Palaeoenvironmental conditions during Pliocene and Pleistocene in the Southwest Iberian Margin: Ichnological analysis of sedimentary record from IODP Expedition 339

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Francisco Javier Rodríguez Tovar, Catedrático de la Universidad de Granada y director de la presente Tesis Doctoral.

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Que la presente tesis titulada ***Palaeoenvironmental conditions during Pliocene and Pleistocene in the Southwest Iberian Margin: Ichnological analysis of sedimentary record from IODP Expedition 339*** ha sido realizada bajo mi dirección y cumple las condiciones necesarias para que su autor, **Javier Dorador Rodríguez**, opte al grado de Doctor en Ciencias Geológicas por la Universidad de Granada.

Granada, enero de 2017

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Place and date

Granada, Spain, January 2017

Francisco Javier Rodríguez Tovar	**Javier Dorador Rodríguez**
Thesis supervisor	**Doctoral candidate**
Signed	**Signed**

A mi familia

A los míos

A Ti

“A man who doesn't spend time with his family can never be a real man”

(D. Vito Corleone)

"May their future generations share my contention that it is a wonderful thing to work as a paleodetective!"

(Adolf Seilacher, Trace Fossil Analysis, 2007)

"La inspiración existe, pero tiene que encontrarte trabajando"

(Pablo Picasso)

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CONTENTS

Abstract

International Ocean Discovery Program Expedition 339 took place in the Gulf of Cadiz and the Western Iberian Margin during the end of 2011 and the beginning of 2012, aimed to arrive at a better understanding of Mediterranean Outflow Water evolution, to study the contourite deposits generated by this water mass, and to derive a marine reference climate section from the Pleistocene. Several disciplines are involved in the study of the drilled cores, ichnology being one of them due to its usefulness in palaeoenvironmental studies, providing information about parameters such as oxygen level, food supply or substrate consistency, and hence about the environmental changes involved (i.e., palaeoclimate, atmosphere/ocean dynamics, etc.). This PhD Thesis, based on ichnological analysis of the retrieved marine cores from the expedition, focuses on its use for palaeoenvironmental interpretations during the Pliocene and Pleistocene. Results regarding the ichnological content throughout the studied cores reveal that, in general, sediments were deposited under good oxygen levels and nutrient availability, although some intervals related with dysaerobic conditions can be also identified. More detailed and integrative studies allow for characterization of the palaeoenvironmental evolution during particular intervals, as those corresponding to Marine Isotope Stages 12 and 11, showing that changes in trace fossil features can be linked to surface productivity and food supply variations, and correlated to foraminifera information. This relation between ichnological attributes and productivity is also demonstrated by *Zoophycos* distribution during glacial-interglacial variations, which may even be used as a proxy, its presence associated with intermediate sedimentation rate and seasonal high productivity in Neogene hemipelagic deposits. All these advances prove the usefulness of ichnology in the study of modern marine cores, supporting the ichnological approach as a tool in drilling expeditions.

RESUMEN

La Expedición 339 del *International Ocean Discovery Program* tuvo lugar en el Golfo de Cádiz y el Margen Occidental Ibérico entre finales de 2011 y principio de 2012, con el fin de mejorar el conocimiento acerca de la evolución de la *Mediterranean Outflow Water*, estudiar los depósitos contorníticos generados por esta corriente y obtener una sección marina climática de referencia para el Pleistoceno. Para ello hay varias disciplinas involucradas en el estudio de los sondeos perforados, siendo la icnología una de ellas debido a su utilidad en estudios paleoambientales aportando información acerca de parámetros como niveles de oxígeno, aporte de nutrientes o consistencia del sustrato entre otros, y en los cambios ambientales originados (paleoclima, dinámica atmosfera/océano, etc.). En este contexto, la presente Tesis se basa en el análisis icnológico de sondeos marinos modernos extraídos durante la expedición, centrándose en su uso para interpretaciones paleoambientales durante el Plioceno y Pleistoceno. Los resultados obtenidos basados en el contenido icnológico de los sondeos estudiados revelan que, en general, los sedimentos fueron depositados bajo condiciones de buena oxigenación y disponibilidad de nutrientes, aunque se encuentran algunos intervalos relacionados con condiciones disaeróbicas. Estudios integrados de más detalle permiten caracterizar la evolución paleoambiental durante intervalos específicos, como aquellos correspondientes a los Estadios Isotópicos Marinos 12 y 11, mostrando que los cambios en las características icnológicas pueden ser relacionados con variaciones de productividad superficial y aporte de nutrientes, siendo correlacionadas con la información aportada por foraminíferos. Esta relación entre bioturbación y productividad es también demostrada en el caso de *Zoophycos* durante variaciones glaciares-interglaciares, pudiendo ser incluso usado como un indicador cuya presencia está asociada a periodos de intermedia tasa de sedimentación y alta productividad estacional en depósitos hemipelágicos del Neógeno. Todo ello pone de manifiesto la utilidad de la icnología en el estudio de sondeos marinos modernos, apoyando el análisis icnológico como una herramienta a considerar en las campañas de perforación.

EXTENDED ABSTRACT

The Gulf of Cadiz and the Western Iberian Margin constitute a very scientifically interesting area due to the water exchange between the Mediterranean Sea and the Atlantic Ocean. The water mass coming from the Mediterranean Sea towards the Strait of Gibraltar, called the Mediterranean Outflow Water (MOW), affects global circulation and generates a well-developed Contourite Depositional System (CDS). For this reason, some cores were drilled by the IODP Expedition 339 to get a better understanding of MOW evolution and contourite deposits and to improve the climate record from the Pleistocene. These aims were considered within a multidisciplinary project involving geochemistry, geophysics, palaeomagnetism or micropalaeontology, among others, in addition to ichnology.

Over the last decades, ichnological analysis has proven useful in palaeoenvironmental studies, providing additional information about environmental parameters such as oxygenation or food supply, among others. However, ichnological analysis of modern marine cores is still underestimated. This fact motivated the detailed ichnological study in cores from IODP Expedition 339 to demonstrate the usefulness of ichnology in the study of cores extracted in a drilling expedition, and the potential use of trace fossils as a tool in palaeoclimatic and palaeoceanographic research. In this context, the present PhD Thesis is centered on ichnological analysis of modern marine cores drilled during IODP Expedition 339. It aims to assess several objectives. First, to analyze ichnological features throughout the cores to characterize the evolution of the macro-bethic tracemaker community. Second, to provide palaeoenvironmental interpretations from Pliocene to Holocene times according to macro-benthic variations inferred from the study of trace fossils. Third, to integrate the ichnological information with micropalaeontological observations, to formulate precise palaeoclimatic and palaeoceanographic interpretations regarding particular intervals of interest. Fourth, to test the global importance of the interpreted relations between trace fossils and certain environmental parameters, beyond the local study area. Finally, but of primary interest for the conducted research, to develop a new methodology facilitating ichnological analysis in modern marine cores, solving the usual problems inherent to working with this material.

This new method is based on high resolution image treatment and can be applied following four sequence steps: 1, image adjustments; 2, digital estimation; 3, pixel counting; and 4, ichnofabric representation. The application of this new methodology improves the visualization of trace fossils and also provides information about other ichnological features, for instance the percentage of bioturbated surface or penetration depth. Its usefulness in the ichnofabric approach, in this case with modern marine cores drilled during IODP Expedition 339, proved very helpful for their characterization. The usefulness of this method in ichnofacies analysis or the color sediment record has been also demonstrated, though it is not included as part of the present volume (Supplementary papers of Part II).

Application of the novel method involved a detailed ichnological analysis of hemipelagic cores drilled in Site U1385, selected to enhance our understanding of the climatic record from the Pliocene to Holocene. Nine ichnotaxa were identified (from more to less abundant: *Planolites*, *Palaeophycus*, *Thalassinoides*, *Thalassinoides*-like, *Taenidium*, *Zoophycos*, *Chondrites*, *Phycosiphon* and ?*Scolicia*), all of them belonging to *Zoophycos* ichnofacies. Based on ichnological features such as trace fossil assemblage, bioturbation degree or tiering, seven ichnofabrics can be differentiated. According to the obtained results, oxygen levels and food supply were relatively good overall, sufficient to maintain a more or less diverse macrobenthic trace-maker community, although several intervals deposited under dysaerobic conditions were also interpreted based on variations in the ichnological attributes. Other palaeoenvironmental parameters, e.g. sedimentation rate and substrate consistency, do not show major changes. The ichnofabric distribution along the cores (included as Supplementary papers of Part III), allows for a precise characterization of palaeoclimate and atmosphere-ocean dynamics, the registered ichnological changes being correlated with short-term (Terminations or Heinrich events, for example) and long-term variations (associated with orbital climate variability).

Further, detailed trace fossil analysis was developed on intervals linked to Marine Isotope Stages (MIS) 12 and 11. This is one of the most extreme glacial/interglacial periods in the Pleistocene, the MIS 11 being similar to the Holocene in terms of climate. The study was conducted integrating ichnological data and foraminifera information for a detailed interpretation of the involved environmental conditions. Noteworthy changes in trace fossil distribution were associated with oxygen level variations and nutrient abundance. Meanwhile, foraminiferal analysis revealed surface productivity and food supply changes that can be correlated with observed ichnological features. Thus, variations in the macro- and micro-benthic communities are related to major changes in deep-sea ventilation, probably linked to thermohaline circulation evolution. In a similar way, Terminations 1, 2 and 4 were studied in detail, and results not included in the present volume (Supplementary papers of Part III) reveal changes linked to oxygen and nutrient availability.

Finally, the relationship between the distribution of *Zoophycos* and sedimentation rate and productivity values was studied for glacial-interglacial variations. A study in detail of those intervals where *Zoophycos* is identified in the last 1.5 Myr revealed that its presence can be linked to periods with an intermediate sedimentation rate and seasonal high productivity. This observation in cores from IODP Expedition 339 agrees with results from other deposits around the world, including the South China Sea or the Western African Margin. Therefore, *Zoophycos* is proposed to be used as a proxy of seasonal organic-matter deposition and primary productivity in Neogene hemipelagic deposits.

Additional results from ichnological studies of contourites and gravity-flow deposits, from the Gulf of Cadiz, point to bioturbation as a very interesting tool for their discernment. This aspect is thus far a preliminary research finding, not included under the main goals of the present Thesis; however, in view of its potential importance and its strong relation with the subject matter of the PhD, it has been added as an Appendix.

RESUMEN EXTENDIDO

El Golfo de Cádiz y el Margen Ibérico Occidental constituyen una región de gran interés científico debido al intercambio de aguas entre el Mar Mediterraneo y el Océano Atlántico. La masa de agua proveniente del Mar Mediterráneo, conocida como *Mediterranean Outflow Water* (MOW), afecta a la circulación global y genera un sistema contornítico deposicional bien desarrollado. Por esta razón, se perforaron una serie de sondeos en la Expedición 339 del *International Ocean Discovery Program* (IODP) con el fin de mejorar el conocimiento acerca de la evolución de la MOW y los depósitos contorníticos, y mejorar el registro climático del Pleistoceno. Estos objetivos se enmarcaron en un proyecto multidisciplinar con especialidades como geoquímica, geofísica, paleomagnetismo o micropaleontología entre otras, incluyendo la icnología como una de ellas.

Durante las últimas décadas el análisis icnológico ha sido probado como una herramienta de gran utilidad en estudios paleoambientales, aportando información sobre una serie de parámetros ambientales como el grado de oxigenación o la disponibilidad de nutrientes entre otros. Sin embargo, el análisis icnológico de sondeos marinos modernos aún está subestimado. Este hecho, motiva el estudio icnológico en detalle de los sondeos de la Expedición 339 del IODP con el fin de demostrar la utilidad de la icnología en el estudio de sondeos extraídos durante una expedición de perforación, y el potencial uso de las trazas fósiles como una herramienta en estudios paleoclimáticos y paleoceanográficos. En este sentido, la presente Tesis se basa en el estudio icnológico de sondeos marinos modernos extraídos durante la Expedición 339 del IODP. Con ello se pretenden abordar diferentes objetivos. En primer lugar, analizar las características icnológicas de una forma general para caracterizar la evolución de la comunidad de organismos bentónicos bioturbadores. Segundo, llevar a cabo interpretaciones paleoambientales desde el Plioceno al Holoceno en base los cambios del macro-bentos inferidos a través del estudios de las trazas fósiles. Tercero, integrar la información icnológica con datos de otras disciplinas como la micropaleontología, para precisar interpretaciones paleoclimáticas y paleoceanográficas en intervalos de particular interés. En cuarto lugar, comprobar la relevancia global de las relaciones interpretadas en el área de estudio para analizar si existe una relación entre determinados ichnotaxones y ciertas condiciones ambientales más allá del área local de estudio. Finalmente, aunque ocupando el primer lugar de la investigación realizada, desarrollar una nueva técnica o metodología que facilitase el análisis icnológico de sondeos marinos modernos, resolviendo los problemas habituales al trabajar con este tipo de materiales.

Esta nueva metodología se basa en el tratamiento digital de imágenes de alta resolución y se puede aplicar siguiendo un proceso secuencial dividido en cuatro pasos: 1, ajustes de imagen; 2, estimación digital; 3, conteo de píxeles; 4, representación de icnofábricas. La aplicación de este método no solo mejora la visibilidad de las trazas fósiles sino que también aporta información icnológica interesante como es el porcentaje de bioturbación o la profundidad de penetración. Su utilidad en el análisis de icnofábricas ha sido demostrada en sondeos de la Expedición 339 del IODP, siendo de gran ayuda a la hora de caracterizar cada una de ellas. La utilidad de este método en la caracterización de icnofacies o en el color de los sedimentos también ha sido demostrada, aunque no forma parte del presente volumen (*Supplementary papers of Part II*).

La aplicación de esta metodología permitió llevar a cabo un análisis icnológico de detalle en los sondeos de materiales hemipelágicos extraídos en el *Site* U1385 con el fin de mejorar el registro climático del Plioceno al Holoceno. Un total de nueve icnotaxones fueron identificados (de mayor a menor abundancia: *Planolites*, *Palaeophycus*, *Thalassinoides*, *Thalassinoides*-like, *Taenidium*, *Zoophycos*, *Chondrites*, *Phycosiphon* y ?*Scolicia*), todos pertenecientes a la icnofacies de *Zoophycos*. En base características icnológicas como la asociación de trazas fósiles, grado de bioturbación o *tiering*, siete icnofábricas fueron diferenciadas. Según los resultados obtenidos, las condiciones de oxigenación y disponibilidad de nutrientes eran generalmente buenas, suficientes para mantener una comunidad más o menos diversa, aunque se identificaron algunos intervalos depositados bajo condiciones disaeróbicas basados en las características icnológicas. Otros parámetros paleoambientales como la tasa de sedimentación y consistencia del sustrato, no se registran variaciones mayores. La distribución de icnofábricas a lo largo de los sondeos (incluido en *Suplemetary papers of Part III*), permite caracterizar el paleoclima y la dinámica atmósfera/océano, siendo los cambios icnológicos relacionados con variaciones de corto (Terminaciones o Eventos Heinrich) o largo rango (cambios orbitales).

Además de este estudio general, la icnología en los intervalos asociados a los Estadios Isotópicos Marinos (MIS según sus siglas en inglés) 12 y 11 fue analizada en detalle. Este intervalo corresponde a uno de los periodos glaciares/interglaciares más extremos del Pleistoceno, siendo el MIS 11 uno de los periodos climáticos más parecidos al del Holoceno. El análisis en detalle se llevó a cabo integrando datos icnológicos con análisis de foraminíferos con el fin aportar una interpretación de detalle de las condiciones ambientales. Cambios notables en la distribución de las trazas fósiles fueron asociados a variaciones en la oxigenación y abundancia de nutrientes. Por otro lado, el análisis de foraminíferos reveló cambios en la productividad superficial y aporte de nutrientes que pueden ser correlacionados con las variaciones observadas en el análisis icnológico. Por lo tanto, las modificaciones de la comunidad macro- y micro-bentónica registradas son asociadas a cambios mayores en la ventilación de aguas profundas, posiblemente ligadas a variaciones de la circulación termohalina. De igual modo se realizó un estudio similar centrado en las Terminaciones 1, 2 y 4, aunque no forma parte de la presente tesis (*Supplementary papers of Part III*), revelando cambios asociados a la disponibilidad de oxígeno y nutrientes.

Finalmente, la relación entre la distribución de *Zoophycos* y determinadas condiciones de sedimentación y productividad fue estudiada en periodos glaciares-interglaciares. Un estudio en detalle de los intervalos donde *Zoophycos* es identificado alrededor de los últimos 1.5 Ma, reveló que su presencia puede ser ligada a periodos caracterizados por una tasa de sedimentación intermedia y una productividad estacionalmente alta. Esta relación es observada no solo en sondeos de la Expedición 339 del IODP, sino también en depósitos mundiales como el Mar del Sur de China o el Margen Occidental de África por ejemplo. Así pues, *Zoophycos* es propuesto como un indicador de periodos de aporte estacional de materia orgánica y productividad primaria en depósitos hemipelágicos a lo largo del Neógeno.

Adicionalmente, el estudio icnológico en depósitos de contornítas y flujos de gravedad probó la bioturbación como una herramienta de gran interés en la diferenciación de este tipo de depósitos. Esta es, por el momento, una investigación preliminar, no ha sido incluida entre los objetivos principales de la tesis. No obstante, debido a su potencial importancia, ha sido añadida como apéndice estrechamente relacionado con la presente Tesis.

PART I

INTRODUCTION AND GENERAL POINTS

Chapter 1

INTRODUCTION

The Southwest Iberian Margin, and concretely the Gulf of Cadiz, has been a focus of many studies during the last decades as it is a very interesting scientific area. Since the opening of the Gibraltar gateway at the end of the Miocene (e.g., Maldonado et al., 1999), an influx of water mass from the Mediterranean Sea to the Atlantic Ocean through the Strait of Gibraltar, called Mediterranean Outflow Water (MOW) (Figure 1.1), has affected this area and global circulation. As a consequence, a Contourite Depositional System (CDS) began to develop 5 Million years (Myr) ago (Stow et al., 2002; Hernández-Molina et al., 2006; Bozec et al., 2011), the Southwest Iberian Margin being recognized as the best contourite laboratory in the world (Expedition 339 Scientists, 2013a).

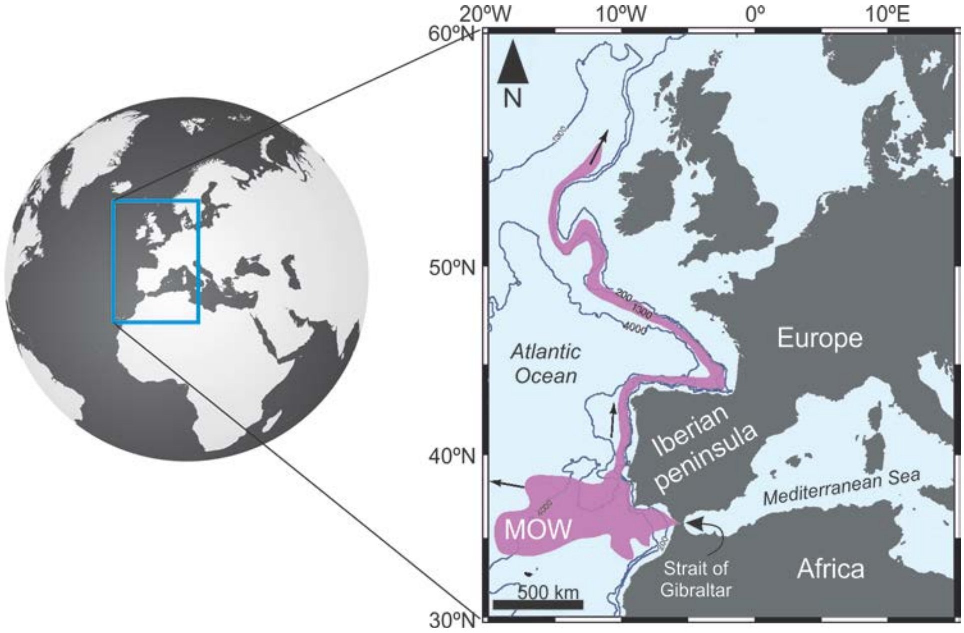

Fig. 1.1. Mediterranean Outflow Water (MOW) distribution (modified from Khélifi et al., 2009).

This CDS is dominated by expanded sedimentary deposits of drift sediments that allow for detailed studies of palaeoenvironmental conditions and their temporal changes (Llave et al., 2006). Moreover, because these deposits are clearly determined by the MOW activity, their analysis reflects MOW dynamics and sheds light on its evolution and influence in global circulation (Bigg et al., 2003).

Given the special scientific interest of this region, an oceanic expedition (IODP Expedition 339 "Environmental significance of the Mediterranean Outflow Water and its global implications") took place at the end of 2011 and beginning of 2012 to drill marine cores from seven sites, and obtain a huge amount of material to be studied in detail. Briefly, the goals of the expedition were related to the study of: a, the influence of the Gibraltar Strait opening; b, the MOW evolution and its impact on global circulation; c, the sedimentary architecture of CDS and the influence of sea level changes; d, tectonic influence in these deposits; and finally, e, an extra goal in a more distal site drilled to obtain a marine reference climate section from the Pleistocene (Expedition 339 Scientists, 2013a). To arrive at answers about these objectives, the expedition was made up of a scientific party of specialists in different disciplines —geochemistry, geophysics, palaeontology and palaeomagnetism, among others— who analyzed different topics to provide a multidisciplinary point of view. One of the key points, especially in this case where the primary sedimentary structures are scarce, is the study of the bioturbation: the ichnological approach. Although ichnology has become a very useful discipline in many studies, it is thus far underestimated in the study of modern marine cores. This fact can be clearly checked looking at the scientific staff of any drilling expedition, where bioturbation is rarely characterized by a specialist in ichnology.

Ichnology is the science that studies structures produced by organisms on or within the substrate, including all issues related to bioturbation, bioerosion and biodeposition (Pemberton et al., 1992; Bromley, 1996; Buatois and Mángano, 2011). This science can be divided in two fields: neoichnology (study of modern traces) and palaeoichnology (study of trace fossils). Both consider processes (interaction between tracemakers and substrate) and their products (resulting traces).

Since the second half of the twentieth century, ichnological studies have grown mainly due to the definition and development of ichnofacies and ichnofabric concepts, so that nowadays ichnology is held to be a very useful tool in palaeoenvironmental studies, especially in basin analysis (e.g., McIlroy, 2004; Buatois and Mángano, 2011; Knaust and Bromley, 2012) and applications to reservoir characterization (e.g., Pemberton, 1992; MacEachern et al., 2005). The ichnofacies model developed by Seilacher (1964, 1967a) entailed empirical observations of trace fossils assemblages associated with parameters related to the distance to coast, used as palaeobathymeters during the early years (Seilacher, 1967a; detailed review in Buatois and Mángano, 2011 and MacEachern et al., 2012). The ichnofacies concept has since been widely expanded to embrace the relationships between trace fossil associations and palaeoenvironmental conditions, not just bathymetry. It includes subtract consolidation, grain size, energy, nutrients, turbidity, or oxygen levels, among others, as well as the role of taphonomy (Buatois and Mángano, 2011; MacEachern et al., 2012). Although there were originally just six archetypical ichnofacies (*Skolithos*, *Cruziana*, *Zoophycos*, *Nereites*, *Glossifungites* and *Scoyenia*), currently 15 invertebrate ichnofacies are defined, including marine and continental ones (Figure 1.2 detailed review in Buatois and Mángano, 2011), and some vertebrate ichnofacies.

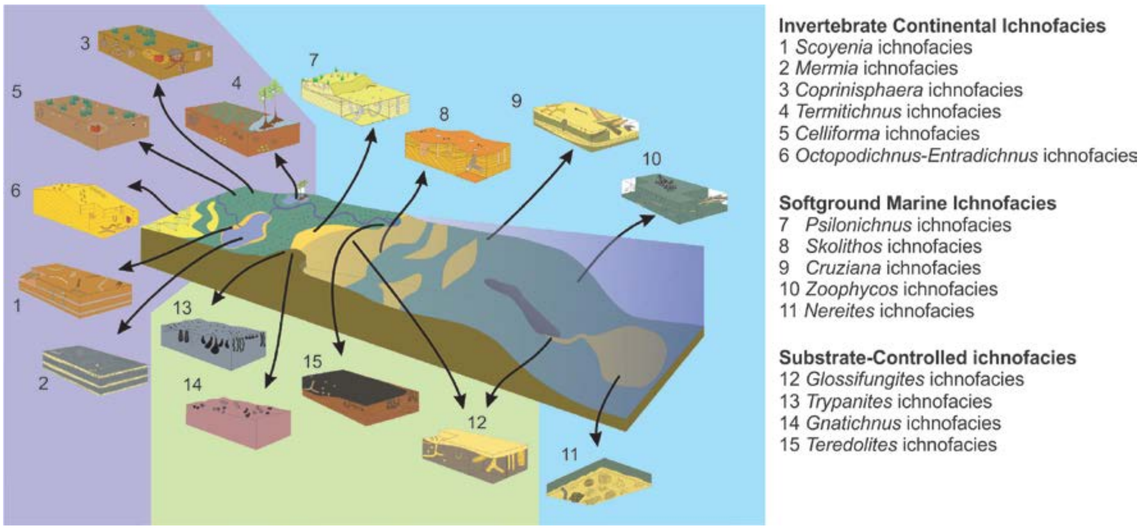

Fig. 1.2. Schematic diagram of invertebrate ichnofacies (slightly modified from Buatois and Mángano, 2011).

Later, in 1980's, Bromley and Ekdale (1986) proposed the ichnofabric concept referred to any textural and structural aspect of the substrate produced by bioturbation or bioerosion at any scale. It considers more features (primary sedimentary structures, diversity, cross-cutting relationships and tiering) than ichnofacies model and takes into account both discrete trace fossils and poorly defined burrow mottling (Bottjer and Droser, 1991; Buatois and Mángano, 2011). Ichnofabrics are divided in simple ichnofabrics, associated to just one ichnotaxa, and composite ichnofabrics where they are characterized by different suites of biodeformational structures (Ekdale et al., 2012). The application to palaeoenvironmental reconstructions (ichnofabric approach) has grown during the last decades (detailed review in Ekdale et al., 2012) based on outcrop and core analysis.

In sum, an integrative ichnological study that takes in ichnofacies and ichnofabric analyses has proven to be the most useful approach in ichnological research (McIlroy, 2008; MacEachern et al., 2010).

One of the most important points surrounding the ichnofabric approach is quantification of the amount of bioturbation. In this sense, several schemes have been proposed and two are commonly used. Firstly, Reineck (1963, 1967) proposed the Bioturbation Index (BI) to evaluate the amount of bioturbation in sediments, an approach that was later reviewed and applied in ichnofabric characterization by Taylor and Goldring (1993). This index comprises a scale of seven degrees from 0 (no bioturbation) to 6 (completely bioturbated), and each of them is accompanied by a short description (Figure 1.3A). In turn, Droser and Bottjer (1986) proposed the ichnofabric indices (*ii*) scale composed of six grades from 1 (no bioturbation) to 6 (completely bioturbated), illustrated by visual charts for different facies (Figure 1.3B).

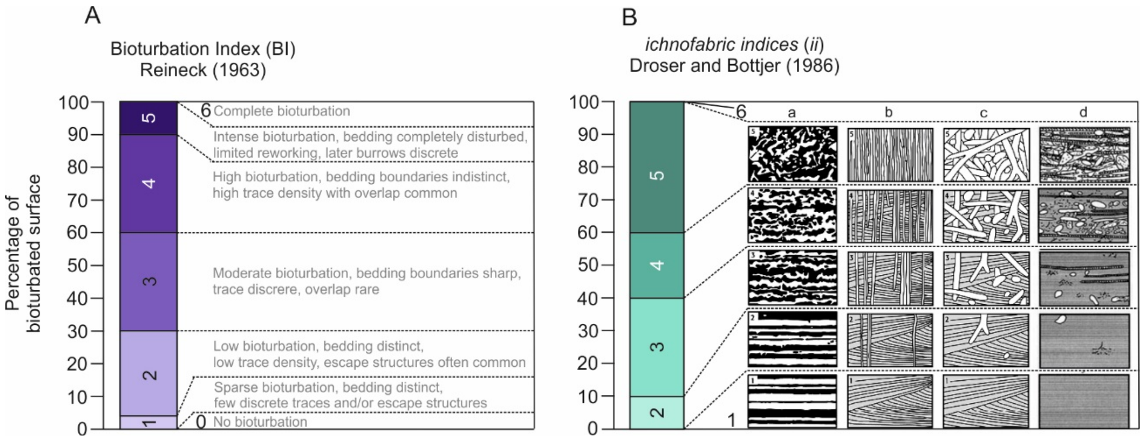

Fig. 1.3. Charts of different indices used to determine the amount of bioturbation. A, Bioturbation Index with short descriptions (extracted and modified from Reineck, 1963); B, ichnofabric indices and visual charts corresponding to: a, Generic Shelfal Ichnofabric; b, *Skolithos* Ichnofabric; c, *Ophiomorpha* Ichnofabric; d, Deep-Sea Ichnofabric (modified from McIlroy, 2004 according to Droser and Bottjer, 1989)

Quantification of bioturbation is very important for determining the intensity of bioturbation and to compare between different deposits. However, as pointed out above, further aspects such as tiering or overlapping must be considered to derive information about the origin of the ichnofabric (Buatois and Mángano, 2011).

In short, ichnological analysis has become a powerful tool in palaeoenvironmental studies and could play a very interesting role within the scope of the IODP Expedition 339. The framework of this Thesis lent us the opportunity to study the ichnology of retrieved modern marine cores from the Gulf of Cadiz and the Western Iberian Margin, to evaluate palaeoenvironmental conditions, palaeoclimatic changes, and atmosphere/ocean dynamics, at the South Iberian margin during the Pliocene and Pleistocene. The data obtained can be integrated with the rest of the information gathered by Expedition 339 in order to approach the main goals of the Expedition (see below).

Chapter 2

Research motivation, Objectives and Layout

The present PhD Thesis is focused on the ichnological analysis of modern marine cores, a topic that has not yet been fully explored. Different disciplines are involved in any drilling expedition, but ichnology is often not considered (unlike the case of IODP Expedition 339), or underestimated; bioturbation may just be included as a feature in sedimentological descriptions. However, it is quite common to find abundant bioturbation in drilled cores and ichnological analysis can provide valuable information about palaeoenvironmental conditions. Therefore, the main motivation of this PhD was to demonstrate the usefulness of ichnology in the study of modern cores extracted in drilling expeditions, based on the detailed ichnological study of cores from IODP Expedition 339. It is my hope that in the wake of the present thesis ichnology will be considered as a key tool in the study of modern marine cores, especially to support palaeoenvironmental interpretations, and that it will be included as a significant proxy in further expeditions.

The IODP Expedition 339 drilled the Gulf of Cadiz in view of its interest for the study of MOW influence, contourite deposits and climate variation since the Pliocene (as briefly described in Chapter 1). In this sense and considering the usefulness of ichnological analysis in palaeoenvironmental reconstructions and basin analysis (e.g., Knaust and Bromley, 2012), the proposed goals of this Thesis were:

1) To conduct a detailed ichnological study in the cores drilled to obtain a marine reference section about climate changes from the Pliocene onward, concretely hemipelagic cores from Site U1385 (details in Chapter 3). The study was focused on the ichnological attributes, their variation and distribution, and their relationship with palaeoenvironmental conditions and palaeoclimate.

