1 02.05.07 | 0 | 18.00 | 8.38 | 106.20 | 32.67 | 76.90 | 4.11 | 43.70 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 18.00 | 8.39 | 93.90 | 34.73 | 81.65 | 4.12 | 44.10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1 | 17.90 | 8.43 | 101.00 | 32.67 | 76.90 | 4.06 | 43.30 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1.6 | 17.90 | 8.45 | 83.40 | 32.67 | 76.90 | 4.00 | 42.50 | 0.76 | 0.16 | 3.58 | 0.59 | 12.62 | 2330.00 | 14080.00 | 329.00 | 982.00 | 274.00 | 8526.00 | 0.36 | 5.51 | 4.50 |
| Albufeira - Lagoa Grande 2 | ALB est.2 02.05.07 | 0 | 20.20 | 8.51 | 85.10 | 28.56 | 68.64 | 3.34 | 40.80 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.6 | 20.40 | 8.58 | 107.80 | 28.56 | 68.64 | 3.75 | 41.50 | 0.83 | 0.37 | 4.37 | 0.57 | 20.71 | 1864.00 | 16942.00 | 335.00 | 1054.00 | 297.00 | 9189.00 | 0.61 | 4.62 | 5.57 |
| Albufeira - Lagoa Pequena | ALB est.3 02.05.07 | 0 | 20.60 | 8.28 | 161.10 | 19.70 | - | 4.76 | 51.60 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.7 | 20.50 | 8.67 | 159.30 | 23.51 | 59.42 | 4.63 | 48.92 | 3.08 | 1.15 | 38.88 | 1.59 | 26.57 | 1871.00 | 13149.00 | 198.00 | 563.00 | 164.00 | 5031.00 | 0.74 | 6.00 | 43.11 |
| Albufeira Lagoa Grande 1 | ALB est.1 09.01.08 | 0 | 14.00 | 8.68 | - | 27.00 | 46.70 | 16.64 | 160.20 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 14.00 |  | - | 30.50 | 48.10 | 13.50 | 130.60 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1 | 13.80 |  | - | 31.20 | 49.20 | 11.60 | 11.60 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1.5 | 12.80 |  | - | 31.60 | 49.70 | 10.50 | 102.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 2 | 12.40 |  | - | 31.90 | 50.20 | 9.53 | 87.30 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 2.5 | 12.20 |  | - | 32.20 | 50.60 | 7.75 | 75.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 3 | 12.00 |  | - | 32.40 | 50.90 | 7.50 | 69.90 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 3.5 | 11.60 |  | - | 32.40 | 51.10 | 7.10 | 65.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 4 | 11.70 |  | - | 32.60 | 51.20 | 7.13 | 62.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 4.5 | 11.60 |  | - | 32.50 | 51.10 | 6.84 | 62.80 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 5 | 11.60 | 8.29 | - | 32.50 | 51.10 | 6.95 | 64.60 | 7.56 | 1.28 | 12.68 | 0.37 | 16.87 | 2653.00 | 17319.00 | 486.60 | 1513.91 | 398.11 | 21097.30 | 0.41 | 5.81 | 21.51 |
| Albufeira - Lagoa Grande 2 | ALB est.2 09.01.08 | 0 | 13.80 | 8.92 | - | 29.90 | 46.80 | 16.30 | 66.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 13.70 |  | - | 30.20 | 47.00 | 15.29 | 148.30 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1 | 13.30 |  | - | 31.40 | 49.30 | 13.40 | 112.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1.5 | 12.50 |  | - | 31.80 | 50.00 | 9.97 | 90.20 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 2 | 12.30 | 8.79 | - | 31.90 | 50.30 | 8.44 | 81.00 | 1.55 | 1.11 | 2.97 | 1.90 | 26.25 | 2358.00 | 12293.00 | 457.63 | 1451.12 | 387.70 | 20362.75 | 0.71 | 8.73 | 5.63 |
| Albufeira - Lagoa Pequena | ALB est.3 09.01.08 | 0 | 14.20 | 8.92 | - | 28.80 | 45.70 | 20.70 | 203.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 13.60 |  | - | 29.70 | 47.10 | 17.00 | 157.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1 | 12.70 |  | - | 31.10 | 49.10 | 7.10 | 71.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1.5 | 12.30 |  | - | 31.70 | 50.00 | 4.80 | 48.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 2 | 12.10 |  | - | 32.00 | 50.30 | 4.38 | 42.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 2.5 | 11.90 | 8.57 | - | 32.00 | 50.40 | 1.19 | 10.40 | 1.61 | 1.64 | 10.03 | 1.43 | 40.39 | 2430.00 | 15739.00 | 489.71 | 1475.92 | 392.58 | 19933.63 | 0.90 | 6.14 | 13.28 |
| Sado - tidal flat | SADO RM 14.02.08 | 0-1,5 | 11.60 | 7.97 | 140.40 | 33.62 | 79.89 | 8.12 | 76.50 | 0.00 | 0.86 | 4.10 | 0.40 | 12.34 | 2513.00 | 18072.00 | 234.51 | 704.86 | 185.86 | 6681.82 | 0.21 | 2.92 | 4.96 |
|  | SADO RM 9.07.08 | 0-0,60 | 22.20 | 7.70 | 77.80 | 30.80 | 47.70 | 4.73 | 64.10 | 1.39 | 0.75 | 2.41 | 0.40 | 32.51 | 2727.00 | 16491.00 | 520.88 | 1608.97 | 440.41 | 22910.61 | 1.16 | 2.92 | 4.55 |
| Melides | MEL B1 29.10.07 | 0 | 17.00 | 8.25 | 114.60 | 1.10 | 4.91 | 8.36 | 85.30 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 17.00 | - | - | 1.10 | 4.91 | 8.35 | 87.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1 | 17.10 | 8.31 | 98.20 | 1.10 | 4.91 | 8.38 | 86.30 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1.5 | 17.10 | - | - | 1.10 | 4.91 | 8.20 | 85.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 2 | 17.10 | 8.34 | 102.80 | 1.20 | 5.06 | 7.38 | 81.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 2.5 | 16.70 | - | - | 1.10 | 4.91 | 8.13 | 86.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 3 | 16.40 | - | - | 1.10 | 3.37 | 8.33 | 85.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 3.25 | 16.40 | 8.32 | 96.40 | 1.10 | 4.75 | 8.65 | 88.10 | 9.23 | 1.48 | 13.94 | 0.30 | 53.65 | 141.00 | 495.00 | 29.55 | 25.22 | 9.46 | 205.00 | 0.25 | 6.97 | 24.65 |
|  | MEL B1 01.07.08 | 0 | 26.40 | 9.44 | 77.00 | 6.74 | 18.09 | 9.80 | 126.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 26.40 | 9.45 | - | 6.74 | 19.30 | 10.10 | 130.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1 | 26.40 | 9.44 | 73.20 | 6.84 | 19.45 | 10.10 | 130.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1.5 | 26.40 | 9.39 | - | 6.94 | 19.60 | 9.30 | 120.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1.75 | 27.00 | 9.03 | - | 8.79 | 24.14 | 8.60 | 113.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 2 | 28.70 | 8.10 | - | 15.87 | 41.55 | 5.10 | 71.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 2.1 | 28.80 | 7.99 | - | 17.41 | 43.82 | 3.40 | 48.00 | 0.93 | 1.15 | 32.52 | 1.66 | 96.84 | 987.00 | 6336.00 | 186.66 | 538.31 | 138.03 | 4488.45 | 0.95 | 6.97 | 34.60 |

Z

| System | Reference | Depth | Temperature | pH | Eh | Salinity | Conductivity | D.O | satD.O. | $NO_3^-$ | $NO_2^-$ | $NH_4^+$ | $PO_4^{3-}$ | $SiO_4^{4-}$ | $SO_4^{2-}$ | $Cl^-$ | $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | $Na^+$ | $Si^{4+}$ | DOC | DIN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | (m) | (ºC) |  | (mV) | (‰) | (mS cm$^{-1}$) | (mg L$^{-1}$) | (%) | (µM) | (µM) | (µM) | (µM) | (µM) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (mg L$^{-1}$) | (µM) |
| Santo André-main channel | SA est.1 11.05.07 | 0 | 20.00 | 8.56 | 55.60 | 28.39 | 68.02 | 3.20 | 35.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.35 | 20.10 | 8.66 | 87.10 | 28.61 | 68.67 | 3.46 | 36.60 | 82.62 | 0.03 | 5.69 | 0.22 | 12.29 | 2128.00 | 15741.00 | 230.00 | 687.00 | 207.00 | 6389.00 | 0.50 | 6.83 | 88.34 |
| Santo André- Margin | SA est.2 11.05.07 | 0.15 | 24.80 | 7.56 | 127.60 | 28.61 | 68.67 | 3.46 | 36.60 | 85.27 | 0.69 | 5.48 | 0.39 | 50.52 | 1427.00 | 11219.00 | 144.00 | 392.00 | 112.00 | 3505.00 | 1.14 | 5.67 | 91.43 |
| Santo André- Alguidares | SA est.3 11.05.07 | 0 | 21.30 | 7.85 | 89.60 | 29.72 | 70.77 | 2.95 | 32.80 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.35 | 21.30 | 7.93 | 91.50 | 29.72 | 70.77 | 2.80 | 33.10 | 36.07 | 0.99 | 4.12 | 0.22 | 24.30 | 2082.00 | 12539.00 | 165.00 | 498.00 | 140.00 | 5004.00 | 0.45 | 5.08 | 41.18 |
| Santo André-main channel | SA est.1 18.12.07 | 0 | 9.70 | 8.74 | 150.00 | 17.54 | 45.42 | 7.50 | 66.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 9.70 | - | - | 17.95 | 45.27 | 7.30 | 64.50 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 1 | 9.70 | 8.55 | 190.00 | 17.44 | 45.27 | 7.35 | 65.00 | 0.20 | 1.24 | 2.39 | 1.77 | 32.12 | 1039.00 | 6580.00 | 277.57 | 782.26 | 208.68 | 6428.66 | 1.06 | 12.90 | 3.83 |
| Santo André- Margin | SA est.2 18.12.07 | 0 | 10.10 | 8.19 | 177.00 | 17.03 | 44.18 | 7.08 | 63.30 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 10.10 | 8.16 | 218.00 | 17.03 | 59.87 | 7.05 | 63.00 | 0.71 | 1.16 | 1.27 | 1.27 | 40.21 | 1155.00 | 6776.00 | 241.04 | 519.16 | 137.53 | 4322.09 | 0.68 | 15.50 | 3.15 |
| Santo André- Alguidares | SA est.3 18.12.07 | 0 | 9.80 | 8.50 | 162.00 | 17.24 | 44.80 | 7.19 | 63.60 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.5 | 9.80 | - | - | 17.24 | 44.80 | 7.02 | 61.80 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.7 | 9.80 | 8.43 | 172.00 | 17.24 | 44.80 | 7.02 | 61.80 | 1.43 | 1.80 | 1.76 | 2.01 | 34.87 | 1156.00 | 5308.00 | 207.41 | 579.49 | 161.81 | 4745.04 | 0.67 | 17.70 | 4.99 |
| Barbaroxa de Baixo | BB 11.05.07 | 0 | 22.80 | 6.38 | 200.00 | 0.52 | 3.29 | 1.08 | 12.30 | 26.20 | 2.31 | 4.83 | 0.42 | 11.29 | 29.30 | 192.60 | 6.70 | 13.00 | 9.30 | 142.00 | 1.34 | 47.76 | 33.34 |
|  |  | 0.5 | 17.10 | 6.46 | 178.20 | 0.55 | 3.31 | 0.38 | 4.00 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.9 | 16.10 | 6.28 | 190.10 | 0.53 | 3.28 | 0.06 | 0.60 | 13.87 | 0.79 | 4.36 | 0.64 | 26.48 | 30.40 | 195.50 | 0.10 | 0.10 | 0.50 | 78.00 | 0.01 | 49.24 | 19.01 |
|  | BB 18.12.07 | 0 | 9.50 | 7.46 | 170.00 | 1.39 | 5.20 | 5.36 | 46.90 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
|  |  | 0.4 | 9.50 | 6.04 | 190.00 | 1.39 | 5.20 | 5.21 | 46.10 | 0.00 | 5.08 | 2.45 | 1.00 | 161.68 | 47.40 | 288.00 | 8.69 | 28.68 | 14.00 | 242.72 | 0.31 | 118.00 | 7.54 |
| Mira - low salt marsh | MIRA BS 18.07.07 | 0 | 22.60 | 8.11 | 92.40 | 36.77 | 83.53 | 3.25 | 37.40 | 9.05 | 0.27 | 3.78 | 0.22 | 12.94 | 2656.00 | 18233.00 | 365.00 | 1050.00 | 320.00 | 9653.00 | 1.99 | 1.13 | 13.09 |
| Mira- tidal flat | MIRA RM 18.07.07 | 0-0,2 | 17.50 | 8.28 | 159.90 | 36.05 | 83.08 | 3.25 | 33.50 | 85.11 | 0.14 | 5.61 | 0.23 | 12.24 | 2648.00 | 19558.00 | 333.00 | 958.00 | 282.00 | 8575.00 | 0.28 | 2.74 | 90.86 |
| Mira - low salt marsh | MIRA BS 19.12.07 | 0 | 15.00 | 7.88 | 201.00 | 33.09 | 80.23 | 4.75 | 46.90 | 2.26 | 1.05 | 17.42 | 0.22 | 12.47 | 2655.00 | 9837.00 | 305.95 | 955.10 | 249.31 | 8695.15 | 0.60 | 2.25 | 20.74 |
| Mira- tidal flat | MIRA RM 19.12.07 | 0-0,2 | 14.60 | 8.12 | 177.10 | 32.58 | 78.99 | 5.10 | 50.40 | 2.13 | 1.28 | 2.86 | 0.47 | 15.73 | 2581.00 | 17981.00 | 293.11 | 907.34 | 244.77 | 8060.34 | 0.47 | 2.64 | 6.27 |

# Appendix II

## II A – DIATOM ABUNDANCE DATA FROM WESTERN IBERIAN ATLANTIC COASTAL ENVIRONMENTS - PRESENT-DAY DATA-SET (≥2 % AT LEAST IN TWO SAMPLES)

| Taxon | Code | VAL | DON | TRA | LOU | XUN | MUR | ILL | BOD | MINBS | MINRM | LIMARM | LVB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Achnanthes brevipes* Agardh 1824 | ACBREV | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Achnanthes fogedii* Hakansson 1978 | ACFOG | 0.22 | 0.00 | 22.36 | 0.00 | 0.00 | 2.25 | 0.00 | 0.00 | 0.92 | 0.00 | 0.00 | 0.00 |
| *Achnanthes lemmermannii* Hustedt 1933 | ACLEM | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.20 | 3.12 | 5.93 | 0.00 |
| *Achnanthes submarina* Hustedt 1956 | ACSUBM | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Achnanthidium minutissimum* (Kützing) Czarnecki 1994 | ACTMIN | 0.22 | 2.16 | 6.63 | 0.00 | 70.26 | 4.25 | 10.51 | 3.32 | 4.67 | 0.24 | 0.64 | 11.65 |
| *Biremis lucens (Hustedt)* Sabbe, Witkowski & Vyverman 1995 | BIRLUC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.20 | 0.96 | 3.60 | 0.00 |
| *Cocconeis costata* var. *costata* Gregory Gregory (1855) | COCCOSC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Cocconeis neodiminuta* Krammer 1990 | COCNEOD | 3.08 | 37.41 | 0.25 | 0.72 | 0.00 | 1.25 | 0.00 | 0.00 | 7.78 | 12.47 | 0.00 | 0.00 |
| *Cocconeis placentula* var. *euglypta* (Ehrenberg) Cleve 1895 | COCPLE | 0.00 | 3.60 | 0.00 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.64 | 0.00 |
| *Cocconeis placentula* var. *lineata* (Ehrenberg) van Heurck 1885 | COCPLL | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 7.33 | 0.00 | 0.00 | 0.00 | 0.00 | 3.64 |
| *Cocconeis placentula* var. *placentula* Ehrenberg 1838 | COCPLP | 9.03 | 0.00 | 1.72 | 2.86 | 0.00 | 3.00 | 0.00 | 44.31 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Cocconeis scutellum* Ehrenberg 1838 | COCSCT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.96 | 2.12 | 0.00 |
| *Cocconeis pseudomarginata* Gregory 1857 | COCPSEU | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Ctenophora pulchella* (Ralfs ex Kützing) Williams & Round 1986 | CTPUL | 1.54 | 0.00 | 3.19 | 0.24 | 0.74 | 3.00 | 1.47 | 0.24 | 0.00 | 0.24 | 0.00 | 0.00 |
| *Cyclotella comensis* Grunow in van Heurck 1882 | CYCCOM | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.64 | 0.00 |
| *Cyclotella meneghiniana* Kützing 1844 | CYMEN | 1.54 | 0.00 | 0.98 | 0.24 | 0.37 | 2.75 | 3.91 | 1.66 | 1.83 | 0.00 | 0.00 | 0.24 |
| *Diploneis bombus* (Ehrenberg) Ehrenberg 1853 | DIPBOM | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.42 | 0.00 |
| *Diploneis didyma* (Ehrenberg) Ehrenberg 1839 | DIPDIDY | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Fallacia clepsidroides* Witkowski 1994 | FALCLEP | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.14 | 9.11 | 2.54 | 0.00 |
| *Gomphonemopsis obscurum* (Krasske) Lange-Bertalot in Lange Bertalot et al. 1996 | GMPMOBS | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Halamphora* aff. *luceae* (Cholnoky) *Levkov 2009* | HALaLUC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.23 | 0.96 | 0.00 | 0.00 |
| *Halamphora coffeaeformis* (Agardh) *Levkov 2009* | AMCOAF | 10.13 | 0.00 | 0.25 | 3.34 | 0.00 | 3.00 | 0.00 | 0.00 | 0.69 | 0.00 | 13.35 | 0.00 |
| *Mastogloia* aff. *angulata* Lewis 1861 | MASTaAN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Mastogloia pumila* Cleve and Moller 1879 | MASTPUM | 14.54 | 0.00 | 0.00 | 0.72 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Navicula* aff. *cryptotenella* Lange-Bertalot in Krammer & Lange-Bertalot 1985 | NAVCRTL | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.46 | 0.00 | 0.00 | 0.00 |
| *Navicula* aff. *paul-schulzii* Witkowski & Lange-Bertalot in A. Witkowski 1994 | NAVaPSC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 25.66 | 26.48 | 0.00 |
| *Navicula* aff. *perminuta Grunow in van Heurck 1880* | NAVaPER | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.89 | 2.16 | 1.48 | 0.00 |
| *Navicula* aff. *antonii* Lange-Bertalot 2000 | NAVaANT | 0.00 | 0.00 | 0.00 | 2.63 | 0.00 | 4.25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Navicula gregaria* Donkin 1861 | NAVGREG | 0.88 | 0.00 | 0.74 | 0.24 | 0.00 | 2.00 | 0.24 | 0.00 | 9.61 | 6.24 | 1.06 | 0.00 |
| *Navicula perminuta* Grunow in van Heurck 1880 | NAVPER | 8.15 | 0.00 | 0.00 | 0.95 | 0.00 | 5.75 | 0.00 | 0.00 | 0.46 | 0.00 | 0.00 | 0.00 |
| *Nitzschia fonticola* (Grunow) Grunow in Van Heurck 1881 | NITFONT | 0.00 | 0.00 | 0.00 | 0.00 | 1.49 | 8.00 | 0.49 | 7.58 | 0.46 | 0.00 | 0.00 | 0.00 |
| *Nitzschia frustulum* (Kützing) Grunow in Cleve & Grunow 1880 | NITFRTF | 17.84 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 2.52 | 0.24 | 0.00 | 0.00 |
| *Nitzschia nana* Grunow in van Heurck 1881 | NITNAN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.50 | 0.00 | 2.37 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia pusilla* Grunow 1862 | NITPUS | 0.66 | 0.00 | 5.65 | 2.63 | 0.00 | 4.00 | 0.00 | 0.00 | 0.46 | 0.72 | 2.75 | 0.00 |
| *Nitzschia valdestriata* Aleem & Hustedt 1951 | NITVLST | 0.00 | 10.55 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.23 | 0.48 | 4.03 | 0.00 |
| *Opephora olsenii* Møller 1950 | OPEOLS | 4.85 | 0.00 | 0.25 | 3.10 | 0.00 | 0.75 | 0.24 | 0.00 | 1.14 | 0.00 | 0.00 | 0.00 |
| *Planothidium* aff. *engelbrechtii* (Cholnoky) Round & L.Bukhtiyarova 1996 | PLAaELG | 1.10 | 11.75 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 8.70 | 7.91 | 3.81 | 0.00 |
| *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova 1996 | PLADEL | 1.54 | 9.83 | 1.97 | 0.00 | 0.00 | 0.00 | 1.96 | 0.00 | 12.36 | 12.23 | 5.72 | 8.25 |
| *Planothidium deperditum* (Giffen) A. Witkowski, H. Lange-Bertalot & D. Metzeltin 2000 | PLADEP | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 6.78 | 0.00 |
| *Pseudostaurosira trainorii* Morales 2001 | PSDTTRN | 1.32 | 0.00 | 48.16 | 72.79 | 1.67 | 23.25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.21 | 6.31 |
| *Pseudostaurosiropsis geocollegarum* (Witkowski) Morales 2002 | PSDOGEO | 4.85 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Rhopalodia brebissonii* Krammer in Lange-Bertalot & Krammer 1987 | ROPBRE | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Staurosira punctiformis* Witkowski, Metzeltin & Lange-Bertalot 2000 | FRGPUN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Staurosirella pinnata* (Ehrenberg) Williams & Round 1987 | STAUPIN | 1.10 | 0.00 | 0.00 | 2.86 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Synedra tabulata* (C.Agardh) Kützing 1844 | SYNTAB | 7.93 | 0.00 | 0.49 | 0.24 | 0.19 | 0.25 | 0.00 | 0.00 | 0.00 | 0.96 | 0.00 | 0.00 |
| | | | | | | | | | | | | | |
| *Chaetoceros* resting spores | CHAEsp | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| Taxon | Code | OB1 | OB2 | ALB1 | ALB2 | ALB3 | SADORM | MELB1 | SA1 | SA2 | SA3 | BB | MIRABS | MIRARM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Achnanthes brevipes* Agardh 1824 | ACBREV | 0.50 | 0.25 | 0.00 | 0.00 | 0.00 | 2.65 | 0.00 | 0.74 | 0.00 | 2.39 | 0.00 | 0.00 | 0.00 |
| *Achnanthes fogedii* Hakansson 1978 | ACFOG | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Achnanthes lemmermannii* Hustedt 1933 | ACLEM | 0.00 | 0.00 | 0.25 | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Achnanthes submarina* Hustedt 1956 | ACSUBM | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 15.63 | 2.87 | 0.00 | 0.00 | 0.00 |
| *Achnanthidium minutissimum* (Kützing) Czarnecki 1994 | ACTMIN | 0.00 | 0.00 | 0.00 | 0.00 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.46 | 0.00 |
| *Biremis lucens (Hustedt)* Sabbe, Witkowski & Vyverman 1995 | BIRLUC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4.36 |
| *Cocconeis costata* var. *costata* Gregory Gregory (1855) | COCCOSC | 8.50 | 12.75 | 12.50 | 7.89 | 2.41 | 1.20 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.94 | 1.53 |
| *Cocconeis neodiminuta* Krammer 1990 | COCNEOD | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.25 | 3.92 |
| *Cocconeis placentula* var. *euglypta* (Ehrenberg) Cleve 1895 | COCPLE | 4.75 | 4.75 | 0.00 | 2.39 | 10.28 | 0.48 | 0.00 | 0.00 | 3.47 | 1.20 | 0.00 | 0.46 | 3.27 |
| *Cocconeis placentula* var. *lineata* (Ehrenberg) van Heurck 1885 | COCPLL | 3.75 | 2.75 | 2.50 | 0.00 | 0.66 | 0.24 | 0.50 | 15.06 | 0.00 | 0.72 | 0.00 | 0.93 | 0.22 |
| *Cocconeis placentula* var. *placentula* Ehrenberg 1838 | COCPLP | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.27 | 0.00 | 0.00 | 3.59 | 0.00 | 0.00 | 0.00 |
| *Cocconeis scutellum* Ehrenberg 1838 | COCSCT | 0.50 | 0.00 | 0.00 | 0.48 | 11.16 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4.41 | 1.09 |
| *Cocconeis pseudomarginata* Gregory 1857 | COCPSEU | 0.00 | 0.25 | 3.75 | 0.24 | 20.57 | 2.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Ctenophora pulchella* (Ralfs ex Kützing) Williams & Round 1986 | CTPUL | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 | 0.50 | 0.24 | 0.99 | 0.00 | 0.00 |
| *Cyclotella comensis* Grunow in van Heurck 1882 | CYCCOM | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.50 | 18.27 | 4.22 | 6.22 | 0.00 | 0.00 | 0.00 |
| *Cyclotella meneghiniana* Kützing 1844 | CYMEN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.13 | 2.76 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Diploneis bombus* (Ehrenberg) Ehrenberg 1853 | DIPBOM | 0.50 | 0.00 | 0.25 | 0.00 | 2.84 | 22.41 | 0.25 | 1.23 | 0.00 | 0.72 | 0.00 | 0.00 | 0.44 |
| *Diploneis didyma* (Ehrenberg) Ehrenberg 1839 | DIPDIDY | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 15.42 | 26.88 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Fallacia clepsidroides* Witkowski 1994 | FALCLEP | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Gomphonemopsis obscurum* (Krasske) Lange-Bertalot in Lange Bertalot et al. 1996 | GMPMOBS | 52.50 | 30.50 | 0.00 | 7.18 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Halamphora* aff. *luceae* (Cholnoky) *Levkov 2009* | HALaLUC | 0.00 | 0.00 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.94 | 2.18 |
| *Halamphora coffeaeformis* (Agardh) *Levkov 2009* | AMCOAF | 0.00 | 0.00 | 1.25 | 3.11 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Mastogloia* aff. *angulata* Lewis 1861 | MASTaAN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.22 | 0.00 | 5.02 | 0.00 | 0.00 | 0.00 |
| *Mastogloia pumila* Cleve and Moller 1879 | MASTPUM | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.76 | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Navicula* aff. *cryptotenella* Lange-Bertalot in Krammer & Lange-Bertalot 1985 | NAVCRTL | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.09 | 7.63 |
| *Navicula* aff. *paul-schulzii* Witkowski & Lange-Bertalot in A. Witkowski 1994 | NAVaPSC | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Navicula* aff. *perminuta Grunow in van Heurck 1880* | NAVaPER | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Navicula* aff. *antonii* Lange-Bertalot 2000 | NAVaANT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Navicula gregaria* Donkin 1861 | NAVGREG | 0.00 | 0.00 | 0.00 | 0.96 | 0.00 | 0.00 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Navicula perminuta* Grunow in van Heurck 1880 | NAVPER | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.26 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.65 |
| *Nitzschia fonticola* (Grunow) Grunow in Van Heurck 1881 | NITFONT | 1.75 | 0.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 30.39 | 0.22 |
| *Nitzschia frustulum* (Kützing) Grunow in Cleve & Grunow 1880 | NITFRTF | 21.50 | 34.25 | 0.00 | 50.96 | 0.00 | 0.00 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 | 0.23 | 0.00 |
| *Nitzschia nana* Grunow in van Heurck 1881 | NITNAN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia pusilla* Grunow 1862 | NITPUS | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.01 | 0.00 | 0.25 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia valdestriata* Aleem & Hustedt 1951 | NITVLST | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.39 | 1.31 |
| *Opephora olsenii* Møller 1950 | OPEOLS | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4.55 | 0.00 | 0.00 | 0.00 |
| *Planothidium* aff. *engelbrechtii* (Cholnoky) Round & L.Bukhtiyarova 1996 | PLAaELG | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova 1996 | PLADEL | 0.00 | 0.00 | 1.25 | 2.15 | 0.00 | 0.72 | 0.25 | 0.00 | 0.00 | 0.00 | 0.00 | 2.09 | 14.16 |
| *Planothidium deperditum* (Giffen) A. Witkowski, H. Lange-Bertalot & D. Metzeltin 2000 | PLADEP | 0.00 | 0.00 | 1.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.78 | 2.61 |
| *Pseudostaurosira trainorii* Morales 2001 | PSDTTRN | 0.00 | 0.00 | 0.00 | 0.00 | 0.22 | 0.00 | 15.83 | 0.00 | 0.00 | 0.00 | 3.47 | 0.00 | 0.00 |
| *Pseudostaurosiropsis geocollegarum* (Witkowski) Morales 2002 | PSDOGEO | 0.00 | 0.00 | 9.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Rhopalodia brebissonii* Krammer in Lange-Bertalot & Krammer 1987 | ROPBRE | 0.00 | 0.00 | 0.00 | 0.00 | 7.88 | 0.00 | 0.00 | 37.28 | 0.00 | 49.04 | 0.00 | 0.00 | 0.00 |
| *Staurosira punctiformis* Witkowski, Metzeltin & Lange-Bertalot 2000 | FRGPUN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5.96 | 0.00 | 5.69 | 0.00 | 0.00 |
| *Staurosirella pinnata* (Ehrenberg) Williams & Round 1987 | STAUPIN | 0.00 | 0.00 | 4.75 | 0.00 | 0.00 | 0.00 | 0.00 | 5.43 | 56.33 | 11.00 | 0.00 | 0.00 | 0.00 |
| *Synedra tabulata* (C.Agardh) Kützing 1844 | SYNTAB | 2.50 | 5.75 | 0.00 | 0.24 | 17.72 | 0.72 | 1.51 | 4.20 | 0.25 | 0.24 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | | | | | |
| *Chaetoceros* resting spores | CHAEsp | 0.00 | 0.00 | 6.50 | 0.24 | 2.63 | 0.00 | 2.26 | 0.00 | 0.00 | 2.39 | 0.00 | 0.00 | 0.00 |