2) To integrate the ichnological data with results from other disciplines so as to derive more detailed and complete information about some interesting intervals (Marine Isotope Stages, Heinrich events, etc.) in the record. Multidisciplinary studies allowed us to gain a global view of the response of the biotic community during periods of major changes in environmental parameters associated with palaeoclimate and atmosphere-ocean dynamics.

3) To elaborate patterns relating the presence and distribution of some interesting ichnotaxa and ichnofabrics to concrete environmental conditions. The application of proposed patterns in different worldwide examples allows us to evaluate if the characterized relationships would be of global interest.

4) To analyze the ichnological content of contourites and associated deposits (i.e., bottom current deposits), and to calibrate the usefulness of the ichnological analysis for interpretation of and discrimination among these deposits. They are widely studied nowadays as a number of controversial points still surround their existence, and bioturbation could be an interesting proxy to be considered. Finally, advances toward this goal have been included as an Appendix due to University requirements.

These were the preliminary or major objectives proposed, but at the beginning of the PhD study we encountered a handicap that probably explains the lack of ichnological studies in these kinds of sediments —the characterization of trace fossils in modern marine cores. As is well-known, when working with core material several limitations must be considered, such as the narrow surface exposed and the 2D view, making ichnological analysis no easy issue (e.g., Bromley 1996; Gerard and Bromley 2008). Obstacles may be even greater when working with modern marine deposits, consisting of softer materials characterized by a weak visibility of biogenic structures. This scarce visibility evidenced in the cores from IODP Expedition 339 led us to the addition of a new, but essential, objective:

5) To develop a methodology to facilitate ichnological analysis in modern marine cores based on high resolution image treatment. We expected to demonstrate the general usefulness of the proposed methodology, for application not only to our case study, but to core research in general.

The results of this PhD Thesis have been published in scientific journals, most of them included in the Science Citation Index, as research papers. Thus, the content and structure of most chapters are maintained, as it is mandatory that the original source be cloned. Additionally, published papers that are not included as the main body of this volume yet are strongly related to it have been added as Supplementary Papers of each part or as an Appendix. Accordingly, the present PhD Thesis is organized as follow:

Part I General introduction, divided into three chapters:

Chapter 1 introduces general points.

Chapter 2 explains the motivation, main objectives and some information about the structure of the present volume.

Chapter 3 describes the study area and provides information about IODP Expedition 339.

Part II Brief explanation of the methods used:

Chapter 4 includes a research paper about the novel method proposed and its application to the ichnofabric approach.

Supplementary papers of Part II are a compilation of those published papers about the new technique developed during the present PhD Thesis.

Part III Ichnological analysis in hemipelagic deposits from Site U1385, focused on palaeoenvironmental applications, palaeoclimate and atmosphere-ocean dynamics.

Chapter 5 consists of a research paper about a detailed ichnofabric analysis of cores drilled at this site.

Chapter 6 shows an integrative paper about the response of microbenthic and macrobenthic tracemaker communities to palaeoenvironmental changes associated with Marine Isotope Stages 12 to 11.

Chapter 7 constitutes an original research paper about a detailed study of *Zoophycos* distribution during glacial-interglacial variations, evaluating its potential use as a proxy.

Supplementary papers of Part III contain the ichnological papers that we have published on hemipelagic sediments from the same core during these years.

Part IV, as the last one, includes the final conclusions of the present PhD Thesis and offers future research recommendations.

Finally, one paper describing certain advances in ichnological analysis applied to the recognition and discrimination of gravity-flow deposits and contourites has been included as an **Appendix**.

Note that to obtain International Mention, the use of both English and Spanish language is mandatory. For this reason, the Abstract, Extended Abstract and part of the Conclusions are included in both languages.

Chapter 3

REGIONAL SETTING AND IODP EXPEDITION 339

3.1. International Ocean Drilling Program and Expedition 339

The International Ocean Drilling Program (IODP), called International Ocean Discovery Program since October 2013, is "*an international marine research collaboration that explores Earth's history and dynamics using ocean-going research platforms to recover data recorded in seafloor sediments and rocks and to monitor subseafloor environments*" (International Ocean Discovery Program, 2016). It is funded by three platforms representing twenty-five countries that provide scientists for marine research expeditions. The expeditions are developed to arrive at answers to fourteen challenging questions proposed in a science plan (International Ocean Drilling Program, 2011) divided in four groups:

Climate and Ocean Change: Reading the Past, Informing the Future
1 How does Earth's climate system respond to elevated levels of atmospheric CO_2?
2 How do ice sheets and sea level respond to a warming climate?
3 What controls regional patterns of precipitation, such as those associated with monsoons or El Niño?
4 How resilient is the ocean to chemical perturbations?

Biosphere Frontiers: Deep Life and Environmental Forcing of Evolution
5 What are the origin, composition, and global significance of deep subseafloor communities?
6 What are the limits of life in the subseafloor realm?
7 How sensitive are ecosystems and biodiversity to environmental change?

Earth Connections: Deep Processes and Their Impact on Earth's Surface Environment
8 What are the composition, structure, and dynamics of Earth's upper mantle?
9 How are seafloor spreading and mantle melting linked to ocean crustal architecture?
10 What are the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater?
11 How do subduction zones initiate and generate continental crust?

Earth in Motion: Processes and Hazards on Human Time Scales
12 What mechanisms control the occurrence of destructive earthquakes, landslides, and tsunami?
13 What properties and processes govern the flow and storage of carbon in the subseafloor?
14 How do fluids link subseafloor tectonic, thermal, and biogeochemical processes?

Concretely, this Thesis is involved in the first group of the science plan and was developed working with cores from IODP Expedition 339, which took place from November 2011 to January 2012 along the Southwestern Iberian Margin (Fig. 3.1). During this Expedition, seven sites were drilled, five of them in the Gulf of Cadiz, and the other two sites off the West Iberian margin. These areas were selected to study the Mediterranean Outflow Water (MOW) and its influence on global climate and circulation. Moreover, the study of contourite deposits was an important goal of the Expedition, as the Gulf of Cadiz is considered a contourite laboratory and more than 4.5 km of contourite cores were recovered.

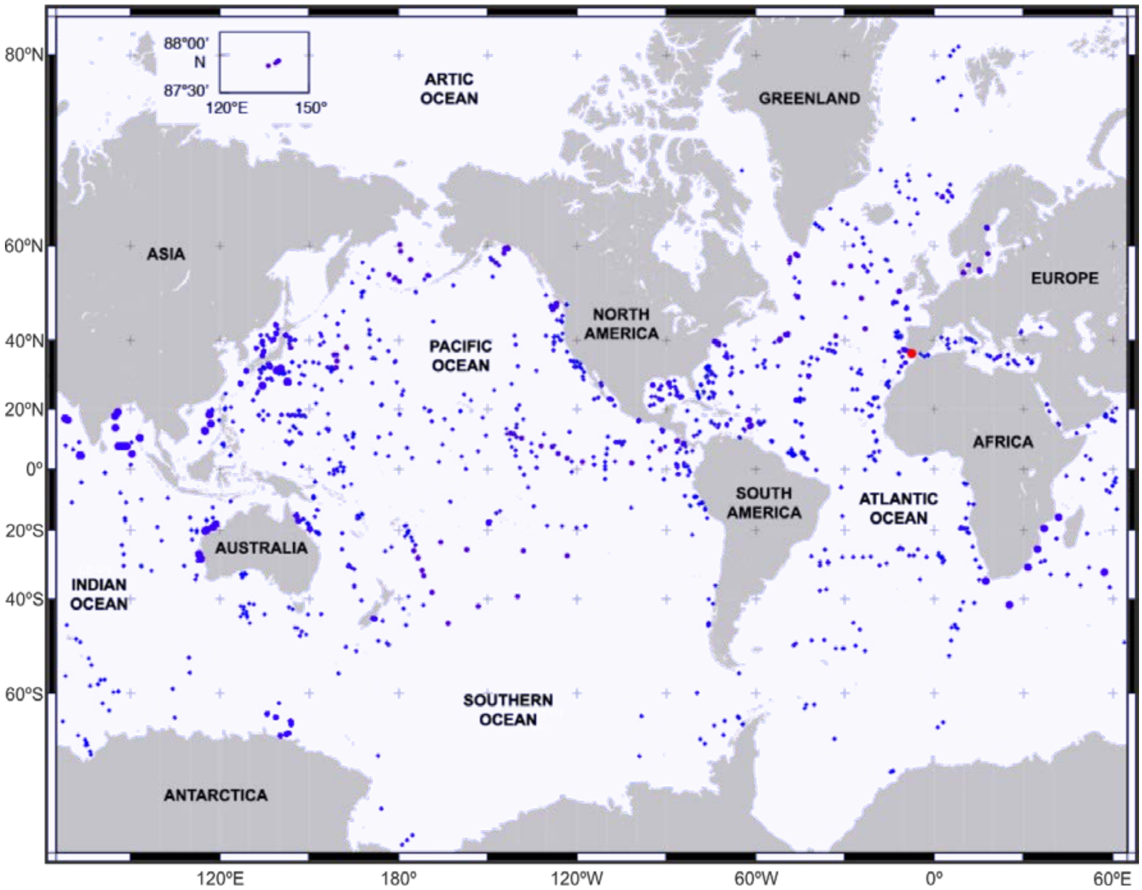

Fig. 3.1. IODP drilled holes (blue points) and Expedition 339 (red point). Modified from http://iodp.tamu.edu/scienceops/maps/iodp_odp_dsdp.jpg.

3.2. IODP Expedition 339 Objectives

Following the main points proposed in the Science Plan, five principal objectives were proposed and clearly expounded in the summary of the IODP Expedition 339 (Expedition 339, Scientists, 2013a), all of them included in the first group of the science plan (see above) about Climate and Ocean Change:

1- The study of oceanic gateways and their influence, as they are recognized as one of the main mechanisms involved in environmental change. In this sense, the Gibraltar Gateway represents a high influx of warmer and more saline water into the Atlantic Ocean.

2- Securing information about climate and palaeocirculation, analyzing the influence of the MOW in the reorganization of global circulation after the Miocene.

3- Analyzing how rapid climate change can determine high-resolution correlations from oceanic sediments. This Expedition drilled deposits that were produced under high sedimentation rates, thus providing a high fidelity record of climate changes that could be correlated with ice-core or terrestrial studies, offering insights as to this influence.

4- Addressing the sedimentary architecture associated with sea level changes. This point is mainly related with the timing, hiatuses, condensed sequences or palaeodepth, dealing with fundamental questions that remain unanswered.

5- Reconstruction of the neotectonic activity that controlled the MOW evolution by means of the influence on ocean topography.

After the expedition, a number of contributions have been published related with these objectives, likewise based on the study of Expedition 339 cores (e.g., Hernández-Molina et al., 2014; Smith, 2014; Bahr et al., 2015; Birner et al., 2016; Kuroda et al., 2016, etc.). Moreover, two monographs were edited in Marine Geology (volume 377) and Global and Planetary Change (Hodell et al., 2016 for more information) during the past few years.

IODP Expedition 339 Sites

The drilled sites (Fig. 3.2) can be arranged in two groups according to the main goal involved:

U1385 (Shackleton Site)

This Site is located off southwest Portugal (37º34.285'N; 10º7.562'W) and was drilled to gather a marine reference section of Quaternary climate evolution (Expedition 339, Scientists, 2013a). Concretely, five holes were drilled and two sets of hemipelagic deposits over the last 1.4 Myr were obtained, allowing for the construction of a complete stratigraphic section without noteworthy gaps or disturbed intervals, thereby improving the precision of climate correlations with polar ice cores and European terrestrial records.

The record from this site is a very uniform sequence mainly dominated by muds and clays with a fraction of biogenic carbonate material (Expedition 339, Scientists, 2013a, b). Although primary sedimentary structures are absent throughout cores, bioturbation is highly abundant, being the main secondary structure that can be observed.

Site U1385 was the most extensively studied in the present Thesis due to the palaeoclimatic goal and the abundance of bioturbation.

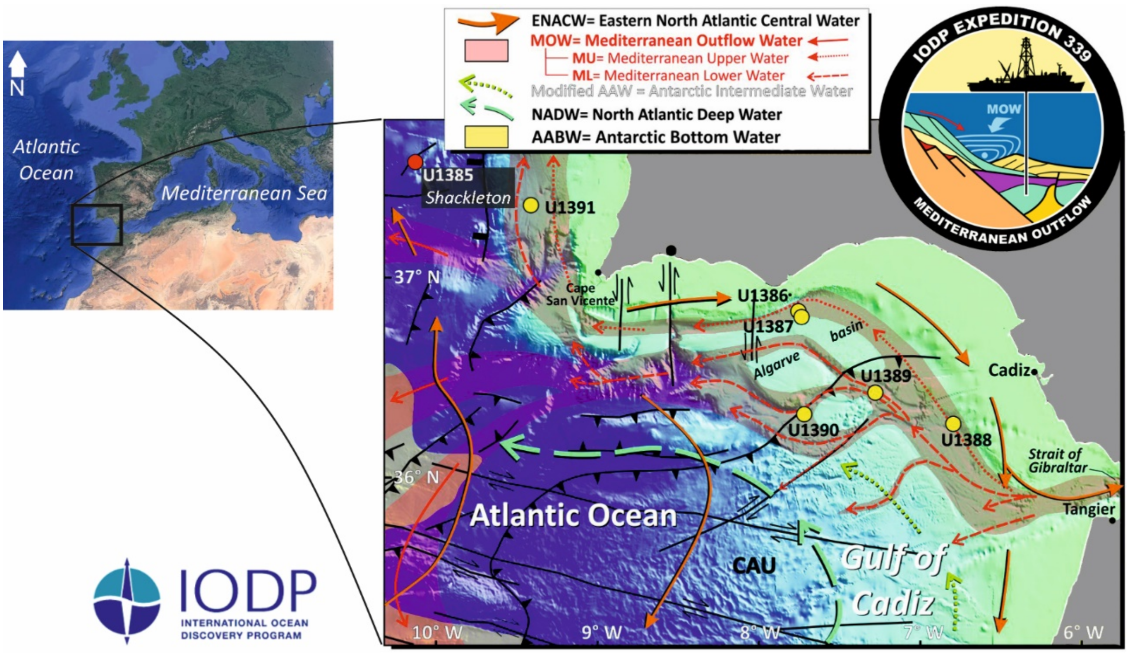

Fig. 3.2. IODP Expedition 339 sites location (modified from Hernández-Molina et al., 2014).

U1386-U1391

These six sites were collected to gather information about the contourite deposits influenced by the MOW, as well as its evolution and environmental implications (Expedition 339 Scientists, 2013a). The contourites were registered during the last 5 Myr, owing to MOW, and provide a detailed record to study the palaeocirculation patterns and evolution. The cores are mainly composed of contouritic deposits and were studied in lesser detail than the previous core in the present Thesis. However, a short description of all of them is included (Expedition 339 Scientists, 2013a):

Site U1386 was drilled on the southern Iberian Margin (36º49.685'N; 7º45.321'W) around 25 km southeast of the city of Faro (Portugal), recovering a thick section of muddy and silty contourites, with some intervals of turbidites, that represents a continuous record during the last 1.9 Myr. There is also evidence of seismic cycles, tectonic activity and slope instability.

Site U1387 is also located by the southern Iberian Margin (36º48.321'N; 7º43.1321'W) close to the previous one (around 4 km between the two). It recovers the same contouritic section, but with some notable differences, representing a continuous record over the last 1.8 Myr. Like Site U1386, it also offers tectonic evidence.

Site U1388 was drilled 50 km southwest of the city of Cadiz (Spain; 36º16.142'N; 6º47.647'W). The record is dominated by sandy contourites, being the best record of this facies, but the recovery was poor due to instability.

Site U1389 is located around 90 km west of Cadiz (36º25.515'; 7º16.683'W), in the channels and ridges area of the Contourite Depositional System (CDS), recording contouritic sediments and some minor hiatuses.

Site U1390 was drilled 130 km west of the city of Cadiz (36º19.110'N; 7º43.178'W), also drilled in the channels and ridges sector. The record is characterized by high sedimentation rates of contouritic muds and clean sands.

Finally, Site U1391 represents the most distal area of MOW influence (37º21.532'; 9º24.656'W), located 50 km northwest of Cape São Vicente. It is richer in mud, but the sedimentation rate is high, and registers several hiatuses representing periods of enhanced MOW activity.

Considering the recovered record in a first view, several points were addressed in the Expedition 339 summary (Expedition 339 Scientists, 2013a). Miocene deposits, drilled in two sites, register strong MOW evidence at 5.3 Ma after the opening of the Gibraltar Gateway. Around 4.2-4.5 Ma the first clear evidence of contourites is found, mixed with downslope resedimented deposits and hiatuses.

Expedition 339 Scientific Participants

The IODP Expedition 339 was composed of staff responsible for education, technical support and a scientific party specialized in several disciplines. Concretely, the scientific team was:

Francisco J. Hernández-Molina (Co-chief Scientist), Dorrik A.V. Stow (Co-chief Scientist), Carlos Alvarez Zarikian (Expedition Project Manager/Staff Scientist), Trevor Williams (Logging Staff Scientist), Johanna Lofi (Logging Staff Scientist), Gary D. Acton (Stratigraphic Correlator), André Bahr (Physical Properties Specialist), Barbara Balestra (Palaeontologist, nannofossils), Emmanuelle Ducassou (Sedimentologist), Roger D. Flood (Sedimentologist), José-Abel Flores (Palaeontologist, nannofossils), Satoshi Furota (Sedimentologist), Patrick Grunert (Palaeontologist, foraminifers), David A. Hodell (Inorganic Geochemist), Francisco J. Jimenez-Espejo (Physical Properties Specialist), Jin Kyoung Kim (Inorganic Geochemist), Lawrence A. Krissek (Sedimentologist), Junichiro Kuroda (Sedimentologist), Baohua Li (Palaeontologist, foraminifers), Estefanìa Llave Barranco (Observer), Lucas Lourens (Stratigraphic Correlator), Madeline D. Miller (Inorganic Geochemist), Futoshi Nanayama (Sedimentologist), Naohisa Nishida (Sedimentologist), Carl Richter (Palaeomagnetist), Francisco Javier Rodríguez Tovar (Ichnologist, shorebase staff), Ana Cristina Freixo Roque (Observer), Maria F. Sanchez Goñi (Palynologist), Francisco J. Sierro Sánchez (Palaeontologist, foraminifers), Arun D. Singh (Palaeontologist, foraminifers), Craig R. Sloss (Sedimentologist), Yasuhiro Takashimizu (Sedimentologist), Alexandrina Tzanova (Organic Geochemist), Antje Voelker (Palaeontologist, foraminifers), Chuang Xuan (Palaeomagnetist).

PART II

METHODOLOGY AND ICHNOLOGICAL APPROACHES

Chapter 4

ICHNOFABRIC CHARACTERIZATION IN CORES: A METHOD OF DIGITAL IMAGE TREATMENT

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ABSTRACT

Ichnofabric analysis, as a relatively young ichnological approach, has evidenced a rapid growth, showing its usefulness in basin analysis, with special attention to palaeoenvironmental interpretations. The ichnofabric approach has evolved from the description of the trace composition and the intensity of bioturbation to integrate detailed information of numerous ichnofabric features as primary sedimentary structures, ichnological diversity, ichnological features, cross-cutting relationships or tiering structure. This development has been associated with its application to the study of deep-sea sediments, especially in core research, which is not easy due to the particular features of cores. Here a method for improving ichnofabric characterization in modern marine cores is presented, based on digital high-resolution image treatment, with special emphasis on quantification of ichnofabric attributes. The proposed methodology is based on the modification of three image adjustments (image adjustment), the estimation of the percentage of the area occupied by bioturbation (digital estimation), the lateral and vertical quantification and comparison of pixel values from the infill of the trace fossils and the host sediment (pixel counting), and the integration of the obtained information in visual representations of ichnofabrics (the ichnofabric representation). The sequential application of these proposed steps allow a better identification of trace fossils, together with cross-cutting relationships, and then characterization of trace fossil assemblage, estimation of the percentage of bioturbation associated to each ichnotaxon, the whole ichnocoenosis, or a complete ichnofabric, differentiation between biodeformational structures and trace fossils, discrimination between ichnotaxa, distinction between passively and actively infilled structures, and evaluation of the depth of penetration and particular tracemakers.

4.1. Introduction

Ichnology has showed a rapid growth with the appearance and development of two significant paradigms: the ichnofacies model and ichnofabric concept (Knaust and Bromley, 2012). Ichnofabric analysis (from the first formal use of the term "ichnofabric" in Ekdale and Bromley, 1983, and the subsequent definition by Ekdale et al., 1984) continues to be of great interest, as is clearly revealed in several book chapters focusing on "The ichnofabric approach" (Buatois and Mángano, 2011), or "The ichnofabric concept" (Ekdale et al., 2012).

Ichnofabric analysis is more than a simple listing of trace fossils. It represents the interaction of numerous environmental conditions determining the original sedimentary fabric together with the bioturbation and bioerosion fabrics, and finally the taphonomic filter (Taylor et al., 2003; Buatois and Mángano, 2011; Ekdale et al., 2012). Ichnofabric characterization has evolved from the description of the trace composition and intensity of bioturbation to include a detailed information of major ichnofabric attributes, including primary sedimentary structures, ichnological diversity, ichnological features (i.e., dimensions of ichnotaxa), cross-cutting relationship and tiering structure (i.e., Taylor et al., 2003; McIlroy, 2004, 2007, 2008). All these features reveal a number of ecological and depositional controlling parameters and determine the usefulness of the ichnofabric approach in palaeoenvironmental interpretations and then in basin analysis.

The ichnofabric approach has been facilitated in several ways, including use of semi-quantitative flashcards to evaluate the intensity of bioturbation, one of the aspects playing an important role in the definition of ichnofabrics (from Reineck, 1963, 1967, to Droser and Bottjer, 1986, 1989, and Miller and Smail, 1997), the visualization of ichnofabric based on the graphic illustrations (Bromley, 1990, 1996; Taylor and Goldring, 1993; Taylor et al., 2003), and the use of computer-aided analysis to improve the visualization of key features on an ichnofabric (Magwood and Ekdale, 1994).

Quantification of bioturbation has been based on different index schemes, as the "Bioturbation Index" (BI) of Reineck (1963, 1967) and the "ichnofabric index" (ii) Droser and Bottjer (1986, 1989) for vertical sections, and the "bedding plane bioturbation index" (BPBI) of Miller and Smail (1997) for bedding planes. However, the variable use of these indices for scaling the degree of bioturbation, and their application when defining ichnofabric, sometimes creates a certain degree of confusion (Buatois and Mángano, 2011; Ekdale et al., 2012).

The illustration of ichnofabrics reveals their special characteristics. As pointed by Bromley (1996, p. 294), "Ichnofabrics are most conveniently communicated in visual terms, and I find it useful to represent them with a cartoon or icon that symbolically sums up the visual expression of each ichnofabric". This view was clearly demonstrated in the computer models for tiered ichnofabrics presented by Bromley (1990), in the Ichnofabric Constituent Diagram of Taylor and Goldring (1993), or in the ichnofabric icon, tiering diagram and percentage of bioturbation per tier illustrated by Bromley (1996). Sketches of tiering patterns, including cross-cutting relationships, associated with ichnofabric analysis have demonstrated explanatory approaches (Uchman et al., 2008; Rodríguez-Tovar and Uchman, 2011; Rodríguez-Tovar et al., 2011b, 2013). The usefulness of these ichnofabric representations is even more evident when working with composite ichnofabrics, associated with the superposition, replacement, of different, successive, communities or by the upward shifting of a tiered community (Bromley and Ekdale, 1986; Ekdale and Bromley, 1991; Ekdale et al., 1991; Lewis and Ekdale, 1992).

Digital enhancement of ichnofabric was revealed as a very useful tool in the description and interpretation of ichnofabrics, especially when working with deep-sea sediments, involving complex ichnofabrics. Magwood and Ekdale (1994) presented a computer analysis of complex ichnofabrics to sort out the episodes of bioturbation. They used matrix values and applied filter and other image transformations to support ichnofabric interpretation.

Previous methods of digital image treatment applied separately to ichnological analysis have been recently developed by the authors (Dorador and Rodríguez-Tovar, 2014; Dorador et al., 2014a, b). These methods show very useful to core analysis, especially when working with modern core material where differentiation between biogenic structures and host sediments can be comparatively difficult respect to well-diagenized cores. Dorador et al. (2014a) present an image treatment based on the modification of some image adjustments (i.e., levels, brightness and vibrance) to improve the ichnotaxa differentiation in cores, based on enhancing visibility of ichnological features, including internal structures. Latterly, a semi-automatic technique to determine the amount of bioturbation using computer software is presented (Ichnological Digital Analysis Images Package in Dorador et al., 2014b). The application of this method allows the determination of the percentage of bioturbated surface in a vertical section produced by each particular ichnotaxon, by a whole ichnocoenosis, or by several ichnocoenoses deriving from the work of different endobenthic communities. Recently, a quantitative study based on the characterization of pixel values from the infilling material of trace fossils and from the host sediment has been developed (Dorador and Rodríguez-Tovar., 2014). Quantification and comparison of pixel values improve the differentiation between ichnotaxa, especially between those with similar recurrent geometry, and between trace fossils in general and biodeformational structures, allowing, moreover, to evaluate the depth of penetration of trace fossils and to appraise the horizon of bioturbation.

Following the idea to advance in the application of digital image treatment methodology in the ichnological analysis, we present here an integrative use of the previous methods, to improve ichnofabric characterization in modern marine cores, All these methods will be sequentially integrated as a whole to approach major attributes of ichnofabrics (i.e., primary sedimentary structures, ichnological diversity, ichnological features, cross-cutting relationship and tiering structure). Moreover, data obtained by the application of this method will be integrated to the diagrams proposed by Taylor and Goldring (1993) and Bromley (1996), increasing the information summarized by both procedures.

4.2. Methods

The proposed digital method consists of successive steps allowing characterization and quantification of major attributes of ichnofabrics, and integrating the obtained information in the ichnofabric diagrams.

4.2.1. Step 1- Image adjustments

The first step (image adjustments) consists of the modification of three image adjustments (levels, brightness and vibrance) using Adobe Photoshop CS6 software (Fig. 4.1; Dorador et al. 2014a). Levels adjustment stretches the histogram of pixel values, increasing the distance between values. Brightness modifies the reflected light and controls the contrast by the modification of two parameters (contrast and brightness). Vibrance adjustment turns the image to less artificial tones resulting from the application of previous adjustments. The three adjustments are applied sequentially: firstly levels were applied to an image to drop the histogram and improve the contrast, secondly the brightness increases the contrast and control the brightness, and finally the vibrance allows slight modifications.

This step improves the visibility of biogenic structures. The resulting image allows a better identification of trace fossils and sometimes reveals some of them that had not been previously identified. Moreover, cross-cutting relationships can be recognized. After the application of this step, the trace fossils assemblage is characterized.

4.2.2. Step 2- Digital estimation

The second step (digital estimation) of the proposed method is applied to the previously treated image, allowing a quantitative evaluation of bioturbation. It consists in the execution of three methods (Similar Pixel Selection Method, SPSM; Magic Wand Method, MWM and Color Range Selection Method, CRSM). These methods are grouped in the 'Ichnological Digital Analysis Images Package' or IDIAP (Dorador et al., 2014b).

The IDIAP allows a quantitative estimation of the surface that is occupied by each ichnotaxon, the whole ichnocoenosis, or a complete ichnofabric. This step is especially relevant to evaluate other major attributes of ichnofabrics, such as is the intensity of bioturbation in terms of the Bioturbation Index (Reineck, 1963, 1967) or the ichnofabric index (Droser and Bottjer, 1986, 1989).

4.2.3. Step 3- Pixel counting

The third step (*pixel counting*) is based on the lateral and vertical quantification and comparison of pixel values from the infilling trace fossils and from the host sediment (Dorador and Rodríguez-Tovar, 2014). Each pixel is characterized by three values corresponding to red, green and blue channels, which are counted using Photoshop CS6 and then plotted with Matlab R2010. In general, fifty measured pixel values are considered the minimum amount to represent an ichnotaxon. The analysis of vertical variations requires a particular treatment with vertical subdivisions into 1 cm-thick portions.

Quantitative pixel analysis allows improve ichnofabric characterization, supporting some of the attributes approached during step 1 (image adjustments), and giving additional information by differentiation between biodeformational structures and trace fossils, discrimination of ichnotaxa, distinction between passively and actively infilled structures, and evaluation the depth of penetration of particular tracemakers.

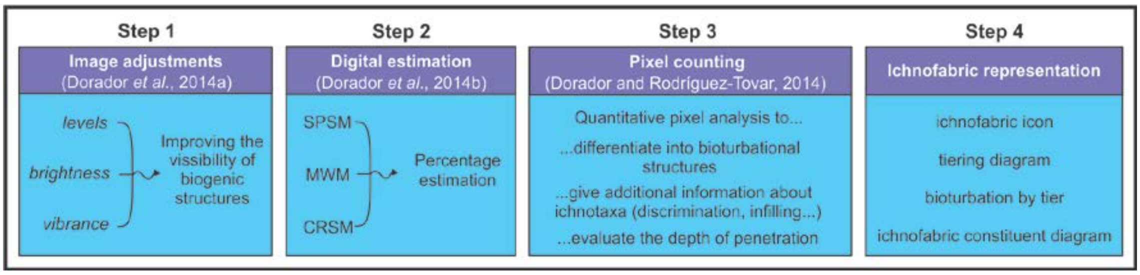

Fig. 4.1. Schematic diagram of the proposed method. SPSM, Similar Pixel Selection Method; MWM, Magic Wand Method; CRSM, Color Range Selection Method.

4.2.4. Step 4- Ichnofabric representation

Information obtained by the application of steps1 to 3 during the digital image treatment allows characterization of the major attributes of ichnofabrics, as primary sedimentary structures, ichnological assemblage, ichnological features, cross-cutting relationship and tiering structure. This information can be integrated in the usual ichnofabric representations, such as the Ichnofabric Constituent Diagram of Taylor and Goldring (1993), or in the ichnofabric icon, tiering diagram and percentage of bioturbation per tier of Bromley (1996) (Fig. 4.2). The digital method described here can support the original information included in the representation of Taylor and Goldring (1993) and Bromley (1996) by providing a better characterization of the trace fossils assemblage, and cross-cutting relationships, as well as by the addition of quantitative data (i.e., percentage of bioturbation by each ichnotaxa and size of structures). Moreover, new information can be added, such as the percentage of bioturbation per tier, which benefit from the quantitative estimations obtained by image treatment procedure, the estimation of the deep of penetration of particular ichnotaxa, and the pixel characterization of the differentiated ichnotaxa (Fig.4. 2).

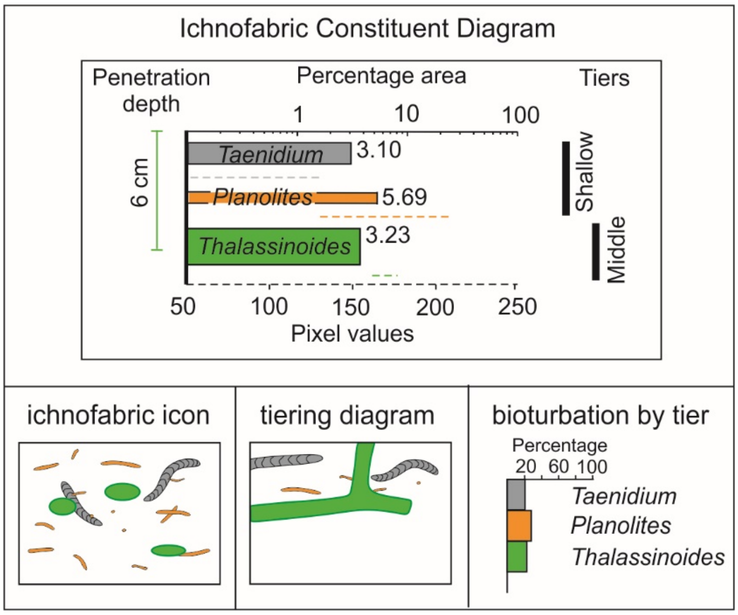

Fig. 4.2. Ichnofabric diagrams of a theoretical interval described in this study.

4.3. Case study

To evaluate the usefulness of the presented method, it has been applied in Pleistocene-Holocene marine cores from hemipelagic sediments drilled in the Gulf of Cádiz during IODP Expedition 339. Two intervals have been studied: A (U1385E-5H-4-A_104-111 cm), and B (U1385D-8H-4-A_74-85 cm). The studied materials were deposited in a hemipelagic setting, characterized by a low sedimentation rate and comparatively good environmental conditions for macrobenthic community. Tracemaker activity is important. Biodeformational structures produced a mottled background, and primary sedimentary structures are not observed. However, the Bioturbation Index values used in this study considers only the discrete traces fossils over the mottled background.

The methodology was applied following the sequential steps 1 to 3, resulting in the images illustrated in Fig. 4.3, and the obtained information was included in the representations used by Taylor and Goldring (1993) and Bromley (1996) (Figs 4.4 and 4.5).

4.3.1. Example A

In the example A (U1385E-5H-4-A_104-111 cm), after sequential application of steps 1 to 3, four ichnotaxa (*Chondrites*, *Palaeophycus*, *Planolites* and *Thalassinoides*) were identified (Fig. 4.3A). Especially relevant is the differentiation of *Chondrites*, which is very difficult to observe in the original image, and the cross-cutting relationships. According to the obtained results, 28.4% of the surface is represented by trace fossils and the rest of them (almost 70%) can be identified merely as biodeformational structures. *Thalassinoides* is the dominant ichnotaxon and represents 20.4% of the occupied area, *Chondrites* 4.1%, *Palaeophycus* 2.5% and *Planolites* 1.4%. Overlapping is identified in several parts; *Palaeophycus* is locally registered cross-cutting *Thalassinoides*, and *Chondrites* is overlapping the rest of ichnotaxa (*Palaeophycus*, *Planolites* and *Thalassinoides*) (Fig. 4.3A). According to these features, a *Thalassinoides* & *Chondrites* ichnofabric could be recognized. The percentage of bioturbation is lower than 30% that corresponds to a Bioturbation Index 2 (low bioturbation).

Integration of the obtained information to the visual ichnofabric representations (Taylor and Goldring, 1993; Bromley, 1996) allows a clear representation of the ichnofossil assemblage, including relative percentage of ichnotaxa, as well as illustration of cross-cutting relationships (Figs. 4.4A, 4.5A). A multi-tiered trace fossil community is differentiated. The first, shallowest tier, is represented by the mottled background and associated biodeformational structures, produced by organisms in the mixed layer. The shallow tier (1.4%) is formed by *Planolites*, produced by vagile deposit feeders. The middle tier (22.9%) is characterized by *Thalassinoides* and *Palaeophycus*, produced by semi-vagile and vagile deposit feeders. In the lower part, a deep tier (4.1%) is represented by *Chondrites*, reflecting permanent structures of possible chemosymbiotic organisms. The Ichnofabric Constituent Diagram of Taylor and Goldring (1993) contains the estimated depth of penetration of *Thalassinoides* belonging to the middle tier (around 4.5 cm of penetration depth), together with data on pixel values. The biodeformational structures are characterized by pixel values lower than 110 and discrete trace fossils from 98 to 203, and they therefore are usually lighter than the mottled background (Fig. 4.5A). Especially interesting is the short range of pixel for *Thalassinoides*, which could be useful for solving controversial situations and for rejecting a doubtful *Thalassinoides* assignment if values of the trace are not in this range.

Applied methodology improves characterization of trace fossil assemblage, with especial attention to *Chondrites*, difficult to differentiate directly on cores images without any treatment, and reveals significant cross-cutting relationship, allowing characterization of a well-developed deep tier. These improvements have significant palaeoecological consequences. Thus, the interpreted tiering structure could reveals gradual changes in the sediment; ichnological changes from shallow to deep tier could be consequence of decreasing oxygen in pore waters and increasing substrate consistency deeper in the sediment (see similar tiering structure in Rodríguez-Tovar and Uchman, 2004a, b).

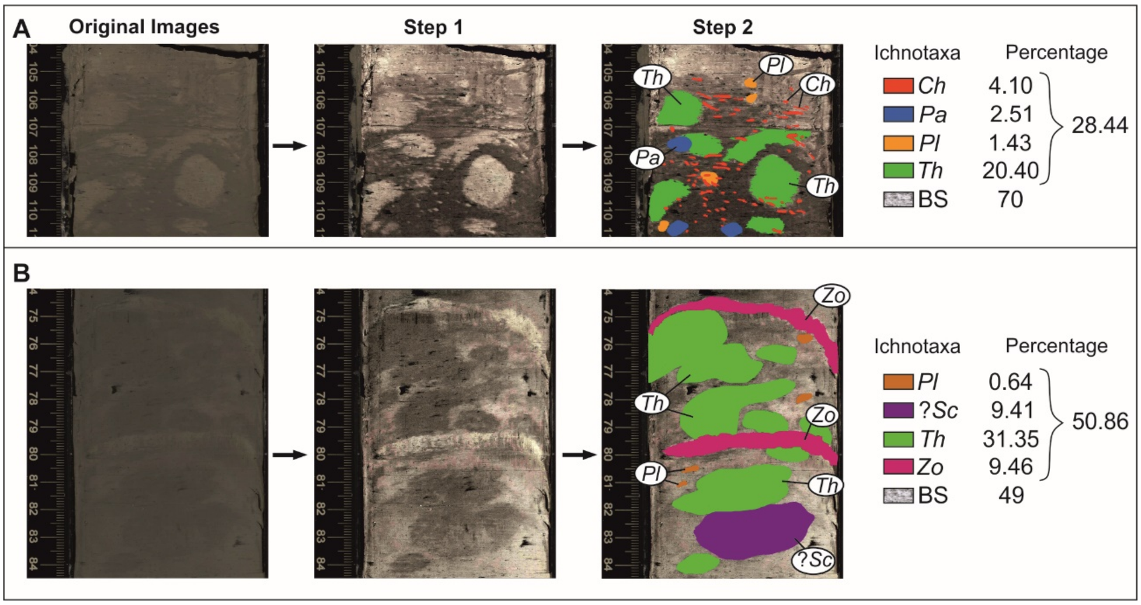

Fig. 4.3. Application of the method in two examples in an IODP core. Original images, results after first and second steps and percentage represented by each ichnotaxa are shown from left to right. *Ch*, *Chondrites*; *Pa*, *Palaeophycus*; *Pl*, *Planolites*; ?*Sc*, ?*Scolicia*; *Th*, *Thalassinoides*; *Zo*, *Zoophycos*; BS, Biodeformational Structures.

4.3.2. Example B

Example B (U1385D-8H-4-A_74-85 cm), reveals the usefulness of the digital image treatment by the great difference between the original image and that obtained after the application of the first step. The trace fossil assemblage is well differentiated and cross-cutting relationship clearly observed (Fig. 4.3B). *Planolites*, ?*Scolicia*, *Thalassinoides* and *Zoophycos* are identified. In this case the 50.9% of the observed interval is occupied by trace fossils and almost the 50% by biodeformational structures. *Thalassinoides* is the dominant structure with a 31.4%, *Zoophycos* and ?*Scolicia* are frequent (9.5% and 9.4%, respectively) and *Planolites* is rare (0.6%). In this example, *Zoophycos* is seen cross-cutting *Thalassinoides*. A *Thalassinoides* and *Zoophycos* ichnofabric can be defined. The bioturbation percentage is almost 51% and therefore the Bioturbation Index is 3, indicative of moderate bioturbation (Reineck, 1963).

As in the first example (A), the obtained information improved visual ichnofabric representations (Figs. 4.4B, 4.5B). In example B, the mottling produced by organisms that bioturbated the mixed layer corresponds to the shallowest tier. The shallow tier is poorly represented by scarce *Planolites* (0.6% of the observed bioturbated area). The middle tier is comparatively well developed, representing ~41% of the bioturbated area, characterized by structures of vagile and semi-vagile deposit feeders, consisting of *Thalassinoides* and ?*Scolicia*. The deepest tier also is well registered (9.5 %) showing the activity of *Zoophycos* tracemakers. As added in the Ichnofabric Constituent Diagram (Fig. 4.5B), *Thalassinoides* belonging to the middle tier coming from 4 to 8 cm above, according to the information provided by the quantitative pixel analysis. In this example, pixel values corresponding to the biodeformational structures are commonly higher than those from the discrete trace fossils, as the mottled background is lighter than traces, except *Zoophycos* that is lighter (Fig. 4.5B). In this *Thalassinoides* and *Zoophycos* ichnofabric, the narrow range of Thalassinoides pixels, is useful for recognition of this structure.

In this example B, applied methodology has been demonstrated very useful for describing the tiering pattern, especially the well-developed middle tier. Differentiation between *Thalassinoides* and ?*Scolicia* has been possible, as well as a detailed characterization of *Thalassinoides*, including the horizon of bioturbation. Thus, good and probably prolonged palaeoenvironmental conditions deeper into the sediment, associated to the middle tier, can be envisaged, as available benthic food and firmer substrates.

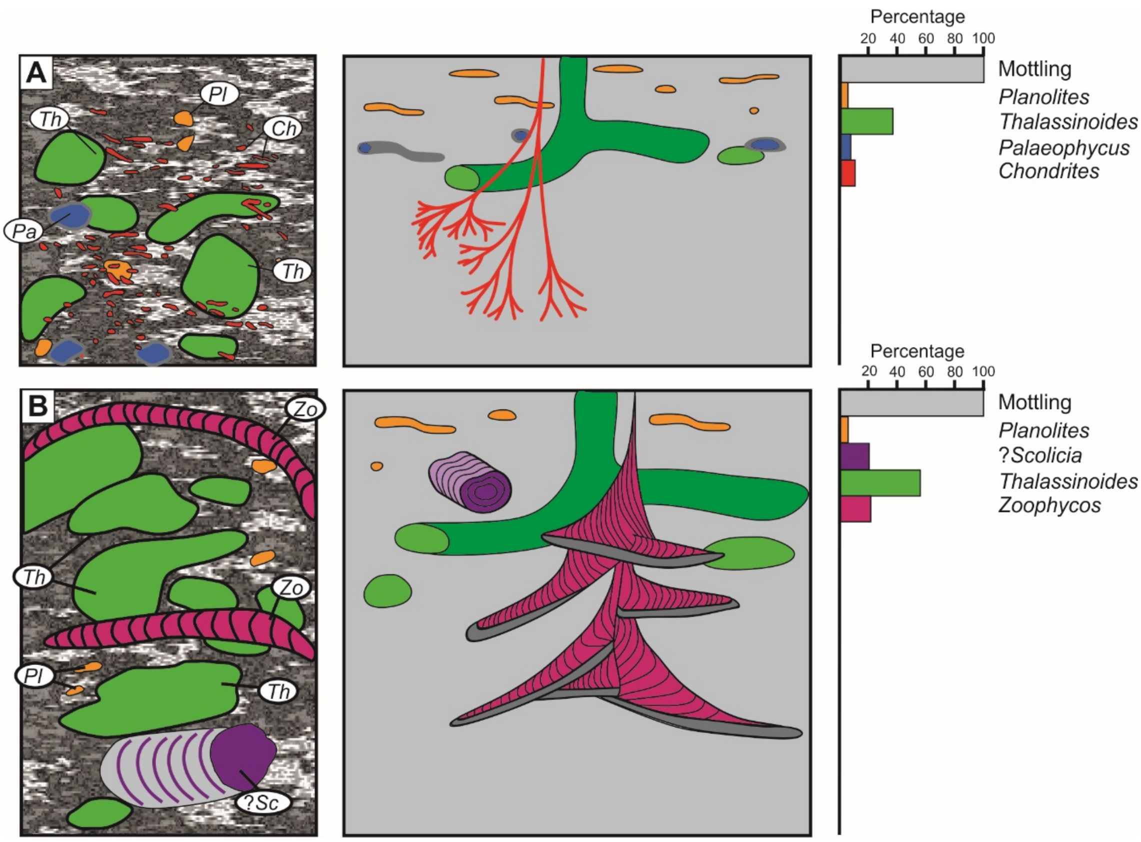

Fig. 4.4. Ichnofabric icon, tiering diagram and amount of bioturbation per tier of example A (above) and B (below). *Ch*, *Chondrites*; *Pa*, *Palaeophycus*; *Pl*, *Planolites*; ?*Sc*, ?*Scolicia*; *Th*, *Thalassinoides*; *Zo*, *Zoophycos*.

4.4. Conclusions

The digital image method, presented here, is a very useful tool for ichnofabric investigations in cores. The methodology provides detailed information on major attributes of ichnofabrics, including primary sedimentary structures, ichnological diversity, ichnological features (i.e., dimensions of ichnotaxa), cross-cutting relationship and tiering structure, with special applications to quantification.

The method consists of four steps: i) the first step (image adjustment) consists of the modification of three image adjustments using Adobe Photoshop CS6 software, allowing a better identification of trace fossils, together with cross-cutting relationships, and then characterization of trace fossil assemblage; ii) the second step (digital estimation) is based on the application of the Ichnological Digital Analysis Images Package (IDIAP) to estimate the percentage of bioturbation associated to each ichnotaxon, the whole ichnocoenosis, or a complete ichnofabric; iii) and the third step (pixel counting) consists of lateral and vertical quantification and comparison of pixel values from the infill of the trace fossils and the host sediment, giving additional information on differentiation between biodeformational structures and trace fossils, discrimination between ichnotaxa, distinction between passively and actively infilled structures, and evaluation the depth of penetration or particular tracemakers; and iv) the last step (ichnofabric representation) consists of the integration of the obtained information in the ichnofabric representations, improving visualization of ichnofabrics.

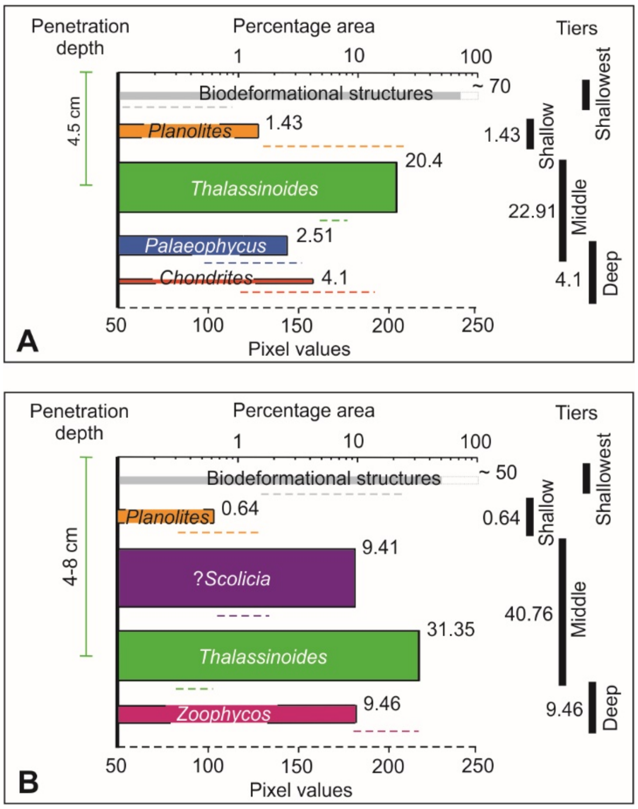

Fig. 4.5. Ichnofabric Constituent Diagram (ICD) of the ichnofabrics characterized in examples A and B. Percentage of surface (bar length), size (bar thickness) and tiering (order) of each ichnotaxon are represented in this diagram. The amount of bioturbation per tier (right), range of pixel values (broken lines) and penetration depth (left) are included in the original ICD in Figure 4.2.

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Supplementary Papers of PART II

- Digital image treatment applied to ichnological analysis of marine core sediments (Facies, 2014)

- Quantitative estimation of bioturbation based on digital image analysis (Marine Geology, 2014)

- A novel application of digital image treatment by quantitative pixel analysis to trace fossil research in marine cores (Palaios, 2014)

- Application of digital image treatment to the characterization and differentiation of deep-sea ichnofacies (Spanish Journal of Palaeontology, 2015)

- High resolution digital image treatment to color analysis on cores from IODP Expedition 339: Approaching lithologic features and bioturbational influence (Marine Geology, 2016)

Facies (2014) 60:39–44
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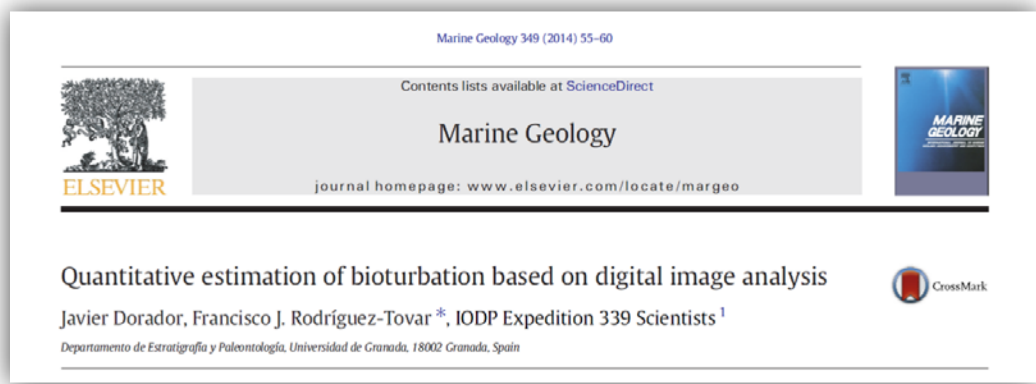
ORIGINAL ARTICLE

Digital image treatment applied to ichnological analysis of marine core sediments

Javier Dorador · Francisco J. Rodríguez-Tovar ·
IODP Expedition 339 Scientists

ABSTRACT

Characterization of trace fossils in marine core sediments is, most times, difficult due to the weak differentiation between biogenic structures and the host sediment, especially in pelagic and hemipelagic facies. This problem is accentuated where a high degree of bioturbation is associated with composite ichnofabrics. Simple methods are presented here based on modifications to image features such as contrast, brightness, vibrance, saturation, exposure, lightness, and color balance using the software Adobe Photoshop CS6 (Adobe Systems, San Jose, CA, USA) to enhance visibility and thus allow for a better identification of the trace fossils. Adjustments involving brightness, levels and vibrance generally give better results. This approach was applied to marine cores of pelagic and hemipelagic sediments obtained from the Integrated Ocean Drilling Program Expedition 339, Site U1385. Enhancing the digital images facilitates ichnological analysis through improving the visibility of weakly observed trace fossils, and in some cases revealing traces not detected previously.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Quantitative estimation of bioturbation based on digital image analysis

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ABSTRACT

Quantitative determination of modification of primary sediment features, by the activity of organisms (i.e., bioturbation) is essential in geosciences. Some methods proposed since the 1960s are mainly based on visual or subjective determinations. The first semiquantitative evaluations of the Bioturbation Index, Ichnofabric Index, or the amount of bioturbation were attempted, in the best cases using a series of flashcards designed in different situations. Recently, more effective methods involve the use of analytical and computational methods such as X-rays, magnetic resonance imaging or computed tomography; these methods are complex and often expensive. This paper presents a compilation of different methods, using Adobe® Photoshop® software CS6, for digital estimation that are a part of the IDIAP (Ichnological Digital Analysis Images Package), which is an inexpensive alternative to recently proposed methods, easy to use, and especially recommended for core samples. The different methods — “Similar Pixel Selection Method (SPSM)”, “Magic Wand Method (MWM)” and the “Color Range Selection Method (CRSM)” — entail advantages and disadvantages depending on the sediment (e.g., composition, color, texture, porosity, etc.) and ichnological features (size of traces, infilling material, burrow wall, etc.). The IDIAP provides an estimation of the amount of trace fossils produced by a particular ichnotaxon, by a whole ichnocoenosis or even for a complete ichnofabric. We recommend the application of the complete IDIAP to a given case study, followed by selection of the most appropriate method. The IDIAP was applied to core material recovered from the IODP Expedition 339, enabling us, for the first time, to arrive at a quantitative estimation of the discrete trace fossil assemblage in core samples.

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A NOVEL APPLICATION OF DIGITAL IMAGE TREATMENT BY QUANTITATIVE PIXEL ANALYSIS TO TRACE FOSSIL RESEARCH IN MARINE CORES

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ABSTRACT

Ichnological analysis in cores has grown substantially in the past two decades because of its importance in fields such as paleoecology, biostratigraphy, or reservoir characterization. Yet core analysis entails some added difficulties in comparison to ichnological outcrop study, especially in modern marine sediments. Quantitative pixel analysis conducted on high-resolution images is used to facilitate the study of bioturbation in marine cores from site U1385 of IODP Expedition 339 in the Gulf of Cádiz. Lateral and vertical variation of pixel values obtained from the infilling trace fossils and from the host sediment are revealed to be highly useful to: (1) differentiate between trace fossils and biodeformational structures, including the host sediment; (2) discriminate between ichnotaxa (i.e., *Palaeophycus* vs. *Planolites*); (3) differentiate between passively and actively infilled structures (e.g., *Thalassinoides* vs. *Planolites*), and (4) characterize the horizon of bioturbation and thus evaluate the depth of penetration of particular tracemakers.

SPANISH JOURNAL OF PALAEONTOLOGY

Application of digital image treatment to the characterization and differentiation of deep-sea ichnofacies

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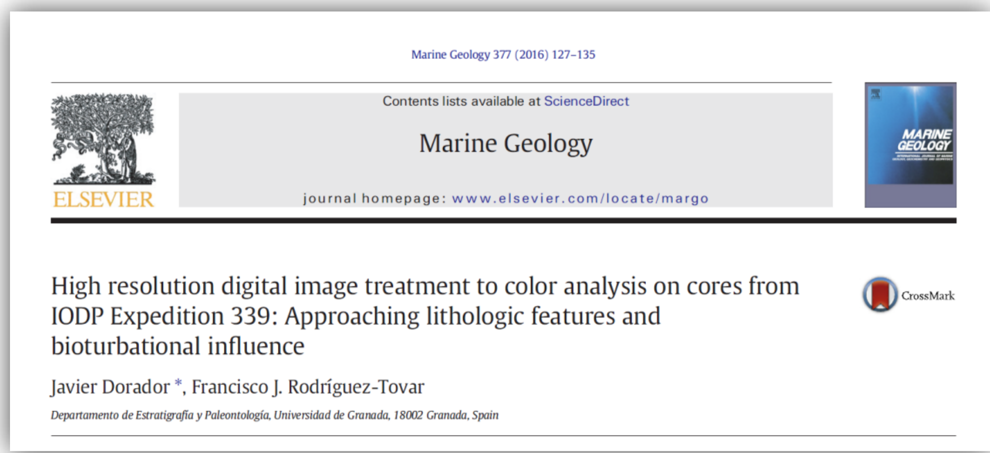
ABSTRACT

The ichnofacies model proposed by Seilacher in the 1960's stands as one of the main tools used in the ichnological research. Based on the integration of numerous ichnological and sedimentological observations, it entails a precise characterization of the trace fossil assemblage. Differentiation of trace fossils may be relatively easy in outcrops, but cores are a different matter, particularly modern marine cores. Difficulties are even more accentuated in deep-sea pelagic and hemipelagic, non-turbiditic, fine-grained deposits. The application of digital image treatment can facilitate trace fossil identification and improve deep-sea ichnofacies characterization on modern cores. The method proposed here was applied to cores from the IODP Expedition 339 (Site U1385). Eight ichnotaxa —*Chondrites*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Taenidium*, *Thalassinoides*, *Thalassinoides*-like structures and *Zoophycos*—as well as some horizontal grouped circular structures interpreted as trails (?*Nereites*) were recognized. The archetypical *Zoophycos* ichnofacies is identified, but characteristic elements belonging to the *Nereites* ichnofacies and to the distal expression of *Cruziana* ichnofacies are locally recognized. Thus, the applied methodology allows differentiating between different expressions of the *Zoophycos* ichnofacies and to approach subtle changes in the involved environmental parameters affecting tracemakers.



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High resolution digital image treatment to color analysis on cores from IODP Expedition 339: Approaching lithologic features and bioturbational influence

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ABSTRACT

Color analysis was conducted on selected cores from Sites U1385 and U1389 from IODP Expedition 339 based on a recently developed high resolution digital image treatment to explore its relationship with lithologic features (e.g., percentage of sand). This first step can be of potential usefulness in characterizing/discriminating between different types of registered sediments in the IODP Expedition 339 — turbidites, contourites and associated sediments — and then for more general studies involving different lithologies, sedimentary parameters and ichnological variations. Differentiation between types of deposits holds particular interest in the context of the Mediterranean Outflow Water (MOW) evolution and related depositional processes, whose study was one of the main aims of IODP Expedition 339. Color characterization was executed on high resolution digital images by applying a method based on adjustment modification — including levels, brightness and vibrance — followed by pixel measurement. The applied methodology allows for a precise characterization of colors, improving upon previous color descriptions by means of Munsell Color conducted on-board, during Expedition 339 itself. The studied interval is subdivided into four parts based on grain size analysis and color. According to pixel values these parts are identified as: A (120), B (90), C (140), and D (160), being well correlated with the corresponding lithology. Parts A and C, with similar pixel values, correspond to calcareous silty mud/mudstone, part B would correlate with calcareous silty sand/sandstones, and part D corresponds to calcareous mud. Sand content distribution throughout the studied interval bears a close relationship with the differentiated parts A to D. Intervals having a higher percentage of sand present a lower mean pixel value and darker color, whereas the finer grained intervals contain sediments lighter in color, represented by higher pixel values. However, as proved, the proposed relationship between color/sedimentological features/type of sediment must be considered with some caution. Ichnological analysis reveals the influence of trace fossils on color variations in the sediment, regardless of the size of traces and amount of bioturbation, the infilling material of trace fossils being the most determinant factor. Thus, lower bioturbated surfaces (6%)

by small trace fossils (*Chondrites*) show higher influence on color variations (102 vs 107) than higher bioturbated surfaces (25%) by large trace fossils (*Thalassinoides*) (110 vs 112), due to the color of the infilling material, 56 in the case of *Chondrites* and 90 in the case of *Thalassinoides*. Thus, a detailed ichnological analysis should accompany the sedimentological study of deep-sea modern cores in order to avoid misinterpretations of the sedimentological parameters involved.

PART III

ICHNOLOGICAL CHARACTERIZATION OF HEMIPELAGIC DEPOSITS FROM IODP SITE U1385

Chapter 5

ICHNOLOGICAL ANALYSIS OF PLEISTOCENE SEDIMENTS FROM THE IODP SITE U1385 "SHACKLETON SITE" ON THE IBERIAN MARGIN: APPROACHING PALAEOENVIRONMENTAL CONDITIONS

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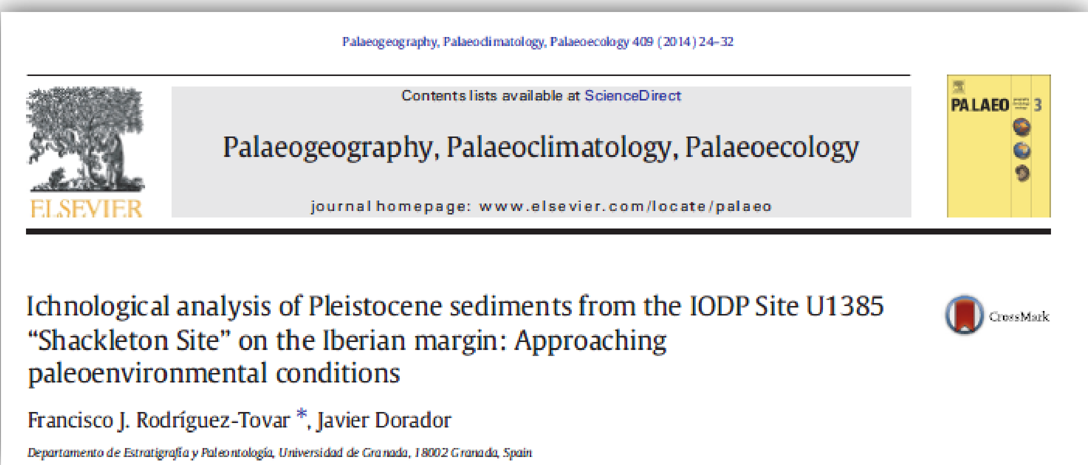

Palaeogeography, Palaeoclimatology, Palaeoecology 409 (2014) 24–32

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Ichnological analysis of Pleistocene sediments from the IODP Site U1385 "Shackleton Site" on the Iberian margin: Approaching paleoenvironmental conditions

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ABSTRACT

Ichnological analysis, focused on trace fossil assemblages and an ichnofabric approach, with special attention to cross-cutting relationships, tiering, relative abundances and bioturbation degrees, has been used to assess environmental parameters affecting the Pleistocene macrobenthic tracemaker community at the IODP Expedition 339, Site U1385 "Shackleton Site" on the Iberian Margin. The trace fossil assemblage consists of abundant *Planolites*, frequent yet sparsely distributed *Palaeophycus*, *Thalassinoides* (and *Thalassinoides*-like structures), and *Taenidium*, and localized *Zoophycos* and *Chondrites*. Other ichnotaxa, such as *Phycosiphon* and ?*Scolicia*, are rare. This assemblage is typical of the *Zoophycos* ichnofacies, though the distal expression of the *Cruziana* ichnofacies has a similar composition. Ichnofabrics reveal variable substrate colonization, with well defined cross-cutting relationships and tiering distribution. Differentiated ichnofabrics are: Green mottled ichnofabric, *Planolites* ichnofabric, *Taenidium* & *Planolites* ichnofabric, *Thalassinoides*-like & *Palaeophycus* ichnofabric, *Planolites* & *Thalassinoides*/*Thalassinoides*-like ichnofabric, *Zoophycos* ichnofabric, and *Chondrites* ichnofabric, usually showing gradual transitions. A multi-tiered assemblage can be envisaged, with differentiation of the shallowest (biodeformational structures), shallow (*Planolites*, *Palaeophycus* and even *Taenidium*), middle (*Thalassinoides*/*Thalassinoides*-like structures), and lower (*Zoophycos* and *Chondrites*) tiers. Overall, good bottom and pore-water oxygen conditions and organic matter availability can be interpreted, but rare dysaerobic intervals might be interpreted, related with an opportunistic, record of *Zoophycos* and *Chondrites*. A constant rate of sedimentation shows only minor variations as revealed by ichnofabric succession. Soupy, soft, and stiffgrounds are interpreted as inducing changes in ichnological features. Salinity and temperature have a minor incidence on the macrobenthic tracemaker community, causing only small changes in the trace fossils.