## II B – DIATOM ABUNDANCE DATA FROM TRA07 CORE (TRABA, GALICIA, SPAIN)
## (≥2 % AT LEAST IN ONE SAMPLE)

| **Taxon** | **Codes/ core depth** | **0.25** | **1.5** | **2.5** | **3.5** | **4.5** | **5.5** | **6.5** | **7.5** | **8.5** | **9.5** | **10.5** | **11.5** | **12.5** | **13.5** | **14.5** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Achnanthidium minutissimum* (Kützing) Czarnecki 1994 | ACTMIN | 19.42 | 19.73 | 13.45 | 29.41 | 26.49 | 32.57 | 42.05 | 35.29 | 26.18 | 29.98 | 34.38 | 28.46 | 35.02 | 21.31 | 13.73 |
| *Brachysira vitrea* (Grunow) R.Ross in Hartley 1986 | BRAVIT | 0.00 | 0.22 | 0.25 | 0.25 | 0.24 | 1.38 | 0.28 | 0.00 | 0.75 | 0.00 | 0.97 | 0.00 | 0.46 | 0.47 | 0.48 |
| *Cocconeis placentula* var. *placentula* Ehrenberg 1838 | COCPLP | 0.49 | 1.35 | 2.79 | 0.00 | 0.72 | 0.23 | 1.70 | 0.53 | 1.50 | 0.00 | 0.24 | 1.26 | 1.15 | 6.09 | 4.34 |
| *Ctenophora pulchella* (Ralfs ex Kützing) D.M.Williams & Round 1986 | CTPUL | 3.88 | 4.93 | 5.33 | 4.66 | 4.30 | 4.82 | 9.09 | 14.17 | 6.23 | 13.19 | 9.69 | 8.56 | 9.68 | 4.92 | 3.86 |
| *Cyclotella atomus* Hustedt 1937 | CYCATM | 0.00 | 0.67 | 0.51 | 1.23 | 0.48 | 0.46 | 0.57 | 0.80 | 0.00 | 0.24 | 0.97 | 0.25 | 0.23 | 0.23 | 0.24 |
| *Diatoma tenuis* C.Agardh 1812 | DIATEN | 0.00 | 0.22 | 0.25 | 0.25 | 0.24 | 0.23 | 0.57 | 0.53 | 0.00 | 0.72 | 0.73 | 0.25 | 0.23 | 0.23 | 0.48 |
| *Encyonopsis subminuta* Krammer & E.Reichardt 1997 | ENCSUB | 0.00 | 0.00 | 0.25 | 0.49 | 0.48 | 0.00 | 0.00 | 0.27 | 0.00 | 0.96 | 0.48 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Fragilaria capucina* var. *gracilis* (Oestrup) Hustedt 1995 | FRGCPG | 0.00 | 1.57 | 0.51 | 0.00 | 1.19 | 1.83 | 0.00 | 0.53 | 0.00 | 1.44 | 1.69 | 3.27 | 2.53 | 0.70 | 1.69 |
| *Gomphonema gracile* Ehrenberg 1838 | GOMGR | 0.00 | 0.90 | 1.02 | 0.74 | 0.48 | 0.00 | 0.28 | 1.60 | 0.00 | 0.00 | 0.00 | 1.01 | 2.30 | 0.23 | 0.48 |
| *Gomphonema parvulum* (Kützing) Kützing 1849 | GOMPAR | 0.00 | 0.22 | 0.25 | 0.00 | 0.48 | 0.92 | 0.57 | 0.53 | 0.75 | 2.40 | 1.45 | 0.25 | 0.00 | 0.00 | 0.00 |
| *Halamphora veneta* (Kützing) Levkov 2009 | AMVEN | 7.04 | 14.35 | 27.16 | 13.48 | 13.13 | 14.68 | 14.77 | 13.64 | 15.71 | 11.99 | 6.30 | 4.53 | 2.30 | 3.28 | 0.48 |
| *Hippodonta hungarica* (Grunow) Lange-Bertalot, Metzeltin & Witkowski 1996 | HIPHUNG | 0.00 | 0.22 | 0.00 | 0.00 | 2.63 | 0.23 | 0.57 | 0.27 | 0.25 | 0.24 | 0.00 | 0.00 | 0.69 | 0.00 | 0.00 |
| *Navicula radiosa* Kützing 1844 | NAVRAD | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Navicula rhynchocephala* Kützing 1844 | NAVRYC | 0.00 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.27 | 0.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.23 | 1.69 |
| *Navicula rotunda* Hustedt 1945 | NAVROT | 0.49 | 0.22 | 2.54 | 1.23 | 0.00 | 0.69 | 0.85 | 0.53 | 1.50 | 0.00 | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 |
| *Nitzschia dissipata* (Kützing) Grunow 1862 | NITDIS | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia fonticola* (Grunow) Grunow in Van Heurck 1881 | NITFONT | 0.00 | 0.00 | 0.51 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.73 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia paleacea* (Grunow in Cleve & Grunow) Grunow in Van Heurck 1881 | NITPALC | 0.49 | 0.00 | 0.25 | 1.23 | 0.00 | 0.00 | 0.85 | 1.87 | 0.50 | 0.00 | 0.97 | 1.01 | 0.92 | 0.70 | 0.24 |
| *Nitzschia pusilla* Grunow 1862 | NITPUS | 3.40 | 3.36 | 2.28 | 1.72 | 3.58 | 5.05 | 3.69 | 6.15 | 4.74 | 2.16 | 10.17 | 5.04 | 0.92 | 0.23 | 0.48 |
| *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova 1996 | PLADEL | 0.97 | 1.12 | 1.02 | 0.49 | 0.95 | 0.92 | 0.57 | 0.80 | 1.50 | 1.92 | 1.69 | 1.51 | 0.92 | 3.28 | 3.37 |
| *Psammnothidium oblongellum* (Oestrup) Van de Vijver 2002 | ACOBL | 14.56 | 13.90 | 12.44 | 32.35 | 34.37 | 20.18 | 0.00 | 12.03 | 15.71 | 12.47 | 15.74 | 7.56 | 9.91 | 6.79 | 5.78 |
| *Pseudostaurosira trainorii* Morales 2001 | PSDTTRN | 45.39 | 31.17 | 23.60 | 8.82 | 7.64 | 12.84 | 18.47 | 5.88 | 16.71 | 16.79 | 9.20 | 29.97 | 28.11 | 44.26 | 52.05 |
| *Stauroforma exiguiformis* (Lange-Bertalot) Flower, Jones & Round 1996 | FRGEXG | 0.97 | 1.12 | 1.02 | 0.00 | 0.00 | 0.23 | 0.28 | 0.00 | 0.50 | 0.48 | 0.97 | 0.76 | 0.00 | 0.23 | 0.24 |

| Taxon | Codes/Depth | 15.5 | 16.5 | 17.5 | 18.5 | 19.5 | 20.5 | 21.5 | 22.5 | 23.5 | 24.5 | 25.5 | 26.5 | 27.5 | 28.5 | 29.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Achnanthidium minutissimum* (Kützing) Czarnecki 1994 | ACTMIN | 15.75 | 13.99 | 10.63 | 8.06 | 5.96 | 2.40 | 4.73 | 3.85 | 5.00 | 4.21 | 5.30 | 6.62 | 3.31 | 3.53 | 0.95 |
| *Brachysira vitrea* (Grunow) R.Ross in Hartley 1986 | BRAVIT | 0.72 | 0.00 | 0.72 | 0.71 | 1.30 | 0.24 | 0.71 | 0.72 | 3.10 | 1.98 | 1.20 | 1.65 | 0.71 | 0.00 | 1.43 |
| *Cocconeis placentula* var. *placentula* Ehrenberg 1838 | COCPLP | 3.10 | 1.55 | 0.97 | 0.71 | 0.52 | 0.00 | 0.95 | 0.24 | 0.00 | 0.50 | 0.00 | 0.71 | 1.42 | 0.94 | 1.19 |
| *Ctenophora pulchella* (Ralfs ex Kützing) D.M.Williams & Round 1986 | CTPUL | 5.73 | 5.96 | 1.93 | 2.61 | 1.30 | 0.24 | 0.71 | 0.24 | 1.43 | 1.49 | 0.48 | 1.42 | 0.71 | 0.71 | 0.48 |
| *Cyclotella atomus* Hustedt 1937 | CYCATM | 0.24 | 0.26 | 0.24 | 0.24 | 0.26 | 0.24 | 0.24 | 0.24 | 0.24 | 0.25 | 0.24 | 0.24 | 0.24 | 0.00 | 0.48 |
| *Diatoma tenuis* C.Agardh 1812 | DIATEN | 0.48 | 0.78 | 0.72 | 2.13 | 0.26 | 0.96 | 1.89 | 0.96 | 1.43 | 0.99 | 0.48 | 1.42 | 1.18 | 0.94 | 0.95 |
| *Encyonopsis subminuta* Krammer & E.Reichardt 1997 | ENCSUB | 0.00 | 0.00 | 0.72 | 0.00 | 3.11 | 0.48 | 0.71 | 1.20 | 1.90 | 1.24 | 0.48 | 0.47 | 0.47 | 1.18 | 0.95 |
| *Fragilaria capucina* var. *gracilis* (Oestrup) Hustedt 1995 | FRGCPG | 2.86 | 0.00 | 3.14 | 2.61 | 2.33 | 2.16 | 2.36 | 3.13 | 0.00 | 1.24 | 1.20 | 1.42 | 0.00 | 1.18 | 0.00 |
| *Gomphonema gracile* Ehrenberg 1838 | GOMGR | 0.48 | 0.00 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.72 | 0.00 | 0.00 | 0.47 | 0.95 |
| *Gomphonema parvulum* (Kützing) Kützing 1849 | GOMPAR | 0.00 | 0.00 | 0.00 | 0.24 | 0.26 | 0.00 | 0.00 | 0.24 | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Halamphora veneta* (Kützing) Levkov 2009 | AMVEN | 1.91 | 3.11 | 2.17 | 1.66 | 0.26 | 0.48 | 2.60 | 1.92 | 0.95 | 0.99 | 1.20 | 0.00 | 0.24 | 0.24 | 0.48 |
| *Hippodonta hungarica* (Grunow) Lange-Bertalot, Metzeltin & Witkowski 1996 | HIPHUNG | 0.48 | 0.00 | 0.24 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 0.25 | 0.00 | 0.00 | 0.47 | 0.24 | 0.00 |
| *Navicula radiosa* Kützing 1844 | NAVRAD | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 0.24 |
| *Navicula rhynchocephala* Kützing 1844 | NAVRYC | 1.67 | 0.78 | 0.97 | 0.71 | 0.52 | 0.00 | 0.00 | 0.24 | 0.95 | 0.25 | 0.00 | 0.47 | 0.24 | 0.24 | 0.95 |
| *Navicula rotunda* Hustedt 1945 | NAVROT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia dissipata* (Kützing) Grunow 1862 | NITDIS | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia fonticola* (Grunow) Grunow in Van Heurck 1881 | NITFONT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 |
| *Nitzschia paleacea* (Grunow in Cleve & Grunow) Grunow in Van Heurck 1881 | NITPALC | 0.00 | 0.78 | 0.48 | 1.18 | 2.59 | 0.72 | 1.42 | 2.16 | 1.67 | 0.74 | 0.00 | 2.84 | 2.13 | 0.71 | 0.24 |
| *Nitzschia pusilla* Grunow 1862 | NITPUS | 0.48 | 3.11 | 2.17 | 4.03 | 8.03 | 1.44 | 2.84 | 4.81 | 5.48 | 2.48 | 1.45 | 5.91 | 2.13 | 5.65 | 3.33 |
| *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova 1996 | PLADEL | 0.72 | 1.04 | 0.97 | 0.95 | 0.52 | 0.48 | 0.95 | 0.96 | 1.43 | 0.74 | 0.96 | 2.13 | 0.47 | 3.06 | 1.43 |
| *Psammnothidium oblongellum* (Oestrup) Van de Vijver 2002 | ACOBL | 8.35 | 9.07 | 5.07 | 3.55 | 0.26 | 0.00 | 0.95 | 0.96 | 0.71 | 0.00 | 0.48 | 0.24 | 0.00 | 0.94 | 1.19 |
| *Pseudostaurosira trainorii* Morales 2001 | PSDTTRN | 46.30 | 54.15 | 60.39 | 65.17 | 68.65 | 86.57 | 74.23 | 73.80 | 70.71 | 76.24 | 79.52 | 69.98 | 81.32 | 75.06 | 80.24 |
| *Stauroforma exiguiformis* (Lange-Bertalot) Flower, Jones & Round 1996 | FRGEXG | 0.95 | 1.30 | 1.69 | 1.18 | 0.52 | 0.72 | 0.95 | 0.96 | 0.95 | 1.98 | 0.96 | 1.18 | 1.89 | 0.71 | 1.43 |

| Taxon | Codes/Depth | 15.5 | 16.5 | 17.5 | 18.5 | 19.5 | 20.5 | 21.5 | 22.5 | 23.5 | 24.5 | 25.5 | 26.5 | 27.5 | 28.5 | 29.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Achnanthidium minutissimum* (Kützing) Czarnecki 1994 | ACTMIN | 15.75 | 13.99 | 10.63 | 8.06 | 5.96 | 2.40 | 4.73 | 3.85 | 5.00 | 4.21 | 5.30 | 6.62 | 3.31 | 3.53 | 0.95 |
| *Brachysira vitrea* (Grunow) R.Ross in Hartley 1986 | BRAVIT | 0.72 | 0.00 | 0.72 | 0.71 | 1.30 | 0.24 | 0.71 | 0.72 | 3.10 | 1.98 | 1.20 | 1.65 | 0.71 | 0.00 | 1.43 |
| *Cocconeis placentula* var. *placentula* Ehrenberg 1838 | COCPLP | 3.10 | 1.55 | 0.97 | 0.71 | 0.52 | 0.00 | 0.95 | 0.24 | 0.00 | 0.50 | 0.00 | 0.71 | 1.42 | 0.94 | 1.19 |
| *Ctenophora pulchella* (Ralfs ex Kützing) D.M.Williams & Round 1986 | CTPUL | 5.73 | 5.96 | 1.93 | 2.61 | 1.30 | 0.24 | 0.71 | 0.24 | 1.43 | 1.49 | 0.48 | 1.42 | 0.71 | 0.71 | 0.48 |
| *Cyclotella atomus* Hustedt 1937 | CYCATM | 0.24 | 0.26 | 0.24 | 0.24 | 0.26 | 0.24 | 0.24 | 0.24 | 0.24 | 0.25 | 0.24 | 0.24 | 0.24 | 0.00 | 0.48 |
| *Diatoma tenuis* C.Agardh 1812 | DIATEN | 0.48 | 0.78 | 0.72 | 2.13 | 0.26 | 0.96 | 1.89 | 0.96 | 1.43 | 0.99 | 0.48 | 1.42 | 1.18 | 0.94 | 0.95 |
| *Encyonopsis subminuta* Krammer & E.Reichardt 1997 | ENCSUB | 0.00 | 0.00 | 0.72 | 0.00 | 3.11 | 0.48 | 0.71 | 1.20 | 1.90 | 1.24 | 0.48 | 0.47 | 0.47 | 1.18 | 0.95 |
| *Fragilaria capucina* var. *gracilis* (Oestrup) Hustedt 1995 | FRGCPG | 2.86 | 0.00 | 3.14 | 2.61 | 2.33 | 2.16 | 2.36 | 3.13 | 0.00 | 1.24 | 1.20 | 1.42 | 0.00 | 1.18 | 0.00 |
| *Gomphonema gracile* Ehrenberg 1838 | GOMGR | 0.48 | 0.00 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.72 | 0.00 | 0.00 | 0.47 | 0.95 |
| *Gomphonema parvulum* (Kützing) Kützing 1849 | GOMPAR | 0.00 | 0.00 | 0.00 | 0.24 | 0.26 | 0.00 | 0.00 | 0.24 | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Halamphora veneta* (Kützing) Levkov 2009 | AMVEN | 1.91 | 3.11 | 2.17 | 1.66 | 0.26 | 0.48 | 2.60 | 1.92 | 0.95 | 0.99 | 1.20 | 0.00 | 0.24 | 0.24 | 0.48 |
| *Hippodonta hungarica* (Grunow) Lange-Bertalot, Metzeltin & Witkowski 1996 | HIPHUNG | 0.48 | 0.00 | 0.24 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 0.25 | 0.00 | 0.00 | 0.47 | 0.24 | 0.00 |
| *Navicula radiosa* Kützing 1844 | NAVRAD | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 0.24 |
| *Navicula rhynchocephala* Kützing 1844 | NAVRYC | 1.67 | 0.78 | 0.97 | 0.71 | 0.52 | 0.00 | 0.00 | 0.24 | 0.95 | 0.25 | 0.00 | 0.47 | 0.24 | 0.24 | 0.95 |
| *Navicula rotunda* Hustedt 1945 | NAVROT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia dissipata* (Kützing) Grunow 1862 | NITDIS | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia fonticola* (Grunow) Grunow in Van Heurck 1881 | NITFONT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 |
| *Nitzschia paleacea* (Grunow in Cleve & Grunow) Grunow in Van Heurck 1881 | NITPALC | 0.00 | 0.78 | 0.48 | 1.18 | 2.59 | 0.72 | 1.42 | 2.16 | 1.67 | 0.74 | 0.00 | 2.84 | 2.13 | 0.71 | 0.24 |
| *Nitzschia pusilla* Grunow 1862 | NITPUS | 0.48 | 3.11 | 2.17 | 4.03 | 8.03 | 1.44 | 2.84 | 4.81 | 5.48 | 2.48 | 1.45 | 5.91 | 2.13 | 5.65 | 3.33 |
| *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova 1996 | PLADEL | 0.72 | 1.04 | 0.97 | 0.95 | 0.52 | 0.48 | 0.95 | 0.96 | 1.43 | 0.74 | 0.96 | 2.13 | 0.47 | 3.06 | 1.43 |
| *Psammnothidium oblongellum* (Oestrup) Van de Vijver 2002 | ACOBL | 8.35 | 9.07 | 5.07 | 3.55 | 0.26 | 0.00 | 0.95 | 0.96 | 0.71 | 0.00 | 0.48 | 0.24 | 0.00 | 0.94 | 1.19 |
| *Pseudostaurosira trainorii* Morales 2001 | PSDTTRN | 46.30 | 54.15 | 60.39 | 65.17 | 68.65 | 86.57 | 74.23 | 73.80 | 70.71 | 76.24 | 79.52 | 69.98 | 81.32 | 75.06 | 80.24 |
| *Stauroforma exiguiformis* (Lange-Bertalot) Flower, Jones & Round 1996 | FRGEXG | 0.95 | 1.30 | 1.69 | 1.18 | 0.52 | 0.72 | 0.95 | 0.96 | 0.95 | 1.98 | 0.96 | 1.18 | 1.89 | 0.71 | 1.43 |