Keywords: Ichnofabrics, Pelagic-hemipelagic core deposits, Integrated Ocean Drilling Program, Expedition 339, Site U1385, Iberian margin

5.1. Introduction

IODP Expedition 339 drilled, from November 2011 to January 2012, a total of five sites in the Gulf of Cádiz (U1386-U1390) and two off the west Iberian margin (U1385 and U1391) (http://iodp.tamu.edu, Fig. 5.1) (Expedition 339 Scientists, 2012, 2013a). The drilled area is especially interesting for palaeocenographic aims; the Gulf of Cádiz is a key location to study the Mediterranean Outflow Water (MOW) through the Gibraltar Gateway and its influence on global circulation and climate, as well as to interpret the effects of tectonic activity on the evolution of the Gibraltar Gateway and on margin sedimentation (Expedition 339 Scientists, 2013a). In particular, the proposed drilling program in the studied area offers the opportunity to approach five broad scientific objectives (Expedition 339 Scientists, 2013a): a) understand the opening of the Gibraltar Gateway and onset of MOW, b) determine MOW palaeocirculation and global climate significance, c) establish a marine reference section of Pleistocene climate, d) identify external controls on sediment architecture of the Gulf of Cádiz contourite depositional system (CDS) and West Iberian margin, and e) ascertain synsedimentary neotectonic control on architecture and evolution of the CDS. From these general goals, especially interesting reveals objective (c), as the establishment of a marine reference section for palaeoclimatic record during Pleistocene. With this general goal, Site U1385 was positioned at the "Shackleton site" on the Portuguese margin (Expedition 339 Scientists, 2013b).

Site U1385 (37º34.285´N, 10º7.562´W) (Fig. 5.1) consist of a continuous record of pelagic-hemipelagic sediments from the Holocene to 1.45 Ma (Fig. 5.2), and became a marine-terrestrial-ice core point of reference for the study of orbital and sub-orbital (millennial-scale) variability. The research of Site U1385 is based on an integrative analysis involving different research specialties, including wireline logging, sedimentology, stratigraphic correlation, sediment physical properties, geochemistry, and micropalaeontology. In this context, an often underestimated approach in core study now underway at Site U1385 consists of detailed ichnological analysis.

Ichnological research underwent rapid growth at the beginning of the twenty-first century, held to be of potential interest in a wide range of fields, from palaeobiology, palaeoecology, biostratigraphy and evolutionary aspects, to sedimentology and even reservoir characterization. Apart from trace fossil assemblages (i.e., their composition, abundance, ichnological features), the ichnofabric approach has recently been applied to evaluate palaeoenvironmental changes due to variations in depositional and ecological parameters affecting tracemakers. Variations in palaeoxygen conditions, nutrient availability, rate of sedimentation, or sub-environmental fluctuations, among others, have been interpreted based on ichnofabric analysis (see Ekdale et al., 2012). Its usefulness is particularly welcome in core samples, whether from shallow and continental environments or deep-sea deposits (Knaust, 2009a).

The aim of the current research is the use of trace fossils as a proxy to interpret paleoenvironmental conditions affecting the macrobenthic environment at the Pleistocene in the western Iberian margin, based on the ichnological analysis of Site U1385; characterization of trace fossil assemblage and ichnofabric approach supported by a digital image treatment of the studied core.

5.2. The "Shackleton Site" (IODP Site U1385)

Site U1385, located off the west Iberian Margin (Fig. 5.1), was drilled near the position of Core MD01-2444 (Skinner and Elderfield, 2007; Voelker and de Abreu, 2011; Channell et al., in press), at 2585 mbsl (meters below sea level). The core MD01-2444 belongs to a series of cores retrieved from the SW Iberian Margin by the R/C Marion Dufresne in 1995, 1999 and 2011, including Core MD95-2042 (the "Shackleton Site"), used as a key archive to approach millennial-scale climate variability over the last glacial cycle (Shackleton et al., 2000, 2004). The "Shackleton Site" on the Iberian Margin (to honour Nick Shackleton's seminal work in highlighting the global importance of these sections; Schackleton et al., 2000), has proven to be a fundamental site for assessing the atmospheric/oceanic dynamics of this region, providing detailed and high-fidelity records of different-scale changes in environmental parameters associated to climate variability (Shackleton et al., 2000, 2004). Correlation of the core MD95-2042 with other records worldwide underlines its significance for interpreting global environmental conditions, as well as for correlating climate events from the marine environment with polar ice cores and European terrestrial sequences (Expedition 339 Scientists, 2013b). Core MD01-2444, has been also extensively studied and provided an important record of millennial-scale variability of the last 190 ka (Vautravers and Shackleton, 2006; Martrat et al., 2007; Skinner et al., 2007; Margari et al., 2010; Hodell et al., 2013; see Expedition 339 Scientists, 2013b for a detailed background).

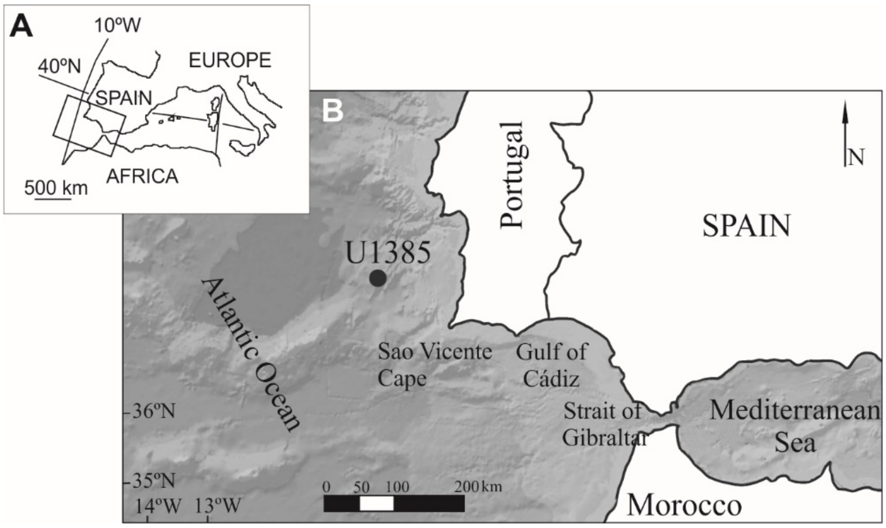

Fig. 5.1. (A) General geographical map showing the west Iberian Margin. (B) Location of site U1385.

Site U1385 on the Portuguese margin, was drilled to create a marine reference section of subMilankovitch (millennial-scale) climate variability and changes in surface and deepwater circulation occurring during Pleistocene (Expedition 339 Scientists, 2013a, 2013b). Five holes were cored at Site U1385 using the advanced piston core system, and a total of around 622 m of core were recovered (Fig. 5.2). This site shows a continuous record, consisting of a single lithologic unit composed of a Pleistocene-Holocene sequence (from 1.45 Ma, Marine Isotope Stage 47, to the Holocene) dominated by bioturbated calcareous muds and calcareous clays (Expedition 339 Scientists, 2013a, 2013b) (Fig. 5.2). No primary sedimentary structures were observed. Analysis of split cores from the five holes shows an accurate correlation among holes, making it possible to elaborate a complete spliced stratigraphic section, containing no notable gaps or disturbed intervals to 166.5 mcd (Expedition 339 Scientists, 2013b). Preliminary analysis allows estimation of a nearly uniform sedimentation rate around 10 cm/ky (Expedition 339 Scientists, 2013b). The completeness of Site U1385 favoured a high-resolution analysis of orbital and suborbital (millennial) variations, associated with changes in the atmosphere/oceanic dynamics, including climate variability. The site extends across the Middle Pleistocene Transition, the interval in which the change in orbital dominance takes place, from the 41 ky obliquity climate cycles to the 100 ky cycles of the late Pleistocene (Expedition 339 Scientists, 2013b).

Ichnological analyses of Quaternary sediments from closed areas of Site U1385 in the southwestern Iberian margin, have been previously conducted [cores PO200-10-(8-2, 6-2, 4-2) in Baas et al., 1997, 1998, and M39036 in Löwemark, 2003; Löwemark et al., 2004b], approaching environmental factors controlling trace fossil assemblages.

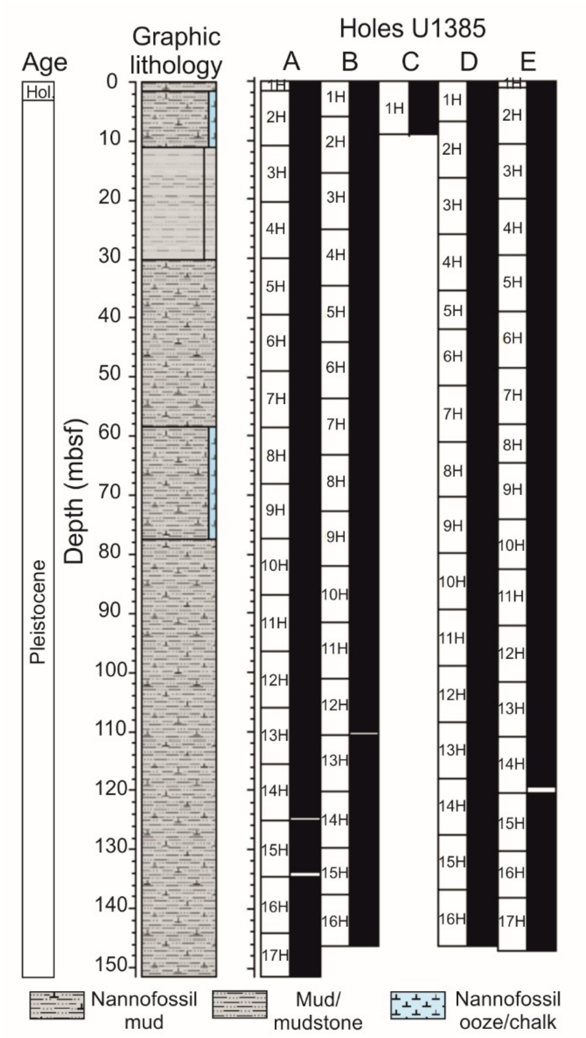

Fig. 5.2. Graphic lithology summary of Hole U1385A, and core recovery of Site 1385 (modified from Expedition 339 Scientists (2013a, b). A to E for holes cored at site U1385.

5.3. Ichnological analysis

5.3.1. Material and methods

Ichnological analysis focused on trace fossil assemblages and an ichnofabric approach, with special attention to cross-cutting relationships, tiering, relative abundances and bioturbation degrees. As usually occurs with core analysis, identification was limited, in most cases, to the ichnogenus level, except for some particular specimens displaying definitive features allowing ichnospecies characterization. Ichnological analysis was conducted on detailed observations of half-cut sections of the core in the IODP core repository at Bremen (Germany), together with high-resolution images. Several techniques of digital image treatment to improve the trace fossil visibility, allowing modifications of numerous parameters, were applied for ichnological characterization (Dorador et al., 2013).

5.3.2. Results

Bioturbational sedimentary structures were separated into biodeformational structures and trace fossils. Biodeformational structures are characterized by undifferentiated outlines and the absence of a defined geometry, impeding an ichnotaxonomical classification (see Uchman and Wetzel, 2011; Wetzel and Uchman, 2012), while revealing a more or less mottled ichnofabric (Virtasolo et al., 2011a). Biodeformational structures are related to the high bioturbation activity of organisms within soupy to soft sediments from the mixed layer, inducing a high disturbance of the sediment and then a more or less developed mottled background. Distinguishing of trace fossils from the host sediment is based on characteristic shape, and different lithological features, such as composition and colour, however this differentiation is, sometimes, difficult.

5.3.2.1. Synopsis of trace fossils

A relatively diverse trace fossil assemblage was recognized, which includes *Chondrites*, *Palaeophycus*, *Planolites*, *Phycosiphon*, ?*Scolicia*, *Taenidium*, *Thalassinoides*, *Thalassinoides*-like structures, and *Zoophycos* (Figs 5.3, 5.4), typical of the *Zoophycos* ichnofacies, although the distal expression of the *Cruziana* ichnofacies has a similar composition. Small vertical structures were moreover observed. Relatively poor preservation precludes in most cases a conclusive differentiation at the ichnospecies level. *Planolites* is the dominant ichnotaxa, while *Palaeophycus*, *Taenidium*, and *Thalassinoides*, and *Thalassinoides*-like structures are frequent. *Chondrites* and *Zoophycos* are concentrated in located parts of the core. Traces such as *Phycosiphon* and ?*Scolicia* are comparatively scarce.

Chondrites Stenberg, 1833 appears as clusters of circular to elliptical spots, and short tubes, showing occasional branching. Smaller forms are 0.5-1.5 mm wide and larger ones 2-3 mm wide. Specimens correspond to variable cross-sections of branched tunnel systems filled with light/dark material (Fig. 5.4). Given the size, smaller forms could correspond to C. intricatus (Brogniart, 1823) and larger forms to C. targionii (Brogniart, 1828). *Chondrites* is considered as a feeding structure, usually registered in deep-tiers, produced by an unknown organism. Several interpretations have been traditionally proposed; as produced by a surface ingestor packing faecal pellets inside the structure (Kotake, 1991a), or as produced by a tracemaker able to live in dysaerobic conditions, at the aerobic-anoxic interface, as a chemosymbiotic organism (Seilacher, 1990; Fu, 1991).

Palaeophycus Hall, 1847 is represented by unbranched forms, mainly as circular to subcircular cyclindrical burrows, smooth and lined. While usually observed as horizontal traces, occasionally it appears oblique, with a variable diameter (3-5 mm) and length (8-11 mm) (Fig. 5.3). Fill is structureless, having the same lithology as the host rock. Palaeophycus is a facies-crossing form, interpreted as an open tube produced by carnivorous or omnivorous invertebrates, mostly polychaetes, and associated to pascichnia or domichnia (Pemberton and Frey, 1982; Keighley and Pickerill, 1995).

Planolites Nicholson, 1873 occurs in the studied core as unbranched, and mainly as circular to subcircular cyclindrical tubular forms, clearly unlined. It is largely registered as horizontal, though there are occasional straight, smooth structures of variable size (diameter 2-7 mm, length 5-20 mm) (Figs 5.3, 5.4). Fill is structureless, showing different lithology from the host rock. *Planolites* is a facies-crossing form, featuring actively filled burrows, interpreted as a pascichnion, occurring in diverse environments, probably produced by different organisms, mainly soft-bodied invertebrates (see Pemberton and Frey, 1982 and Keighley and Pickerill, 1995 for discussion).

Phycosiphon Fischer-Oster, 1858 is registered in patches, oriented randomly, as horizontal, curved small lobes (less than 5 mm wide) and dark, fine-grained cylindrical to circular cores (less than 1 mm in diameter). Dark filling of the core is encircled by lighter-colored material. This trace is interpreted as produced by deposit-feeders, fodinichnion, associated with high quantities of particulate organic matter in the sediment (Pervesler and Uchman, 2007). *Phycosiphon* is registered in fine-grained, low energetic environments (Wetzel and Bromley, 1994; Pervesler et al., 2008, 2011), being common in poorly oxygenated sediments (e.g., Ekdale and Mason, 1988; Pervesler and Uchman, 2007).

?*Scolicia* de Quatrefages, 1849 appears as horizontal cylindrical/subcylindrical forms, 40-50 mm long, with meniscate backfill, having an oval cross-section, ~26 mm wide and ~20 mm high, with slightly concave top and bottom. *Scolicia* is produced by irregular echinoids, signaling full marine conditions, from shallow to deep-sea environments, as locomotion and feeding structure (e.g., Bromley and Asgaard, 1975; Smith and Crimes, 1983). According to Fu and Werner (2000), Scolicia is associated with more particular conditions than *Chondrites*, *Planolites* and *Zoophycos*, mainly occurring in coarse silty to fine sandy sediments.

Taenidium Heer, 1877 is observed as horizontal to oblique tubular meniscate forms, 30-51 mm long, and 5-10 mm in diameter, simple, straight to sinuous, unlined (Fig. 5.3). Locally, differentiation between *Taenidium* and *Zoophycos* is difficult; presence of isolated tubular meniscate forms, with not repeated occurrence, allow designation to *Taenidium*. *Taenidium* is a common facies-crossing trace fossil most likely produced by deposit feeders in shallow to mid-tiers, in some cases related to non-vagile worms that maintain a connection to the sediment surface or to shallowly burrowing worms keeping pace with sediment accumulation (Locklair and Savrda, 1998).

Thalassinoides Ehrenberg, 1944 is observed as oval spots, circular to subcircular (6-11 mm wide), together with straight or slightly winding, horizontal to oblique smooth cylinders (22-43 mm long), corresponding to variable cross-sections of branching burrow systems (Figs 5.3, 5.4). *Thalassinoides* is mainly interpreted as a dwelling and feeding structure (domichnial and fodinichnial) produced by crustaceans, mostly decapods (Frey et al., 1984). This facies-crossing form is found in a great variety of marine environments, from intertidal to deep sea, usually associated with oxygenated, soft but cohesive sediments (see Fürsich, 1973; Ekdale et al., 1984; Ekdale, 1992; Schlirf, 2000, for a detailed discussion of this ichnogenus).

Thalassinoides-like structures occur as circular to subcircular sections, 6-12 mm wide, and more or less cylindrical structures, 15-20 mm long, showing a variably developed irregular wall, and diffuse shape (Figs 5.3, 5.4). Shape similar to *Thalassinoides*, but without a well defined smooth-wall, discard a conclusive assignation to *Thalassinoides*.

Zoophycos Massalongo, 1855, is registered as repeated, more or less horizontal, spreiten structures. Spreiten lamellae are obliquely distributed, consisting of alternating dark and light material. Observed spreiten structures (4-11 mm wide; Fig. 5.4) correspond to cross-sections of helical coiled systems of protrusive oblique to horizontal lobes. The number of staked lobes belonging to a unique structure is variable, as is the depth of penetration. In some cases cross-sections of tubes were observed, corresponding to the marginal tube that constitutes the outer border of the spreiten structure. *Zoophycos* is generally considered to be produced by a yet undiscovered deposit-feeder, which is referred to siphunculids (Wetzel and Werner, 1981), polychaete annelids, arthropods (Ekdale and Lewis, 1991), or echiuran worms (Kotake, 1992). Ethological interpretations are variable, including consideration as fodinichnia (Seilacher, 1967b; Wetzel and Werner, 1981; Ekdale and Lewis, 1991; Olivero and Gaillard, 1996), or as produced by surface ingestors of organic detritus (Kotake, 1989; Kotake, 1991b); more recently, lobes in its lowermost part were interpreted as sulphide wells for chemosymbiotic bacteria (Bromley and Hanken, 2003). Younger *Zoophycos* spreite fill than the host sediment suggests episodic surface feeding of the producers (Löwemark and Wener, 2001; Leuscher et al. 2002; Löwemark and Schäfer, 2003; Löwemark and Grootes, 2004). Thus, several ethological models have been proposed, as deposit feeder, detritus feeding, refuse dump, cache, gardening, or chemosymbosis, among others (Bromley, 1991; see Bromley and Hanken, 2003, Löwemark et al., 2004a, and Zhang, 2014 for a review). As occurs with the ethology, the palaeoenvironmental significance and control environmental conditions of *Zoophycos* tracemakers are discussed, being associated to variations in energy, sedimentation rate, food content, or bottom-water oxygenation. Highly lobed *Zoophycos* were linked to unstable environments and an opportunistic strategy, while simple unlobed *Zoophycos* could be associated to stable environments and a more specialized strategy (Olivero and Gaillard, 2007).

5.3.2.2. Ichnofabrics at the studied interval

Seven ichnofabric types and several subtypes were differentiated, showing a gradual/transitional change between successive ichnofabrics in most cases, thereby complicating the position of their corresponding boundaries. A detailed analysis to evaluate a possible recurrence of the differentiated ichnofabrics is actually under study. Differentiated ichnofabrics are the following: Green mottled ichnofabric, *Planolites* ichnofabric, *Taenidium* & *Planolites* ichnofabric, *Thalassinoides*-like & *Palaeophycus* ichnofabric, *Planolites* & *Thalassinoides*/*Thalassinoides*-like ichnofabric, *Zoophycos* ichnofabric (with discrete *Zoophycos* subichnofabric, and diffuse *Zoophycos* subichnofabric), and *Chondrites* ichnofabric.

Green mottled ichnofabric (abundant shallowest tier traces)

The green mottled ichnofabric is characterized by the presence of a well developed greenish mottled ichnofabric superimposed upon a structureless greenish matrix (Figs 5.3, 5.5), on which only diffuse trace fossils assigned to *Planolites* are locally observed. Biodeformational structures can be envisaged as determining this mottled appearance. This ichnofabric was caused by complete destruction of primary physical structures by shallowest organisms (BI=6).

Planolites ichnofabric (scarce shallow tier traces)

The *Planolites* ichnofabric consists of scarce and diffuse *Planolites* on a greenish slightly/medium mottled lithology (Figs 5.3, 5.5). Locally, fabric is characterized by a high amount of carbonaceous particles. The mottled background and biodeformational structures, as well as the scarce presence of *Planolites*, may be related to a colonization of soupy and softground by the shallower tiering assemblages.

Taenidium & *Planolites* ichnofabric (scarce shallow/middle tier traces)

The *Taenidium* & *Planolites* ichnofabric (Figs 5.3, 5.5) consists of dominant, but relatively sparse, *Taenidium* mainly occurring in a dark greenish/grey mudstone and local slightly mottled fabric, together with punctual records of *Planolites*. Moreover, *Thalassinoides*, and rare *Physicosiphon*, and ?*Scolicia*, were observed. Degree of bioturbation is variable, showing a gradual increase from low (1) when *Taenidium* is exclusive in the mudstone, to medium (2-3) when *Planolites* is registered on the slightly mottled fabric. Locally, *Taeinidum* cross-cuts *Planolites* and *Thalassinoides* (Figs 5.3, 5.5).

Thalassinoides-like & *Palaeophycus* ichnofabric (scarce shallow/middle tier traces)

The *Thalassinoides*-like & *Palaeophycus* ichnofabric is characterized by scarce shallow and middle tier, low diversity of traces, mainly dominated by *Thalassinoides*-like, and locally *Palaeophycus*, visible on a light grey mudstone, with a locally slightly mottled fabric (Figs 5.3, 5.5). Rare *Phycosiphon* and undeterminable vertical structures are present. Bioturbation degree 1, locally BI= 2 can be present.

Planolites & *Thalassinoides*/*Thalassinoides*-like ichnofabric (abundant shallow/middle tier traces)

The *Planolites* & *Thalassinoides*/*Thalassinoides*-like ichnofabric is characterized by a relatively abundant and diverse shallow and middle tier assemblage in a mudstone showing slightly mottled grey fabric (Figs 5.4, 5.5). *Planolites* and *Thalassinoides* are dominant, with

Thalassinoides-like, *Palaeophycus*, and sparsely distributed ?*Scolicia*. Generally, *Thalassinoides* and *Thalassinoides*-like are registered separately into the ichnofabric, with *Thalassinoides*-like substituting *Thalassinoides* and viceversa. Degree of bioturbation fluctuates from medium (2-3) to high (4). No cross-cutting relationships were observed.

Zoophycos ichnofabric (middle/deep tier traces)

The *Zoophycos* ichnofabric is characterized by the presence of *Zoophycos* in a light mudstone or slightly mottled fabric (Figs 5.4, 5.5). Together with *Zoophycos*, a relatively diverse trace fossil assemblage is recognized, consisting mainly of *Palaeophycus*, *Planolites*, and *Thalassinoides*. *Zoophycos* cross-cuts *Planolites* and *Thalassinoides*. The degree of bioturbation varies from 1 to 3. Occasionally, two subtypes can be differentiated based on the variations in the abundance of shallow/middle tier traces and outlines: a) discrete *Zoophycos* subichnofabric; comparatively scarce shallow/middle tier traces (*Planolites* and *Thalassinoides*) and conspicuous, well outlined *Zoophycos* showing cross-cuts relationships on a light grey mudstone, and b) diffuse *Zoophycos* subichnofabric; more diverse shallow/middle tier traces (*Palaeophycus*, *Planolites*, *Taenidium* and *Thalassinoides*) and diffuse *Zoophycos*, showing unclear cross-cutting relationships, on a mudstone light grey/mottled fabric.

Chondrites ichnofabric (middle/deep tier traces)

The *Chondrites* ichnofabric is characterized by the presence of light *Chondrites* on a grey to greenish mudstone or slightly mottled fabric (Figs 5.4, 5.5). Degree of bioturbation varies from 1 to 3, and ichnodiversity is high. Apart from *Chondrites*, *Planolites* and *Thalassinoides* are common, and *Taenidium* rare. *Chondrites* tunnels are slightly flattened. *Chondrites* cross cuts *Planolites* and *Thalassinoides*.

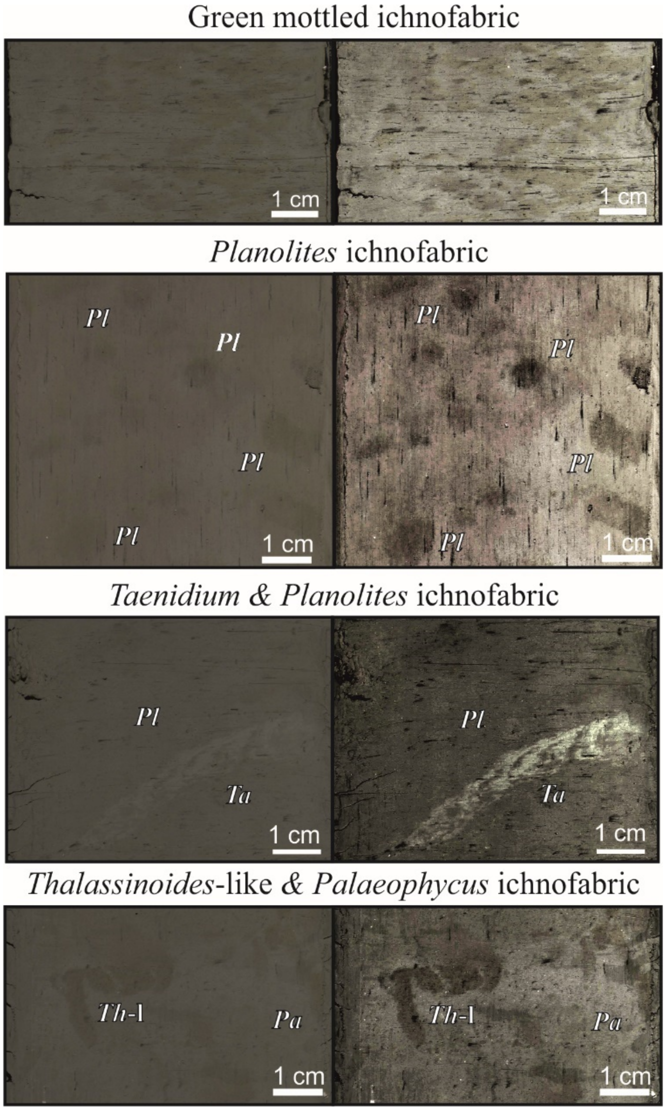

Fig. 5.3. Differentiated ichnofabrics. Left for not-treated high-resolution images, and right for same images with digital image treatment. Green mottled ichnofabric (1385D-13H-5-A; 11-16 cm), *Planolites* ichnofabric (1385A-6H-2-A; 10-17 cm), *Taenidium* & *Planolites* ichnofabric (1385A-4H-6-A; 14-19 cm), and *Thalassinoides*-like & *Palaeophycus* ichnofabric (1385E-13H-6-A; 128-133 cm). *Palaeophycus* (*Pa*), *Planolites* (*Pl*), *Taenidium* (*Ta*), and *Thalassinoides*-like (*Th*-l).

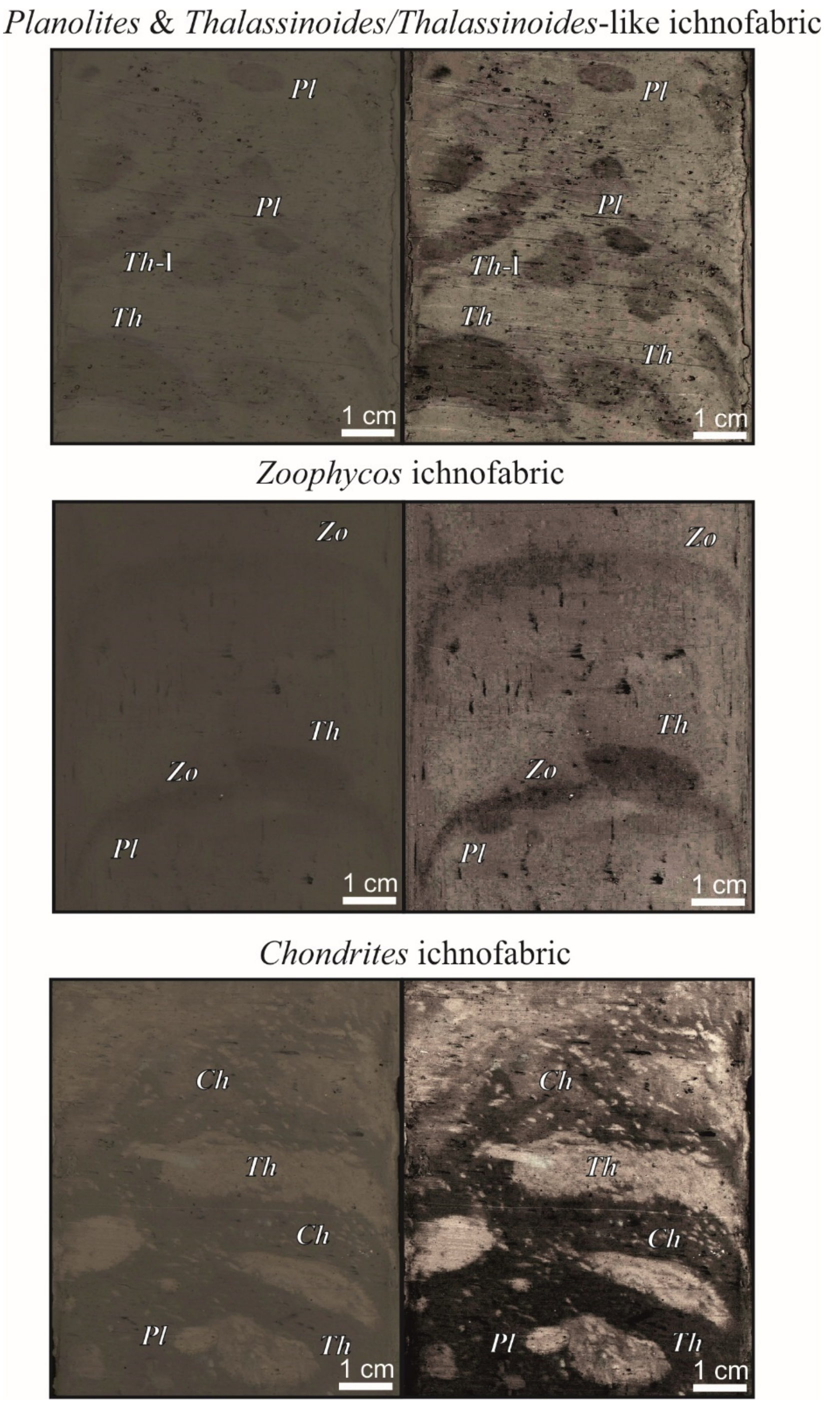

Fig. 5.4. Differentiated ichnofabrics: *Planolites* & *Thalassinoides*/*Thalassinoides*-like ichnofabric (1385B-3H-3-A; 46-54 cm), *Zoophycos* ichnofabric (1385A-6H-5-A; 20-28 cm), and *Chondrites* ichnofabric (1385B-5H-2-A; 113-122 cm). *Chondrites* (*Ch*), *Planolites* (*Pl*), *Thalassinoides* (*Th*), *Thalassinoides*-like (*Th*-l), and *Zoophycos* (*Zo*). Note: Left for not-treated high-resolution images, and right for same images with digital image treatment.

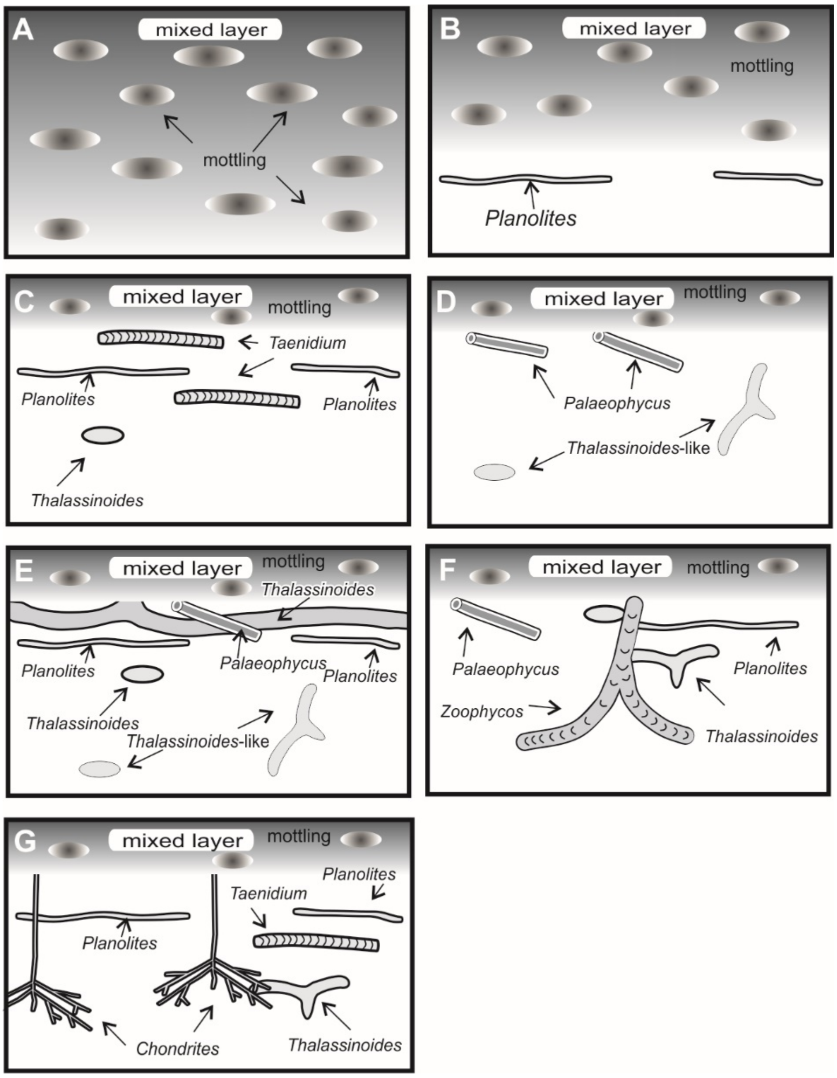

Fig. 5.5. Tiering patterns for the differentiated ichnofabrics. (A) Green mottled ichnofabric. (B) *Planolites* ichnofabric. (C) *Taenidium* & *Planolites* ichnofabric. (D) *Thalassinoides*-like & *Palaeophycus* ichnofabric. (E) *Planolites* & *Thalassinoides*/*Thalassinoides*-like ichnofabric. (F) *Zoophycos* ichnofabric. (G) *Chondrites* ichnofabric.

5.4. Interpretation and discussion

Generally a multi-tiered ichnofaunal assemblage can be envisaged (Fig. 5.6). The mottled background, determined by biodeformational structures, reveals colonization of uppermost tiers, on or just below the seafloor, associated with relatively good life conditions. Maintenance of these favourable conditions facilitate the shallowest benthic activity and extension of the green mottled ichnofabric, with scarce presence of shallow, upper, tier traces (*Planolites*). *Planolites*, as dominant, and then *Palaeophycus* and even *Taenidium* conform trace fossil assemblages from the upper tier, mostly representing pascichnia. Dominance/exclusiveness of *Planolites* could be related to better conditions in shallower tiers. Deeper within the sediment, in an intermediate tier, *Taenidium*, *Thalassinoides*-like and *Thalassinoides* mainly represent the activity of dwelling feeding structures (domichnial and fodinichnial); a relative abundance of *Thalassinoides*-like/*Thalassinoides* could be associated with variation in environmental parameters (see below). Finally, the deep tier is represented by *Zoophycos* and *Chondrites*, showing more complex and variable behavior, and associated with the final phases of colonization by the community, as revealed by the cross-cutting relationships with *Planolites* and *Thalassinoides*. To date we have not observed any cross-cutting relationship between *Chondrites* and *Zoophycos*, and thus cannot differentiate subtiers within the deep tier. The interpreted tiering pattern is similar to others from deep-sea trace fossil communities (e.g., Ekdale and Bromley, 1984, 1991; Ekdale et al., 1984; Frey and Bromley, 1985; Bromley and Ekdale, 1986; Ekdale, 1988; Bromley, 1996; Rodríguez-Tovar and Uchman, 2004b).

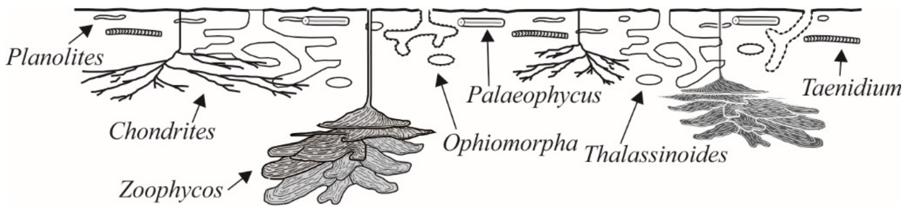

Fig. 5.6. Idealized cross-cutting relationship and tiering pattern of trace fossil assemblage in Pleistocene sediments at IODP Site U1385, on the Iberian Margin.

5.4.1. Palaeoenvironmental conditions in the western Iberian Margin

In deep-sea environments, mainly characterized by pelagic-hemipelagic sediments, the principal environmental parameters —in most cases interrelated— determining bioturbation refer to organic-matter availability, sedimentation rate and oxygenation (Uchman and Wetzel, 2011; Wetzel and Uchman, 2012). Further parameters, such as temperature or salinity, bear a comparatively minor incidence on the macrobenthic habitat in deep-sea environments.

Previous ichnological analyses on Quaternary sediments from cores located close to the studied Site U1385, revealed the presence of different ichnocoenoses characterized by a variable trace fossil record of *Chondrites*, *Planolites*, *Thalassinoides* and *Zoophycos* (Baas et al., 1997, 1998; Löwemark et al., 2004b). Trace fossil assemblages were mainly related to bottom-water oxygenation during the last 40 kyrs during Heinrich events H1 to H4 (Baas et al., 1998), and with bottom-water environmental conditions (bottom-water oxygenation and particulate organic matter content) linked to Mediterranean Outflow Water strength from back to around 34 kyrs (Löwemark et al., 2004b).

5.4.1.1. Oxygenation level and organic matter content

In the case study, the absence of physical primary structures, the presence of mottled ichnofabrics, and the dominance of shallow tier trace fossils (e.g., *Planolites*, *Palaeophycus*) allow us to interpret generalized good palaeoenvironmental conditions at the sediment-water interface or just below the sea floor during the studied interval. Oxic bottom and pore waters in the upper parts of the bioturbated zone, as well as available organic matter, can be envisaged. In this favourable generalized macrobenthic habitat at the Pleistocene, the punctual and localized record of *Chondrites* and *Zoophycos*, and their corresponding ichnofabrics, may reveal occasional palaeoenvironmental changes favouring the presence of *Zoophycos* and *Chondrites* tracemakers. Their producers have been considered as opportunistic organisms, usually bioturbating organic-rich, oxygen-depleted (dysaerobic conditions) sediments, especially when occur together. The relative independence of *Zoophycos* and *Chondrites* tracemakers from substrate features would allow for colonization of sediments with comparative low oxygenation and food content, because both maintain an open tube to the sediment surface that make it possible to obtain oxygen from the water pumped into the burrow system (e.g., Bromley and Ekdale, 1984; Rodríguez-Tovar and Uchman, 2006, 2008). Therefore, the presence of *Chondrites* and *Zoophycos* could reflect changes in the ecological/depositional conditions favouring opportunistic behaviors when environmental conditions are unfavourable for the rest of the macrobenthic tracemaker community (see Zhang, 2014 to interpreting *Zoophycos* tracemaker as opportunistic organisms in storm sequences). Low oxygen content, leading to dysaerobic conditions, and/or high organic matter could be envisaged. Yet there is no single relationship between the two parameters, even more when variations in the rate of sedimentation are considered (see Wetzel and Uchman, 2012, for a detailed review). Thus, although the incidence of oxygenation and/or organic matter content in the macrobenthic tracemaker community at the Pleistocene in the western Iberian Margin is recognized, a conclusive evaluation on the relative significance of both parameters is, at the moment, difficult. It would moreover be necessary to consider, in some instances, the possibility of a vertical partitioning of a single multi-tiered community in a well-oxygenated environment, the upper tiers (e.g., biodeformational structures, *Planolites*, *Palaeophycus*) being associated with good oxygen conditions, and the middle (e.g., *Taenidium*, *Thalassinoides*, *Thalassinoides*-like) and deep (e.g., *Zoophycos*, *Chondrites*) tiers reflecting the gradually decreasing oxygen in pore waters deeper in the sediment.

Benthic foraminiferal associations and trace-fossil assemblages from cores located close to the studied Site U1385, allow interpretation of changes in the degree of bottom-water oxygenation during the last 40 ka, with a major drawdown (to low-oxic and dysoxic conditions) during Heinrich events linked to reduction or even halting of deep water formation in the North Atlantic, and characterized by massive occurrences of *Chondrites* bellow the Heinrich layers (Baas et al., 1998). Variations of the ichnocoenoses (ichnofabrics dominated by *Thalassinoides*, by *Planolites* and indistinct bioturbation, and by *Chondrites*), from about 29 ka to the Holocene at the southwestern Portuguese continental slope, were related to changes in bottom and pore-water oxygenation and in particulate organic matter content (Löwemark et al., 2004b). These changes were associated to variations in the current velocity of the MOW as well as in the North Atlantic thermohaline overturn. Massive occurrence of *Chondrites* probably was a response to low current velocities and enhanced deposition of particulate organic matter in the rough sediment surface, leading to low-water oxygen level; in this context opportunistic *Chondrites* tracemakers took advantage against larger organisms (Löwemark et al., 2004b).

A possible recurrent record of *Chondrites* and *Zoophycos* ichnofabrics in the studied Site U1385 could be associated to variations in the global climate and in the MOW palaeocirculation, determining changes in bottom-water conditions and organic matter content.

5.4.1.2. Sedimentation rate and substrate consistency

The Site U1385 contains no notable gaps or disturbed intervals to 166.5 mcd (Expedition 339 Scientists, 2013b); an average, nearly uniform, sedimentation rate of 10 cm/ky has been proposed by the entire section cored at Site U1385, which is normal for a hemipelagic continental margin environment (Expedition 339 Scientists, 2013b). In a context of a generally constant sedimentation rate, minor changes could be interpreted based on the registered ichnofabrics. Accordingly, the presence of green mottled ichnofabric could indicate comparative diminution in the sedimentation rate, favouring bioturbation by the shallowest tracemakers at the water-sediment interface or just below the seafloor; the occasional presence of carbonaceous remains could confirm a decrease in sedimentation rate and availability of organic matter near the seafloor, allowing colonization by the shallowest tiers and hence the mottled appearance. The succession of ichnofabrics observed, from those mainly consisting of shallow tier ichnotaxa to those with dominant middle tiers, might reflect a slight increase in the rate of sedimentation, and probably more organic matter available in deeper levels (sedimentation rate controls the burial of organic matter in deep-sea sediments; Uchman and Wetzel, 2011).

In the case of vertical partitioning of a single multi-tiered community existing in a well-oxygenated environment, the registered tiering agrees with an increase in consistency from the shallowest to deep tiers, with traces as *Planolites* and *Palaephycus* colonizing softgrounds and *Zoophycos* registered in stiffgrounds. Observed variations in the *Zoophycos* ichnofabric between discrete *Zoophycos* subichnofabric, with conspicuous, well outlined *Zoophycos*, and diffuse *Zoophycos* subichnofabric, could evidence minor variations in substrate consistency but not enough to impede colonization for *Zoophycos* tracemaker. The separate presence of *Thalassinoides* and *Thalassinoides*-like (with diffuse shape) within the *Planolites* & *Thalassinoides*/*Thalassinoides*-like ichnofabric, may be related to variations in substrate consistency, with softer grounds associated to *Thalassinoides*-like structures.

5.4.1.3. Salinity and temperature

As previously indicated, parameters such as temperature or salinity have a comparatively minor incidence on the macrobenthic tracemaker habitat in deep-sea environments, and they are also more difficult to recognize based exclusively on the ichnological record. The opposite is true of marginal marine, brackish, environments, which may display significant salinity changes reflected in ichnology record (e.g., Buatois and Mángano, 2011; Virtasolo et al., 2011b).

However, in a full marine environment, as in the studied Site 1385U with generally constant salinity and temperature, the oceanic dynamics associated with the Mediterranean Outflow Water, and significant climatic changes related to glacial-interglacial periods could induce fluctuations in salinity and temperature that can be referred to some ichnological features in the case study. Given the extreme sensitivity of echinoids to salinity changes (stenohaline organisms), *Scolicia* are usually related to full marine conditions, being very rare in environments stressed by lowered or fluctuating salinity (Demírcan and Uchman, 2012); salinity variations could even be a possible killing mechanism (Bernardi et al., 2010). Fu and Werner (2000) indicate that the distribution pattern of *Scolicia* is influenced mainly by depositional factors, by bottom currents, grain size, sedimentation rate and the faunal association; preservation and record of *Scolicia* are facilitated during times of restricted competition by organisms of deeper-burrowing tiers. In the study case, the sporadic occurrence of ?*Scolicia* through the studied interval may be related to fluctuations in salinity in the range of full marine conditions. Sporadic delivery of fresh water could cause a temporal change in salinity, unfavourable for echinoids. Replacement of *Scolicia*, associated with full marine conditions by *Thalassinoides*, a salinity tolerant crustacean burrow (Frey et al., 1984), could therefore be linked to changes in salinity (Pervesler and Uchman, 2007).

Application of ichnology in palaeoclimatology is relatively scarce (Miller III, 2007; Ekdale et al., 2013 for recent researches). Based on modern examples applied to the fossil record, Goldring et al. (2004, 2007) proposed the existence of three climatic zones: tropical and subtropical zones (latitudes 0-35º) with *Ophiomorpha* and echinoid trace fossils (*Bichordites* or *Scolicia*); a temperate zone (35º-66º) where echinoid burrows are also present, along with associated thalassinean burrow *Thalassinoides* but without *Ophiomorpha*; and an artic zone (cold waters) with only a molluscan and annelid trace fossil association. In our case study, because the palaeolatitude is close to the boundary between subtropic and temperate —the latitude of Site U1385 is around 37°N— agree with the presence of echinoid burrows associated with trace of the thalassinidian group (*Thalassinoides* and *Thalassinoides*-like structures).

5.5. Conclusions

The trace fossil assemblage at the Pleistocene in the "Shackleton Site" (IODP Expedition 339, Site U1385) on the Iberian Margin consists of abundant *Planolites*, frequent and sparsely distributed *Palaeophycus*, *Taenidium*, *Thalassinoides*, and *Thalassinoides*-like, and localized *Zoophycos* and *Chondrites*. *Phycosiphon* and ?*Scolicia*, are rare. This assemblage can be considered typical of the *Zoophycos* ichnofacies, even though distal expression of the *Cruziana* ichnofacies is of a similar composition.

Ichnofabrics largely show gradual transitions. They include green mottled ichnofabric, *Planolites* ichnofabric, *Taenidium* & *Planolites* ichnofabric, *Thalassinoides*-like & *Palaeophycus* ichnofabric, *Planolites* & *Thalassinoides*/*Thalassinoides*-like ichnofabric, *Zoophycos* ichnofabric, and the *Chondrites* ichnofabric.

A multi-tiered assemblage can be envisaged; biodeformational structures revealing colonization of uppermost tiers, above or just below the seafloor, with *Planolites*, *Palaeophycus* and even *Taenidiun* as upper tier traces, *Thalassinoides*-like/ *Thalassinoides* occupy a middle tier, and *Zoophycos* and *Chondrites* as deep tier forms associated with the final phases of colonization.

In a generalized context of good bottom and pore-water oxygen conditions and organic matter availability, sporadic dysaerobic intervals could be interpreted as determining the record of *Zoophycos* and *Chondrites*.

A constant sedimentation rate gives rise to a sequential colonization of soupy, soft, and even stiff conditions. Minor changes in sedimentation rate are envisaged based on ichnofabric succession, as well as on substrate consistency revealed by the diffusiveness of traces.

Salinity and temperature do not have a significant incidence on the macrobenthic tracemaker community, although local changes in particular ichnotaxa could point to variations in both parameters.

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Chapter 6

RESPONSE OF MACROBENTHIC AND FORAMINIFER COMMUNITIES TO CHANGES IN DEEP-SEA ENVIRONMENTAL CONDITIONS FROM MARINE ISOTOPE STAGE (MIS) 12 TO 11 AT THE "SHACKLETON SITE"

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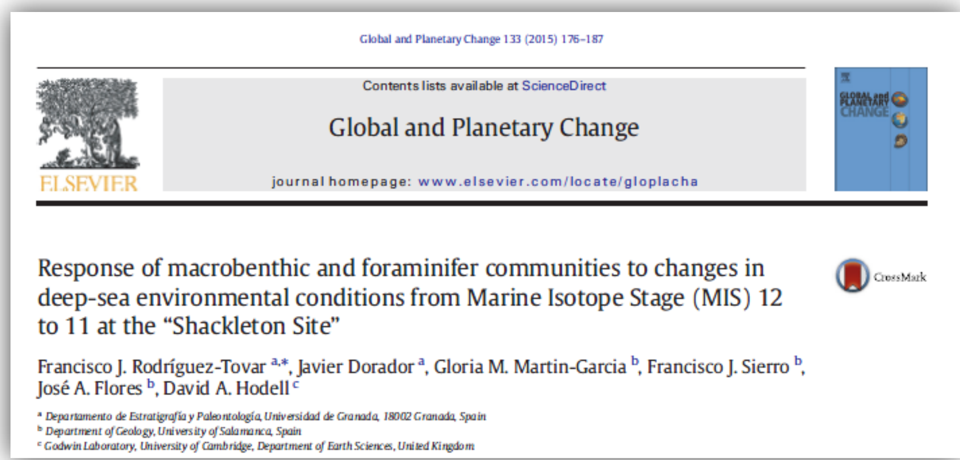
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Response of macrobenthic and foraminifer communities to changes in deep-sea environmental conditions from Marine Isotope Stage (MIS) 12 to 11 at the "Shackleton Site"

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ABSTRACT

Integrative research including facies characterization, ichnological composition and foraminifer analysis has been conducted on cores from Site U1385 of the IODP Expedition 339 to evaluate the incidence of Marine Isotope Stage (MIS) 12 and MIS 11 on deep-sea environmental changes. Four color facies groups have been differentiated, showing variable transitions between them (bioturbated, gradual and sharp contacts). Trace fossil assemblage, assigned to the *Zoophycos* ichnofacies, consists of light and dark filled structures, with *Alcyonidiopsis*, *Chondrites*, *Nereites*, *Planolites*, *Spirophyton*, *Thalassinoides*, *Thalassinoides*-like structures, and *Zoophycos*. A deep-sea multitiered trace fossil community is interpreted, revealing predominance of well-oxygenated bottom and pore waters, as well as abundance of food in the sediment for macrobenthic tracemaker community. Changes in environmental parameters are interpreted to be associated with significant variations in trace fossil distribution according to the differentiated intervals (A to M). Benthic foraminifer concentration in the sediments and variations of the planktonic foraminifer assemblages suggest significant changes in surface productivity and food supply to the sea floor since the ending of MIS 13 to the end of MIS 11 that could be correlated with the registered changes in facies and trace fossil assemblages. At the end of MIS 13 values of annual export productivity were very low, that together with the presence of light-color sediments and the continuous presence of light *Planolites* and *Thalassinoides*, reveal lower organic carbon flux to the bottom and high oxygen conditions (interval A). Afterwards the organic matter supply increased rapidly and remained very high until Termination V, determining an eutrophic environment, expressed by high benthic foraminifer accumulation rates, and reduced availability of oxygen, that correlate with the record of *Spirophyton* and *Zoophycos*, and the presence of *Chondrites*, observed in intervals B and D. Lower benthic foraminifer accumulation rates during MIS 11 suggest an oligotrophic environment at the bottom consistent with lower inputs of organic carbon, associated with high oxygen content of bottom waters that agrees with the lighter color of the sediments as well as by the continuous presence of light *Planolites* and *Thalassinoides* in the differentiated interval M. The evolution of the microbenthic tracemaker community during MIS 12 and MIS 11 responds to major changes in bottom water ventilation probably linked to variations in deep water (North Atlantic) thermohaline circulation, determining variations in oxygen and food availability.

Keywords: Integrated Ocean Drilling Program, Expedition 339, Site U1385, Marine Isotope Stages 12 and 11, Trace fossils, Planktonic and benthic foraminifers

6.1. Introduction

Glacial/interglacial climatic cycles occurring during the Quaternary have been extensively studied due to their incidence on variations in the atmosphere/ocean dynamics and on the involved biota, including hominids. From several glacial/interglacial episodes, some of them are of special interest, as occurs with those corresponding with the Marine Isotope Stage (MIS) 12 and 11 (MIS 12 and MIS 11). The time interval involving MIS 12 and MIS 11 is considered one of the most extreme glacial and interglacial periods of the middle Pleistocene. The glacial MIS 12 is characterized by strong cold conditions, and the interglacial MIS 11 is one exceptionally long interglacial warm period. The Mid-Brunhes Event (MBE), close to the MIS 12/MIS 11 transition, at around 450 ka BP, a climatic transition between MIS 13 and MIS 11, separates 2 significantly different climatic modes, with interglacials characterized by only moderate warmth previous to this event (early Middle Pleistocene interglacials; 780–450 ka), and interglacial characterized by greater warmth after this event (Middle and Late Pleistocene interglacials; after 450 ka) (i.e., Candy et al., 2010). The transition MIS 12/11, corresponding with Termination V, is the longest glacial Termination of the past 450 ka, having major incidence for the biogeography and human occupation (Candy et al., 2014).

MIS 11 is considered as one of the appropriate climate analogs for the Holocene, being of special interest even for the analysis of future climate variations, which is reflected by the amount of information obtained on this episode (see two consecutive reviews by Droxler et al., 2003; Candy et al., 2014). All this information allows a detailed characterization of MIS 11, the warm climatic features, and the induced changes in the atmosphere/ocean dynamics. Thus, according to the last revision by Candy et al. (2014), and references therein, several features of MIS 11 are the following: a) the warm episode MIS 11 consists of an interglacial (MIS 11c) and several interstadial and stadial events (i.e., MIS 11a and MIS 11b), with differences in the number and magnitude according to the studied records, b) MIS 11c is a long warm climate period that lasted for about 25–30 ka, c) temperature data reveals that MIS 11 was an interglacial of relatively moderate warmth, similar to, or slightly cooler than the Holocene, and d) most of the evidences suggest that MIS 11c is characterized by sea levels significantly above those from the Holocene, even turnovers in fauna are consistent with prolonged period of lower sea levels at the beginning and middle part of MIS 11c.

Detailed analyses of MIS 11 and MIS 12 have been conducted in a number of studies on marine, ice core, lacustrine and terrestrial sequences, involving numerous biotic (i.e., pollen and foraminiferal assemblages) and abiotic (i.e., stable isotope and elemental chemistry) proxies, allowing interpretation of environmental parameters such as the global ice volume or sea surface temperatures. In this sense, as pointed out by Candy et al. (2014) for the identification of MIS 11 in British terrestrial record, terrestrial deposits contain numerous proxies allowing interpretation of different environmental parameters, whereas ice and marine core records contain, frequently, a single proxy. In marine cores the usually applied biotic proxies are foraminiferal (benthic and planktonic) assemblages. In this sense, little attention has been focused on the ichnological record; being very scarce, near absent, the approaches are based on the study of the trace fossil assemblage (see Löwemark et al., 2006a, 2012, on trace fossil assemblage studies including MIS 11 in the eastern Mediterranean Sea and Artic Ocean, respectively). Here we present a detailed ichnological analysis of MIS 11 and MIS 12 on cores from IODP Expedition 339 Site U1385, in order to interpret changes in deep-sea environmental conditions, affecting the macrobenthic environment. Integration with information from benthic and planktonic foraminifers, allows integrative interpretations. Moreover, paleoceanographic implications will be assessed.

6.2. Site U1385 at IODP Expedition 339

IODP Site U1385 is located off the west Iberian Margin (37°34.285'N, 10°7.562'W; Fig. 6.1), on a spur, the Promontorio dos Principes de Avis, along the continental slope of the southwestern Iberian margin, at a water depth of 2578 mbsl (Hodell et al., 2013a). This Site U1385, was drilled near the position of core MD01-2444 (Vautravers and Shackleton, 2006; Martrat et al., 2007; Skinner and Elderfield, 2007; Margari et al., 2010; Expedition 339 Scientists, 2013b; Hodell et al., 2013b), one of the cores retrieved from the SW Iberian Margin by the R/V Marion Dufresne in 1995, 1999 and 2011, including Core MD95-2042 (the "Shackleton Site") used as a key archive to approach millennial-scale climate variability over the last glacial cycle (Shackleton et al., 2000, 2004). Site U1385 was drilled to create a marine reference section of sub-Milankovitch (millennial-scale) climate variability and changes in surface and deep-water circulation occurring during the Pleistocene (Expedition 339 Scientists, 2013a, b).

At Site U1385 five Holes were cored, recovering a total of around 622 m of a uniform lithologic unit dominated by bioturbated calcareous muds and calcareous clays (Expedition 339 Scientists, 2013a, b), with no notable gaps or disturbed intervals to 166.5 mcd (Expedition 339 Scientists, 2013b; Hodell et al., 2013a). Recently a very low sedimentation rate, a condensed section in which the complete interval from 415 to 431 ka is compressed into 4 cm, has been recognized at the early MIS 11 (Hodell et al., 2015; Sánchez-Goñi et al., 2016). The site contains a complete record from the Holocene to 1.43Ma (MIS 46), allowing a fine-tuning by correlation of millennial events to ice core and speleothem records for the last 800 ka (Hodell et al., 2013a, 2015). High-resolution sampling at 1 cm intervals enables resolving millennial climate events, as well as glacial–interglacial cycles, including their corresponding Terminations.

Site U1385 is close to site MD01-2443 (Fig. 6.1; de Abreu et al., 2005) in the South of the West Iberian Margin, that yielded significant records of MIS 11 for the interpretation of the involved climatic changes. On this base, Site U1385 is of major interest to study MIS 11 and MIS 12.

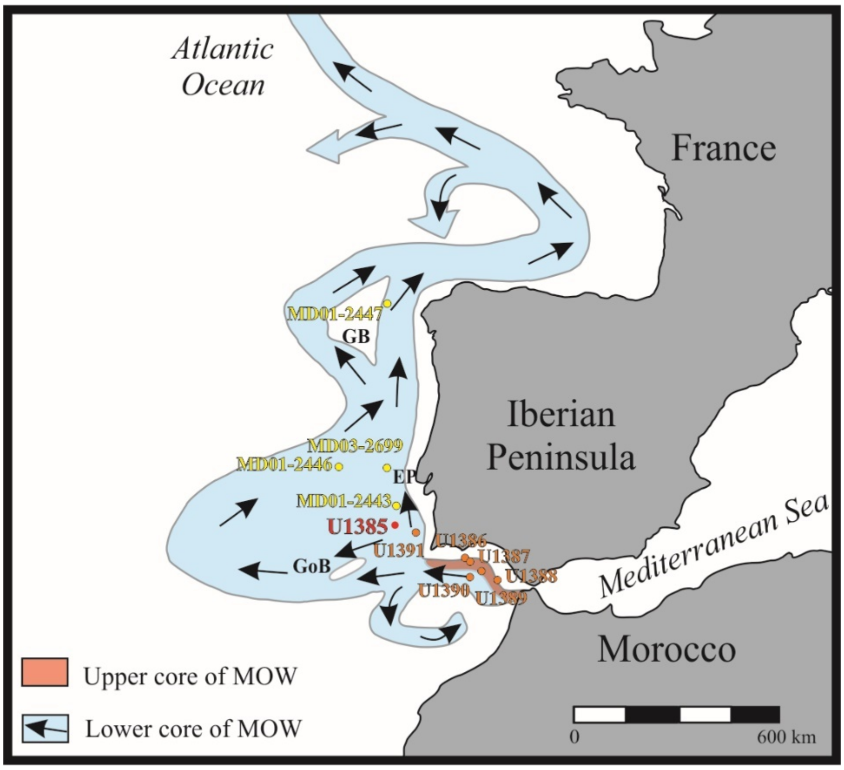

Fig. 6.1. General circulation pattern of the Mediterranean Outflow Water(MOW) (Expedition 339 Scientists, 2013b), with location of IODP Expedition 339 drill sites (red point for Site U1385 and orange points for the rest of sites), together with sites MD01-2447 (Desprat et al., 2005) in the North, MD01-2446 and MD03-2699 (Voelker et al., 2010) in the central, andMD01-2443 (de Abreu et al., 2005) in the South of the West Iberian Margin (blue points). Note: GB, Galicia Bank; EP, Extremadura Promontory; GoB, Gorringe Bank.

6.3. Material and methods

The research has been conducted on Cores 7H-4 to 7H-1 from Hole U1385D ("Shackleton Site"). Facies characterization has been integrated with the analysis of trace fossils, and benthic/planktonic Foraminifers.