| **Taxon** | **Codes/Depth** | **30.5** | **31.5** | **32.5** | **33.5** | **34.5** | **35.5** | **36.5** | **37.5** | **38.5** | **39.5** | **40.5** | **41.5** | **42.5** | **43.5** | **44.25** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Achnanthidium minutissimum* (Kützing) Czarnecki 1994 | ACTMIN | 5.58 | 5.71 | 4.34 | 10.13 | 6.64 | 4.33 | 7.47 | 8.90 | 6.08 | 8.82 | 7.22 | 7.91 | 7.64 | 9.90 | 8.94 |
| *Brachysira vitrea* (Grunow) R.Ross in Hartley 1986 | BRAVIT | 1.02 | 1.83 | 1.69 | 1.29 | 3.79 | 2.40 | 5.93 | 3.20 | 4.05 | 4.64 | 6.09 | 5.87 | 3.10 | 5.33 | 3.86 |
| *Cocconeis placentula* var. *placentula* Ehrenberg 1838 | COCPLP | 0.25 | 0.23 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.68 | 0.00 | 0.00 | 0.23 | 0.00 | 0.00 | 0.00 | 0.48 |
| *Ctenophora pulchella* (Ralfs ex Kützing) D.M.Williams & Round 1986 | CTPUL | 1.02 | 0.00 | 0.00 | 1.51 | 0.95 | 1.68 | 0.52 | 1.60 | 1.52 | 1.39 | 0.45 | 0.26 | 1.19 | 1.52 | 3.14 |
| *Cyclotella atomus* Hustedt 1937 | CYCATM | 0.25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 0.77 | 0.68 | 1.01 | 1.86 | 2.48 | 0.77 | 0.24 | 0.51 | 0.00 |
| *Diatoma tenuis* C.Agardh 1812 | DIATEN | 0.76 | 0.68 | 0.72 | 1.29 | 1.42 | 1.92 | 3.09 | 1.83 | 1.27 | 0.23 | 0.68 | 0.26 | 0.72 | 0.76 | 0.97 |
| *Encyonopsis subminuta* Krammer & E.Reichardt 1997 | ENCSUB | 1.78 | 2.05 | 3.86 | 5.82 | 4.98 | 6.25 | 6.70 | 4.79 | 5.06 | 3.71 | 3.61 | 5.36 | 2.86 | 4.06 | 3.62 |
| *Fragilaria capucina* var. *gracilis* (Oestrup) Hustedt 1995 | FRGCPG | 1.02 | 1.37 | 1.93 | 1.29 | 0.71 | 1.20 | 3.61 | 2.74 | 1.77 | 0.93 | 1.13 | 0.51 | 3.58 | 2.28 | 1.21 |
| *Gomphonema gracile* Ehrenberg 1838 | GOMGR | 0.25 | 0.46 | 0.48 | 0.22 | 0.24 | 0.72 | 0.00 | 0.91 | 0.25 | 0.23 | 0.45 | 0.00 | 0.95 | 0.00 | 0.72 |
| *Gomphonema parvulum* (Kützing) Kützing 1849 | GOMPAR | 0.00 | 0.00 | 0.00 | 0.22 | 0.24 | 0.00 | 0.00 | 0.00 | 0.25 | 0.00 | 0.00 | 0.26 | 0.24 | 0.00 | 0.00 |
| *Halamphora veneta* (Kützing) Levkov 2009 | AMVEN | 0.51 | 1.14 | 0.72 | 1.29 | 1.90 | 0.72 | 1.55 | 1.14 | 2.53 | 3.25 | 2.71 | 0.77 | 1.19 | 1.02 | 0.24 |
| *Hippodonta hungarica* (Grunow) Lange-Bertalot, Metzeltin & Witkowski 1996 | HIPHUNG | 0.00 | 0.46 | 0.48 | 0.22 | 0.24 | 0.48 | 0.00 | 0.68 | 0.00 | 0.00 | 0.00 | 0.51 | 0.95 | 0.00 | 0.00 |
| *Navicula radiosa* Kützing 1844 | NAVRAD | 0.00 | 0.00 | 0.00 | 0.22 | 0.71 | 0.48 | 0.52 | 0.46 | 2.53 | 0.93 | 1.13 | 0.51 | 1.43 | 1.02 | 0.24 |
| *Navicula rhynchocephala* Kützing 1844 | NAVRYC | 0.76 | 0.00 | 0.24 | 0.22 | 0.95 | 0.72 | 0.52 | 2.05 | 0.76 | 0.23 | 0.23 | 0.77 | 0.95 | 1.52 | 0.48 |
| *Navicula rotunda* Hustedt 1945 | NAVROT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia dissipata* (Kützing) Grunow 1862 | NITDIS | 0.00 | 2.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.52 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia fonticola* (Grunow) Grunow in Van Heurck 1881 | NITFONT | 0.00 | 0.46 | 0.00 | 0.86 | 0.24 | 1.20 | 0.00 | 0.23 | 1.01 | 2.09 | 2.26 | 2.55 | 1.19 | 1.02 | 0.97 |
| *Nitzschia paleacea* (Grunow in Cleve & Grunow) Grunow in Van Heurck 1881 | NITPALC | 0.25 | 0.91 | 1.20 | 0.86 | 1.90 | 1.20 | 0.26 | 4.34 | 1.27 | 1.16 | 0.68 | 0.77 | 0.00 | 0.00 | 0.24 |
| *Nitzschia pusilla* Grunow 1862 | NITPUS | 2.79 | 0.00 | 1.20 | 1.94 | 2.37 | 4.57 | 4.90 | 2.74 | 1.77 | 5.34 | 7.22 | 7.14 | 2.39 | 7.11 | 5.80 |
| *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova 1996 | PLADEL | 4.31 | 3.20 | 5.06 | 6.47 | 5.92 | 4.81 | 4.12 | 4.11 | 2.78 | 2.78 | 2.71 | 3.32 | 3.58 | 0.76 | 1.21 |
| *Psammnothidium oblongellum* (Oestrup) Van de Vijver 2002 | ACOBL | 0.00 | 0.23 | 0.00 | 0.43 | 0.00 | 0.00 | 0.00 | 1.37 | 0.00 | 0.00 | 0.23 | 0.26 | 0.24 | 0.00 | 4.83 |
| *Pseudostaurosira trainorii* Morales 2001 | PSDTTRN | 74.87 | 72.83 | 74.46 | 60.78 | 59.95 | 57.69 | 50.77 | 49.32 | 57.22 | 54.52 | 51.69 | 49.23 | 54.89 | 55.58 | 54.11 |
| *Stauroforma exiguiformis* (Lange-Bertalot) Flower, Jones & Round 1996 | FRGEXG | 1.27 | 1.83 | 2.17 | 2.59 | 1.90 | 3.37 | 4.64 | 4.11 | 5.06 | 4.64 | 4.74 | 6.89 | 5.49 | 3.30 | 2.90 |

## II C – DIATOM ABUNDANCE DATA FROM LM6 CORE (MELIDES, PORTUGAL) (≥2 % AT LEAST IN ONE SAMPLE)

| Taxon | Codes/Depth | 0.5 | 2.5 | 4.5 | 6.5 | 8.5 | 10.5 | 12.5 | 14.5 | 16.5 | 18.5 | 20.5 | 22.5 | 24.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Achnanthes brevipes* C.Agardh 1824 | ACBREV | 0.00 | 0.00 | 0.75 | 0.97 | 0.72 | 2.46 | 1.72 | 3.47 | 4.36 | 4.12 | 3.83 | 6.23 | 8.55 |
| *Achnanthes lemmermannii* Hustedt 1933 | ACLEM | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Bacillaria paxillifera* (O.F.Müller) Marsson 1901 | BACPAX | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Cavinula* spp. | CAVsp | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Cocconeis placentula* var. *euglypta* (Ehrenberg) Cleve 1895 | COCPLE | 1.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.98 | 0.99 | 1.45 | 4.12 | 4.31 | 7.23 | 3.42 |
| *Cocconeis placentula* var. *lineata* (Ehrenberg) van Heurck 1885 | COCPLL | 2.37 | 16.82 | 10.25 | 8.25 | 8.21 | 4.18 | 2.70 | 7.18 | 4.84 | 4.35 | 6.94 | 9.48 | 9.40 |
| *Cocconeis placentula* var. *placentula* Ehrenberg 1838 | COCPLP | 14.01 | 6.45 | 4.25 | 5.10 | 5.80 | 11.06 | 12.99 | 20.30 | 7.75 | 19.45 | 16.75 | 27.43 | 22.44 |
| *Ctenophora pulchella* (Ralfs ex Kützing) Williams & Round 1986 | CTPUL | 0.22 | 1.84 | 1.25 | 1.94 | 2.66 | 0.98 | 0.00 | 0.99 | 0.73 | 0.69 | 0.48 | 0.50 | 0.64 |
| *Cyclotella comensis* Grunow in van Heurck 1882 | CYCCOM | 10.13 | 0.23 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.00 | 0.00 | 0.24 | 0.00 | 0.00 |
| *Cyclotella meneghiniana* Kützing 1844 | CYMEN | 6.25 | 0.23 | 0.25 | 0.49 | 0.00 | 0.49 | 0.00 | 0.25 | 2.18 | 0.69 | 0.48 | 0.75 | 0.43 |
| *Cymbella* aff. *affiniformis* Krammer 2002 | CYMBaAFF | 2.80 | 3.23 | 3.25 | 2.18 | 3.86 | 1.23 | 1.23 | 1.73 | 2.18 | 1.83 | 4.07 | 2.49 | 1.71 |
| *Diploneis smithii* (Brébisson) Cleve 1894 | DIPSMI | 0.22 | 0.00 | 0.25 | 0.49 | 0.00 | 0.00 | 0.98 | 1.24 | 3.15 | 0.00 | 0.24 | 0.00 | 0.00 |
| *Epithemia turgida* (Ehrenberg) Kützing 1844 | EPITURG | 0.22 | 0.46 | 0.75 | 0.97 | 0.48 | 0.74 | 1.23 | 2.23 | 0.97 | 0.46 | 0.48 | 0.25 | 2.35 |
| *Fallacia tenera* (Hustedt) D.G.Mann in Round, Crawford & Mann 1990 | FALTEN | 0.43 | 0.00 | 3.75 | 1.94 | 2.42 | 2.46 | 1.23 | 0.50 | 0.24 | 0.00 | 0.72 | 0.25 | 0.00 |
| *Fragilaria atomus* Husted 1931 | FRGAT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Fragilaria canariensis* Lange-Bertalot 1993 | FRGCAN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Fragilaria construens* var. *subsalina* Hustedt 1925 | FRGSUBS | 0.43 | 0.00 | 0.00 | 0.00 | 0.72 | 0.00 | 1.72 | 1.24 | 2.18 | 0.92 | 1.20 | 0.00 | 1.92 |
| *Fragilaria construens* var. *venter* (Ehrenberg) Hamilton 1992 | FRGCONTV | 0.22 | 0.23 | 0.00 | 27.43 | 0.00 | 0.49 | 0.25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Halamphora acusticula* (Kützing) Levkov 2009 | HALCUST | 5.39 | 1.84 | 1.25 | 0.24 | 0.00 | 0.25 | 0.49 | 0.25 | 0.24 | 0.00 | 0.00 | 0.00 | 0.64 |
| *Halamphora* aff. *coffeaeformis* (C.Agardh) Levkov 2009 | AMaCOAF | 4.53 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Mastogloia braunii* Grunow 1863 | MASTBRAU | 0.00 | 1.15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Mastogloia pumila* Cleve and Moller 1879 | MASTPUM | 11.64 | 12.44 | 1.75 | 0.97 | 0.72 | 1.47 | 0.00 | 1.24 | 0.00 | 0.46 | 0.96 | 2.24 | 1.71 |
| *Melosira lineata* (Dillwyn) C.Agardh 1824 | MELLIN | 0.65 | 0.23 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.23 | 0.00 | 1.25 | 0.00 |
| *Navicula gregaria* Donkin 1861 | NAVGRG | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Navicula microdigitoradiata* Lange-Bertalot 1993 | NAVMDG | 0.00 | 1.61 | 1.75 | 0.49 | 0.72 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.48 | 0.00 | 0.00 |
| *Navicula perminuta* Grunow in van Heurck 1880 | NAVPER | 0.00 | 0.69 | 0.75 | 0.49 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Navicula* aff. *phyllepta* Kützing 1844 | NAVaPHY | 6.03 | 4.61 | 1.00 | 1.21 | 0.48 | 0.98 | 0.00 | 0.25 | 0.00 | 0.00 | 0.00 | 0.50 | 0.21 |
| *Nitzschia acuminata* (Smith) Grunow 1880 | NITACUM | 0.43 | 0.46 | 0.25 | 0.97 | 0.00 | 0.74 | 0.49 | 0.50 | 0.73 | 1.14 | 0.24 | 1.75 | 1.07 |
| *Nitzschia elegantula* Grunow 1881 | NITELG | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Nitzschia frustulum* (Kützing) Grunow in Cleve & Grunow 1880 | NITFRTF | 3.66 | 0.23 | 0.00 | 0.24 | 0.48 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.25 | 0.00 |
| *Nitzschia pusilla* Grunow 1862 | NITPUS | 0.86 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.23 | 0.00 | 0.00 | 0.00 |
| *Opephora guenter-grassii* (Witkowski & Lange-Bertalot) Sabbe & Vyverman, 1995 | OPEGG | 0.22 | 0.00 | 1.25 | 3.40 | 4.59 | 5.65 | 5.64 | 3.22 | 0.97 | 1.14 | 7.66 | 2.00 | 0.21 |
| *Pseudostaurosira brevistriata* (Grunow) Williams & Round 1987 | PSDTBRV | 0.00 | 3.46 | 0.50 | 0.73 | 0.00 | 0.98 | 0.00 | 0.25 | 0.24 | 1.14 | 0.00 | 0.75 | 0.21 |
| *Pseudostaurosira trainorii* Morales 2001 | PSDTTRAI | 10.99 | 27.65 | 41.00 | 20.87 | 44.69 | 50.86 | 40.44 | 27.72 | 28.09 | 13.96 | 32.06 | 9.98 | 12.82 |
| *Pseudostaurosiropsis geocollegarum* (Witkowski) E.A.Morales 2002 | PSDOGEO | 0.22 | 1.61 | 3.00 | 1.21 | 2.17 | 1.23 | 2.45 | 1.49 | 0.97 | 0.92 | 1.20 | 0.25 | 0.00 |
| *Rhopalodia acuminata* Krammer 1987 | ROPAC | 4.09 | 3.23 | 9.75 | 7.77 | 5.07 | 5.16 | 13.48 | 12.13 | 15.98 | 18.99 | 5.26 | 6.98 | 14.10 |
| *Rhopalodia musculus* (Kützing) Müller 1900 | ROPMUS | 0.00 | 2.07 | 1.00 | 2.91 | 0.48 | 0.00 | 0.49 | 0.00 | 0.00 | 0.69 | 0.24 | 0.00 | 0.00 |
| *Staurophora salina* (Smith) Mereschkowsk 1903 | STASAL | 0.86 | 0.23 | 0.00 | 0.24 | 1.21 | 0.74 | 1.47 | 0.25 | 4.12 | 6.86 | 1.20 | 3.49 | 4.27 |
| *Synedra tabulata* (C.Agardh) Kützing 1844 | SYNTAB | 0.86 | 2.07 | 5.25 | 4.13 | 5.07 | 2.95 | 3.92 | 6.44 | 8.23 | 8.92 | 5.74 | 4.24 | 6.20 |

| Taxon | Codes/Depth | 26.5 | 28.5 | 30.5 | 32.5 | 34.5 | 36.5 | 38.5 | 40.5 | 42.5 | 44.5 | 46.5 | 48.5 | 50.5 | 52.5 | 54.5 | 56.5 | 58.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Achnanthes brevipes* C.Agardh 1824 | ACBREV | 9.50 | 9.25 | 3.74 | 3.74 | 6.48 | 0.63 | 2.00 | 2.01 | 2.50 | 0.72 | 1.32 | 0.74 | 1.96 | 2.46 | 1.42 | 1.00 | 0.00 |
| *Achnanthes lemmermannii* Hustedt 1933 | ACLEM | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.22 | 0.00 | 0.00 | 0.00 |
| *Bacillaria paxillifera* (O.F.Müller) Marsson 1901 | BACPAX | 0.00 | 0.00 | 2.99 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Cavinula* spp. | CAVsp | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.49 |
| *Cocconeis placentula* var. *euglypta* (Ehrenberg) Cleve 1895 | COCPLE | 1.50 | 4.25 | 2.00 | 2.49 | 2.00 | 3.13 | 2.00 | 2.01 | 1.25 | 1.44 | 1.32 | 4.20 | 4.90 | 2.46 | 2.59 | 2.75 | 1.23 |
| *Cocconeis placentula* var. *lineata* (Ehrenberg) van Heurck 1885 | COCPLL | 11.25 | 11.25 | 18.95 | 9.73 | 13.97 | 10.83 | 19.20 | 11.31 | 9.50 | 6.49 | 6.62 | 6.67 | 10.54 | 8.62 | 8.02 | 10.50 | 8.60 |
| *Cocconeis placentula* var. *placentula* Ehrenberg 1838 | COCPLP | 27.50 | 28.00 | 21.95 | 34.91 | 29.93 | 27.50 | 26.93 | 32.91 | 36.75 | 25.24 | 18.76 | 16.54 | 25.25 | 20.20 | 14.15 | 13.50 | 16.46 |
| *Ctenophora pulchella* (Ralfs ex Kützing) Williams & Round 1986 | CTPUL | 0.50 | 0.25 | 0.50 | 2.00 | 1.75 | 0.63 | 1.50 | 1.26 | 1.25 | 0.96 | 0.44 | 0.25 | 0.49 | 0.00 | 0.94 | 0.25 | 0.25 |
| *Cyclotella comensis* Grunow in van Heurck 1882 | CYCCOM | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 | 0.00 |
| *Cyclotella meneghiniana* Kützing 1844 | CYMEN | 0.25 | 0.00 | 0.25 | 0.00 | 0.50 | 0.21 | 0.25 | 1.01 | 0.50 | 1.20 | 1.10 | 0.74 | 0.98 | 0.00 | 0.00 | 0.75 | 0.00 |
| *Cymbella* aff. *affiniformis* Krammer 2002 | CYMBaAFF | 2.00 | 1.50 | 1.50 | 0.50 | 2.74 | 0.83 | 0.50 | 0.50 | 2.25 | 1.20 | 0.88 | 0.74 | 1.47 | 1.23 | 0.00 | 1.00 | 0.25 |
| *Diploneis smithii* (Brébisson) Cleve 1894 | DIPSMI | 0.25 | 0.50 | 0.50 | 0.25 | 0.00 | 0.63 | 0.75 | 0.00 | 0.50 | 0.72 | 1.10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Epithemia turgida* (Ehrenberg) Kützing 1844 | EPITURG | 1.50 | 2.00 | 0.00 | 0.50 | 0.50 | 0.00 | 0.00 | 0.50 | 0.25 | 1.20 | 0.44 | 0.74 | 0.49 | 0.99 | 0.24 | 1.75 | 0.74 |
| *Fallacia tenera* (Hustedt) D.G.Mann in Round, Crawford & Mann 1990 | FALTEN | 0.00 | 0.25 | 0.75 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Fragilaria atomus* Husted 1931 | FRGAT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.48 | 1.55 | 5.19 | 0.98 | 5.42 | 5.42 | 10.75 | 8.11 |
| *Fragilaria canariensis* Lange-Bertalot 1993 | FRGCAN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.75 | 3.85 | 3.53 | 4.20 | 4.17 | 5.91 | 6.37 | 7.75 | 4.67 |
| *Fragilaria construens* var. *subsalina* Hustedt 1925 | FRGSUBS | 2.00 | 0.25 | 0.00 | 0.75 | 3.74 | 1.04 | 0.50 | 0.50 | 0.00 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 1.42 | 0.00 | 0.00 |
| *Fragilaria construens* var. *venter* (Ehrenberg) Hamilton 1992 | FRGCONTV | 0.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.00 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Halamphora acusticula* (Kützing) Levkov 2009 | HALCUST | 0.25 | 0.25 | 1.25 | 0.00 | 0.25 | 0.42 | 0.50 | 2.01 | 0.25 | 0.48 | 0.00 | 0.00 | 0.74 | 0.00 | 0.24 | 0.25 | 0.25 |
| *Halamphora* aff. *coffeaeformis* (C.Agardh) Levkov 2009 | AMaCOAF | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.25 | 2.00 | 1.51 | 1.00 | 0.72 | 2.21 | 0.99 | 0.98 | 0.25 | 0.47 | 0.00 | 0.00 |
| *Mastogloia braunii* Grunow 1863 | MASTBRAU | 0.00 | 0.00 | 0.00 | 2.49 | 0.25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Mastogloia pumila* Cleve and Moller 1879 | MASTPUM | 1.25 | 0.25 | 0.00 | 0.25 | 1.00 | 0.00 | 0.00 | 0.25 | 0.75 | 1.68 | 1.10 | 0.00 | 0.00 | 0.00 | 0.71 | 0.50 | 0.00 |
| *Melosira lineata* (Dillwyn) C.Agardh 1824 | MELLIN | 0.75 | 3.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.75 | 1.00 | 0.24 | 0.66 | 0.00 | 1.23 | 0.49 | 2.12 | 2.00 | 0.74 |
| *Navicula gregaria* Donkin 1861 | NAVGRG | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.50 | 0.96 | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 | 0.00 |
| *Navicula microdigitoradiata* Lange-Bertalot 1993 | NAVMDG | 0.25 | 0.00 | 3.74 | 0.00 | 0.00 | 0.21 | 0.25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.49 | 0.00 | 1.42 | 0.50 | 0.74 |
| *Navicula perminuta* Grunow in van Heurck 1880 | NAVPER | 0.00 | 0.00 | 0.25 | 0.00 | 0.00 | 0.63 | 0.00 | 0.00 | 0.00 | 1.68 | 0.22 | 0.00 | 0.49 | 0.00 | 0.47 | 0.00 | 0.00 |
| *Navicula* aff. *phyllepta* Kützing 1844 | NAVaPHY | 0.00 | 0.00 | 8.98 | 0.00 | 0.00 | 3.33 | 1.00 | 2.51 | 0.25 | 1.68 | 3.97 | 3.95 | 3.43 | 3.94 | 2.12 | 0.25 | 5.90 |
| *Nitzschia acuminata* (Smith) Grunow 1880 | NITACUM | 1.00 | 0.00 | 3.24 | 1.25 | 0.50 | 2.71 | 1.25 | 0.75 | 1.50 | 0.96 | 0.66 | 0.25 | 1.96 | 1.48 | 0.00 | 0.00 | 1.47 |
| *Nitzschia elegantula* Grunow 1881 | NITELG | 0.00 | 0.00 | 9.73 | 0.00 | 0.00 | 4.38 | 1.50 | 0.50 | 0.00 | 1.68 | 0.66 | 1.98 | 0.49 | 0.00 | 2.36 | 1.25 | 1.47 |
| *Nitzschia frustulum* (Kützing) Grunow in Cleve & Grunow 1880 | NITFRTF | 0.00 | 0.00 | 4.74 | 0.00 | 0.00 | 21.88 | 13.97 | 18.84 | 5.75 | 11.06 | 21.19 | 16.30 | 6.62 | 7.14 | 6.60 | 3.50 | 11.79 |
| *Nitzschia pusilla* Grunow 1862 | NITPUS | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4.17 | 3.49 | 0.00 | 0.00 | 2.64 | 0.44 | 2.47 | 0.49 | 0.49 | 0.47 | 0.00 | 1.47 |
| *Opephora guenter-grassii* (Witkowski & Lange-Bertalot) Sabbe & Vyverman, 1995 | OPEGG | 0.00 | 0.25 | 0.00 | 0.00 | 0.75 | 0.83 | 0.25 | 1.51 | 3.00 | 2.88 | 6.62 | 6.91 | 6.13 | 6.65 | 10.14 | 11.75 | 5.90 |
| *Pseudostaurosira brevistriata* (Grunow) Williams & Round 1987 | PSDTBRV | 0.00 | 0.00 | 0.00 | 1.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Pseudostaurosira trainorii* Morales 2001 | PSDTTRAI | 7.25 | 11.25 | 6.98 | 13.22 | 18.20 | 5.83 | 5.74 | 7.54 | 9.75 | 9.62 | 6.62 | 5.93 | 5.15 | 10.10 | 14.39 | 13.75 | 12.78 |
| *Pseudostaurosiropsis geocollegarum* (Witkowski) E.A.Morales 2002 | PSDOGEO | 0.00 | 0.50 | 0.25 | 0.75 | 0.50 | 0.83 | 1.25 | 1.76 | 2.25 | 1.68 | 3.97 | 3.95 | 1.47 | 3.45 | 4.25 | 6.25 | 5.90 |
| *Rhopalodia acuminata* Krammer 1987 | ROPAC | 16.25 | 6.75 | 0.50 | 12.47 | 6.23 | 1.25 | 4.49 | 3.27 | 7.00 | 5.29 | 5.74 | 7.41 | 7.84 | 6.16 | 5.90 | 0.00 | 1.23 |
| *Rhopalodia musculus* (Kützing) Müller 1900 | ROPMUS | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Staurophora salina* (Smith) Mereschkowsk 1903 | STASAL | 3.25 | 4.75 | 0.00 | 0.50 | 1.75 | 0.42 | 0.00 | 0.75 | 0.50 | 2.16 | 0.66 | 0.25 | 0.25 | 0.74 | 0.71 | 0.75 | 0.00 |
| *Synedra tabulata* (C.Agardh) Kützing 1844 | SYNTAB | 4.75 | 6.25 | 3.74 | 7.23 | 3.74 | 2.08 | 1.75 | 1.76 | 2.00 | 2.40 | 0.88 | 2.22 | 3.68 | 2.46 | 1.42 | 3.25 | 1.72 |