Facies analysis is based on the study of lithological composition, type of contacts, and primary sedimentary structures, with special attention to stratigraphic variations. Digital image treatment allows recognition of variations in color, difficult to recognize based, exclusively, on visual observations (Dorador and Rodríguez-Tovar, 2016). Ichnological analysis focused on trace fossil assemblages, including trace fossil composition, infilling material, cross-cutting relationships, tiering structure, and relative abundances. Ichnotaxonomical classification was conducted as the ichnogenus level, as usual for core analysis. Ichnological analysis consists of detailed observations of half-cut sections of the core in the IODP core repository at Bremen (Germany), together with the study of high-resolution images. Several techniques of digital image treatment to improve the trace fossil visibility were applied for ichnological characterization (Dorador and Rodríguez-Tovar, 2014; Dorador et al., 2014a, b; Rodríguez-Tovar and Dorador, 2014, 2015).

Sampling for export productivity (Pexp) reconstruction and isotope studies was performed every 20 cm providing an estimated average 2 ka resolution record, and for counts on both benthic and planktonic foraminifers sampling was performed at an average 4.6 cm separation, providing an estimated average 0.79 ka resolution. Samples (1 cm-thick) were freeze-dried, weighed and washed over a 63 µm mesh sieve. The N63 µm residue was dried, weighed and sieved again to separate and weigh the N150 µm fraction. Counts on planktonic and benthic foraminifer taxa were conducted on this sediment fraction, which was successively split until a minimum of 300 specimens were obtained. Planktonic species were used to reconstruct Pexp with the modern analog technique (MAT) (Hutson, 1980) and the modern analog database compiled by Salgueiro et al. (2010). Stable isotopes were measured on the planktonic foraminifer *Globigerina bulloides* picked from the 250 to 355 µm size fraction and the benthic foraminifer *Cibicidoides wuellerstorfi* from the N212 µm fraction (see Hodell et al., 2015). Isotopic measurements were performed at the Godwin Laboratory (University of Cambridge, Cambridge, United Kingdom) on a VG SIRA mass spectrometer with automatic carbonate preparation system and calibrated to the Vienna Peedee Belemnite (VPB) standard, allowing an analytical precision better than 0.08‰.

The age model of the studied section is based on the correlation of the benthic oxygen isotope record to the global benthic LR04 isotope stack (Lisiecki and Raymo, 2005; see Hodell et al., 2015).

6.4. Results

6.4.1. Facies characterization

As in general for the entire Site U1385, the studied interval consists of bioturbated calcareous muds and calcareous clays (Expedition 339 Scientists, 2013a, b). Primary sedimentary structures (i.e., lamination) are near absent; occasionally horizontal lamination into the darker/black intervals is observed (Expedition 339 Scientists, 2013a, b). Moreover, no significant changes in grain size are observed. In this general, homogenized, pattern, clear differentiations can be recognized, mainly related to variations in color, probably associated with the organic matter content, usually linked to changes in the trace fossil assemblage (see below). These variations in color can be observed directly on cores, but are even more evident when digital image treatment is applied (Dorador and Rodríguez-Tovar, 2016). Thus, mainly according to variations in color, upper and lower contacts, and ichnological composition, several intervals have been differentiated (A to M); see Table 6.1 and Fig. 6.2 for a detailed characterization of the intervals. These intervals can be grouped into four color groups, from light tone gray/greenish, middle dark tone gray/greenish, very dark tone gray/greenish and dark/black, showing variable transitions between them (bioturbated, gradual and sharp contacts). From here we will refer to gray tone in substitution for gray/greenish.

Table 6.1. Differentiated intervals with lithological and ichnological features.

Interval (thickness/location)	**Facies color**	**Contacts**	**Background**	**Light Traces**	**Dark traces**	**Cross-cutting relationships**
A (75 cm): from 150 to around 75 cm of U1385 7H4	Light tone grey	Bioturbated upper contact	Mottled background	Diffuse *Thalassinoides* (l*Th*) & *Planolites* (l*Pl*)	*Chondrites* (d*Ch*) from 89 to 75 cm	d*Ch* crosscutting l*Th* & l*Pl*
B (14 cm): from 75 to 61 cm of U1385 7H4	Dark/black	Gradual upper contacts	Mottled background	*Thalassinoides* from 67 to 61 cm	Dominant *Chondrites* (d*Ch*). *Planolites* (d*Pl*) & *Thalassinoides* (d*Th*) at the base	*dCh* crosscutting d*Th* & d*Pl*
C (43 cm): from 61 to 18 cm of U1385 7H4	Middle dark tone grey	Bioturbated upper contact	Mottled background	Diffuse *Thalassinoides* (l*Th*) and *Planolites* (l*Pl*)	Dominant *Chondrites* (d*Ch*), *Planolites* (d*Pl*), *Thalassinoides* (d*Th*), *Spirophyton* (d*Sp*) & *Zoophycos* (d*Zo*)	Dark traces crosscutting light traces & d*Ch* crosscutting d*Pl*, d*Tha* & d*Sp*
D (13 cm): from 18 to 5 cm of U1385 7H4	Dark/black	More or less shap upper contact			Dominant *Chondrites* (d*Ch*) & *Zoophycos* (d*Zo*). *Thalassinoides* (d*Th*) at the base	*dCh* crosscutting d*Th*
E (35 cm): from 5 cm of U1385D 7H4 to 119 cm of U1385 7H3	Light tone grey	Sharp upper contact, channel morphology	Mottled background, especially on top	Discrete, dominant *Thalassinoides* (l*Th*), and few *Planolites* (l*Pl*)		
F (58 cm): from 119 to 61 cm of U1385 7H3	High dark tone grey, with increasing darker upward	Sharp upper contact	Mottled background	*Planolites* (l*Pl*), on top	*Planolites* (d*Pl*) &*Thalassinoides* (d*Th*), then *Zoophycos* (d*Zo*). Probable *Thalassinoides*-like (d*Th*-l)	d*Zo* cross-cutting d*Th* on top

Table 6.1. (continue). Differentiated intervals with lithological and ichnological features.

Interval (thickness/location)	Facies color	Contacts	Background	Light Traces	Dark traces	Cross-cutting relationships
G (74 cm): from 61 of U1385 7H3 to 137 cm of U1385 7H2	Middle dark tone grey, with a thick (56 cm) darker horizon at the middle part	Bioturbated upper contact	Mottled background at the lighter parts	*Thalassinoides* (l*Th*) and *Planolites* (l*Pl*) as exclusive in the lighter part, and also in the upper part of the darker horizon	Diffuse, abundant *Zoophycos* (d*Zo*), but also *Thalassinoides* (d*Th*-l), and probable *Planolites* (*dPl*) in the darker horizon *Alcyonidiopsis* (d*Al*), *Chondrites* (d*Ch*), *Planolites* (d*Pl*), *Thalassinoides* (d*Th*) & *Zoophycos* (d*Zo*) in the upper light interval, coming from the next dark interval	d*Zo* cross-cutting d*Th* *dCh* cross-cutting the rest of traces
H (33 cm): from 137 to 104 cm of U1385 7H2	High dark tone grey	Bioturbated upper contact	Mottled background	Probable *Thalassinoides* (l*Th*) on top	Dominant, near exclusive, *Zoophycos* (d*Zo*)	
I (12 cm): from 104 to 92 cm of U1385 7H2	Middle dark tone grey	Sharp/bioturbated upper contact? Minor erosion?	Mottled background	*Planolites* (l*Pl*) & probable *Thalassinoides* (l*Th*)	*Planolites* (d*Pl*), *Thalassinoides* (d*Th*) & dominant, diffuse, *Zoophycos* (d*Zo*)	d*Zo* cross-cutting d*Pl* and d*Th*
J (18 cm): from 92 to 74 cm of U1385 7H2	High dark greyish/blue/pink	Mixture of sediments Sharp/bioturbated upper contact?	Mottled background	*Thalassinoides* (l*Th*) & *Planolites* (l*Pl*)	Diffuse *Planolites* (d*Pl*) *Thalassinoides*,(d*Th*) and *Zoophycos* (d*Zo*)	d*Zo* cross-cutting d*Th*
K (47 cm): from 74 to 27 cm of U1385 7H2	Middle to high dark tone grey/pink	Darker color upward. Sharp upper contact?	Mottled background	Diffuse *Planolites* (l*Pl*) & *Thalassinoides* (l*Th*)	Diffuse *Zoophycos* (d*Zo*)	
L (12 cm): from 27 to 15 cm of U1385 7H2	High dark greyish/blue/pink	Gradual contact to lighter colour & decreasing bioturbation	Mottled background	*Thalassinoides* (l*Th*) & *Planolites* (l*Pl*), sinuous traces	*Planolites* (d*Pl*), sinuous, bifurcate traces	
M (165 cm); from 15 cm of U1385D 7H2 to 0 of U1385D 7H1	Light tone grey with darker intercalation	Gradual alternations in color	Mottled background	Diffuse *Planolites* (l*Pl*), *Thalassinoides* (l*Th*) & local *Nereites* (l*Ne*)	Diffuse *Planolites* (d*Pl*) and *Thalassinoides* (d*Th*), probably *Zoophycos* (d*Zo*),	

As a general picture, light tone gray sediments are dominant, mainly registered and thicker in the lower/middle part of Core U1385D-7H-4 (interval A), and in the upper part of U1385D-7H-2 and the entire U1385D-7H-1 (interval M). Another thinner light interval is registered at the base of Core U1385D-7H-3 (interval E). In general these intervals show a relatively scarce trace fossils filled with light material.

At the opposite, dark/black intervals are scarce and thin, being located exclusively in the middle and upper parts of Core U1385D-7H-4 (intervals B and D). These intervals are characterized by dark trace fossils, which occasionally are also observed downward into the upper parts of the lighter intervals below (intervals A and C).

Middle and dark gray tone intervals are dominant in Cores U1385D-7H-2 and 3 (intervals F, G, H, I, J, K, and L), and are also registered in the upper part of Core U1385D-7H-4 (interval C).Middle gray tone intervals (intervals C, G, I, and lower K) mainly consist of a well developed light trace fossil assemblage on a mottled background. In the very dark tone gray intervals (intervals F, H, J and upper K) light and dark trace fossils are observed on a light/dark mottled background. Two intervals (intervals J and L) into the dark gray intervals show slight differences in color, with the presence of grayish/blue/pink sediments.

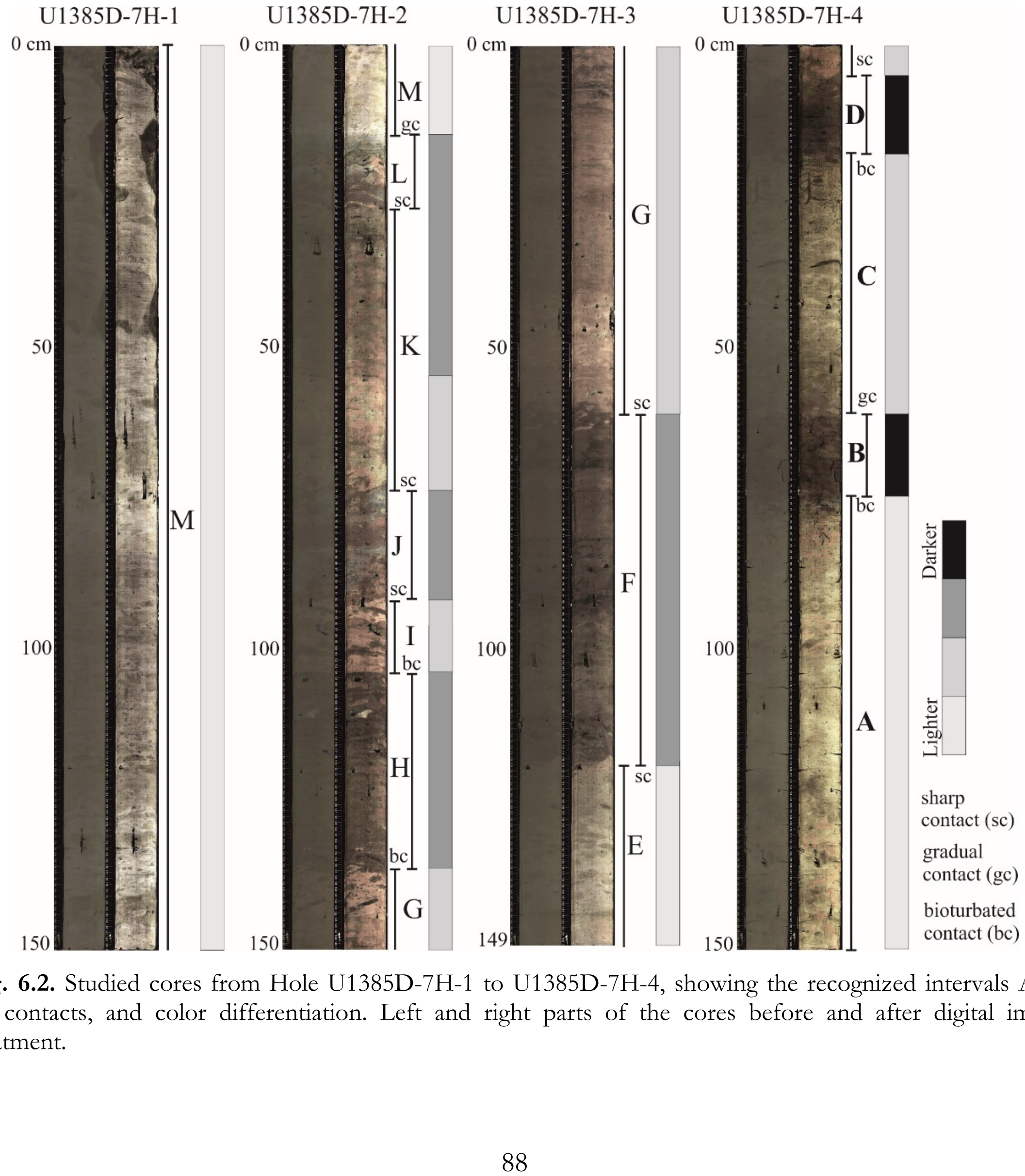

Fig. 6.2. Studied cores from Hole U1385D-7H-1 to U1385D-7H-4, showing the recognized intervals A to M, contacts, and color differentiation. Left and right parts of the cores before and after digital image treatment.

6.4.2. Ichnological analysis

Digital image treatment allows a clear differentiation between biodeformational structures and trace fossils (Dorador and Rodríguez-Tovar, 2014; Dorador et al., 2014a, b; Rodríguez-Tovar and Dorador, 2014, 2015). Biodeformational structures, showing undifferentiated outlines and the absence of a defined geometry, which impede an ichnotaxonomical classification (see Uchman and Wetzel, 2011; Wetzel and Uchman, 2012), are registered as a mottled background, with color mixture and predominance of lighter or darker sediments related to the recognized intervals. Trace fossils show a variable degree of diffusiveness, from diffuse to discrete structures, as well as variable infilling material, from light to dark, being clearly distinguished from the host sediment based on their characteristic shape, although, sometimes, this differentiation is difficult.

6.4.2.1. Trace fossil assemblage

In general, a relatively diverse trace fossil assemblage was recognized, including structures filled with light and dark sediments (light and dark filled structures), consisting of *Alcyonidiopsis*, *Chondrites*, *Nereites*, *Planolites*, *Spirophyton*, *Thalassinoides*, *Thalassinoides*-like structures, and *Zoophycos* (Figs. 6.3, 6.4). Moreover, undifferentiated sinuous traces have been observed in interval L. Light infilling traces refer to those light traces slightly darker than the light host sediment. Light infilling *Planolites* and *Thalassinoides* are the dominant, near exclusive, ichnotaxa, whereas light *Nereites* are locally observed (Fig. 6.3). Dark infilling traces can be produced into the middle and very dark tone gray intervals or into the dark/black sediments. In the dark trace fossil assemblage *Zoophycos* is dominant, Planolites and *Thalassinoides* are frequent, while *Alcyonidiopsis*, *Chondrites*, *Spirophyton*, and *Thalassinoides*-like structures are rare (Fig. 6.4).

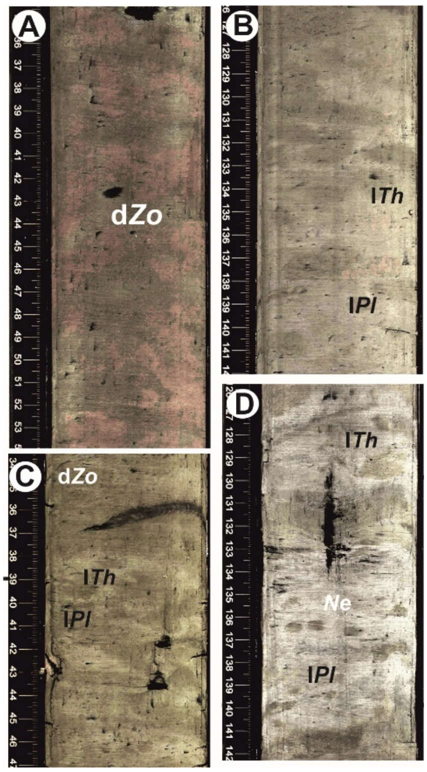

Fig. 6.3. Light trace fossils and local dark *Zoophycos* from gray (light, middle and dark tones) intervals. (A) Diffuse dark *Zooophycos* (d*Zo*) from dark tone gray interval K (U1385D-7H-2) on a well-developed mottled background. (B) Light *Thalassinoides* (l*Th*) and *Planolites* (l*Pl*) from light tone gray interval E (U1385D-7H-3). (C) Light *Thalassinoides* (l*Th*) and *Planolites* (l*Pl*), and dark *Zoophycos* (d*Zo*) from middle tone gray interval C (U1385D-7H-4). (D) Light *Thalassinoides* (l*Th*) and *Planolites* (l*Pl*), and *Nereites* (*Ne*) from light tone gray interval E (U1385D-7H-1).

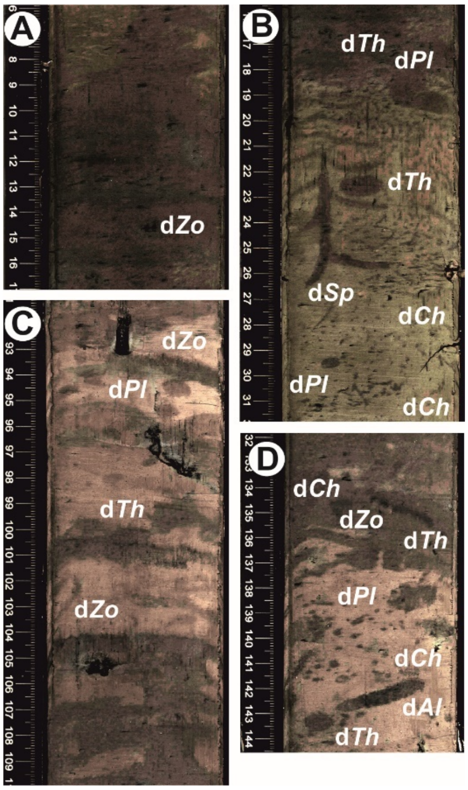

Fig. 6.4. Dark trace fossils from gray (middle and dark tone) and dark/black intervals. (A) Dark *Zoophycos* (d*Zo*) from the dark/black interval D (U1385-7H-4). (B) Dark *Chondrites* (d*Ch*), *Planolites* (d*Pl*), *Spirophyton* (d*Sp*) and *Thalassinoides* (d*Th*) from the upper part of the middle gray tone interval C transition to dark/black interval D (U1385-7H-4). (C) Dark *Thalassinoides* (d*Th*) and dark *Zoophycos* (d*Zo*) from the upper part of dark gray tone interval H to middle gray tone interval I (U1385-7H-2) (D) Dark *Alcyonidiopsis* (d*Al*), *Chondrites* (d*Ch*), *Planolites* (d*Pl*), *Thalassinoides* (d*Th*) and *Zoophycos* (d*Zo*) from the upper part of the middle gray tone interval G transition to dark gray tone interval H (U1385-7H-2).

The trace fossil assemblage can be assigned to the *Zoophycos* ichnofacies, typical for deep-sea environments, as was previously proposed for Site U1385 (Rodríguez-Tovar and Dorador, 2014). As a general rule, dark trace fossils are registered as cross-cutting light ones. Into the dark trace fossil assemblage, usually *Chondrites* and *Zoophycos* are observed cross-cutting the rest of traces, such as *Planolites*, *Spirophyton* and *Thalassinoides*. A brief description of the differentiated ichnotaxa is as follows:

Alcyonidiopsis corresponds to a single elongate cylinder, slightly oblique, dark filled, 30 mm long and 6 mm wide, showing a pelloidal like outline (see Uchman, 1999; Rodríguez-Tovar and Uchman, 2010 for interpretation).

Chondrites is generally observed as dense clusters of circular to elliptical spots, and short tubes, filled with dark sediment; occasionally branching. Mainly small forms (1.5 mm wide) are observed that could correspond to *Chondrites intricatus* (Brongniart, 1823).

Nereites consists of small-medium size (2–5 mm diameter) circular to elliptical forms, with a dark-filled internal zone surrounded by a light filled envelope, observed as closed (paired) structures in horizontal planes.

Planolites occurs as unlined, unbranched, and mainly as circular to subcircular cylindrical tubular forms (4–7 mm in diameter, 5–2.5 mm in length). It is largely registered as horizontal or slightly oblique, filled with light or dark sediment, with a variable grade of diffusiveness. Fill is structureless, with different lithologies from the host rock.

Spirophyton is registered as a single trace consisting of a central, axial, J-shaped shaft (around 8 cm high), with alternating horizontal structures (around 2–3 mm wide and 20 mm long) extending from the axial shaft. Spreite has not been observed. Similar to *Zoophycos*, it differs by the small size and shape of horizontal structures.

Thalassinoides is observed as large, oval spots, circular to subcircular (6–12 mm wide), together with straight or slightly winding, horizontal to oblique smooth cylinders (20–43 mm long), showing a variable grade of diffusiveness. Structures are filled with light or dark sediment. Occasionally, mainly light filled *Thalassinoides*, are observed in clusters of circular to elliptical spots, corresponding to variable cross-sections of branching burrow systems.

Thalassinoides-like structures occur locally as circular to subcircular sections, 6–12 mm wide, filled with dark sediment. The shape is similar to *Thalassinoides*, but showing a variably developed irregular wall, resembling *Ophiomorpha*.

Zoophycos, is registered as repeated, more or less horizontal, spreiten structures (2–8 mm wide), consisting of alternating dark and light material. A variable degree of diffusiveness is observed, determining a more or less clear differentiation of the lamellae into the lamina. Frequently several horizontal traces (up to 6), probably belonging to a unique structure, are observed, evidencing a depth of penetration at least of 16 cm.

6.4.2.2. Distribution

The trace fossil assemblage shows clear variations along the differentiated intervals that can be related to the features (color) of the host sediment (Fig. 6.5). Light trace fossil assemblage, consisting of *Planolites* and dominant *Thalassinoides*, is registered in most of the intervals, except, in the dark/black interval D, being dominated by light and middle gray tone intervals (A, C, E, G, I and M). However, in the light tone intervals (A and M), this light trace fossil assemblage is comparatively scarce, and the mottled background is less developed. The light trace fossil assemblage represents the bioturbation of tracemakers during deposition of the lighter host sediment. The dark trace fossil assemblage consists of frequent *Planolites* and *Thalassinoides*, associated with middle and very dark gray tone intervals, reflecting the mixture of phases of sedimentation corresponding to different colors; bioturbation by shallowest and shallow tier organisms produces the observed mixture of colored sediment. These trace dark *Planolites* and *Thalassinoides* are also observed in intervals showing a more or less developed alternation, not mixture, of colored sediments, such as in interval M. Occasionally, this assemblage is also registered at the base of black/dark color sediment (intervals B and D), probably reflecting a progressive, gradual, change. *Zoophycos* is the dominant dark trace fossil, observed in middle and very dark gray intervals, as well as in the black/dark ones. This trace originated during deposition of darker sediments, probably revealing latter phases of bioturbation by the dark trace fossil community, after *Planolites* and *Thalassinoides* producer. *Chondrites* and *Spirophyton* are mainly related to the dark/black intervals (B and D), are even located downward in the lighter intervals below, and associated with the particular environmental conditions of these dark (black) sediments.

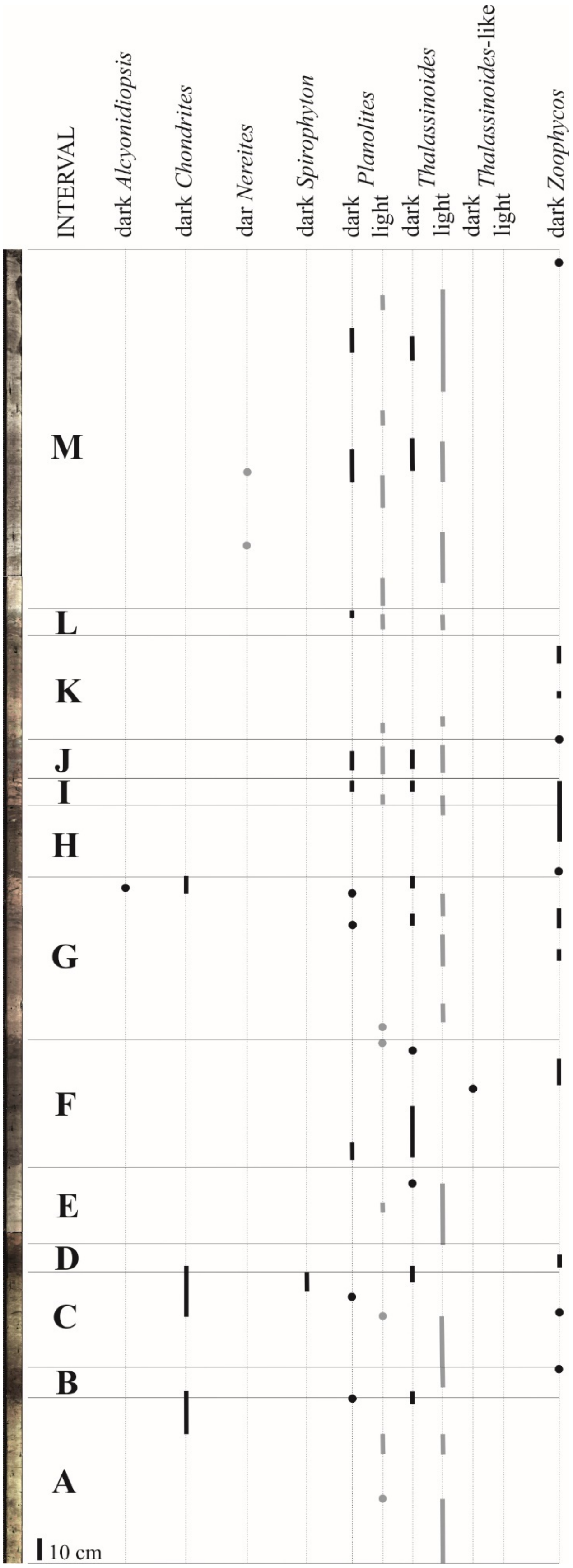

Fig. 6.5. Distribution of light and dark trace fossils in the studied cores from Hole 1385D-7H-4.

6.4.3. Micropaleontological analysis

Benthic oxygen-isotope values have been used to identify MIS 13 to MIS 11 in the sediment cores. Based on the benthic oxygen isotope record glacial Termination V was recorded in IODP Site U1385 at around 55.70 crmcd (corrected revised meter composite depth). The previously described intervals A to M correspond to the final stages of MIS 13 (intervals A, B and half of the C), MIS 12 (half of interval C, intervals D–L and the first 20 cm of interval M), and early MIS 11 (the rest of interval M) (Fig. 6.6).

Analysis of the planktonic/benthic foraminifer ratio (Fig. 6.6d) reveals that planktonic microfauna is more abundant, in general, during interglacial conditions. However, during early glacial substage MIS 12b (and coinciding with interval G) elevated percentages of planktonic foraminifers were also recorded. These high planktonic/benthic values are mainly due to low benthic production, expressed both by concentration (Fig. 6.6e) and accumulation rate (Fig. 6.6f). Benthic accumulation rate (measured in number of tests per cm2 and ka) is higher during the glacial stage, especially at the beginning and end of the stage. The extraordinarily high number of benthic foraminifers per mass of sediment (Fig. 6.6e) during the glacial maximum MIS 12a, is probably due to low accumulation of other sedimentary components at this time (Fig. 6.6). Export productivity (Pexp) is low during MIS 11 and much higher in MIS 12, especially in the early part of this stage, as well as during the last part of MIS 13. In consequence, during the interglacial periods MIS 11 and MIS 13 low Pexp at the surface corresponds to low concentration of benthic foraminifers at the sea floor (Fig. 6.6e, h). By contrast, high Pexp in MIS 12 is linked, in general, to higher benthic foraminifer production.

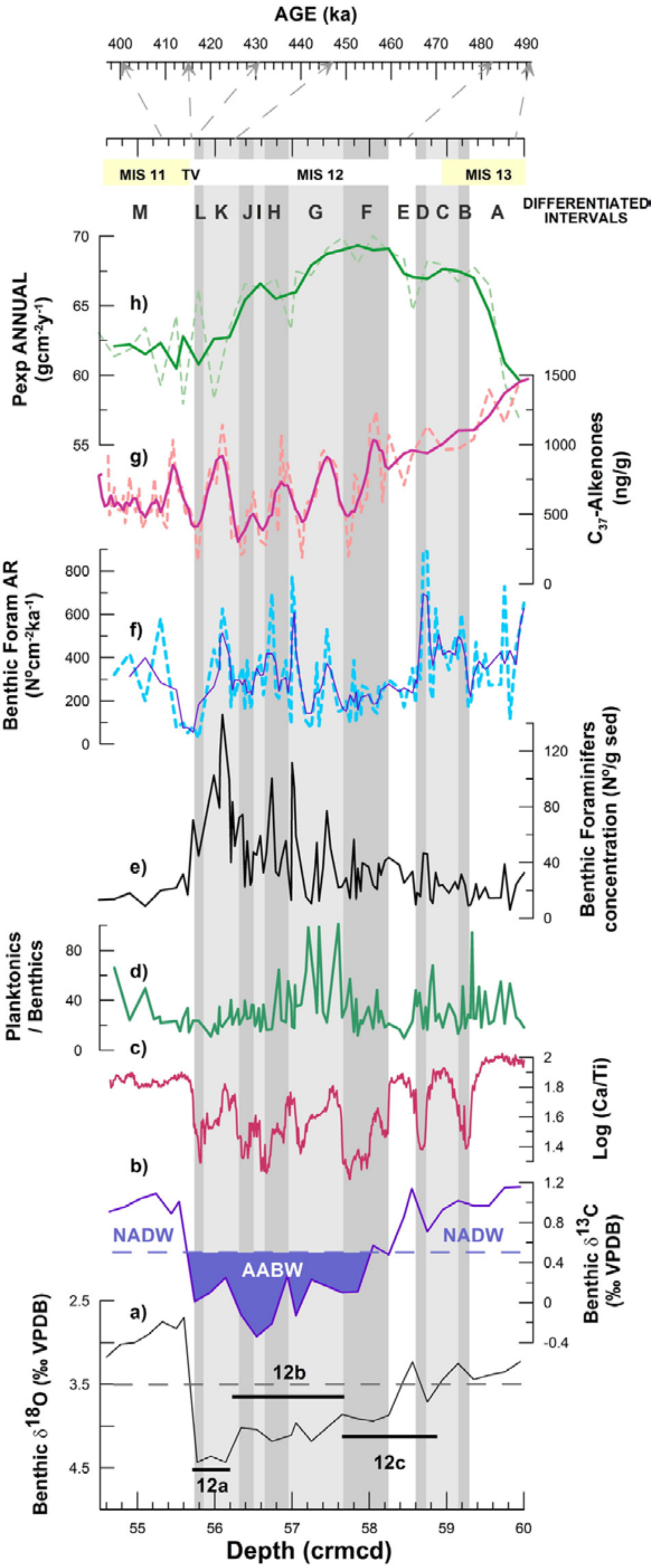

Fig. 6.6. Stratigraphic and temporal distribution of intervals A to M, differentiated according to color and trace fossil assemblage, and comparison with foraminifer records and other data from IODP-U1385. a) Benthic $\delta^{18}O$ (‰ VPDB) (Hodell et al., 2015); substages are named according to Railsback et al. (2015); horizontal dashed line shows the ice volume threshold separating stable and unstable climatic conditions (McManus et al., 1999). b) Benthic δ13C record (‰VPDB); filling indicates typical values for Antarctic Botom Water (AABW) according to Adkins et al. (2005). c) Log Ca/Ti record (Hodell et al., 2015). d) Planktonic/benthic foraminifer ratio. e) Benthic foraminifer concentration in number of tests per gram of dry sediment. f) Benthic foraminifer accumulation rate in number of tests per cm^2 and ka (dashed line) and 3-point running mean (solid). g) Total alkenone concentration (ng/g) of 37 carbon atoms (Maiorano et al., 2015; courtesy of T. Rodrigues) reflects the coccolithophore productivity (dashed line) and 5-point running mean (solid). h) Export productivity (dashed line) and 3-point running mean (solid). Glacial and interglacial stages are highlighted by horizontal bands. Vertical bands correspond to the differentiated intervals with lithological and ichnological features, with its facies color highlighted: light gray (in white)–middle dark gray–very dark/black. Control points linking depth (crmcd) to LR04-reconstructed age (Hodell et al., 2015) are represented by arrows.