| **Taxon** | **Codes/Depth** | **60.5** | **62.5** | **64.5** | **66.5** | **68.5** | **70.5** | **72.5** | **74.5** | **76.5** | **78.5** | **80.5** | **82.5** | **84.5** | **86.5** | **87.5** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Achnanthes brevipes* C.Agardh 1824 | ACBREV | 0.25 | 1.00 | 0.99 | 0.24 | 0.49 | 1.70 | 0.25 | 2.16 | 0.75 | 0.50 | 2.00 | 0.25 | 1.75 | 0.74 | 1.00 |
| *Achnanthes lemmermannii* Hustedt 1933 | ACLEM | 0.50 | 0.50 | 0.25 | 0.00 | 0.00 | 0.24 | 0.00 | 0.00 | 1.00 | 0.25 | 0.00 | 1.25 | 0.75 | 0.00 | 0.25 |
| *Bacillaria paxillifera* (O.F.Müller) Marsson 1901 | BACPAX | 0.00 | 0.25 | 0.25 | 0.48 | 0.00 | 0.73 | 0.25 | 0.24 | 1.00 | 0.50 | 0.00 | 0.50 | 0.50 | 0.25 | 0.00 |
| *Cavinula* spp. | CAVsp | 1.49 | 0.75 | 0.25 | 0.00 | 0.73 | 0.49 | 3.71 | 1.44 | 2.49 | 1.00 | 1.25 | 0.75 | 1.75 | 3.47 | 1.99 |
| *Cocconeis placentula* var. *euglypta* (Ehrenberg) Cleve 1895 | COCPLE | 1.73 | 2.00 | 3.47 | 2.90 | 2.93 | 2.68 | 1.98 | 1.44 | 2.24 | 1.99 | 3.25 | 2.50 | 1.00 | 1.49 | 3.98 |
| *Cocconeis placentula* var. *lineata* (Ehrenberg) van Heurck 1885 | COCPLL | 7.92 | 7.50 | 8.44 | 9.18 | 5.61 | 5.35 | 6.19 | 6.24 | 9.73 | 8.21 | 13.25 | 6.00 | 10.50 | 4.70 | 10.20 |
| *Cocconeis placentula* var. *placentula* Ehrenberg 1838 | COCPLP | 13.12 | 19.25 | 20.35 | 18.36 | 16.59 | 25.79 | 12.13 | 13.91 | 15.21 | 13.43 | 20.25 | 30.25 | 16.75 | 26.24 | 26.62 |
| *Ctenophora pulchella* (Ralfs ex Kützing) Williams & Round 1986 | CTPUL | 0.50 | 1.00 | 0.74 | 1.21 | 0.49 | 0.73 | 0.50 | 0.48 | 0.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Cyclotella comensis* Grunow in van Heurck 1882 | CYCCOM | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Cyclotella meneghiniana* Kützing 1844 | CYMEN | 0.00 | 0.00 | 0.25 | 0.00 | 1.22 | 0.73 | 0.00 | 0.24 | 0.00 | 0.00 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| *Cymbella* aff. *affiniformis* Krammer 2002 | CYMBaAFF | 0.50 | 1.25 | 0.25 | 0.97 | 0.98 | 1.22 | 1.49 | 0.96 | 0.00 | 0.50 | 0.25 | 0.50 | 0.00 | 0.00 | 0.00 |
| *Diploneis smithii* (Brébisson) Cleve 1894 | DIPSMI | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.25 | 0.00 | 0.00 | 0.00 |
| *Epithemia turgida* (Ehrenberg) Kützing 1844 | EPITURG | 0.00 | 0.25 | 1.49 | 0.72 | 1.71 | 2.68 | 1.73 | 0.48 | 0.00 | 0.00 | 0.25 | 1.75 | 1.25 | 0.00 | 1.74 |
| *Fallacia tenera* (Hustedt) D.G.Mann in Round, Crawford & Mann 1990 | FALTEN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 |
| *Fragilaria atomus* Husted 1931 | FRGAT | 7.67 | 2.00 | 0.00 | 1.45 | 0.98 | 0.24 | 3.47 | 4.08 | 12.22 | 10.45 | 4.25 | 2.50 | 3.25 | 2.72 | 5.97 |
| *Fragilaria canariensis* Lange-Bertalot 1993 | FRGCAN | 2.23 | 0.75 | 0.00 | 0.24 | 0.00 | 0.49 | 1.24 | 1.68 | 1.00 | 0.00 | 1.00 | 1.75 | 2.50 | 0.25 | 2.74 |
| *Fragilaria construens* var. *subsalina* Hustedt 1925 | FRGSUBS | 0.00 | 0.25 | 0.25 | 0.00 | 0.00 | 0.00 | 1.24 | 0.00 | 0.50 | 0.25 | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 |
| *Fragilaria construens* var. *venter* (Ehrenberg) Hamilton 1992 | FRGCONTV | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Halamphora acusticula* (Kützing) Levkov 2009 | HALCUST | 0.00 | 1.50 | 0.74 | 0.00 | 0.49 | 0.73 | 0.99 | 0.48 | 0.75 | 0.25 | 0.25 | 1.00 | 0.00 | 0.00 | 1.00 |
| *Halamphora* aff. *coffeaeformis* (C.Agardh) Levkov 2009 | AMaCOAF | 0.74 | 0.75 | 0.50 | 0.24 | 0.73 | 0.24 | 2.72 | 0.48 | 0.00 | 0.25 | 0.00 | 0.00 | 0.25 | 0.00 | 0.50 |
| *Mastogloia braunii* Grunow 1863 | MASTBRAU | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Mastogloia pumila* Cleve and Moller 1879 | MASTPUM | 0.99 | 0.25 | 0.99 | 0.72 | 0.73 | 0.97 | 1.24 | 1.68 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.00 |
| *Melosira lineata* (Dillwyn) C.Agardh 1824 | MELLIN | 0.74 | 2.25 | 4.71 | 1.69 | 2.20 | 2.43 | 3.47 | 2.88 | 1.25 | 2.49 | 3.75 | 4.75 | 2.75 | 3.22 | 1.74 |
| *Navicula gregaria* Donkin 1861 | NAVGRG | 0.00 | 0.00 | 1.24 | 1.45 | 2.93 | 2.68 | 0.00 | 1.68 | 1.00 | 0.25 | 2.00 | 0.25 | 1.25 | 0.74 | 2.49 |
| *Navicula microdigitoradiata* Lange-Bertalot 1993 | NAVMDG | 0.50 | 0.25 | 0.50 | 0.24 | 0.98 | 0.24 | 0.00 | 0.00 | 0.25 | 0.00 | 0.00 | 2.00 | 2.25 | 0.99 | 0.50 |
| *Navicula perminuta* Grunow in van Heurck 1880 | NAVPER | 0.00 | 1.00 | 1.24 | 1.21 | 0.49 | 2.92 | 1.24 | 0.72 | 0.50 | 0.25 | 0.50 | 0.00 | 0.25 | 0.25 | 0.00 |
| *Navicula* aff. *phyllepta* Kützing 1844 | NAVaPHY | 5.69 | 5.00 | 1.99 | 2.42 | 4.88 | 1.46 | 6.93 | 6.71 | 8.23 | 11.19 | 10.50 | 5.00 | 8.00 | 15.35 | 7.96 |
| *Nitzschia acuminata* (Smith) Grunow 1880 | NITACUM | 0.99 | 1.00 | 0.74 | 0.48 | 1.46 | 1.22 | 0.74 | 0.72 | 2.24 | 1.24 | 1.50 | 3.75 | 0.75 | 1.24 | 0.00 |
| *Nitzschia elegantula* Grunow 1881 | NITELG | 2.72 | 0.25 | 0.99 | 2.42 | 3.66 | 2.19 | 2.72 | 0.96 | 2.49 | 0.75 | 0.25 | 0.00 | 0.75 | 0.00 | 0.00 |
| *Nitzschia frustulum* (Kützing) Grunow in Cleve & Grunow 1880 | NITFRTF | 12.13 | 17.00 | 17.37 | 14.25 | 23.66 | 11.44 | 12.38 | 14.39 | 7.23 | 10.45 | 9.00 | 5.25 | 15.75 | 16.83 | 12.69 |
| *Nitzschia pusilla* Grunow 1862 | NITPUS | 0.99 | 0.75 | 0.50 | 1.93 | 2.68 | 0.24 | 3.22 | 4.08 | 2.00 | 1.99 | 2.75 | 1.50 | 0.00 | 4.46 | 1.00 |
| *Opephora guenter-grassii* (Witkowski & Lange-Bertalot) Sabbe & Vyverman, 1995 | OPEGG | 6.44 | 3.75 | 2.48 | 2.90 | 1.95 | 1.95 | 1.98 | 4.80 | 5.24 | 10.70 | 2.50 | 2.00 | 5.75 | 1.24 | 3.23 |
| *Pseudostaurosira brevistriata* (Grunow) Williams & Round 1987 | PSDTBRV | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Pseudostaurosira trainorii* Morales 2001 | PSDTTRAI | 12.87 | 13.00 | 18.36 | 19.57 | 10.73 | 12.41 | 9.41 | 7.19 | 9.98 | 8.96 | 7.00 | 6.25 | 9.00 | 5.45 | 3.48 |
| *Pseudostaurosiropsis geocollegarum* (Witkowski) E.A.Morales 2002 | PSDOGEO | 8.66 | 2.75 | 1.49 | 0.97 | 1.22 | 0.49 | 1.98 | 2.88 | 1.75 | 1.99 | 1.50 | 2.25 | 0.50 | 0.50 | 0.50 |
| *Rhopalodia acuminata* Krammer 1987 | ROPAC | 3.71 | 4.75 | 3.47 | 2.66 | 1.22 | 4.38 | 4.95 | 5.28 | 2.49 | 2.99 | 5.50 | 4.00 | 1.75 | 1.24 | 3.23 |
| *Rhopalodia musculus* (Kützing) Müller 1900 | ROPMUS | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Staurophora salina* (Smith) Mereschkowsk 1903 | STASAL | 0.50 | 0.50 | 0.00 | 1.21 | 0.73 | 0.49 | 0.25 | 0.48 | 0.00 | 0.25 | 0.00 | 0.25 | 0.75 | 0.50 | 0.25 |
| *Synedra tabulata* (C.Agardh) Kützing 1844 | SYNTAB | 0.99 | 1.50 | 1.99 | 2.17 | 1.46 | 1.46 | 1.24 | 1.20 | 1.75 | 1.49 | 1.50 | 3.75 | 2.00 | 0.50 | 1.99 |

# Appendix III - *Diatom plates*

## III A – WESTERN IBERIAN ATLANTIC COASTAL ENVIRONMENTS PRESENT DATA-SET

### IMAGES ACQUIRED WITH JEOL JSM 6400 SCANNING ELECTRON MICROSCOPE AT UDC

Samples
Doniño (DON)
Louro (LOU)
Muro (MUR)
Xuño (XUN)
Bodeira (BOD)

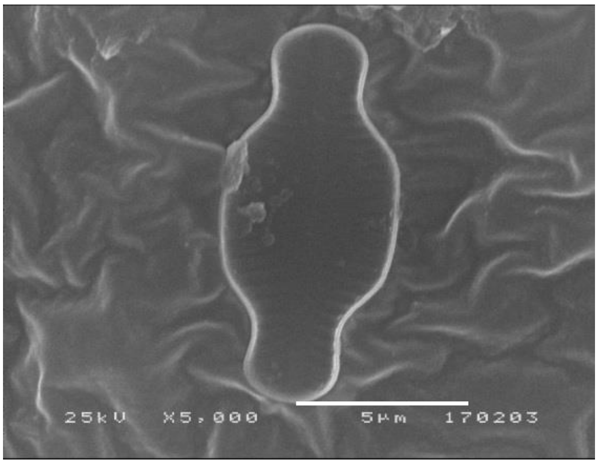
### IMAGES ACQUIRED WITH JEOL JSM-5200LV SCANNING ELECTRON MICROSCOPE AT FCUL

Samples
Albufeira (ALB)
Santo André (SA)

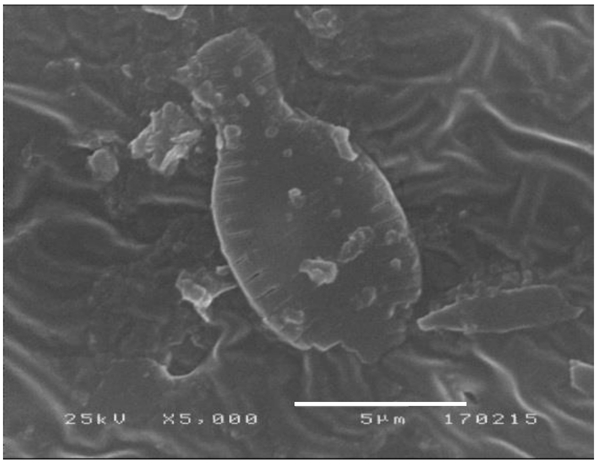
Plate 1

| | |
|---|---|
| Fig. 1-2 | *Achnanthes submarina* Hustedt |
| Fig. 3-6 | *Achnanthidium minutissimum* (Kützing) Czarnecki (*sensu lato*) |

| | |
|---|---|
| Fig. 1-2 | SA2 18.12.07 |
| Fig. 3-4 | MUR 20.11.07 |
| Fig. 5-6 | BOD 21.11.07 |


25kV X5,000 5µm 170203

1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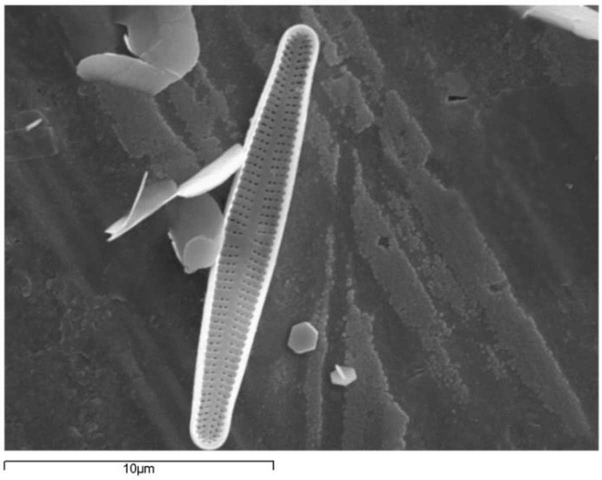
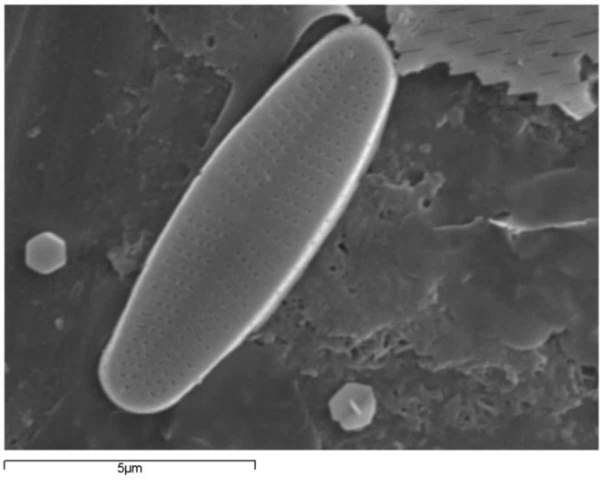
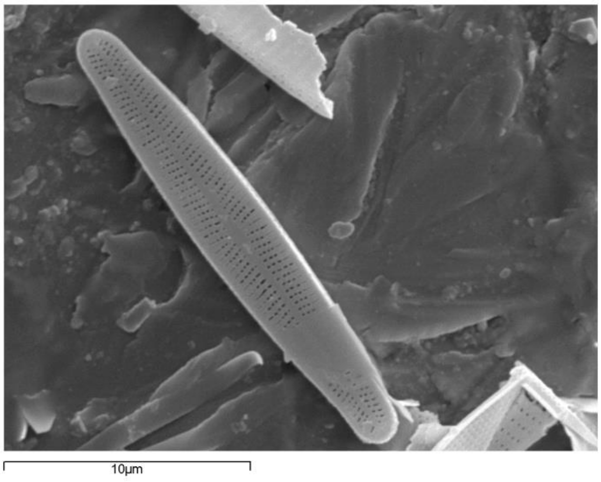
2


10µm

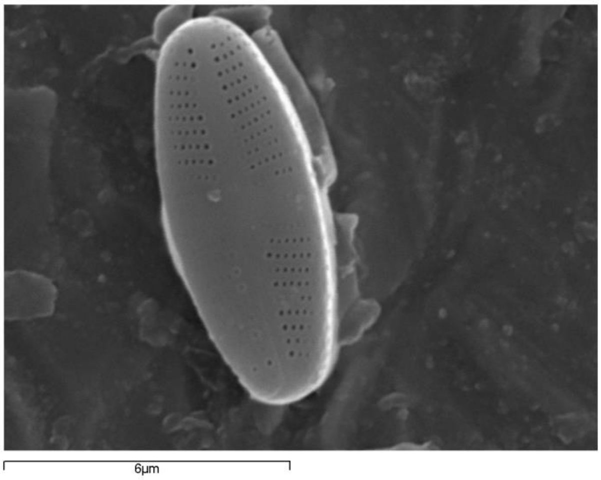
3


5µm

4


10µm

5

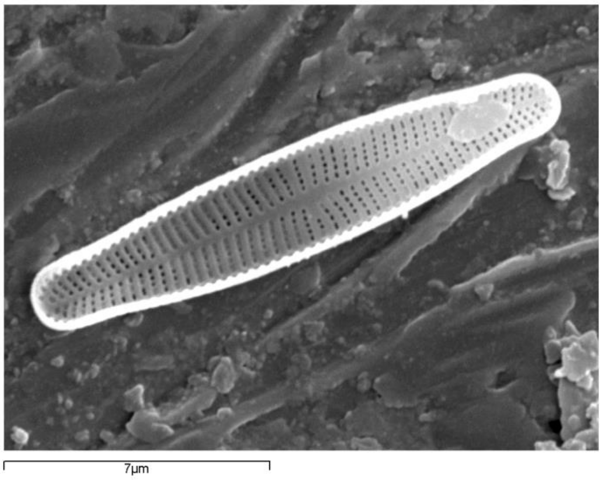

6µm

6

Plate 2

| | |
|---|---|
| Fig. 7-10 | *Achnanthidium minutissimum* (Kützing) Czarnecki (*sensu lato*) |
| Fig. 11 | *Cocconeis costata var. costata* Gregory |
| Fig. 12 | *Cocconeis placentula* Ehrenberg (*sensu lato*) |

| | |
|---|---|
| Fig. 7-10 | BOD 21.11.07 |
| Fig. 11 | ALB2 9.1.08 |
| Fig. 12 | DON 16.11.07 |



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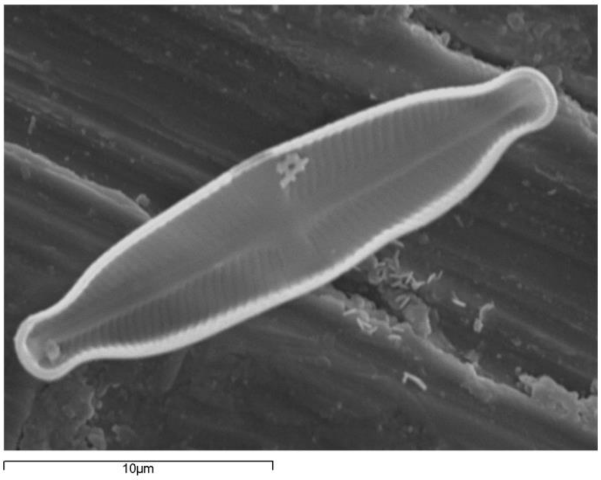

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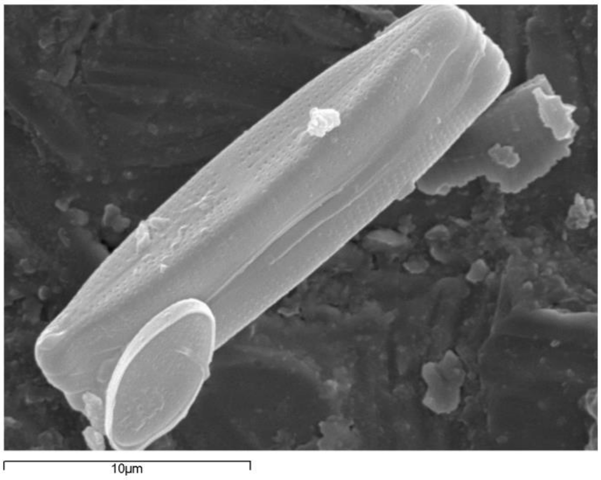

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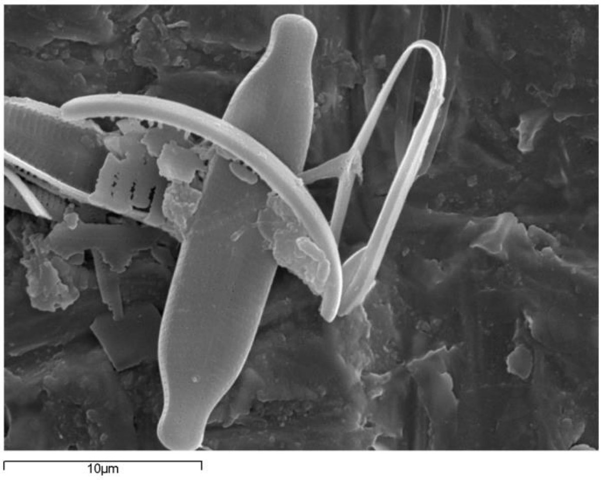

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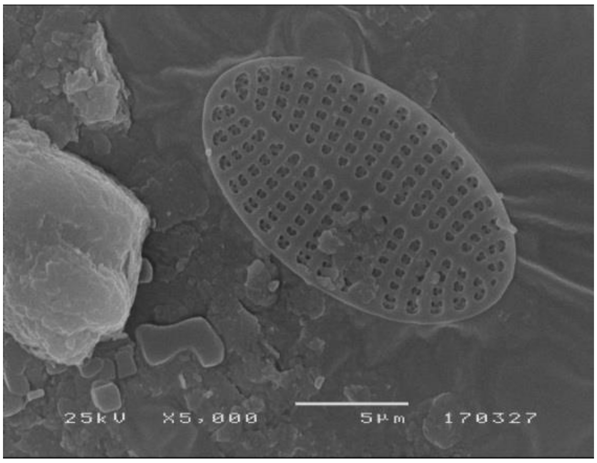

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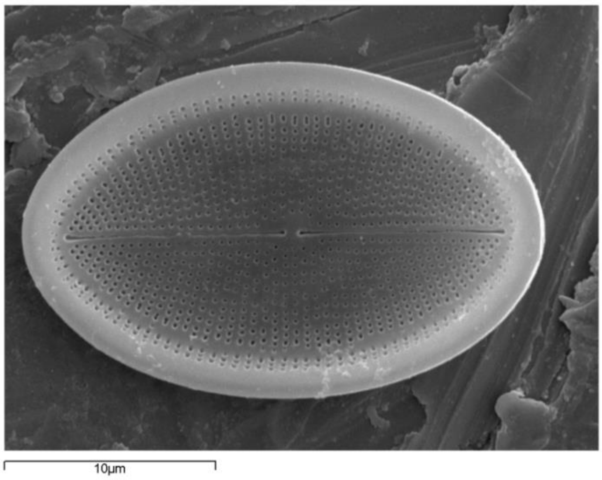
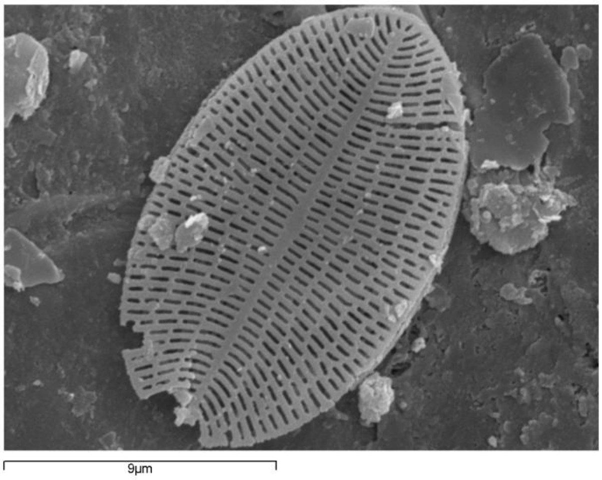


12

Plate 3

Fig. 13-18 *Cocconeis placentula* Ehrenberg (*sensu lato*)

| | |
|---|---|
| Fig. 13 - 14 | LOU 19.11.07 |
| Fig. 15 | MUR 20.11.07 |
| Fig. 16-17 | BOB 21.11.07 |
| Fig. 18 | SA3 18.12.07 |



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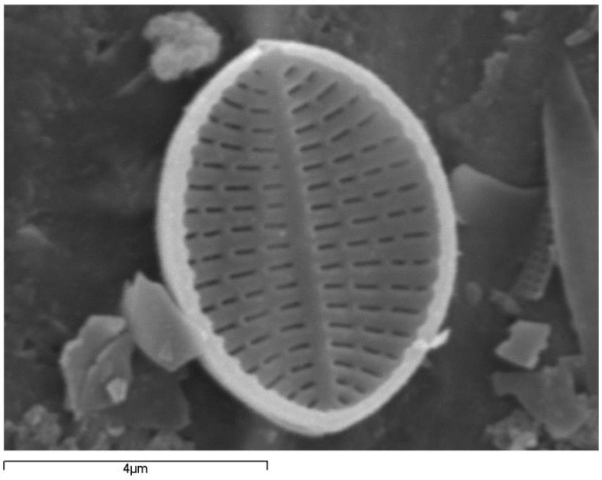

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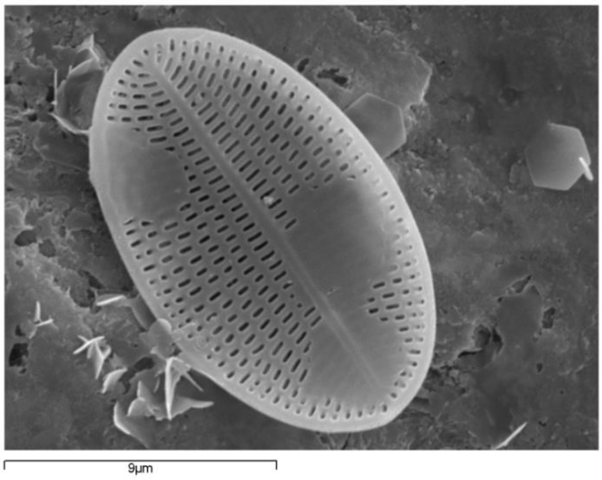

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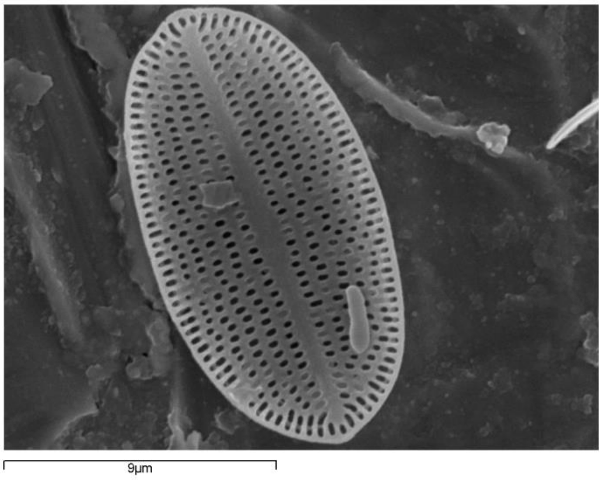