6.5. Interpretation and discussion

6.5.1. Facies distribution and trace fossil composition

Major factors determining ichnological features (i.e., abundance, composition and diversity of trace fossil assemblages) in a deep-sea setting are food availability, bottom and pore-water oxygenation, substrate consistency, and rate of sedimentation (Wetzel, 1991; Uchman et al., 2008, 2013a,b; Rodríguez-Tovar et al., 2009a,b; Rodríguez-Tovar and Uchman, 2010; Uchman and Wetzel, 2011; Wetzel and Uchman, 2012; Rodríguez-Tovar and Reolid, 2013; Rodríguez-Tovar and Dorador, 2014). In the case study, the generalized mottled background, together with the observed trace fossil assemblage, reveals a deep-sea multi-tiered trace fossil community, interpreted as revealing predominance of well-oxygenated bottom and pore-waters, as well as abundance of food in the sediment for macrobenthic tracemaker community, as previously interpreted for Site U1385 (Rodríguez-Tovar and Dorador, 2014). In the generalized context of relatively good environmental conditions for the macrobenthic habitat, several changes can be interpreted, determining variations in facies and ichnological features.

Lighter sediments, as those represented by intervals A, E and M, are characterized by a relatively poorly developed mottled background together with light *Thalassinoides* and *Planolites*. *Thalassinoides* and *Planolites*, as facies-crossing forms, are found in a great variety of marine environments, usually associated with oxygenated sediments. *Thalassinoides* is related to soft but cohesive sediments (see Fürsich, 1973; Ekdale et al., 1984; Ekdale, 1992; Schlirf, 2000), and *Planolites*, an actively filled burrow, is interpreted as a pascichnion in shallow tiers (see Pemberton and Frey, 1982; Keighley and Pickerill, 1995 for discussion). Thus, good environmental conditions (mainly bottom and pore-water oxygenation, and food availability) can be interpreted, at least in the upper centimeters of the substrate, where shallowest and shallow tier communities are developed. Variations in the relative abundance of light *Planolites* and *Thalassinoides*, as well as in the diffusiveness can correspond with the rate of deposition and the firmness. The presence of dark *Planolites* and *Thalassinoides*, together with the local record of *Nereites* at interval M could reveal fluctuations in the organic matter content probably associated with variations in the detrital input and in the surface export productivity as revealed by planktonic foraminifer-reconstructed Pexp (Fig. 6h); the latter is interpreted as a shallow tier, pascichnia structure, in deep-marine, low energetic, oxygenated, environments (Uchman, 1995; Mángano et al., 2002; Wetzel, 2002; Löwemark et al., 2012), associated with increase food flux, feeding on microbes that occur in high concentrations (Wetzel, 2002; Löwemark et al., 2012).

Dark/black sediments, as represented by intervals B and D, reveal significant changes in the environmental conditions. The presence of dark *Planolites* and *Thalassinoides* at the base of the intervals, and then *Zoophycos* and dominant *Chondrites* could be interpreted as a gradual deterioration of the environmental conditions, probably related to increase in the organic matter content and decreasing oxygenation more favorable for *Zoophycos* and *Chondrites* tracemakers. Both, *Zoophycos* and *Chondrites* are deep tier feeding structures. In general, *Zoophycos* producer has been related to variations in energy, sedimentation rate, food content, or bottom-water oxygenation; its relative independence of substrate features would allow for colonization of sediments with comparative low oxygenation, or even to collect food particles from the sea floor (e.g., Löwemark and Schäfer, 2003; Rodríguez-Tovar and Uchman, 2006, 2008). Several ethological models have been proposed of *Zoophycos* tracemaker (see Löwemark and Werner, 2001; Bromley and Hanken, 2003; Löwemark and Schäfer, 2003; Löwemark et al., 2004a; Löwemark, 2015). *Chondrites* tracemaker is associated with poorly oxygenated bottom or pore waters, able to live in dysaerobic conditions, at the aerobic–anoxic interface, as a chemosymbiotic organism (Seilacher, 1990; Fu, 1991). Upwards in the dark/black intervals, a progressive return improvement can be envisaged by the presence of light structures (i.e., light *Thalassinoides*) in the upper part. The presence in the interval D of a well-developed dark trace fossil assemblage consisting of discrete structures, could be associated with a decrease in the sedimentation rate, increase in firmness and higher time of bioturbation, together with local concentration of food. This agrees with the record of delicate, complex, structures of *Spirophyton* and *Zoophycos*. Spirophyton has been interpreted, mainly for marine-margin deposits, as revealing an opportunistic strategy; formed rapidly after sudden influxes of organic material (Miller and Johnson, 1981; Miller, 1991, 2003; Bromley, 1996; Gaillard et al., 1999). The *Zoophycos* tracemaker is interpreted as bioturbating firmer, organic rich substrates with oxygen depleted pore waters (e.g., Rodríguez-Tovar and Uchman, 2004a, b; Rodríguez-Tovar and Dorador, 2014, and references therein).Distribution of *Zoophycos* has been related to Milankovicth orbital scale climatic changes, determining variations in the organic matter content and flux (Rodríguez-Tovar et al., 2011a).

Middle and dark gray tone sediments, corresponding to intervals C, F, G, H, I, J, K, and L, reveal, in general, variable intermediate cases between dark/black sediments and the lighter ones. Both types of sediments consist of a well-developed mottled background in the first case with dominance of light color sediments while in the second a mixture between light and dark sediments is observed. In both cases *Planolites* and *Thalassinoides* are the most abundant traces, being light structures dominant in the first case while in dark gray tone sediments dark *Planolites* and *Thalassinoides* are also observed. Dark *Zoophycos* are also registered, especially in the dark gray tone intervals, but dark *Chondrites* are not observed. Middle and dark gray tone sediments could reflect a generalized good bottom and pore-water oxygen conditions and higher abundance in the organic matter content at the surface but also in the first centimeters of the sediment, allowing bioturbation by shallowest, shallow and middle tiers tracemakers. When input of organic matter content (as indicated by Pexp) is maintained during a comparatively long time (Intervals F, or H to K), deep tier traces, i.e., *Zoophycos*, can be developed, probably reflecting a comparatively higher organic matter content and a slight decrease in oxygenation probably related to the presence of the poorly ventilated and benthic δ13C-deplected Antarctic bottom water AABW (Adkins et al., 2005; Hoogakker et al., 2006) (Fig. 6.6b).

6.5.2. Environmental conditions during MIS 13–MIS 11 and the macrobenthic and foraminifer record

The benthic foraminifer concentration in the sediments and variations of the planktonic foraminifer assemblages suggest significant changes in surface water productivity and food supply to the sea floor occurring in the Portuguese margin during MIS 12 and MIS 11 that could be correlated with the registered changes in facies and trace fossil assemblages (Fig. 6.6). Similar changes occurred across the more recent Terminations IV, II and I (Grunert et al., 2015; Rodríguez-Tovar et al., 2015a).

Benthic communities living at the sea floor are limited by the flux of organic carbon reaching the sea floor that, in turn, are a function of Pexp and oxygen content along the water column and interstitial waters within the sediments. Higher densities of benthic foraminifers in bottom sediments have been related to higher rates of organic carbon supply to the sea floor, both in the same Site U1385 (Grunert et al., 2015; Rodríguez-Tovar et al., 2015a) and in other locations (Schmiedl et al., 1997; Wollenburg et al., 2004; Mojtahid et al., 2009).

A trend of increased productivity both primary, according to coccolithophores (NAR) and alkenone data (Maiorano et al., 2015), and secondary, according to planktonic foraminifer reconstructed Pexp (Fig. 6.6g–h), occurred during the final stage of MIS 13 coinciding with warm SST inferred from the Ca/Ti record in our site (Hodell et al., 2015). Low abundance of the coccolithophore *Florisphaera profunda* (Maiorano et al., 2015), suggests a less stratified upper water column. During MIS 11 Pexp was very low and both intervals coincided with the presence of light-color sediments as well as with the continuous presence of light *Planolites* and *Thalassinoides* in the differentiated intervals A and M (Fig. 6.6). By contrast, during MIS 12 Pexp is higher, especially in the early part, but decreases towards the end of the stage. Benthic foraminifer accumulation rates do not follow this trend. This decoupling between Pexp, and benthic accumulation rates can be the result of the changing conditions of water column oxidation that are mainly reflected by the benthic δ13C record. The high benthic δ13C during MIS 11 and MIS 13 reflects the high bottom water oxygenation during these interglacial periods. Higher bottom water ventilation tends to decrease the accumulation of organic matter in the sediments and therefore reduce food availability for the macrobenthic and microbenthic communities.

Microbenthic fauna proliferated during the glacial stage as reflected by the higher benthic foraminifer accumulation rates, which can reach values over 800 individuals/cm^2 ka. Similar enhanced fluxes of organic matter occurred also in the South Atlantic upwelling region during this glacial period (Scmiedl and Mackensen, 1997). This high organic carbon flux to the bottom, due to high Pexp and/or poor bottom water ventilation, allowed an eutrophic environment expressed by high benthic foraminifer accumulation rates. Nevertheless, high amounts of organic matter reaching the bottom could reduce the availability of oxygen and produce a subsequent impoverishment of the benthic habitat when bottom water ventilation is low (Grunert et al., 2015; Rodríguez-Tovar et al., 2015a). These conditions happened during short intervals along MIS 12 and in Termination V when the Site was under the influence of less oxygenated bottom water (AABW), and are registered by the micro-benthos, as a decrease in benthic foraminifer accumulation rate coupled with increase in both Pexp and total alkenone production (Fig. 6.6). Macrobenthos also reveals the punctual pulse (increasing) in organic matter reaching the bottom, by the record of *Spirophyton* and *Zoophycos*, and the associated decrease in oxygen availability mainly revealed by the presence of *Chondrites*, observed in intervals B and D (Fig. 6.6). Differentiation of several intervals (A to L) during the ending of MIS 13 and the whole MIS 12, based on the trace fossil record agrees with the idea that tracemakers are more sensitive than foraminifers to depth variations in the redox boundary in near-surface sediments leading to the movement of trace-fossil tiers, as indicated by Baas et al. (1998) and also recently demonstrated by Rodríguez-Tovar et al. (2015a). Termination V, similarly to more recent Terminations II and IV and in opposition to Termination I (Rodríguez-Tovar et al., 2015a), was characterized by increasing Pexp and accumulation of organic matter without depletion of oxygenation, as increasing $\delta^{13}C$ coinciding with the lighter color interval M suggests (Fig. 6.6).

By contrast with MIS 12, lower benthic foraminifer accumulation rates during MIS 11 indicate an oligotrophic environment at the bottom and are consistent with lower inputs of organic carbon inferred from total alkenone accumulation (Maiorano et al., 2015) and planktonic foraminifer Pexp, as well as with low NAR (Maiorano et al., 2015). This oligotrophic environment is characteristic of peak interglacial periods in this region, as studies on sediments ranging from MIS 6 to the Holocene show (Pailler and Bard, 2002). Oxygen consumption in deep seawaters during MIS 11 due to the weak organic carbon supply was low which, together with the presence of the more ventilated North Atlantic Deep Water (NADW) as can be inferred from the high values of benthic $\delta^{13}C$ (Fig. 6.6b), resulted in higher oxygen content of bottom waters. This agrees with the lighter color of the sediments in the differentiated interval M, as well as by the continuous presence of light *Planolites* and *Thalassinoides*. This higher bottom-water oxygen concentration during the interglacial compared to the previous glacial maximum occurred on the Portuguese margin also during the last two climatic cycles (Hoogakker et al., 2015), and can be related to increased ventilation linked to a reorganization of ocean circulation after deglaciations (McManus et al., 2004). Oscillations in Pexp during these interglacial produced fluctuations of the organic matter content in the bottom, which is registered in the macrobenthos by the presence of dark *Planolites* and *Thalassinoides*, and the local record of *Nereites*. North Atlantic coccolithophore analyses allow for envisaging a relationship between lighter color sediments and high coccolith content in MIS 11 (Amore et al., 2012; Marino et al., 2014; Maiorano et al., 2015).

The low availability of organic matter for benthic macro- and microfauna along MIS 11 could evidence a possible stratification of the superficial water masses in the area, as indicated by higher percentage of the coccolithophore *F. profunda* compared with the previous interglacial (Maiorano et al., 2015), or be related to a reduced input of land-derived nutrients during the sea level highstand (Rodrigues et al., 2011). Such possibility should be explored with the study of planktonic fauna and the evolution of the sea surface conditions for the same period in the same site.

In a few cases, trace fossil assemblage in sediments corresponding to MIS 12 and MIS 11 has been characterized. At the eastern Mediterranean Sea, and in relation with the ichnological response to late Quaternary sapropel formation, a detailed trace fossil analysis was conducted on two cores from the last 400 ka, involving the base part of MIS 11 (Löwemark et al., 2006a). As a general pattern, the sediment in the two cores is characterized by mottled burrows, with few trace fossils of *Scolicia*, *Thalassinoides*, *Chondrites*, and *Trichichnus*, attributed to well oxygenated and warm bottom waters in an oligotrophic environment typical for non-sapropel times (Löwemark et al., 2006a). Recently, variability in trace fossil abundance and diversity associated with glacial–interglacial cycles, including MIS 11, was recognized in Late Quaternary sediment cores from the Artic Ocean; during interglacial periods the increase food flux, rather than changes in deep water circulation, is responsible for higher abundance and diversity (i.e., *Scolicia*, *Planolites* or *Nereites*), while in glacial interval characterized by extremely low food flux consist of impoverished ichnofauna dominated by *Trichichnus* and *Chondrites* (Löwemark et al., 2012).

Obtained results allow addressing interpretations on local (?) paleoceanographic dynamics. Although higher resolution climatic records need to be carried out in this time period, benthic $\delta^{13}C$ data prove that the evolution of macrobenthic tracemaker community during MIS 12 and MIS 11 responded to major changes in bottom water ventilation probably linked to variations in deep water thermohaline circulation, determining variations in oxygen and food availability.

During glacial MIS 12 a higher planktonic foraminifer-reconstructed Pexp from surface waters, together with reduced deep water formation in the North Atlantic probably resulted in higher accumulation rates of organic matter in the sea floor, favoring the development of macrobenthic communities typically living in these environments, characterized by comparatively high food, and low oxygen availability. This was probably more intense at some particular time periods such as intervals B and D that may be linked to times of extremely poor bottom-water ventilation associated with cooling events at the surface. In particular, dark intervals during MIS 12 show low Ca/Ti ratios (Fig. 6.6c) that are usually associated with cool stadials in the Portuguese margin (Hodell et al., 2013b, 2015). The low benthic $\delta^{13}C$ values during MIS 12, especially in the dark intervals, indicate low bottom water ventilation probably due to a higher influence of AABW during this time period. Low bottom water oxygenation favored the preservation of organic matter, increasing food availability for the benthic macrofauna, even though the flux of organic matter from the surface was low.

By contrast, intense North Atlantic deep water formation during MIS 11 (interval M) (Poirier and Billups, 2014), and probably late MIS 13 (interval A), together with lower export production at the surface led to more oxygenated bottom waters in the Portuguese margin, determining a well-developed deep-sea tiered assemblage.

Near Termination V an extremely low sedimentation rate has been recognized based on the chronology elaborated for this site (Hodell et al., 2015). The lowermost 40 cm at the base of MIS 11 (bottom of interval lM) represent a condensed interval of 30 ka, with a more extreme condensation recorded in the first 5 cm at the base of this interval.

6.6. Conclusions

The present study including facies characterization, ichnological composition and foraminifer analysis, allowed interpretation of deep-sea paleoenvironmental conditions during the transition MIS 13/MIS 12, MIS 12 and MIS 11.

A generalized context of well-oxygenated bottom and pore-waters, as well as abundance of food in the sediment for microbenthic tracemaker community can be interpreted, with marked changes in these paleoenviromental factors as revealed by variations in composition and distribution of trace fossils according to the differentiated intervals A to M.

Benthic foraminifer concentration in the sediments and variations of the planktonic foraminifer assemblages suggest significant changes in surface productivity and food supply to the sea floor during MIS 12 and MIS 11 that could be correlated with the registered changes in facies and ichnology.

The end of MIS 13 is characterized by low values of annual export productivity, that together with the presence of light-color sediments and the continuous presence of light *Planolites* and *Thalassinoides* at interval A, reveals relatively low organic carbon flux to the bottom and high oxygen conditions. These initial conditions were changed during development of MIS 12, showing the rapid increase in the organic matter supply and then remaining very high until Termination V, determining a eutrophic environment, as is revealed by high benthic foraminifer accumulation rates. This change and the associated reduced availability of oxygen, correlate with the record of *Spirophyton* and *Zoophycos*, and the presence of *Chondrites*, observed in intervals B and D. During MIS 11 lower benthic foraminifer accumulation rates are registered suggesting an oligotrophic environment at the bottom, associated with lower inputs of organic carbon, and high oxygen content of bottom waters, in agreement with the lighter color of the sediments as well as the continuous presence of light *Planolites* and *Thalassinoides* at interval M.

In conclusion, the evolution of macrobenthic tracemaker community during MIS 12 and MIS 11 responded to major changes in bottom water ventilation probably linked to variations in deep water (North Atlantic) thermohaline circulation.

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Appendix A. Planktic foraminifer species and morphotypes used to reconstruct export productivity

Beella digitata

Globigerina bulloides

Globigerina falconensis

Globigerinella calida

Globigerinella siphonifera (aequilateralis)

Globigerinita glutinata

Globigerinoides ruber (pink)

Globigerinoides ruber (white)

Globigerinoides sacculifer

Globigerinoides trilobus

Globorotalia hirsuta

Globorotalia inflata

Globorotalia scitula

Globorotalia truncatulinoides

Globoturborotalita rubescens

Globoturborrotalita tenella

Neogloboquadrina dutertrei

Neogloboq. pachyderma (dextral)

Neogloboq. pachyderma (sinistral)

Orbulina

Pulleniatina obliquiloculata

Turborotalita humilis

Turborotalia quinqueloba

Chapter 7

ZOOPHYCOS IN DEEP-SEA SEDIMENTS INDICATES HIGH AND SEASONAL PRIMARY PRODUCTIVITY: ICHNOLOGY AS A PROXY IN PALAEOCEANOGRAPHY DURING GLACIAL–INTERGLACIAL VARIATIONS

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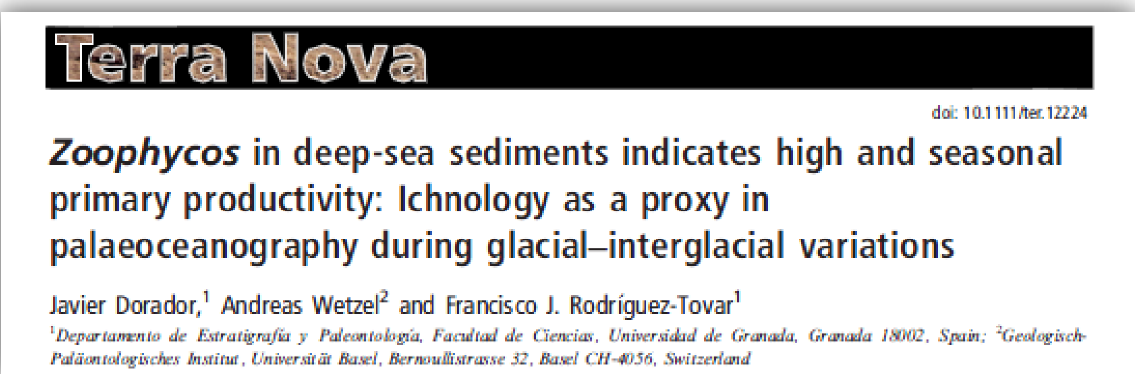
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Zoophycos in deep-sea sediments indicates high and seasonal primary productivity: Ichnology as a proxy in palaeoceanography during glacial–interglacial variations

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ABSTRACT

Trace fossils provide valuable paleoenvironmental information in hemipelagic settings. This is particularly true in the case of *Zoophycos*, an easily recognizable trace fossil in core. At IODP site U1385, *Zoophycos* was found throughout an interval representing 1.5 Myr, covering 45 glacial-interglacial cycles mediated by obliquity (41-kyr) and short-term eccentricity (100-kyr). *Zoophycos* is most common in sediments deposited during glacial times and when sedimentation rate was intermediate and primary production was high and seasonal. Occurrences of *Zoophycos* elsewhere support a similar relationship to seasonal organic-matter deposition. This is particularly significant considering that seasonality of organic matter deposition is difficult to decipher from the sediment record. *Zoophycos* appears to represent a useful proxy to characterize high and seasonal organic-matter deposition and primary productivity in Neogene hemipelagic deposits.

7.1. Introduction

Over the last decades, trace fossils have been increasingly used as paleoceanographic tools in paleoenvironmental studies (see Knaust and Bromley, 2012, and contributions therein). In Cenozoic hemipelagic sediments, *Zoophycos* has been mainly related to quiet environmental conditions, and used to interpret energy variations, sedimentation rates, and food availability (Wetzel, 1983; Löwemark et al., 2006b; Wetzel et al., 2011; Kotake, 2014; Löwemark, 2015; Monaco et al., 2016). *Zoophycos* is a protrusive spreiten structure produced by the lateral shift of a U- or J-shaped causative tube (Wetzel and Werner, 1981). Normally, it is represented by a helicoidal spiraled or irregular spreite, surrounding a central axis (Uchman, 1995; Löwemark and Schäfer, 2003; Löwemark, 2015). The ethological interpretation of *Zoophycos* is still a matter of debate (e.g., Bromley, 1991; Ekdale and Lewis, 1991; Olivero and Gaillard, 2007; Knaust, 2009b; Kotake, 2014; Löwemark, 2015). Nonetheless, arguments favor the cache behavior (Jumars and Wheatcroft, 1989; Bromley, 1991; see recent review by Löwemark, 2015); i.e., the producer collect nutritious material on the sediment surface during bloom times and store it within the sediment to be utilized during times of low food availability. *Zoophycos* apparently is produced when its habitat is experiencing high, but strongly seasonal organic matter deposition on the seafloor (e.g., Wetzel, 2010). Changes in lifestyle and habitat of the *Zoophycos* producer during the Cretaceous recently have been associated with an increased flux of phytodetrital material and the resulting increase in benthic food content on the deep seafloor (Kotake, 2014).
An advantage of studying *Zoophycos* in cores is that the spreiten structures are easily recognized in vertical section. Some ichnotaxa are difficult to identify in cores, especially in modern soft sediments, because of the narrow exposed surface and often low color contrast (e.g., Wetzel, 2010; Dorador and Rodríguez-Tovar, 2014; Dorador et al., 2014a, b). However, *Zoophycos* identification is easy because the structures appear as roughly parallel, sub-horizontal to inclined spreiten, that commonly traverse the whole core (Löwemark and Schäfer, 2003; Fig. 7.1). Moreover, its record in narrow core sections is not affected by patchy distribution (Wetzel, 1981). With its high environmental significance and easy recognition *Zoophycos* qualifies as a useful tool for paleoceanographic studies.

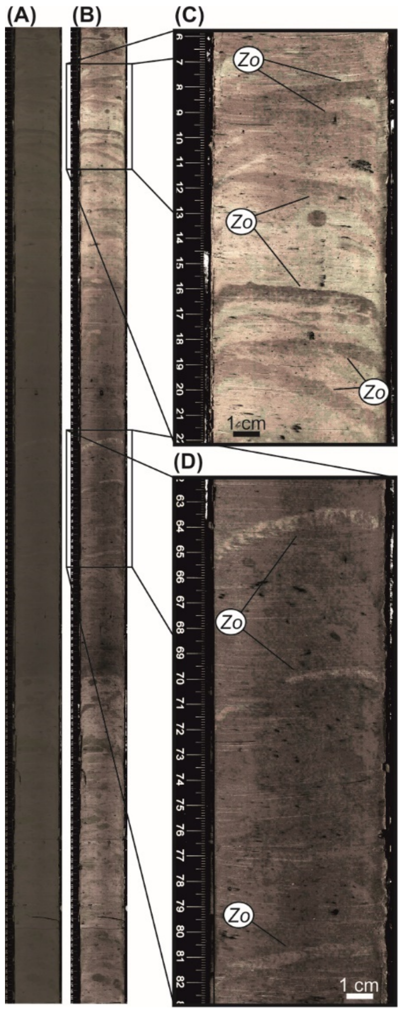

Fig. 7.1. Examples of *Zoophycos* in core. (A,B) (A) Original and (B) treated, according to Dorador et al. (2014a,b), images from core 339-U1385E-4H-4-A (approximate location between Marine Isotope Stages 7 and 5). (C,D) Enlarged images of those sections containing *Zoophycos* (*Zo*). Core segment is 1.5 m long.

The temporal distribution of modern and Pleistocene *Zoophycos* has been previously studied in sediments of the Nordic Seas (Löwemark, 2012), NW African continental margin (Wetzel, 1981, 1983), and South China Sea (Löwemark et al., 2006b; Rodríguez-Tovar et al., 2011a; Wetzel et al., 2011), with a focus on characterization of habitat and ethology of the producer. Despite the extensive study of *Zoophycos* in recent years, this ichnotaxon has rarely been employed as a paleoceanographic/paleoclimatic proxy, although its potential has been suggested (e.g., Wetzel, 1981, 1983, 2008; Löwemark et al., 2006b; Wetzel et al., 2011; Löwemark, 2015; Rodríguez-Tovar et al., 2011a, 2015a, b).

In the current study, the stratigraphic distribution of *Zoophycos* is analyzed in sediments from IODP site U1385 on the West Iberian Margin. This site provides a continuous record for the last 1.5 Ma, covering 45 glacial-interglacial periods, including the Middle Pleistocene Transition (MPT) and the associated change from 41-kyr obliquity-forced climate cycles of the earlier Pleistocene to the 100-kyr eccentricity-forced cycles in the later Pleistocene. The observed distribution pattern of *Zoophycos* is not random. Rather, occurrences of *Zoophycos* are related to specific environmental conditions. A comparison with other areas of the world's oceans indicates that *Zoophycos* appears to be a useful proxy in paleoceanography, especially in upwelling settings. In this paper, relationships between *Zoophycos* distribution, glacial-interglacial periods, and seasonal primary productivity are addressed.

7.2. Geological setting

Zoophycos distribution was studied in sediment cores drilled during IODP Expedition 339 at site U1385 (Expedition 339 Scientists, 2013b). This site is located 2578 m below sea level, on a spur elevated above the abyssal plain, along the continental slope of the southwestern Iberian margin (37°34.285'N, 10°7.562'W, Fig. 7.2.) (Hodell et al., 2013a). Site U1385 sediments consist of bioturbated nannofossil mud and terrigenous mud. These sediments contain no primary sedimentary structures and appear not to have been affected by contour currents (Expedition 339 Scientists, 2013b).

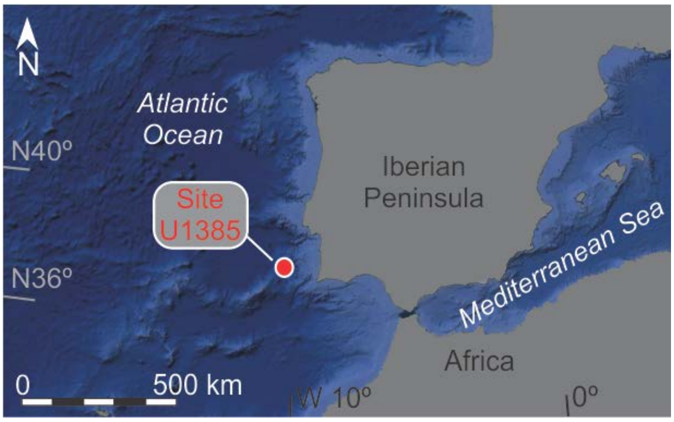

Fig. 7.2. Location of IODP site U1385.

7.3. Methods

The stratigraphic distribution of *Zoophycos* at site U1385 (Table 1 in appendix) was analyzed on a complete spliced 166-m-thick stratigraphic section, 'DE splice' in Expedition 339 Scientists (2013b) , that contains no notable gaps or disturbed intervals and thus represents a continuous sequence deposited from 1.427 Ma through the Holocene (Expedition 339 Scientists, 2013b; Hodell et al., 2013a). Stratigraphic distribution of *Zoophycos* at the DE splice was characterized considering those intervals where spreiten structures are identified. The burrowing depth, commonly between few centimeters and half a meter (see Löwemark, 2015 for a recent review), was not corrected because it is not relevant in a record longer than 150 m and it does not affect the main findings of this study. To facilitate *Zoophycos* identification, core photographs were treated using the image processing based on the modification of image adjustments (levels, brightness and vibrance) proposed by Dorador et al. (2014a). The depth below seafloor was transformed to time based on the age model developed for this site (Hodell et al., 2015).