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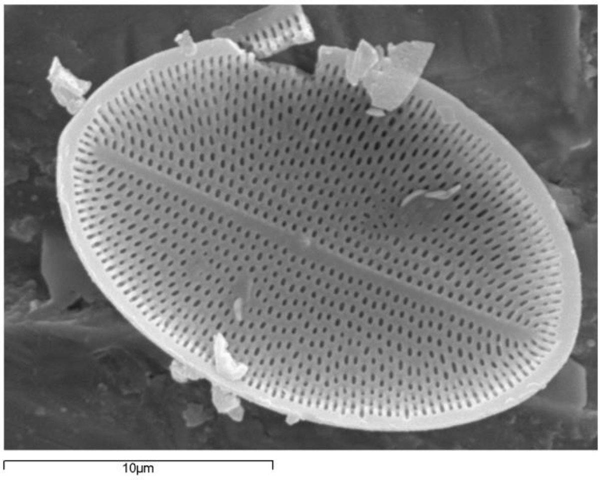

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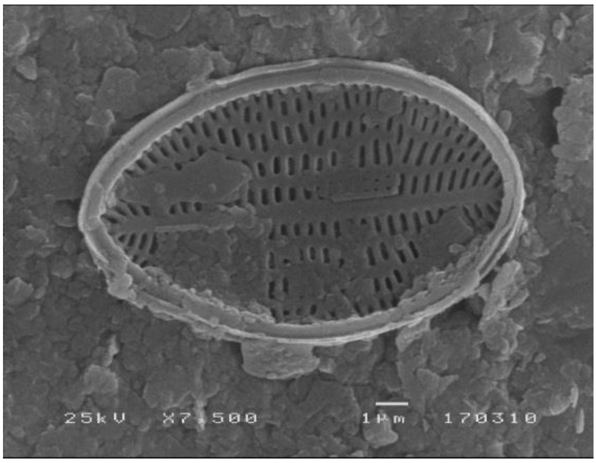
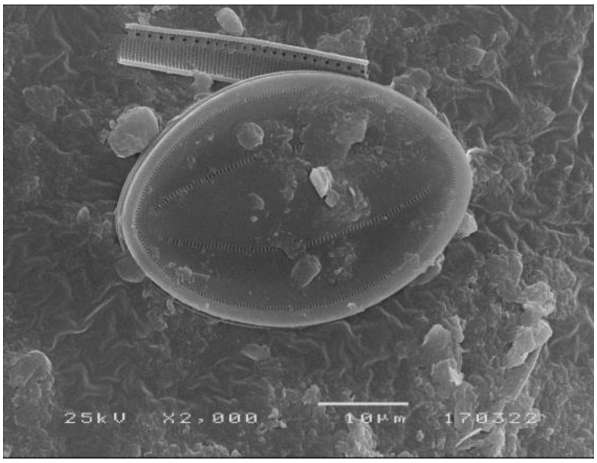


18

Plate 4

| | |
|---|---|
| Fig. 19-22 | *Cocconeis pseudomarginata* Gregory |
| Fig. 23 -24 | *Ctenophora pulchella* (Ralfs ex Kützing) Williams & Round |

| | |
|---|---|
| Fig. 19 | ALB2 9.1.08 |
| Fig. 20 | ALB1 9.1.08 |
| Fig. 21-22 | ALB2 9.1.08 |
| Fig. 23 - 24 | MUR 20.11.07 |



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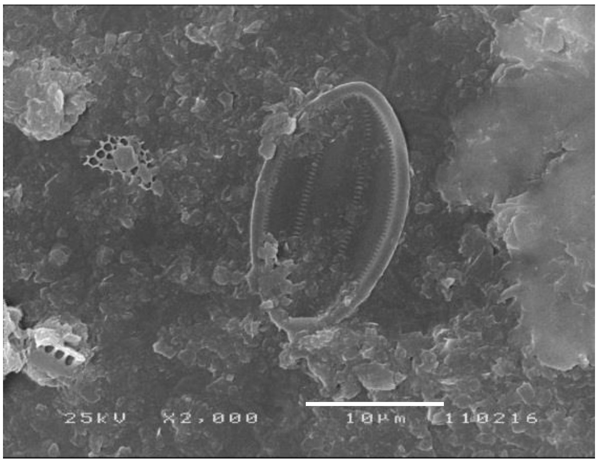
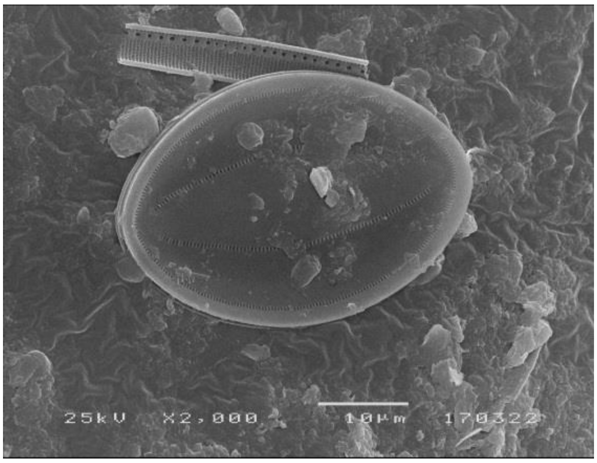


20



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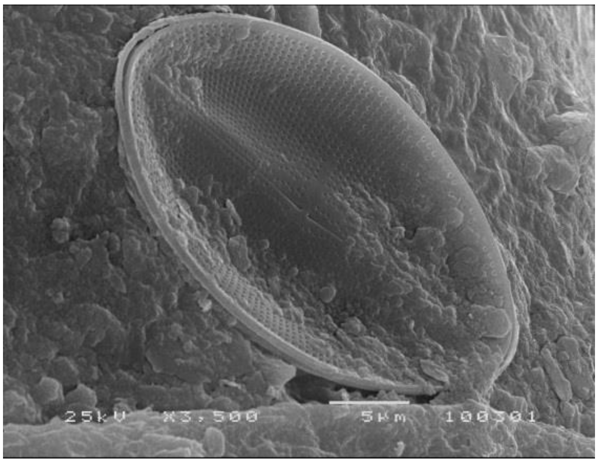

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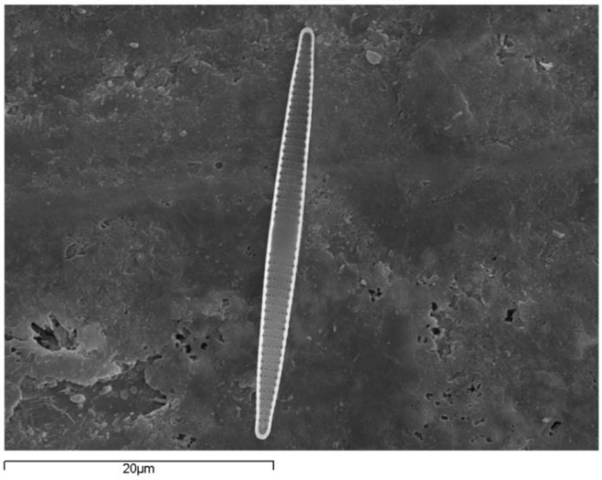

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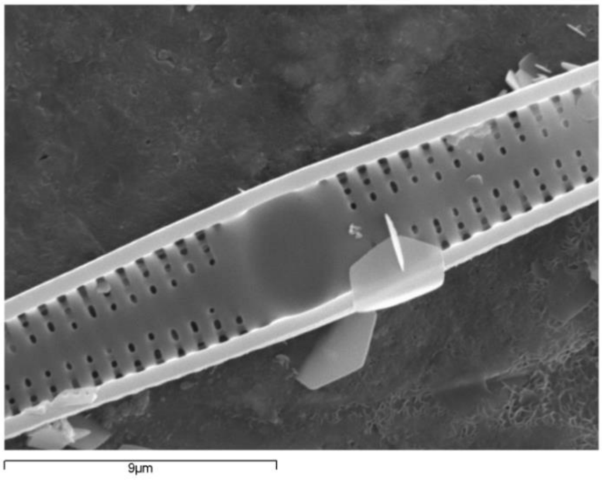
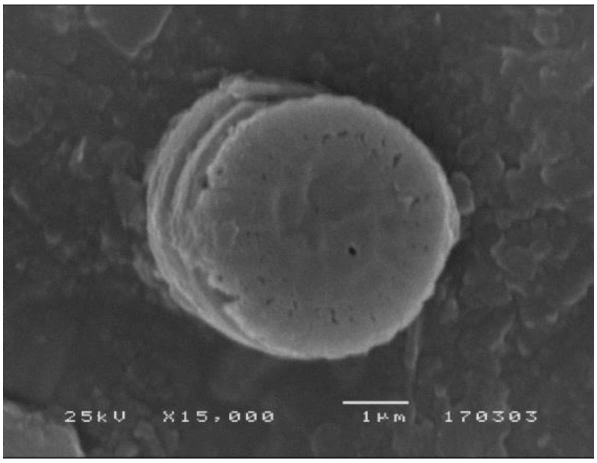


24

Plate 5

| | |
|---|---|
| Fig. 25 | *Cyclotella atomus* Hustedt |
| Fig. 26 | *Encyonopsis subminuta* Krammer & E.Reichardt |
| Fig. 27 | *Eunotia implicata* Nörpel, Lange-Bertalot & Alles |
| Fig. 28 | *Eunotia naegeli* Migula |
| Fig. 29-30 | *Navicula perminuta* Grunow |

| | |
|---|---|
| Fig. 25 | SA3 18.12.07 |
| Fig. 26 | XUN 20.11.07 |
| Fig. 27 | MUR 20.11.07 |
| Fig. 28 | XUN 20.11.07 |
| Fig. 29-30 | MUR 20.11.07 |



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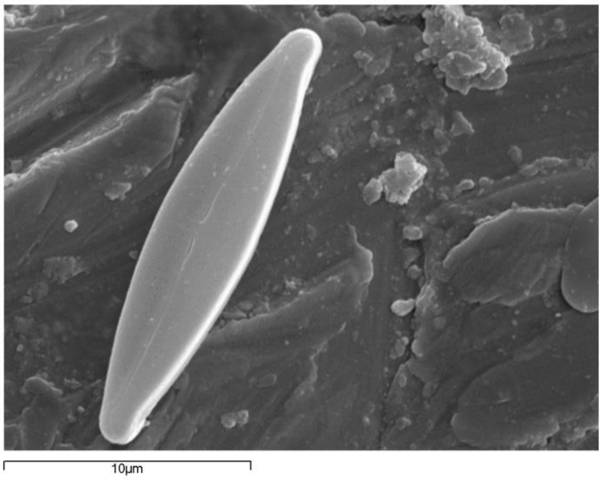

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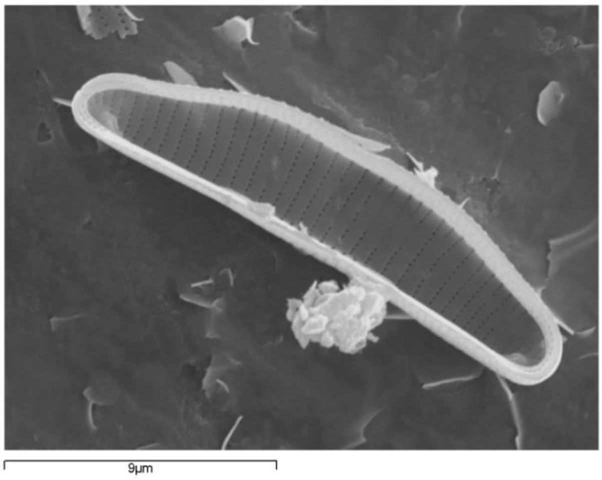

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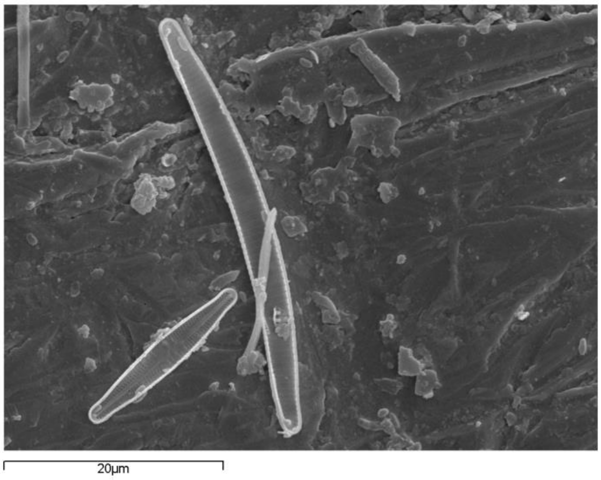

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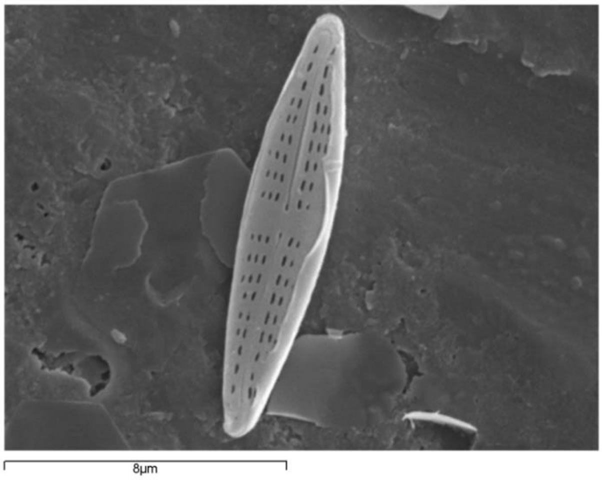

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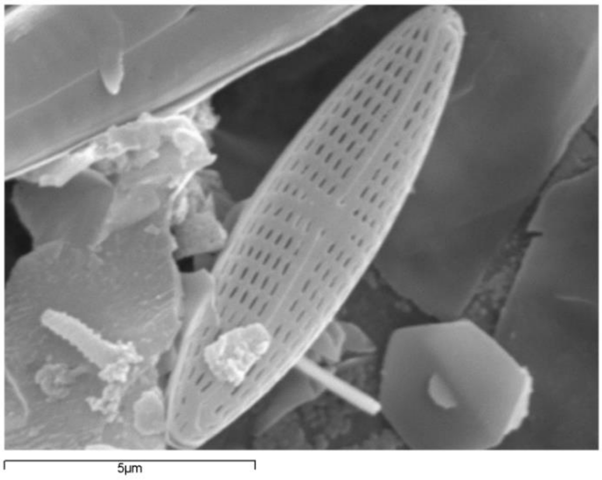
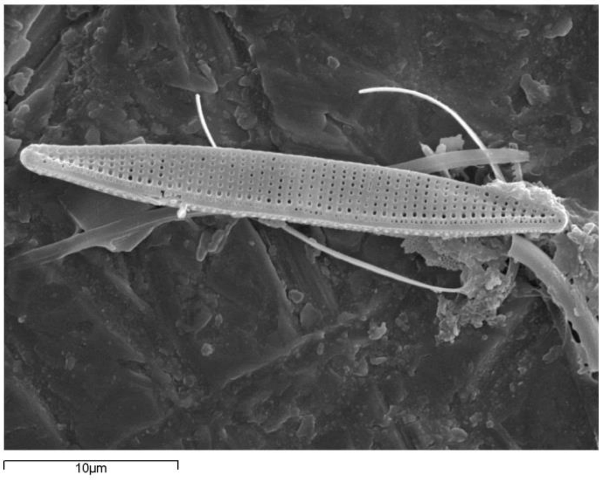


30

Plate 6

| | |
|---|---|
| Fig. 31 | *Nitzschia fonticola* (Grunow) Grunow |
| Fig. 32-35 | *Nitzschia frustulum* (Kützing) Grunow |
| Fig. 36 | *Nitzschia nana* Grunow |

| | |
|---|---|
| Fig. 31 | BOD 21.11.07 |
| Fig. 32 | XUN 20.11.07 |
| Fig. 33-35 | ALB2 9.1.08 |
| Fig. 36 | MUR 20.11.07 |



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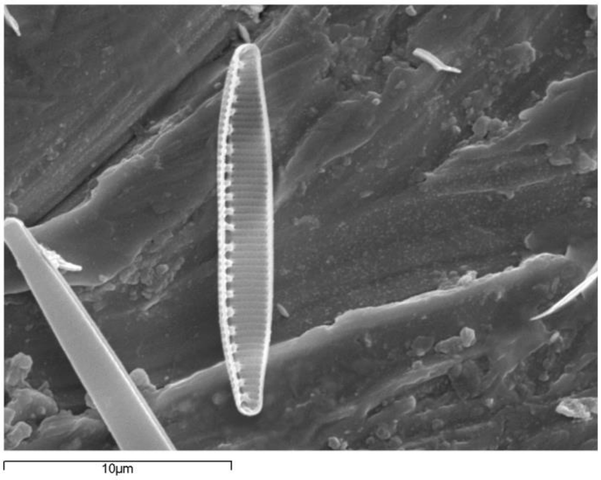

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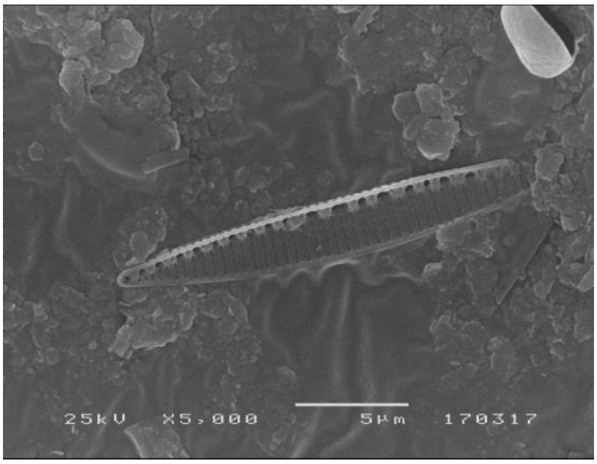

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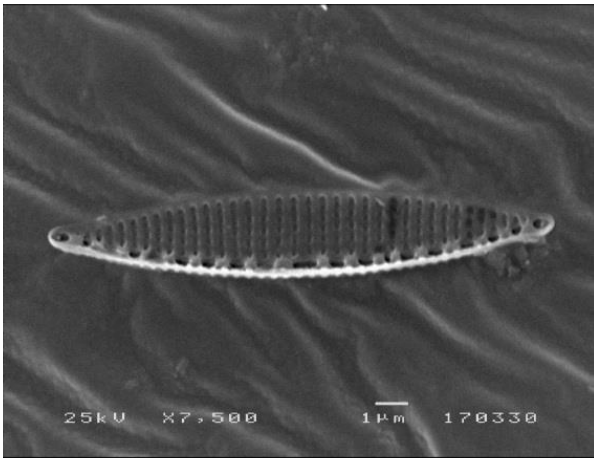

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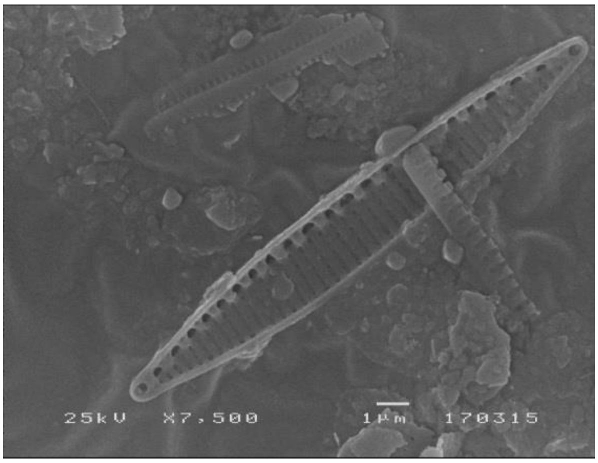

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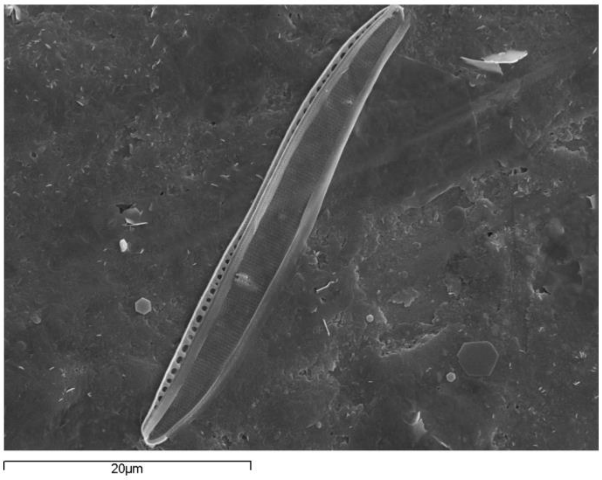
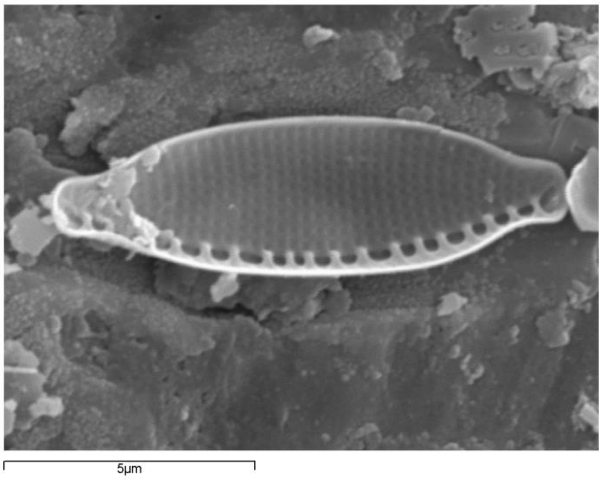


36

## Plate 7

| | |
|---|---|
| Fig. 37-39 | *Nitzschia pusilla* Grunow |
| Fig. 40 | *Opephora olsenii* Møller |
| Fig. 41-42 | *Pseudostaurosira trainorii* Morales |

| | |
|---|---|
| Fig. 37 | LOU 19.11.07 |
| Fig. 38-39 | MUR 20.11.07 |
| Fig. 40 | LOU19.11.07 |
| Fig. 41-42 | LOU19.11.07 |



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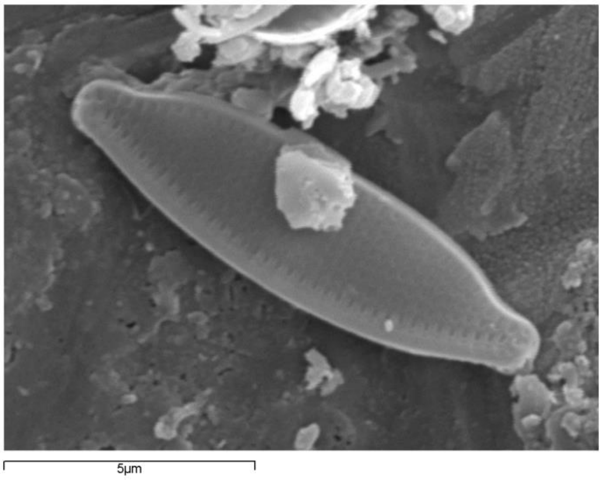

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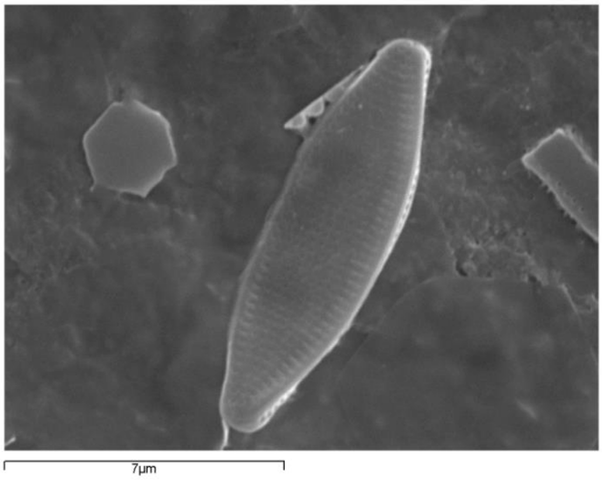

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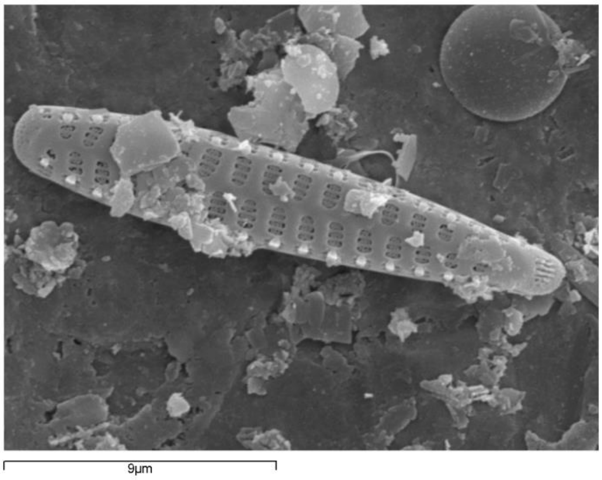

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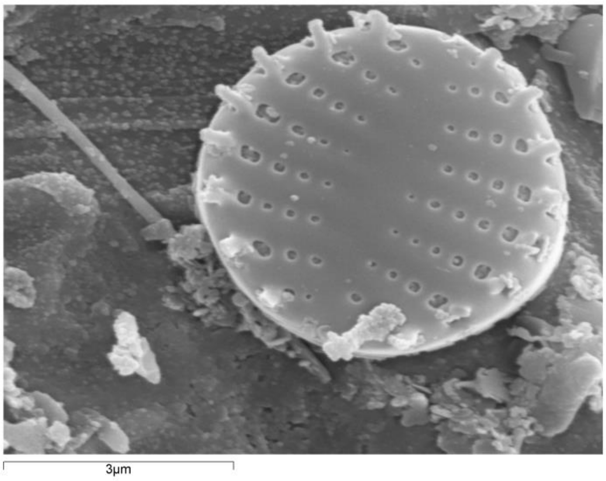

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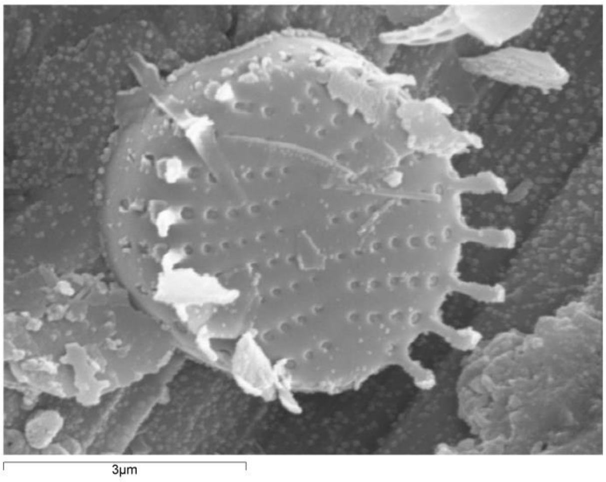
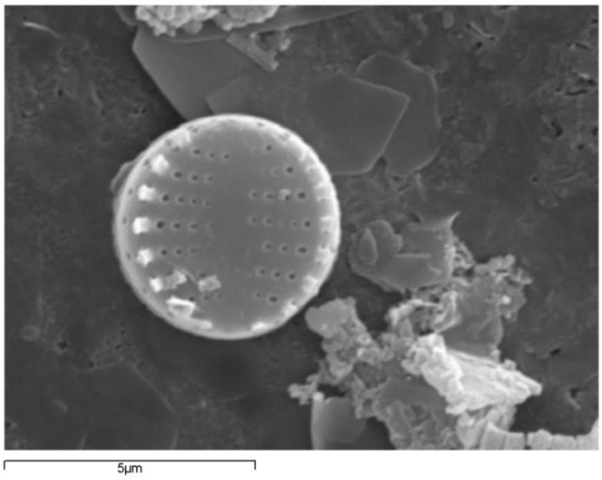


42

Plate 8

| | |
|---|---|
| Fig. 43-45 | *Pseudostaurosira trainorii* Morales |
| Fig. 46-47 | *Rhopalodia musculus* (Kützing) Müller |
| Fig. 48 | *Staurosira punctiformis* Witkowski, Metzelt in & Lange-Bertalot |

| | |
|---|---|
| Fig. 43-45 | MUR 20.11.07 |
| Fig. 46 | SA1 18.12.07 |
| Fig. 47 | SA3 18.12.07 |
| Fig. 48 | LOU 19.11.07 |



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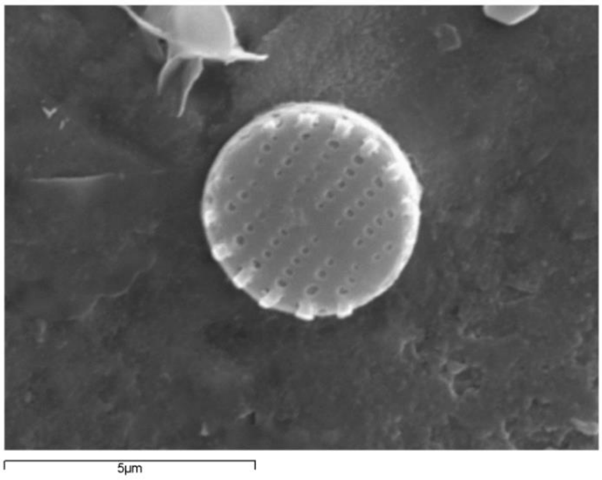

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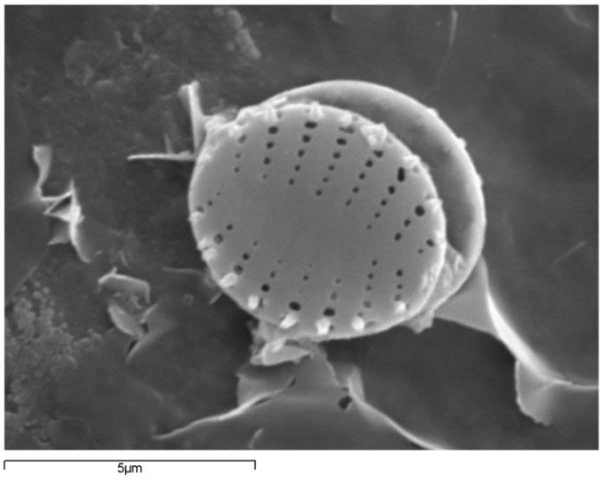

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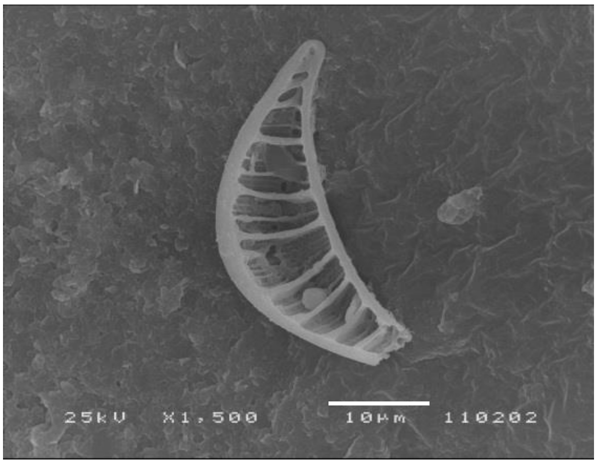

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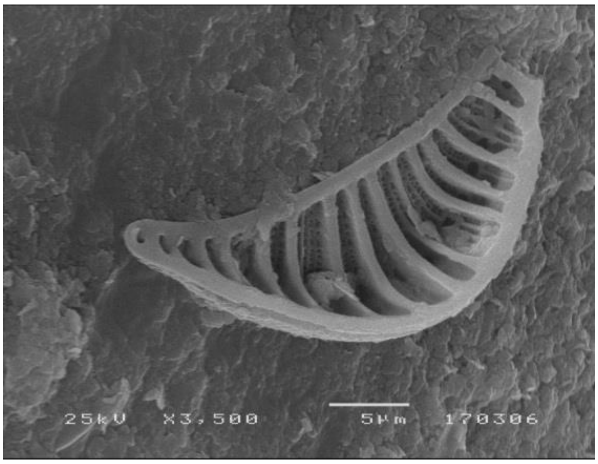

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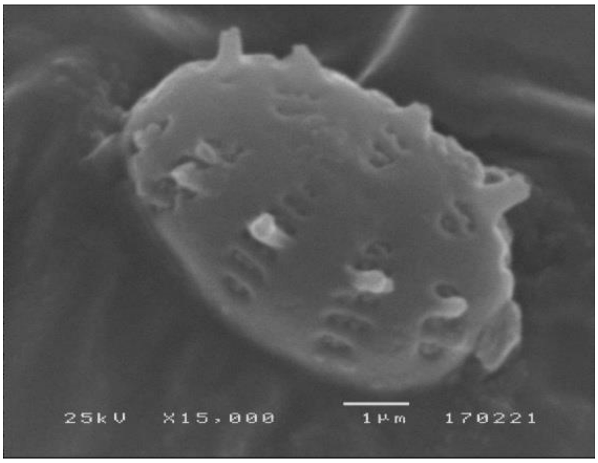
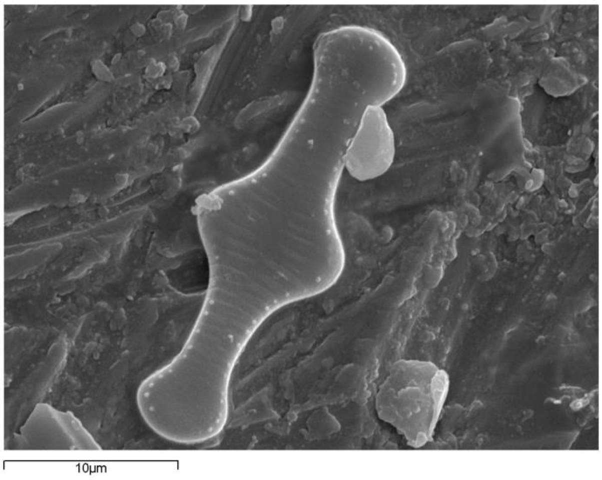


48

Plate 9

Fig. 49 *Tabellaria ventricosa* Kützing

Fig. 49 XUN 20.11.07



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# Appendix III - *Diatom plates*

## III B– DIATOMS FROM TRABA CORE – TRA07

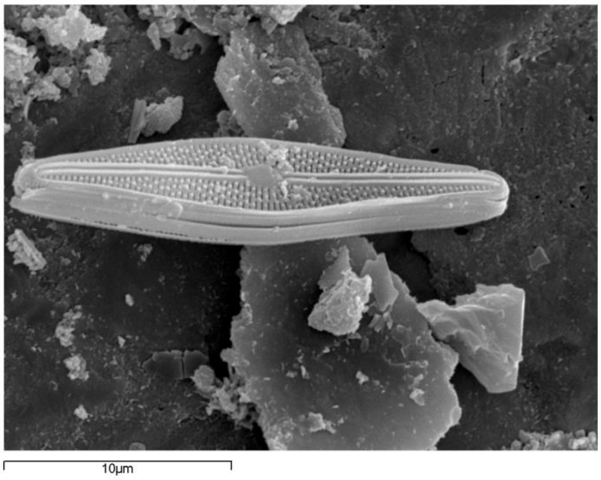
IMAGES ACQUIRED WITH JEOL JSM 6400 SCANNING ELECTRON MICROSCOPE AT UDC

Sample (cm)
TRA07-A1 36-37

Plate 1

| | |
|---|---|
| Fig. 1 | *Achnanthidium minutissimum* (Kützing) Czarnecki |
| Fig. 2 | *Brachysira vitrea* (Grunow) R.Ross in Hartley |
| Fig. 3 - 4 | *Cyclotella cryptica* Reimann, Lewin & Guillard |
| Fig. 5 - 6 | *Encyonopsis subminuta* Krammer & E.Reichardt |

1



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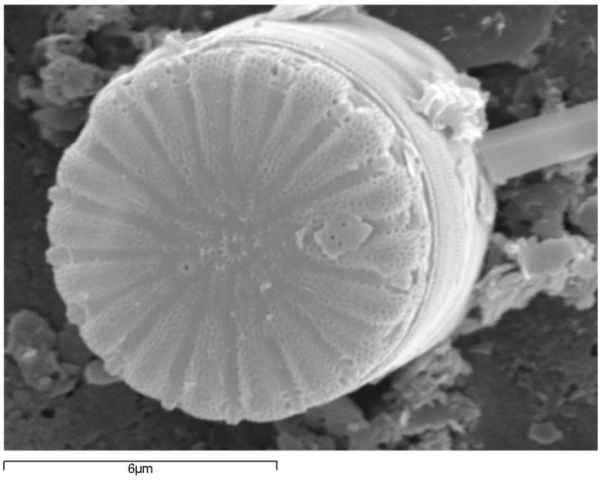

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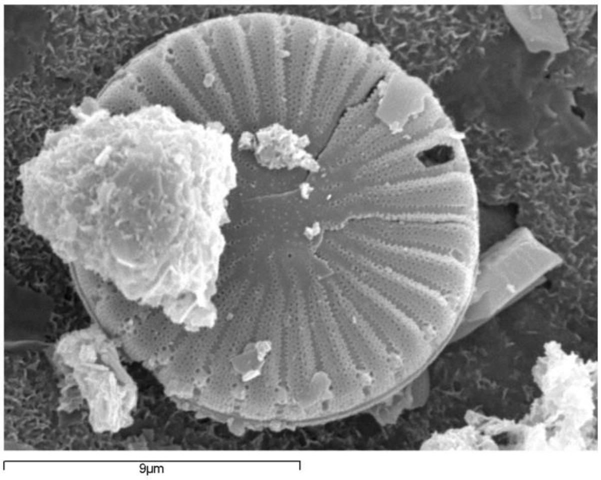

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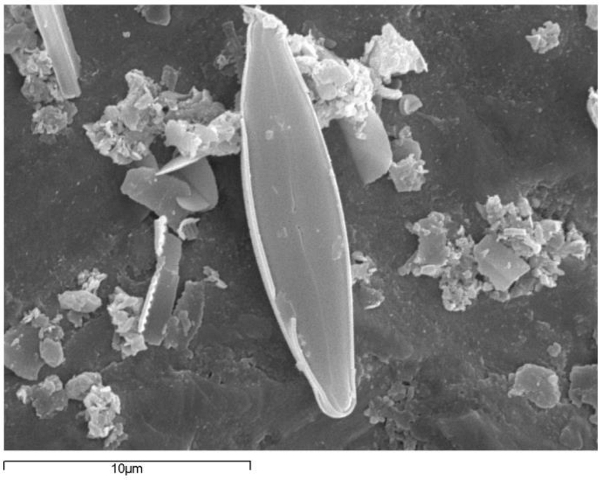

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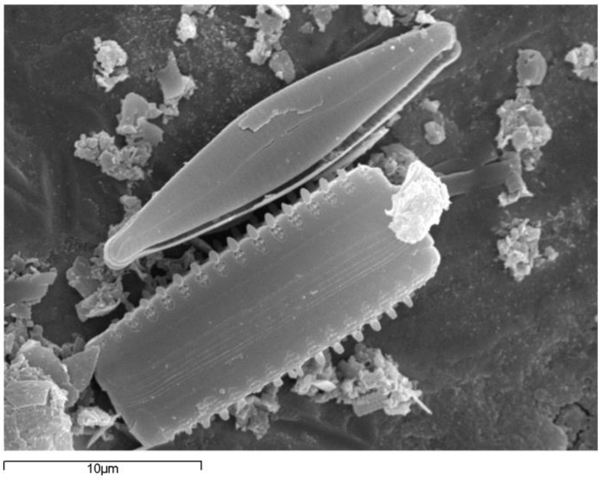
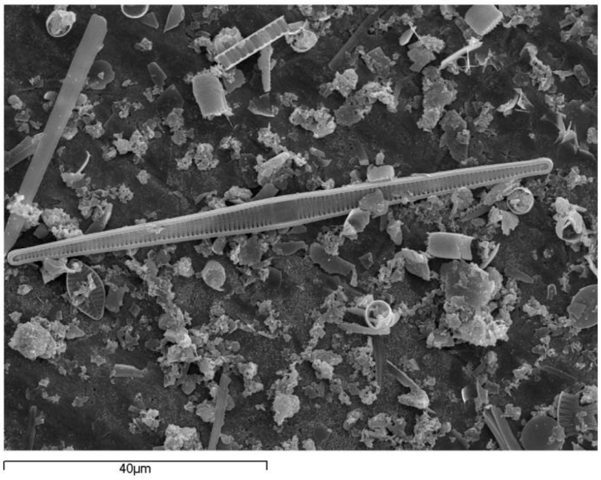


6

Plate 2

| | |
|---|---|
| Fig. 7 | *Fragilaria capucina* var. *gracilis* (Oestrup) Hustedt |
| Fig. 8 - 10 | *Planothidium delicatulum* (Kützing) Round & Bukhtiyarova |
| Fig. 11 | *Psammnothidium oblongellum* (Oestrup) Van de Vijver |
| Fig. 12 | *Pseudostaurosira trainorii* Morales |



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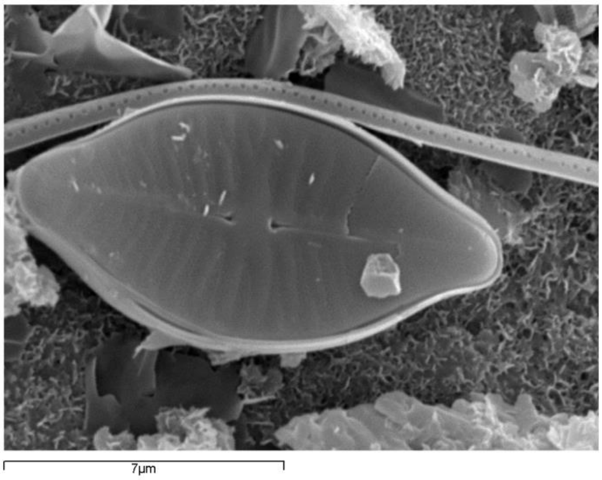

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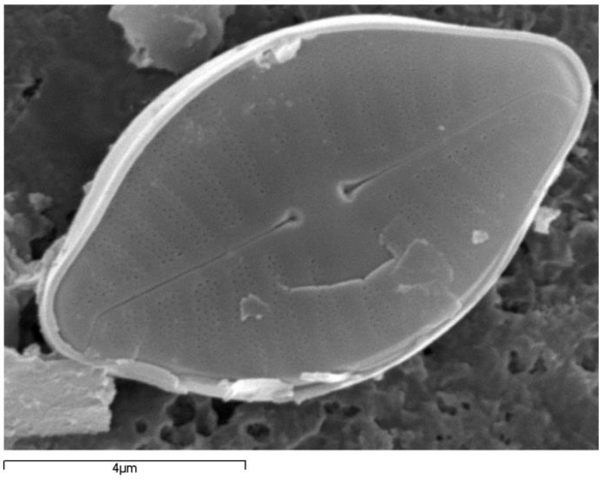

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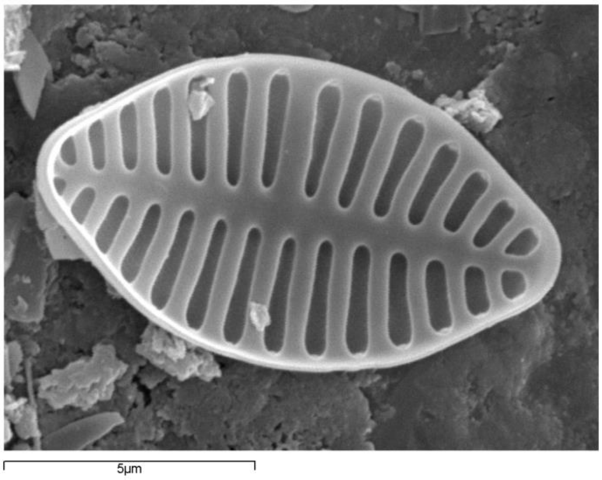

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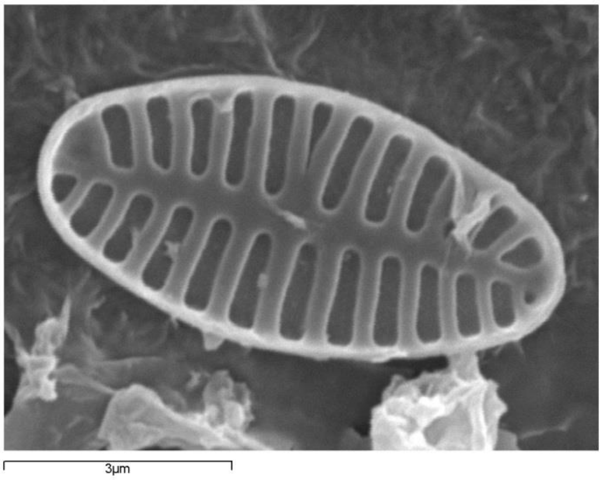

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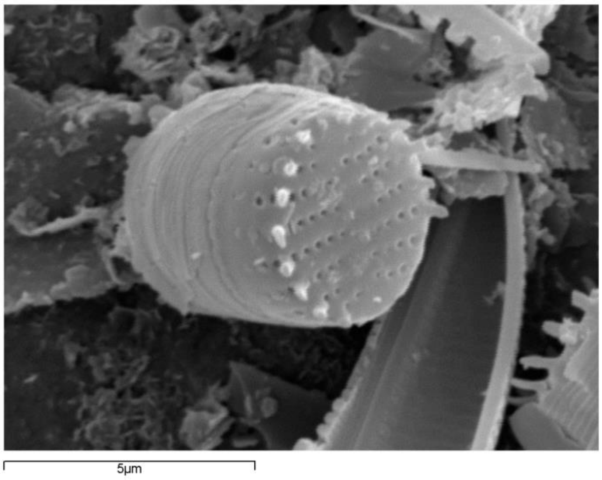
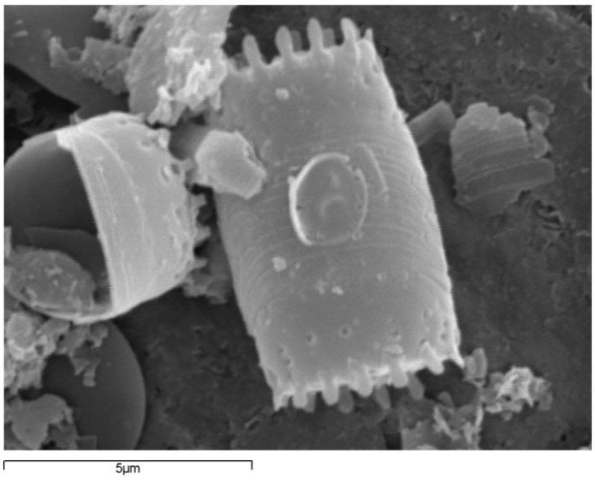


12

Plate 3

Fig. 13 - 18 *Pseudostaurosira trainorii* Morales



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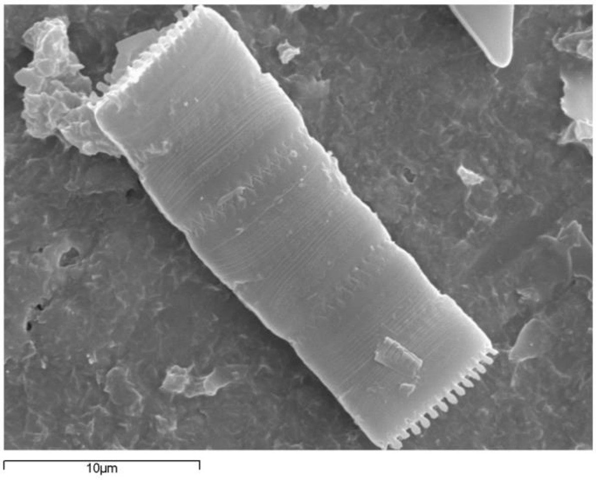

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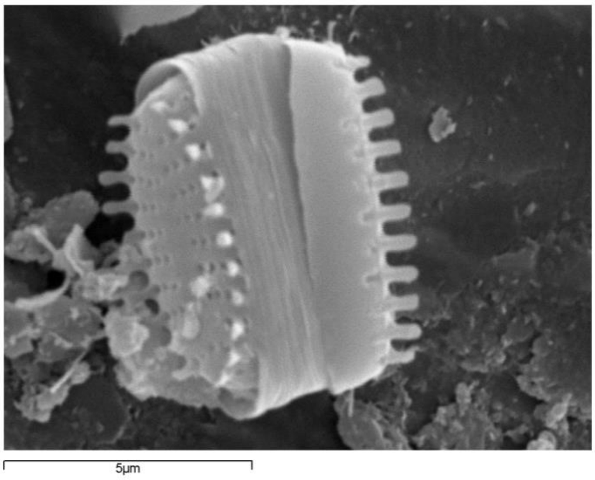

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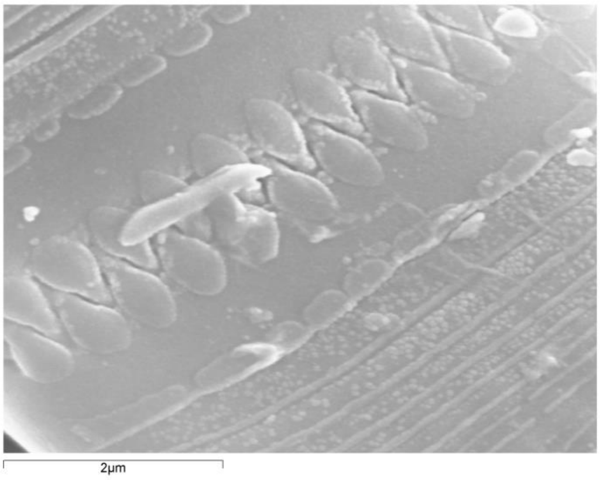

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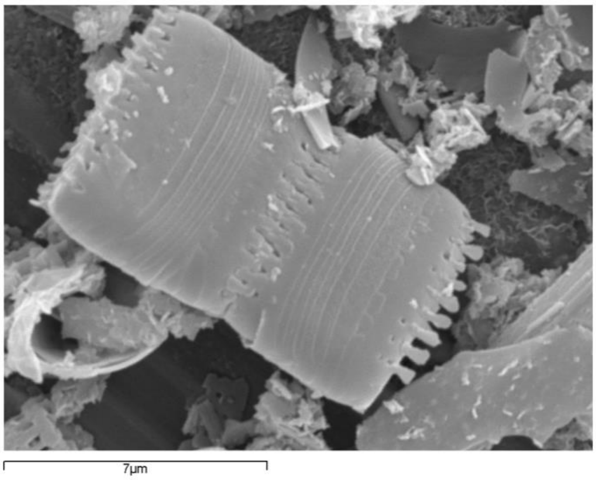

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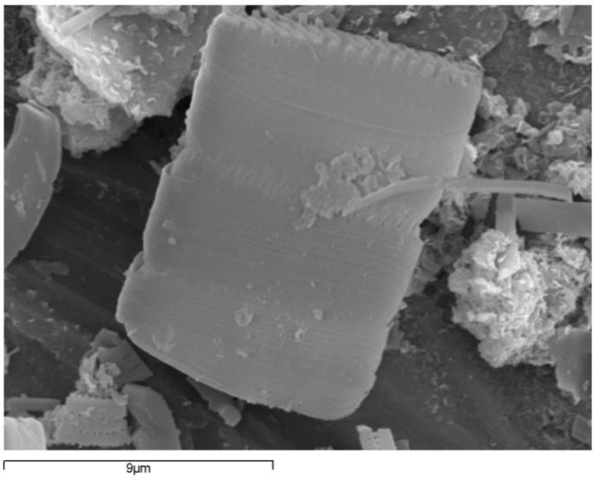

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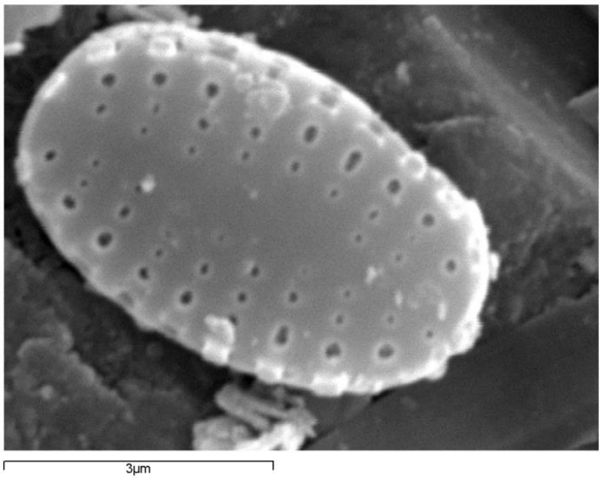
Plate 4

Fig. 19 - 24 *Pseudostaurosira trainorii* Morales



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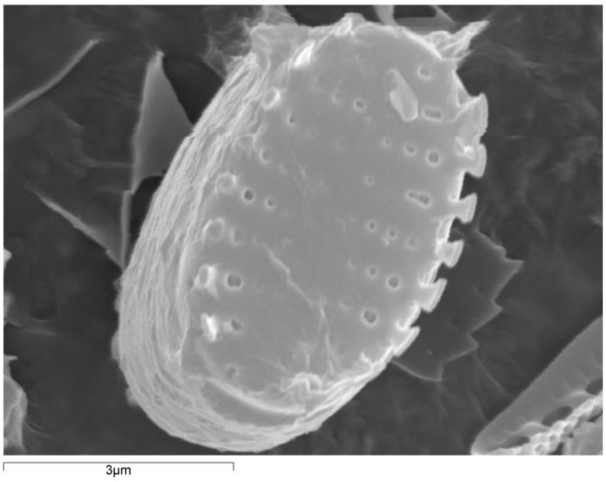

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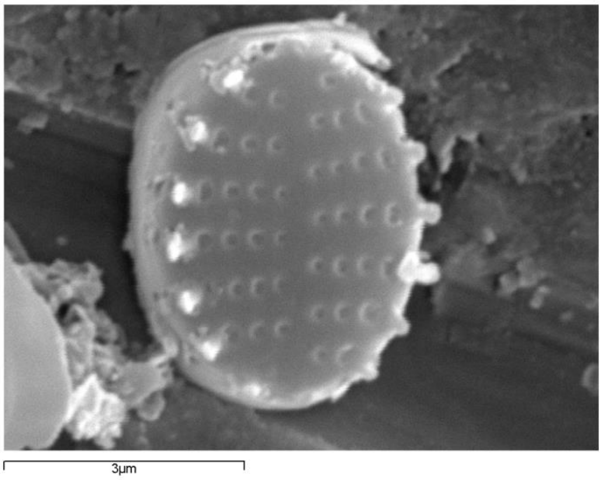

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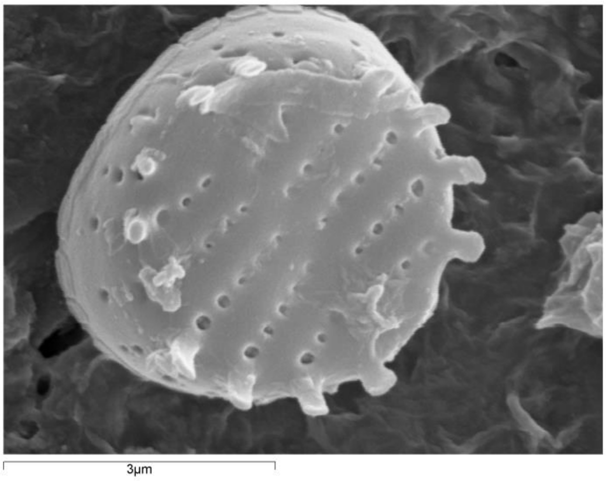

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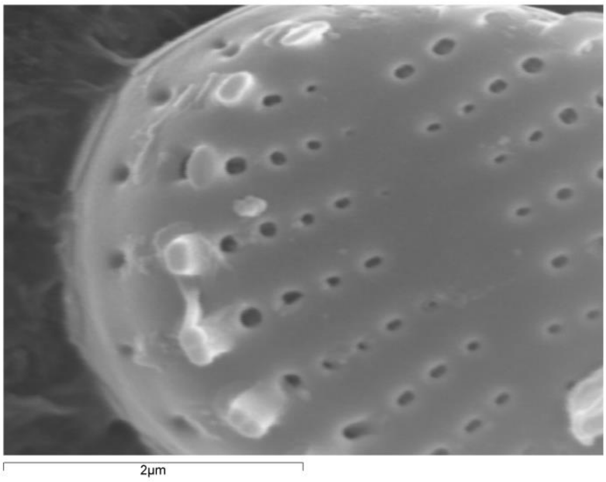

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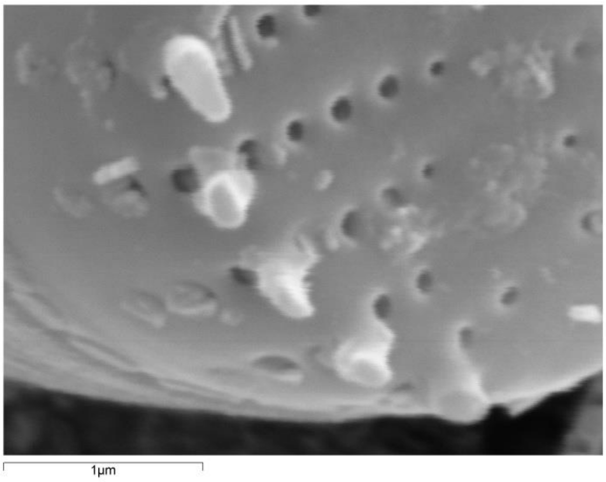
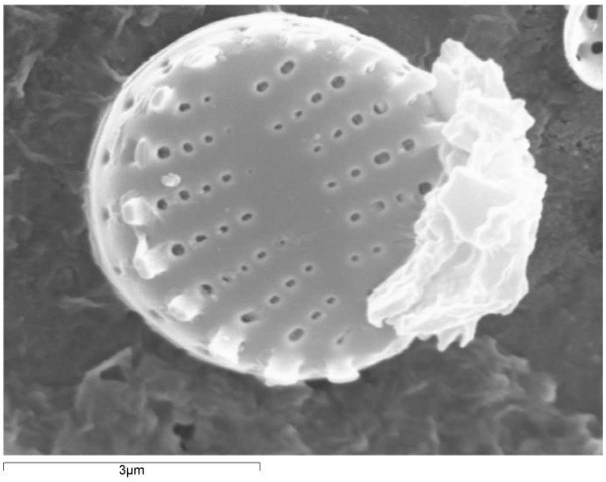


24

Plate 5

Fig. 25 - 30 *Pseudostaurosira trainorii* Morales



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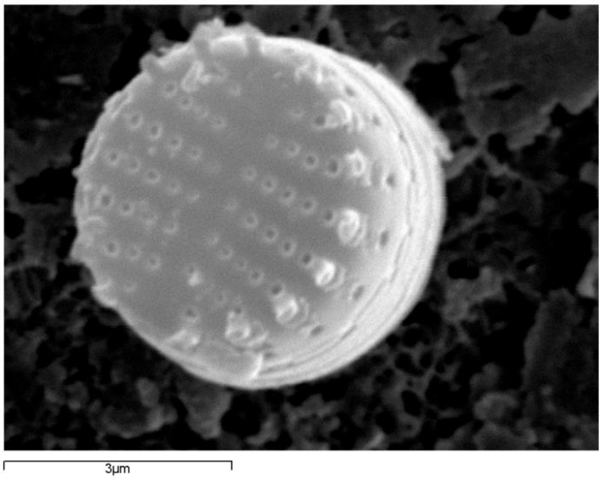

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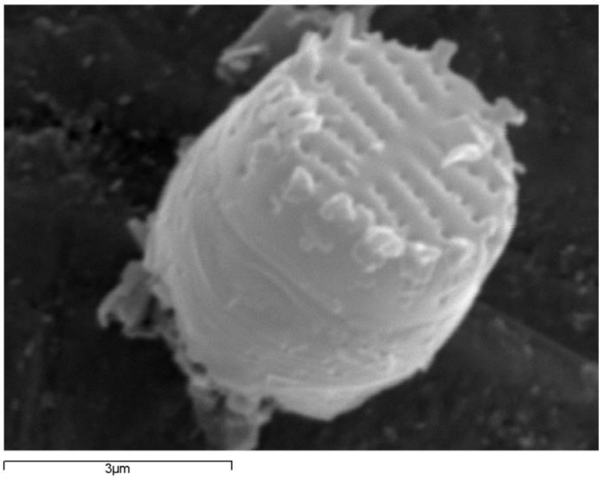

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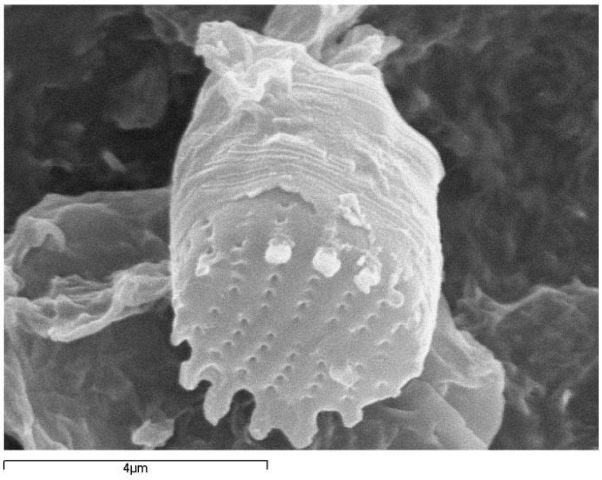

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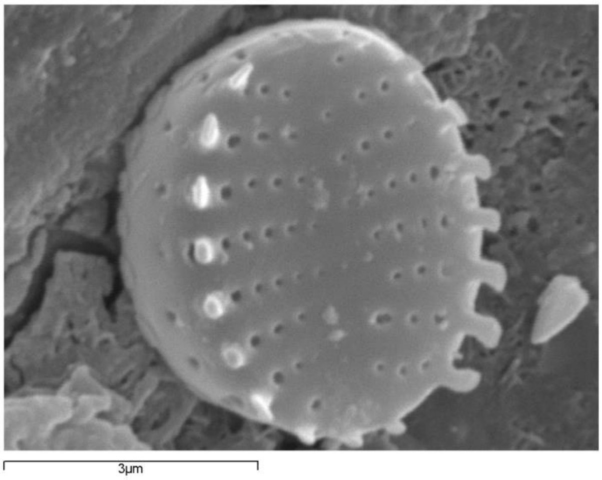

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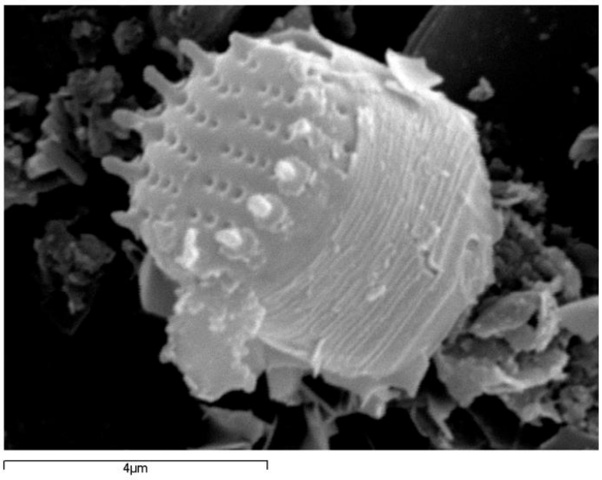
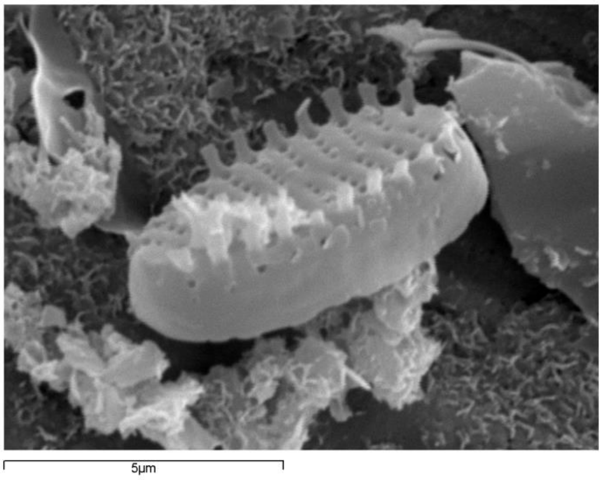


30

Plate 6

Fig. 31 - 32 *Pseudostaurosira trainorii* Morales
Fig. 33- 36 *Stauroforma exiguiformis* (Lange-Bertalot) Flower, Jones & Round



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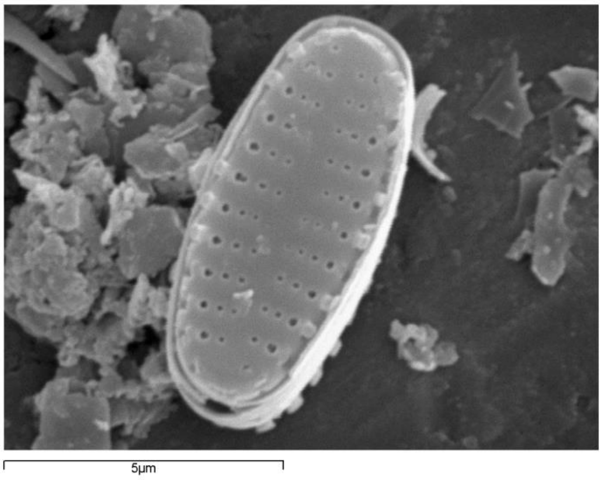

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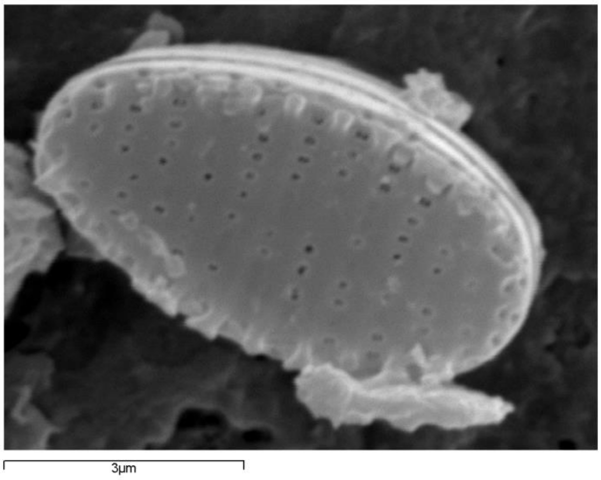

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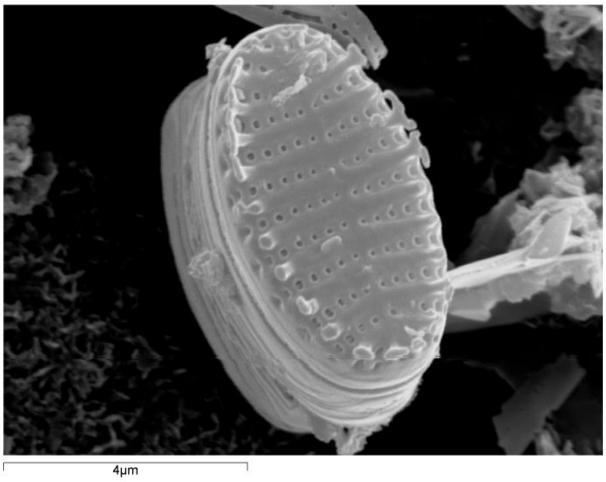

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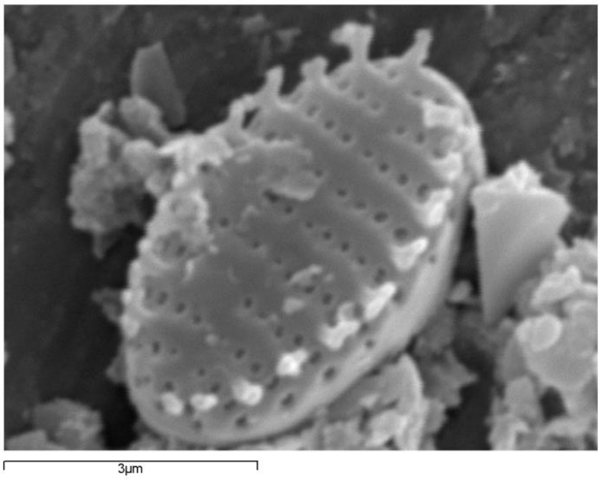

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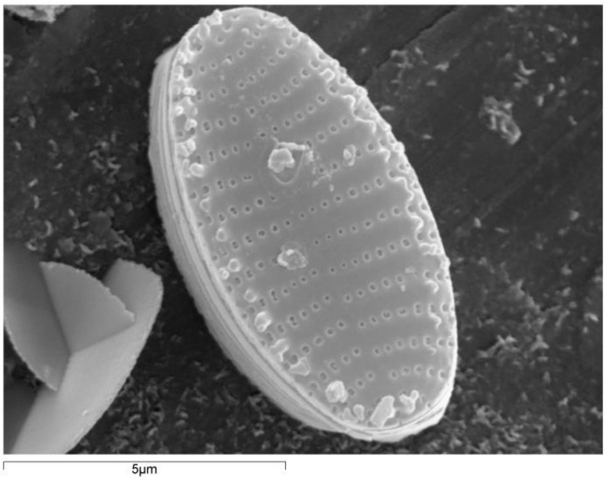
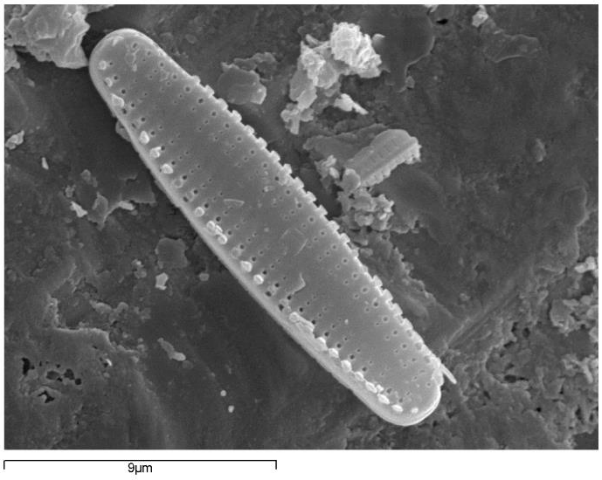


36

Plate 7

Fig. 37 - 40 *Stauroforma exiguiformis* (Lange-Bertalot) Flower, Jones & Round



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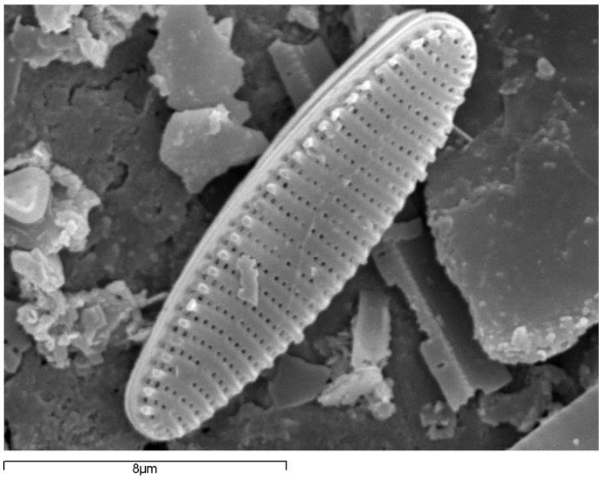

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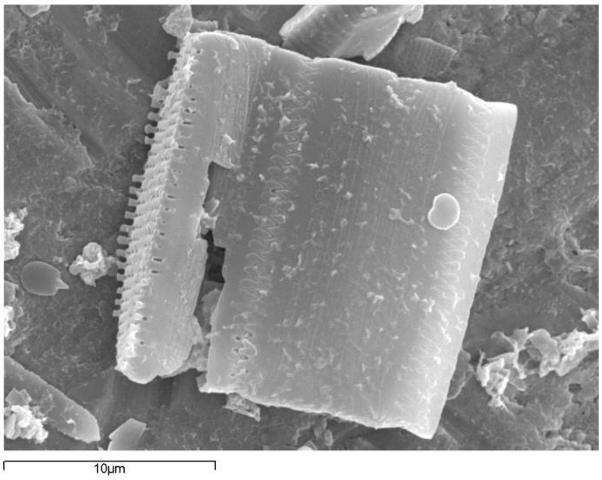

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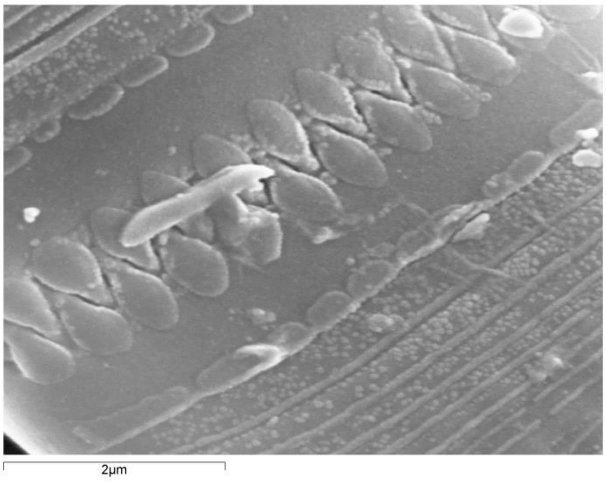


40

# Appendix III - *Diatom plates*

## III C – DIATOMS FROM MELIDES CORE - LM6

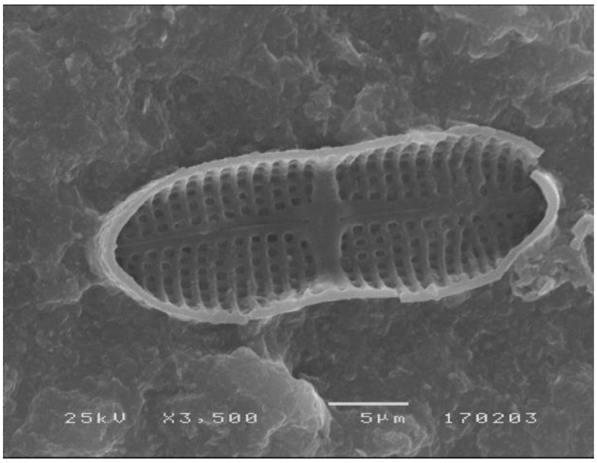
## IMAGES ACQUIRED WITH JEOL JSM-5200LV SCANNING ELECTRON MICROSCOPE AT FCUL

Samples (cm)
LM6 0-1
LM6 4-5
LM6 18-19
LM6 28-29
LM6 46-47
LM6 76-77

## Plate 1

| | |
|---|---|
| Fig. 1-5 | *Achnanthes brevipes* Agardh |
| Fig. 6 | *Achnanthes lemmermannii* Hustedt |

| | |
|---|---|
| Fig. 1-2 | sample 28-29 |
| Fig. 3 | sample 4-5 |
| Fig. 4-5 | sample 46-47 |
| Fig. 6 | sample 76-77 |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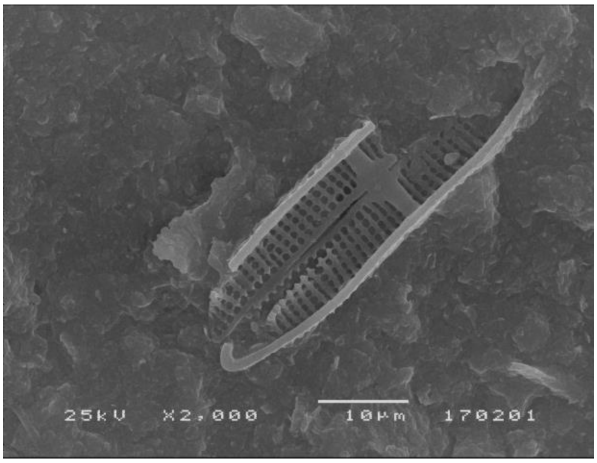
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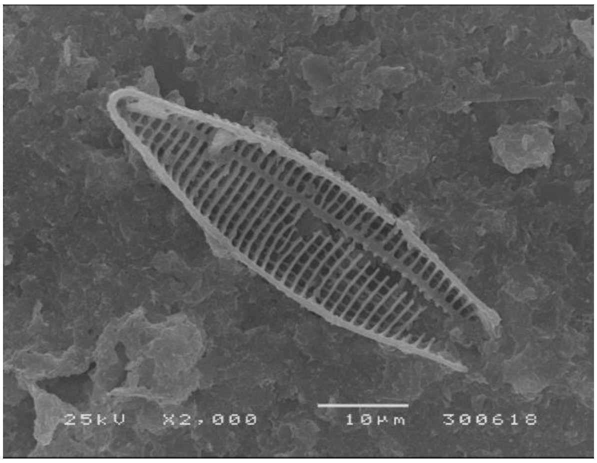
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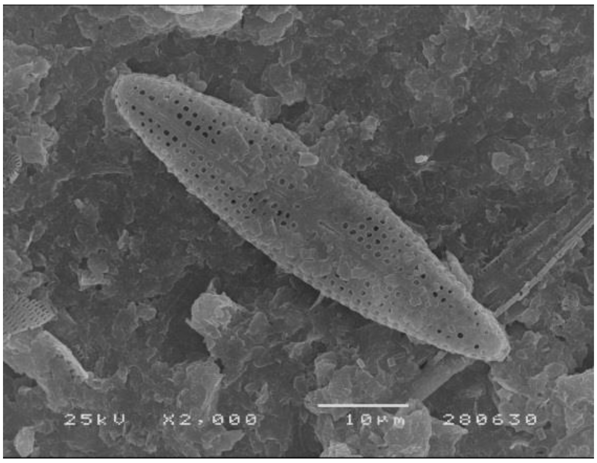
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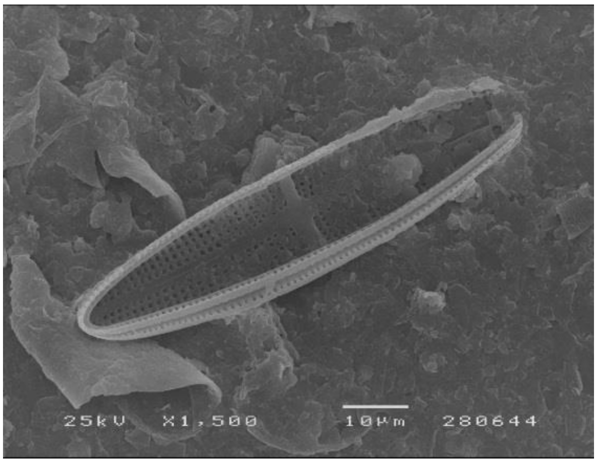
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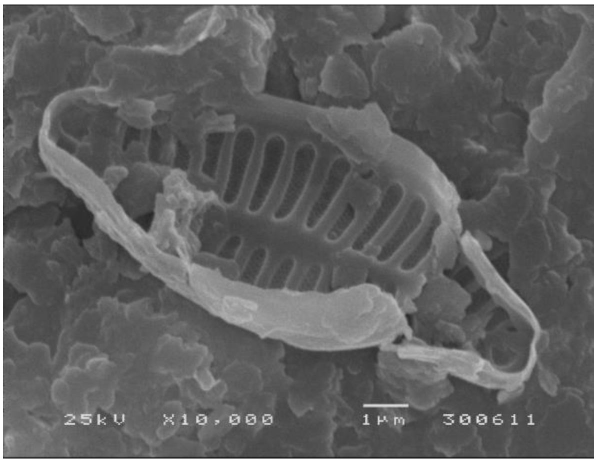
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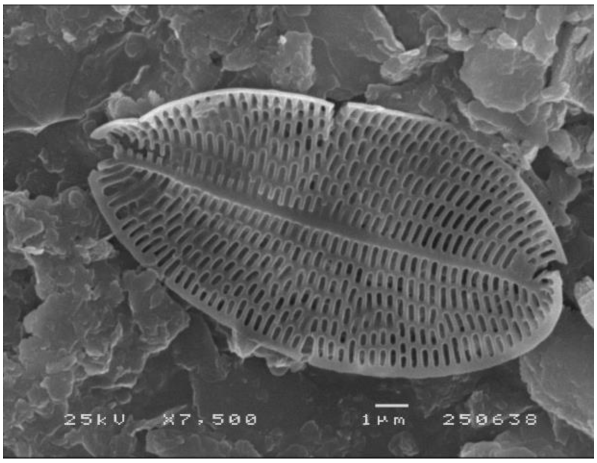
6

Plate 2

| | |
|---|---|
| Fig. 7-11 | *Cocconeis placentula* Ehrenberg (*sensu lato)* |
| Fig. 12 | *Cyclotella meneghiniana* Kützing |

| | |
|---|---|
| Fig. 7 - 9 | sample 0-1 |
| Fig. 10-11 | sample 46-47 |
| Fig. 12 | sample 0-1 |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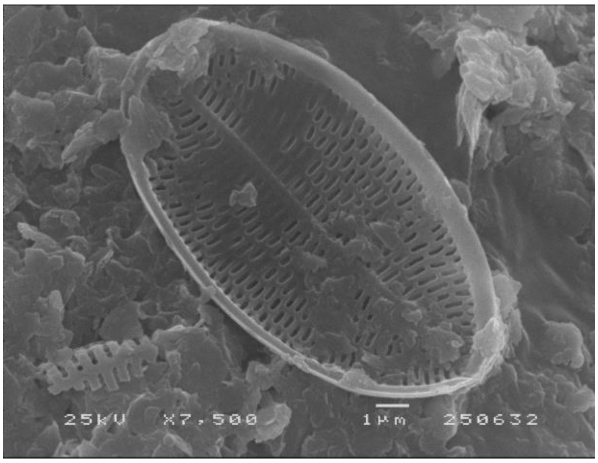
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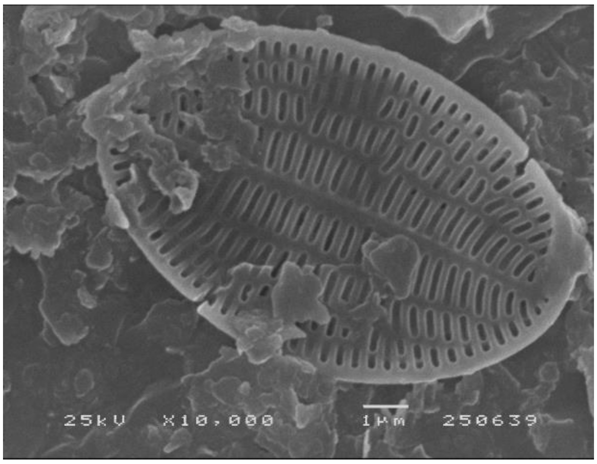
25kV X10,000 1µm 250639

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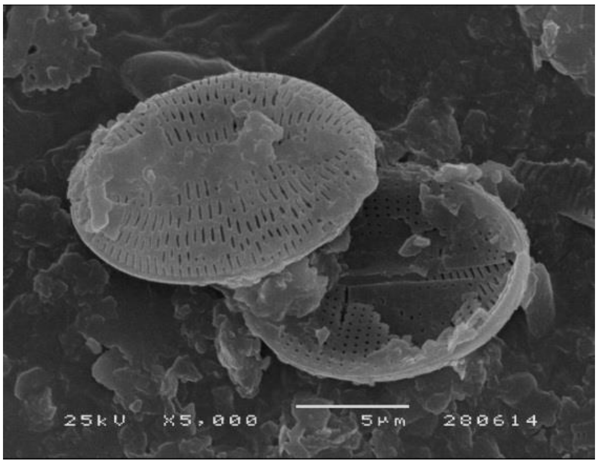
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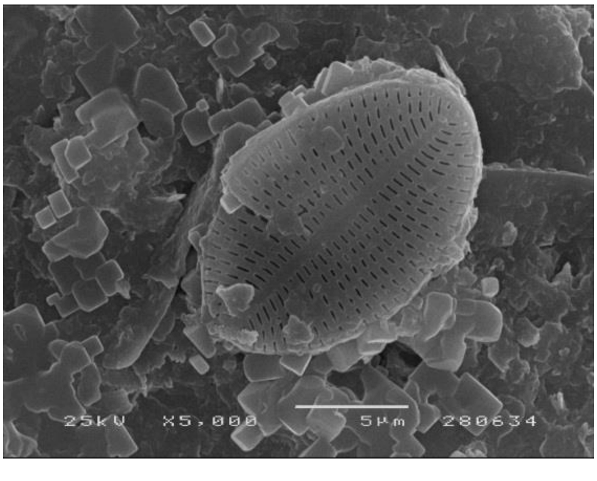
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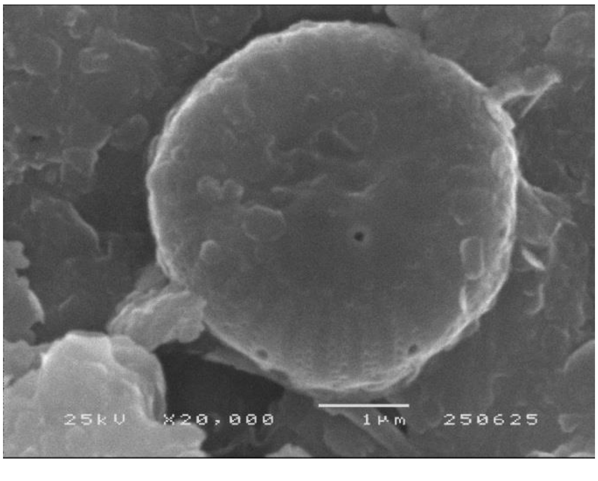
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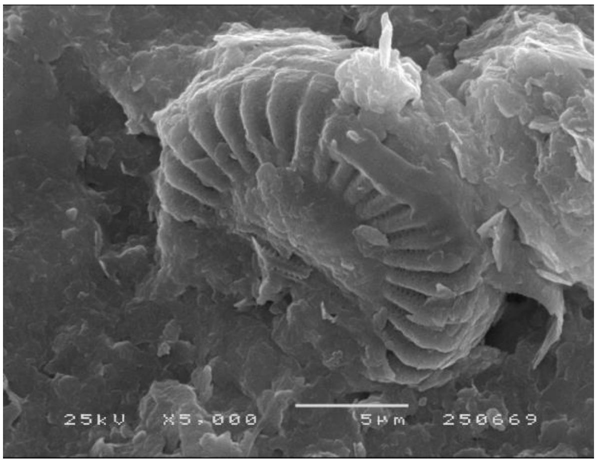
12

Plate 3

| | |
|---|---|
| Fig. 13-14 | *Cyclotella meneghiniana* Kützing |
| Fig. 15-16 | *Fallacia forcipata* (Greville) Stickle & Mann |
| Fig. 17 - 18 | *Mastogloia pumila* Cleve and Moller |

| | |
|---|---|
| Fig. 13 | sample 0-1 |
| Fig. 14 | sample 46-47 |
| Fig. 15 | sample 0-1 |
| Fig. 16 | sample 46-47 |
| Fig. 17-18 | sample 0-1 |



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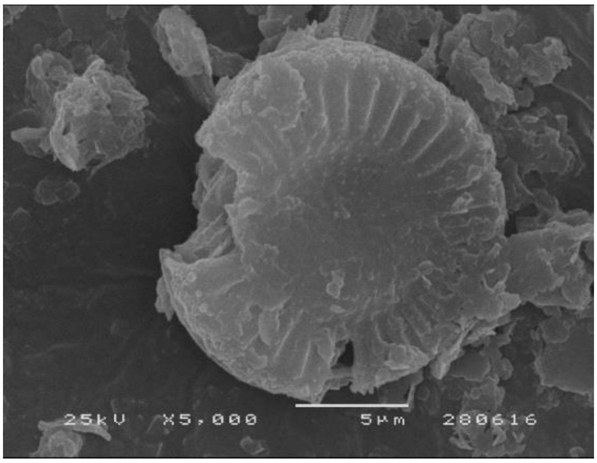

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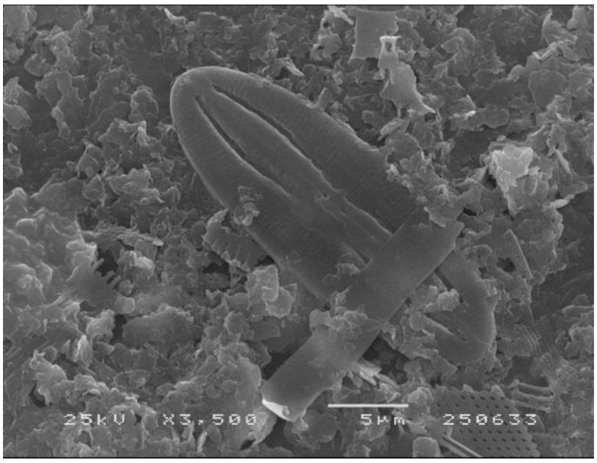

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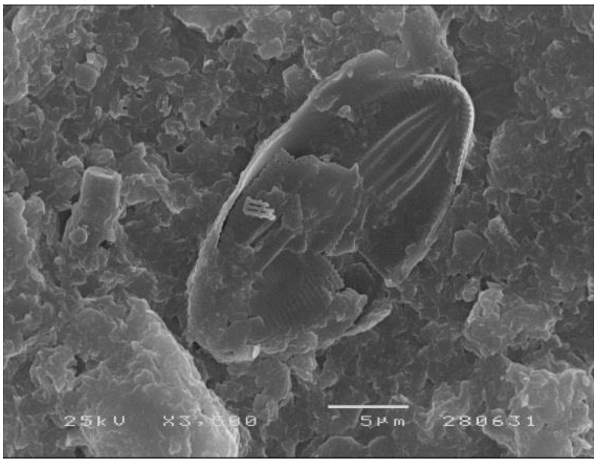

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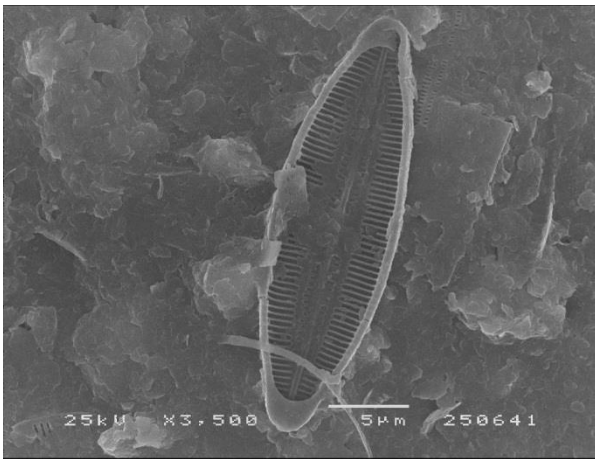

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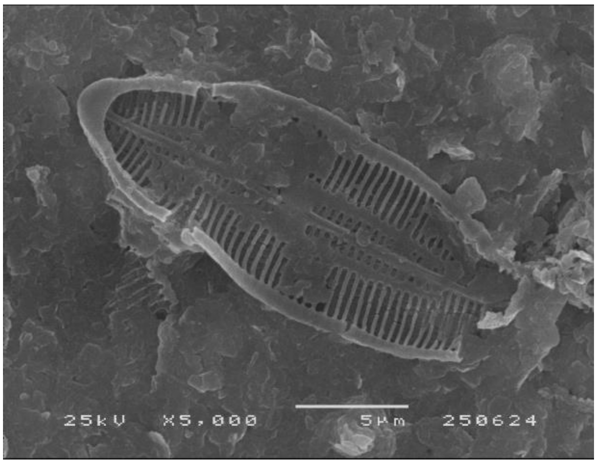
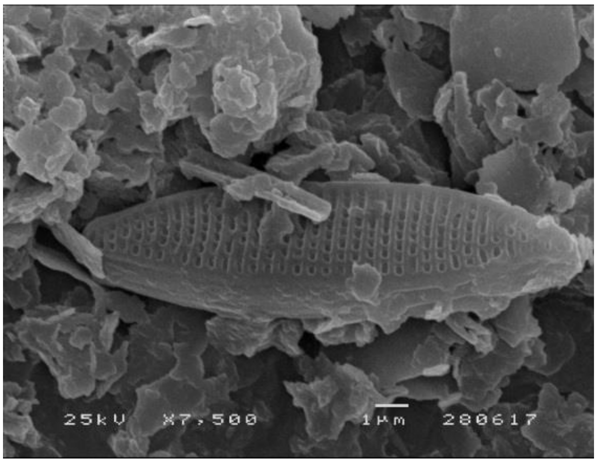


18

Plate 4

| | |
|---|---|
| Fig. 19 | *Nitzschia frustulum* (Kützing) Grunow |
| Fig. 20 | *Nitzschia* aff. *microcephala* Grunow |
| Fig. 21 - 24 | *Pseudostaurosira trainorii* Morales |

| | |
|---|---|
| Fig. 19-20 | sample 0-1 |
| Fig. 21 | sample 4-5 |
| Fig. 22 - 24 | sample 46-47 |



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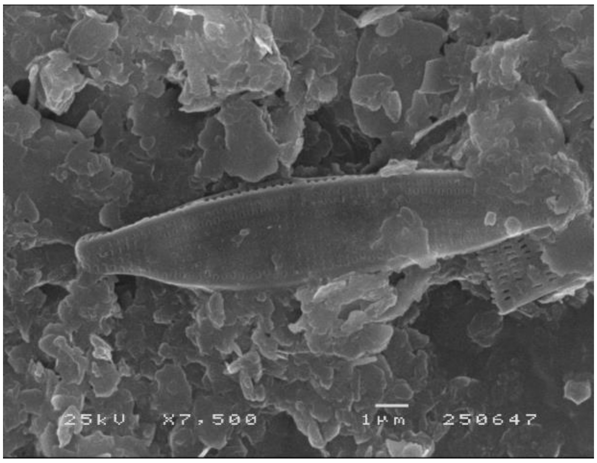

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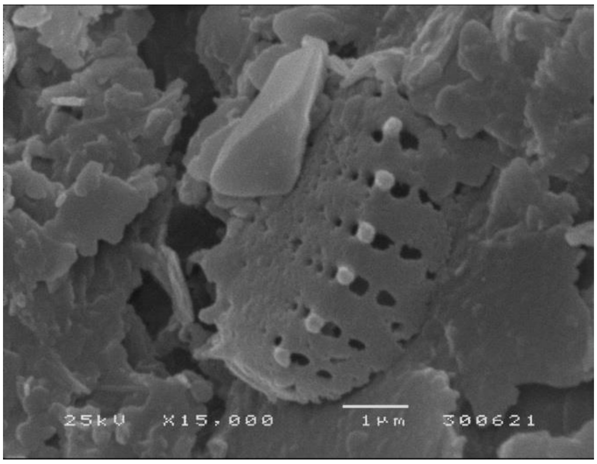

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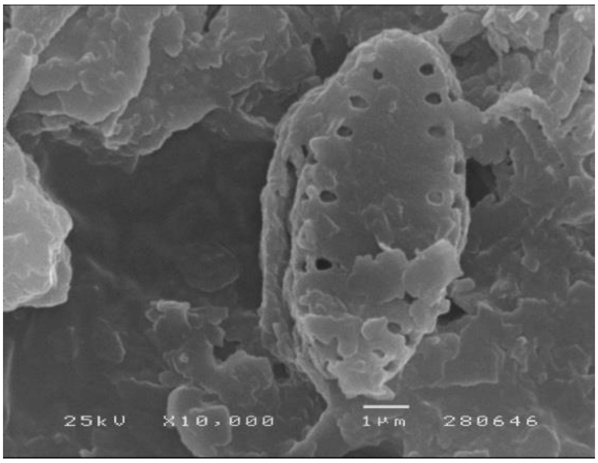

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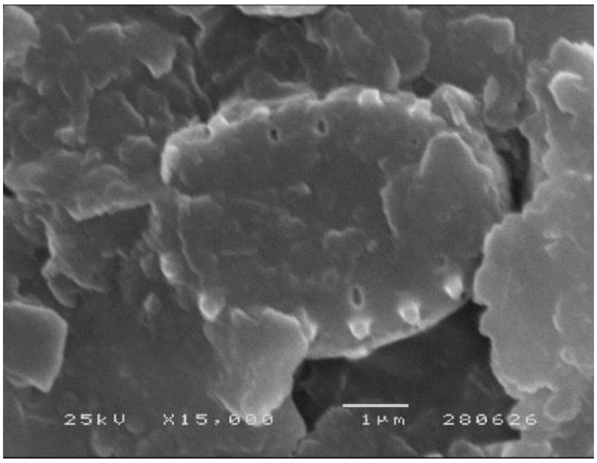

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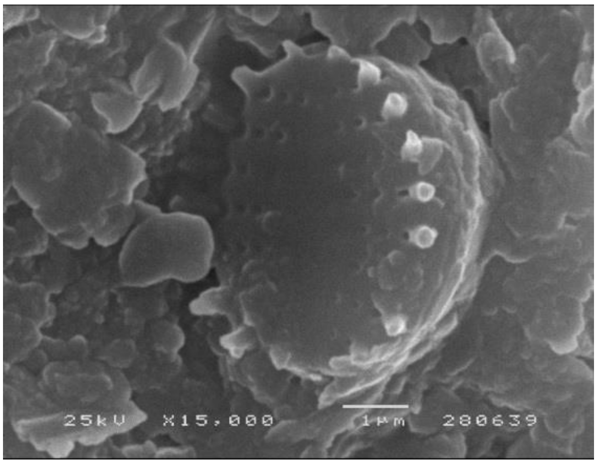
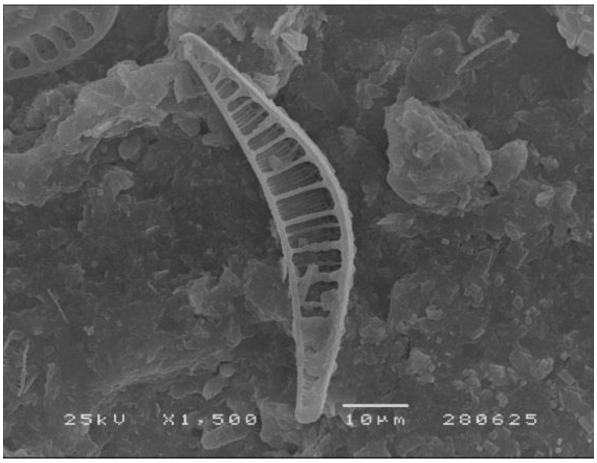


24

Plate 5

| | |
|---|---|
| Fig. 25 | *Rhopalodia musculus* (Kützing) Müller |
| Fig. 26 | *Staurophora salina (*Smith) Mereschkowsk |
| Fig. 27 | *Staurosira elliptica* (Schumann) D.M.Williams & Round |
| Fig. 28 | *Surirella striatula* Turpin |

| | |
|---|---|
| Fig. 25 | sample 46.47 |
| Fig. 26 | sample 0-1 |
| Fig. 27 | sample 76-77 |
| Fig. 28 | sample 76-77 |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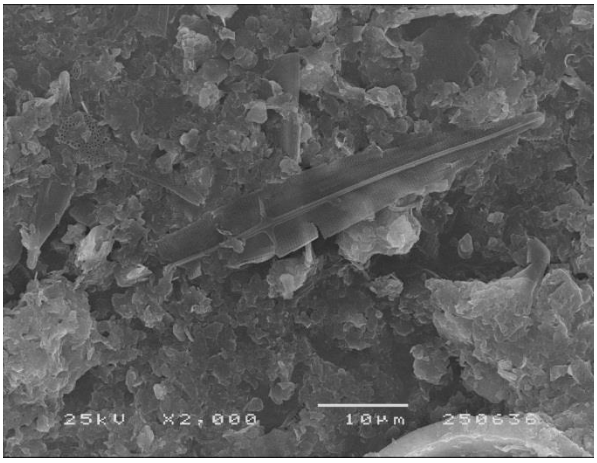
25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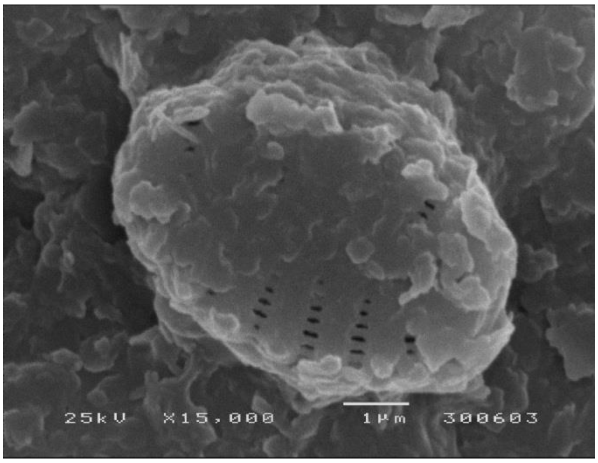
26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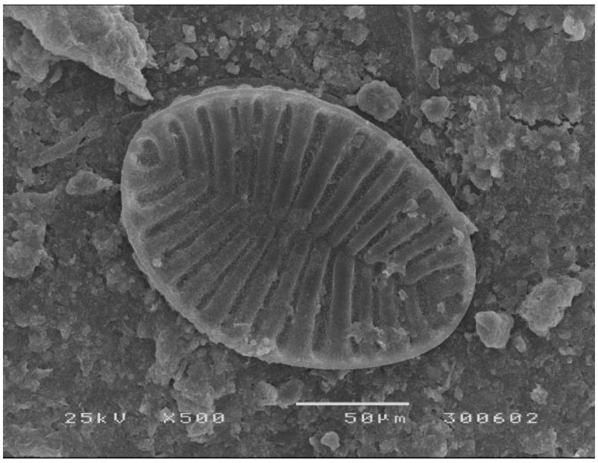
27


25kV X500 50µm 300602

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