7.4. Stratigraphic distribution

Zoophycos is recognized throughout the drilled section (Rodríguez-Tovar and Dorador, 2014), but in varying abundances. On the upper part of the section (down to 100 m; 900 ka), *Zoophycos* is generally less common than below. Nevertheless, throughout the cored interval, *Zoophycos* is most common in sediments deposited during glacial periods, in particular at glacial terminations. In contrast, *Zoophycos* is rare to absent in sediments representing warmer phases of the interglacial periods (i.e., those characterized by low $\delta^{18}O$ values; Hodell et al. (2015), Fig. 7.3). This is valid both above and below the MPT (between Marine Isotope Stages 21 and 25; e.g., Pena and Goldstein (2014)), within which the dominant periodicity of insolation changed from the 41-kyr obliquity cycle to the 100-kyr eccentricity cycle.

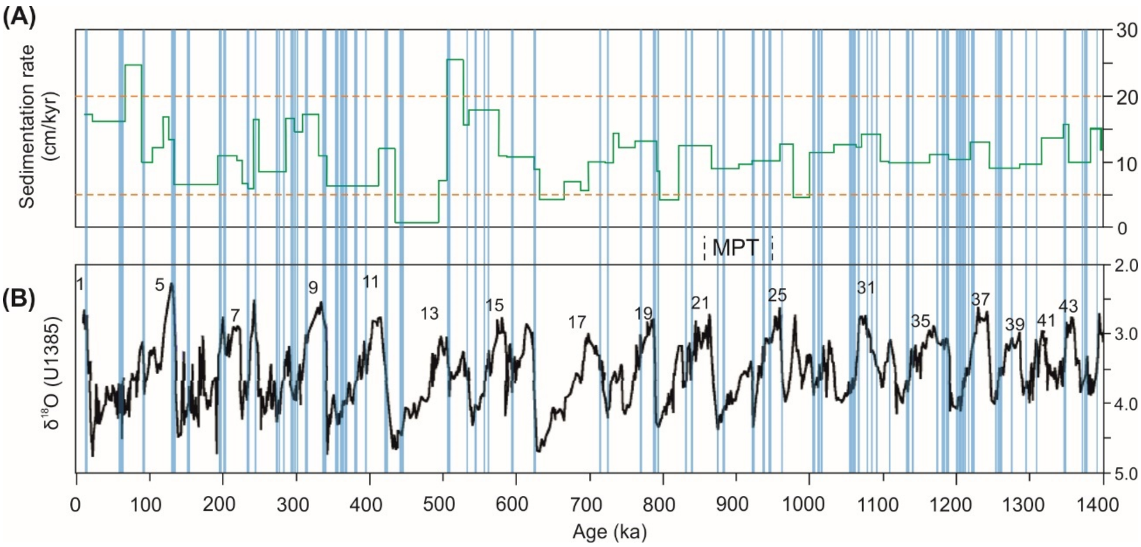

Fig. 7.3. Sedimentation rate, stratigraphic distribution of *Zoophycos* and glacial–interglacial periods at site U1385. (A) Sedimentation rate (from Hodell et al., 2015). (B) Stratigraphic distribution of *Zoophycos* (vertical lines) in relation to the benthic $\delta^{18}O$ record at site U1385 (Hodell et al., 2015). Widths of vertical lines represent the interval thicknesses in which *Zoophycos* is observed. Numbers indicate Marine Isotope Stages. MPT, Middle Pleistocene Transition. Broken lines mark minimum and maximum threshold values of sedimentation rate between which *Zoophycos* are most commonly emplaced.

Furthermore, *Zoophycos* appearance is related to sedimentation rate (Fig. 7.3.). At site U1385, sedimentation rates, evaluated based on the biostratigraphic analysis of calcareous nannofossils and foraminifers (Expedition 339 Scientists, 2013b), are typical of hemipelagic deposits, varying between 1 to > 25 cm/kyr (Hodell et al., 2015). *Zoophycos* is nearly absent in intervals characterized by rates higher than 20 cm/kyr (70-90 and 510-530 ka approximately) and lower than 5 cm/kyr (around 440-490, 630-660, 790-820 and 980-1000 ka). Thus, *Zoophycos* is mostly restricted to intervals of intermediate sedimentation rates between 5 and 20 cm/kyr. Notably, only 2.6% of identified *Zoophycos* (i.e., 2 spreiten) occur outside this range (Fig. 7.4.).

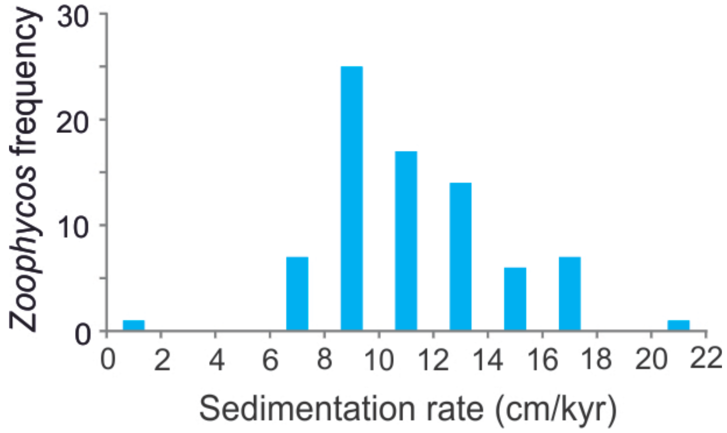

Fig. 7.4. Histogram of *Zoophycos* occurrence (considering intervals where spreiten structures are observed) vs. sedimentation rate.

7.5. Discussion

In the studied cores *Zoophycos* is not randomly distributed. Rather its position in the core is related to both sedimentation rate and the glacial-interglacial cycles. *Zoophycos* is mostly present in intervals deposited at sedimentation rates ranging from 5 to 20 cm/kyr. This fact, previously recognized by Wetzel (1981), is consistent with the cache behavior —a really special nutritional strategy (e.g., Jumars et al., 1990)— proposed by Bromley (1991) and recently tested by Löwemark (2015). The *Zoophycos* producer collects nutritious material on the sediment surface and stores it deep in the sediment to prevent oxidation and to avoid utilization by other organisms (Löwemark and Schäfer, 2003). When sedimentation rate is lower than 5 cm/kyr, pore water tends to become oxic. Exposure time of organic matter to oxygen becomes so long that essentially no organic matter is preserved within sediment (e.g., Müller and Suess, 1979; Burdige, 2007). Oxidation of organic matter on the sediment surface is very rapid and takes a few weeks to months (Wetzel, 2008, 2010 and references therein). In fact, all intervals lacking *Zoophycos* in the studied core are characterized by very low sedimentation rate (<5 cm/kyr, Fig. 3) and exhibit a reddish color, the latter being a good indication of oxic pore water (e.g., König et al., 1997). In contrast, when sedimentation rates were higher (>20 cm/kyr), so much organic matter is buried and stored in sediment that a specialized behavior is not necessary (Wetzel, 1981, 1991). Consequently, *Zoophycos* producers no longer follow a cache behavior, and *Zoophycos* is no longer present.

According to previous studies (e.g., Lebreiro et al., 1997; Salgueiro et al., 2014), the supply of organic matter provided by the Portuguese upwelling system was enhanced during glacial periods on the Iberian Margin. These authors linked peaks of benthic *Uvigerina* during some glacial stages with poorly oxygenated bottom water and greater food availability on the seafloor both related to increased primary productivity. Recent studies of site U1385 cores demonstrate that for glacial Terminations 1, 2 and 4, Zoophycos is associated with hyaline benthic foraminifers and an increased accumulation of organic matter (Rodríguez-Tovar et al., 2015a). Additional data from benthic/planktonic foraminifers, stable isotopes, and alkenone, confirm the rapid increase in organic matter supply during Termination 5, implying a eutrophic environment (Rodríguez-Tovar et al., 2015b). Consequently, these data support the promise that *Zoophycos* appears to have been produced at times of enhanced and seasonal productivity on the Portuguese margin.

7.6. Worldwide observations

The relations outlined above for the Iberian margin also have been observed in other areas, such as the Nordic Seas, off NW Africa, and in the South China Sea, although with local variations (i.e., associated to glacial or interglacial phases) according to the particular area (Wetzel, 1981, 1983; Löwemark et al., 2006b; Wetzel et al., 2011; Löwemark, 2015).

The record of *Zoophycos* from the Nordic Seas in interglacial sediments, when primary productivity is high and seasonal, has been interpreted by Löwemark (2015) to be a response to quiet sedimentation and strong seasonal variations in food supply. During glacial times, the Artic was characterized by perennial sea-ice cover, stagnant deep water circulation, and strongly decreased food flux to the sea floor, conditions that which likely were unsuitable for *Zoophycos* producers (Löwemark, 2015).

Off NW Africa, between 15° N and 24° N in 2000 to 4000 m water depth, *Zoophycos* is ubiquitous in sediments deposited during glacial periods making it useful for stratigraphic correlation (Wetzel, 1981, 1983; Werner and Wetzel, 1981). During glacial periods, upwelling and hence, primary productivity was significantly enhanced but strongly seasonal (Sarnthein et al., 1988; Schmiedl and Mackensen, 1997). Consequently, the *Zoophycos* producers needed to store organic matter (cache behavior) efficiently within the sediment for times when benthic food content on the sediment surface was low. This strategy is more efficient for settings receiving 5 to 20 cm/kyr sediment.

Observations in the South China Sea strongly support the link between of *Zoophycos* emplacement and times of enhanced seasonal productivity (Löwemark et al., 2006b; Rodríguez-Tovar et al., 2011a; Wetzel et al., 2011). The entire region of the South China Sea is under the influence of the monsoon system (e.g., Tomczak and Godfrey, 1994; Liu et al., 2002). There is, however, a strong shift in monsoon regime between glacial and interglacial conditions (e.g., Wang and Li, 2009). During interglacial times, strong northeasterly winds induce pronounced coastal upwelling off southern Vietnam in summer (e.g., Xie et al., 2003). During the high season of the monsoon, particle flux to the seafloor increases by a factor of 3 to 4 accounting for ~70% of the total annual organic matter flux to the deep sea (Wiesner et al., 1996). Glacial periods, in contrast, are characterized by weak summer monsoon and strong winter monsoon (e.g., Wang et al., 1999; Liu et al., 2007). The strengthening of winter monsoon intensified upwelling and inflow of nutrient-rich waters from the Pacific Ocean into the northern South China Sea, which in turn enhanced primary production seasonally (Wang et al., 1999). In the southern South China Sea, *Zoophycos* occurs in sediments associated with interglacial times (Wetzel, 2008; Wetzel et al., 2011), whereas in the northern South China Sea, at preferentially occurs in sediments deposited during glacial times (Löwemark et al., 2006b). Löwemark et al. (2006b) found that *Zoophycos* preferably were located in sediments deposited from glacial maxima to the termination in the northern South China Sea; showing for the last 425 kyr a Milankovitch-scale variability mainly related to monsoon (Rodríguez-Tovar et al., 2011a).

Therefore, *Zoophycos* is normally located in intervals deposited during high and seasonal productivity with intermediate sedimentation rates. *Zoophycos* is commonly present in hemipelagic deep-sea sediments since the Upper Cretaceous (see compilations by Chamberlain, 1975; Ekdale, 1977). Its easy recognition, its global distribution, and its indication of high, but seasonal organic matter accumulation on the deep seafloor qualify *Zoophycos* as a tool to characterize depositional conditions. These findings apply to *Zoophycos* since the Late Cretaceous, the time period when *Zoophycos* become a common component of deep sea (Seilacher, 1977; Chamberlain, 2000). *Zoophycos* provides easily accessible information about seasonality of primary production, if sedimentation rate can be estimated. This phenomenon has been especially demonstrated in upwelling areas but could be expanded to other settings in further studies.

7.7. Conclusions

The stratigraphic distribution of *Zoophycos* within a continuous 1.5-Myr-long stratigraphic record on the Iberian Margin is not random. This ichnotaxon is generally present in intervals deposited during glacial periods with high and seasonal productivity and intermediate sedimentation rates (5-20 cm/kyr). *Zoophycos* emplacement episodes are characterized by high flux of nutrients provided by the Portuguese upwelling and sedimentation rates sufficient to preclude complete oxidation of organic matter. The link of *Zoophycos* to these specific environmental conditions on the seafloor also has been observed in other areas around the world including the Nordic Seas, the NW Africa margin, and in the South China Sea. Thus, the presence of *Zoophycos* in deep-sea sediments is indicative of high and seasonal productivity and intermediate sedimentation rates. Because *Zoophycos* is easily recognized and has a wide geographic distribution, *Zoophycos* is revealed as an appropriate paleoceanographic proxy for recognizing high and seasonal productivity since the Late Cretaceous.

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Supplementary Papers of

PART III

- Deep-sea trace fossil and benthic foraminiferal assemblages across glacial Terminations 1, 2 and 4 at the "Shackleton Site" (IODP Expedition 339, Site U1385) (Global and Planetary Change, 2015)

- Stratigraphic variation in ichnofabrics at the "Shackleton Site" (IODP Site U1385) on the Iberian Margin: Paleoenvironmental implications (Marine Geology, 2016)

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Deep-sea trace fossil and benthic foraminiferal assemblages across glacial Terminations 1, 2 and 4 at the "Shackleton Site" (IODP Expedition 339, Site U1385)

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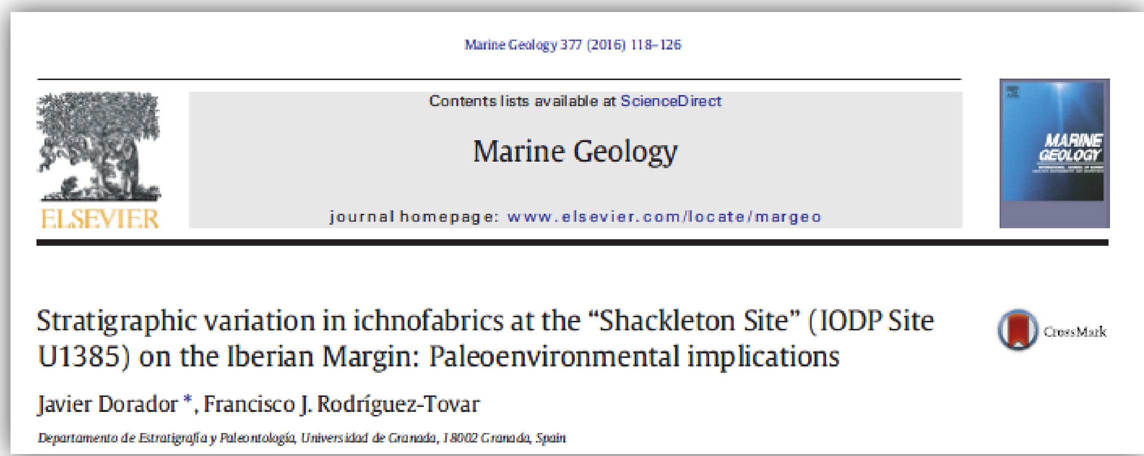
ABSTRACT

Numerous studies focused on the transitions between glacial and interglacial periods, the so-called terminations, due to the associated significant reorganizations of the ocean–atmosphere system. However, analyses combining macro- and micropaleontological information are near absent. In this research, an integrative study of trace fossils and benthic foraminiferal assemblages is conducted in order to improve the characterization of Terminations 1, 2 and 4, as revealing the response of the macro-and microbenthic habitats to the involved paleoenvironmental changes. For this purpose, selected cores from Site U1385 (IODP Expedition 339) located off the western Iberian Margin, have been studied. Changes in trace fossils and benthic foraminifera related to both long-term variations at the glacial/interglacial scale, and short-term millennial-scale climatic events. Food and oxygen availability have been identified as the main factors determining variations in the macro and microbenthic community structure across glacial terminations in the context of changes in water mass distribution and productivity in the NE Atlantic. A deep-sea multi-tiered tracemaker community, consisting of biodeformational structures, *Chondrites*, ?*Nereites*, *Palaeophycus*, *Planolites*, *Thalassinoides*, and *Zoophycos*, suggest generally well-oxygenated bottom and pore-water conditions during interglacial as well as glacial intervals, with punctual decreases in oxygenation. Short-climatic events registered during Terminations 1, 2, and 4 induce a similar response of trace fossil and benthic foraminifera communities to the variable incidence of food and oxygen availability. Termination 1 shows a severe deterioration of oxic conditions and increasing food availability during the YD and HS 1, favoring appearance/dominance of *Zoophycos*, together with the lowest miliolid and the highest deep infaunal taxa abundances. Short-term climatic events (HS 11, IRE 10.1) associated with Terminations 2 and 4 are characterized by a major incidence of export productivity and accumulation of organic matter respect to depletion oxygenation, especially affecting the microbenthic habitat. Dark sediment intervals of HS 11 and IRE 10.1 are characterized by higher abundances of *Zoophycos*, together with strong peaks in hBFAR values, significant lows in miliolids and lower abundance of deep infaunal taxa. The presence of *Chondrites* during IRE 10.1 also indicates the impoverishment in pore-water conditions deep within the sediment.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Stratigraphic variation in ichnofabrics at the "Shackleton Site" (IODP Site U1385) on the Iberian Margin: Paleoenvironmental implications

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ABSTRACT

Ichnofabric analysis was conducted on cores from Site U1385 (IODP Expedition 339) to interpret paleoenvironmental conditions at the southwest margin of the Iberian Peninsula during the Pleistocene. Site U1385 provides an important record for the study of orbital and suborbital-scale climate variability, changes related to ocean/atmosphere dynamics, and affected environmental parameters. A detailed study of the ichnofabric characterization is presented, focusing on the types of ichnofabrics, relative abundance, amount of bioturbation, grouping, ichnofabric succession/transitions and vertical distribution. Seven ichnofabrics were differentiated; green mottled ichnofabric, *Planolites* ichnofabric, *Taenidium* & *Planolites* ichnofabric, *Thalassinoides*-like & *Palaeophycus* ichnofabric, *Planolites* & *Thalassinoides*/*Thalassinoides*-like ichnofabric, *Zoophycos* ichnofabric, and *Chondrites* ichnofabric. They exhibit significant differences in terms of ichnofabric features as well as in their stratigraphic distribution. The most abundant ichnofabrics are *Planolites* & *Thalassinoides*/*Thalassinoides*-like ichnofabric and green mottled ichnofabrics, with a dominance of the middle tier ichnofabrics. The degree of bioturbation is moderate, with a mean BI around 3, but showing a clear bimodal distribution: one group of intervals is characterized by high bioturbation (BI=6), while another displays low-moderate BI values (BI=1–2). In general, ichnofabric features confirm generally good environmental conditions (oxic environment and high food availability) for the macrobenthic tracemaker community, especially favorable in the uppermost part of the sediment. A complete ichnofabric succession, from deep to shallow tier ichnofabrics, is commonly registered (i.e., *Zoophycos* ichnofabric or *Chondrites* ichnofabric to *Planolites* & *Thalassinoides*/*Thalassinoides*-like ichnofabric, and then either to green mottled ichnofabric, or to *Planolites* ichnofabric and then green mottled ichnofabric). However, there are some intervals where an incomplete succession between deep and shallow ichnofabrics is observed (i.e., *Chondrites* ichnofabric to green mottled ichnofabric or *Zoophycos* ichnofabric to green mottled ichnofabric), indicating relevant modifications of environmental parameters such as oxygen or food supply. Types of ichnofabrics and the Bioturbation Index show significant short-term changes through the studied core. Such variations are probably correlated to millennial-scale climatic perturbations, such as glacial terminations and related phenomena (Heinrich

events, ice-rafting events, etc.), or long-term cyclic patterns related to orbital climate variability. The patterns could be tied to a significant change in the climate system, such as the one associated with the middle Pleistocene transition.

PART IV
CONCLUSIONS

Chapter 8

CONCLUSIONS

CONCLUSIONES

8.1. Conclusions

The main objective of the present PhD Thesis was to conduct a detailed ichnological analysis of cores from IODP Expedition 339 with the motivation to demonstrate the relevant role of ichnology in this sort of multidisciplinary project. A precise study of ichnological features (including trace fossil assemblages, ichnofabric and ichnofacies) was developed, providing palaeoenvironmental interpretations involving changes in palaeoclimate and atmosphere-ocean dynamics at different scales, not only regional, but also in a global context. The obtained results have been published as research papers, some of them included as chapters from this volume or as supplementary papers, showing the usefulness of ichnology as a proxy for the study of modern marine cores. Considering all the advances achieved in the framework of the PhD, general conclusions can be divided in two groups clearly discerned: methodological aspects and palaeoenvironmental context.

8.1.1. Methodological aspects

Visualization and identification of biogenic sedimentary structures (both biodeformational structures and trace fossils) in the studied cores was not an easy matter, due to the well-known limitations when working with modern marine cores (i.e., limited size, restricted surface, and almost exclusive availability of 2D information, among others). Thus, before attempting any ichnological analysis of cores from Expedition 339 it was necessary to implement a new methodology permitting the study of biogenic sedimentary structures. The method developed is based on high resolution image treatment. Its usefulness was first proven in cores from IODP Expedition 339, and then in other unconsolidated and consolidated cores; it facilitates differentiation between biodeformational structures and trace fossils and ichnogenera identification, as well as providing information about other ichnological features, such as degree of bioturbation, tiering or penetration depth.

Its application is divided in four sequential steps. The first one (*image adjustment*) is based on the original image adjustment modification (levels, brightness and vibrance). The second step (*digital estimation*), allows the percentage of bioturbated surface to be calculated, analyzing those pixels that belong to trace fossils in a semi-automatic way. The third step (*pixel counting*) provides additional information about some ichnotaxa and estimates the penetration depth by the quantitative pixel analysis. Finally, the fourth one (*ichnofabric representation*) consists of the integration of all the obtained ichnological information in the commonly used ichnofabric representations. Its usefulness in ichnofacies analysis, concretely in deep-sea settings, has been also demonstrated.

In addition, this method was applied to characterize sedimentary attributes of cores as color variations, through the comparison of color from infilling material of trace fossils and that from the surrounding host sediment. This approach provides further information on color data, allowing the influence of trace fossils on color variations in the sediment to be evaluated, thereby avoiding misinterpretations based exclusively on color changes.

8.1.2. Palaeoenvironmental context

Ichnological analysis, mainly conducted on cores from Site U1385, led us to identify a relatively diverse trace fossil assemblage consisting of nine ichnotaxa (*Planolites*, *Palaeophycus*, *Thalassinoides*, *Thalassinoides*-like, *Taenidium*, *Zoophycos*, *Chondrites*, *Phycosiphon* and ?*Scolicia* from most to least abundant), belonging to *Zoophycos* ichnofacies, and characterizing 8 ichnofabrics. In general, a completely bioturbated background is recognized in the studied materials, representing the shallowest benthic activity at the uppermost tiers (on or just below the seafloor). This mottled background is overlapped by discrete trace fossils, corresponding to tracemakers which bioturbate several tiers into the substrate, and reflecting different phases of colonization. This ichnological pattern indicates generalized favorable conditions for the macrobenthic tracemaker community, e.g. good oxygen levels and nutrient availability during the last 1.5 Ma, with only short-range changes associated with dysaerobic intervals and/or minor variations in productivity.

Higher-frequency variations in the palaeoenvironmental conditions were observed when a detailed analysis was conducted focusing on Marine Isotope Stages (MIS) 12 and 11, based on an integrative ichnological and micropalaeoentological approach. The evolution of the macrobenthic tracemaker community during MIS 12 and MIS 11 responds to major changes in bottom water ventilation, probably linked to variations in deep water thermohaline circulation, and foraminifer assemblages point to significant changes in surface productivity and nutrient influx to the sea floor.

In this context, it has been proven that the high seasonal food supply, here related with the Portuguese upwelling, influences the distribution and abundance of *Zoophycos*. Its record in the IODP Site U1385 during the last 1.5 Ma is linked to glacial periods characterized by high and seasonal productivity conditions and intermediate sedimentation rate (5-20 cm/ka). This relationship is also observed in deposits from Nordic Seas, Northwestern African Margin and South China Sea. Together with the data obtained from IODP Expedition 339 cores, these observations come to support the use of *Zoophycos* record as a proxy of high and seasonal productivity from hemipelagic Neogene deposits.

Consequently, and in keeping with the motivation behind this research, the results obtained in the framework of this PhD demonstrate the power of ichnological studies for the analysis of modern cores, as the ones retrieved from IODP Expedition 339. All the information provided by the ichnological approach is revealed as very interesting and pertinent for palaeoenvironmental interpretations, signaling ichnology as a highly useful tool in ocean drilling research.

8.2. Conclusiones

El principal objetivo de la presente Tesis era el de realizar un análisis icnológico en detalle en aquellos sondeos extraídos durante la Expedición 339 del IODP con la motivación de poner de manifiesto la importancia de la icnología y sus aplicaciones en este tipo de proyectos multidisciplinares. Para ello se realizó un estudio en detalle de las características icnológicas (incluyendo asociación de trazas fósiles, icnofábricas e icnofacies), aportando interpretaciones paleoambientales relacionadas con cambios del paleoclima y la dinámica atmósfera/océano a distintas escalas, no solo regional, sino en un contexto global. Los resultados han dado lugar a una serie de publicaciones, algunas de ellas incluidas como capítulos en este volumen y otras como material adicional, que han puesto de manifiesto la utilidad del análisis icnológico como indicador en el estudio de sondeos marinos modernos. Considerando todos estos avances realizados durante la tesis, las conclusiones generales pueden dividirse en dos grupos claramente diferenciados: consideraciones metodológicos y contexto paleoambiental.

8.2.1. Consideraciones metodológicas

La visualización e identificación de estructuras sedimentarias biogénicas (tanto estructuras biodeformacionales como trazas fósiles) no fue una tarea sencilla en los sondeos estudiados, debido a las conocidas limitaciones cuando se trabaja con sondeos marinos modernos (tamaño limitado, superficie restringida, y exclusiva disponibilidad de información en 2 dimensiones, entre otras). Por ello, previo a cualquier análisis icnológico en los sondeos de la Expedición 339, fue necesario implementar una nueva metodología que permitiese el estudio de estructuras sedimentarias biogénicas. La técnica desarrollada se basa en el tratamiento digital de imágenes de alta resolución. Este método, cuya eficacia fue primeramente probada en sondeos de la Expedición 339 y posteriormente en otros sondeos tanto consolidados como no-consolidados, facilita la diferenciación entre estructuras biodeformacionales y trazas fósiles, la identificación de icnogéneros, a la vez que proporciona información acerca de varias características icnológicas como el grado de bioturbación, el *tiering* o la profundidad de penetración de las estructuras.

Su aplicación se lleva a cabo siguiendo una serie de cuatro pasos secuenciales. El primero (ajustes de imagen) se basa en la modificación de ciertos ajustes de la imagen original (niveles, brillo e intensidad). El segundo (estimación digital), permite evaluar el porcentaje de superficie bioturbada seleccionando aquellos píxeles que corresponden a trazas fósiles de forma semi-automática. El tercer paso (conteo de píxeles) aporta información adicional sobre determinados icnotaxones y permite estimar la profundidad de penetración mediante el análisis cuantitativo de píxeles. Finalmente el cuarto paso (representación de icnofábricas) consiste en la integración de toda la información icnológica en las representaciones de icnofábricas usadas normalmente. La utilidad en el análisis de icnofacies, concretamente en ambientes marinos profundos, ha sido también demostrada.

De forma adicional, este método se aplicó en la caracterización de características sedimentarias de los sondeos como variaciones del color, mediante la comparación del color registrado en el interior de las trazas fósiles y en el sedimento que las rodea. Con ello se aporta información adicional sobre el dato de color, permitiendo evaluar la influencia de las trazas fósiles en los cambios de color del sedimento, y evitando interpretaciones erróneas basadas exclusivamente en los cambios de color.

8.2.2. Contexto paleoambiental

El análisis icnológico se desarrolló principalmente sobre los sondeos extraídos en la localización U1385 permitiendo identificar una asociación de trazas fósiles relativamente diversa compuesta por nueve icnotaxones distintos (*Planolites*, *Palaeophycus*, *Thalassinoides*, *Thalassinoides*-like, *Taenidium*, *Zoophycos*, *Chondrites*, *Phycosiphon* y ?*Scolicia* por orden de abundancia), típica de la icnofacies de *Zoophycos*, y un total de 8 icnofábricas. De forma general se puede apreciar un fondo completamente bioturbado en los materiales estudiados, que representa la actividad bentónica más somera (desarrollada en o justo bajo la superficie). Trazas fósiles discretas se encuentra superpuestas a este moteado, correspondientes a las estructuras producidas por organismos bioturbadores a mayor profundidad en el sustrato, y reflejando diferentes fases de colonización. El patrón icnológico indica unas condiciones favorables generalizadas para la comunidad macro-bentónica en cuanto a niveles de oxígeno y disponibilidad de nutrientes a lo largo de los últimos 1.5 Ma, con tan solo cambios de corto periodo asociados a intervalos disaeróbicos y/o variaciones menores en la productividad.

Cambios de mayor frecuencia en las condiciones paleoambientales fueron observadas al analizar de forma detallada los MIS 12 y 11, en base a un análisis integrado de icnología y micropaleontología. La evolución de la comunidad macro-bentónica durante los MIS 12 Y 11 responden a cambios mayores en la ventilación del agua de fondo probablemente relacionadas con variaciones de la circulación termohalina de aguas profundas, mientras que las asociaciones de formainíferos revelan cambios significativos de la productividad superficial y el aporte de nutrientes en el fondo.

En este contexto, se probó que el alto aporte de nutrientes de forma estacional, en este caso relacionado con upwelling, condiciona la distribución y abundancia de *Zoophycos*. Su registro en los sondeos del *Site* U1385 del IODP durante los últimos 1.5 Ma se relaciona con periodos glaciares caracterizados por unas condiciones de alta productividad estacional y valores de tasa de sedimentación intermedios (5-20 cm/ka). Esta misma relación ha sido observada en depósitos de los Mares Nórdicos, el Margen Noroeste Africano o del Mar del Sur de China. Estas observaciones, junto con los datos obtenidos en sondeos de la Expedición 339, nos permiten poder usar el registro de *Zoophycos* con un indicador de periodos de alta y estacional productividad en depósitos hemipelágicos del Neógeno.

En consecuencia, siguiendo la motivación de la presente investigación, todos los resultados obtenidos durante esta Tesis han demostrado la importancia de los estudios icnológicos en el análisis de sondeos marinos modernos, como los extraídos en el marco de la Expedición 339 del IODP. La información obtenida a partir de estos análisis es de gran interés, principalmente en interpretaciones paleoambientales, siendo la icnología considerada como una herramienta de gran utilidad en la investigación de perforaciones oceánicas.

8.3. Forthcoming research

The present PhD dissertation may be considered as a first step in the application of ichnological analysis in the study and interpretation of modern marine cores, revealing significant results, while at the same time opening the doors of new challenges. In this context, several key points should be addressed in the future:

- Regarding methodological aspects, some new advances are in progress, based on the application of the proposed methodology to other types of sediments, including non-lithified and lithified materials, as well as to different images. The method has been recently applied to high resolution images from consolidated cores, core radiographs and CT-images, obtaining interesting yet preliminary results after the modification of certain image parameters (e.g., Cunningham et al., 2016; Hodel et al., under review). Therefore, expanding the range of applications of this method for different materials and images can be underlined as one point to be approached in further studies.

- With respect to palaeoecological interpretations, the proven relationship between ichnological features, palaeoenvironmental conditions, and palaeoclimate and atmosphere/ocean dynamic changes would encourage advancing along this line of research. One open question is the appraisal of the ichnological approach in the characterization of short-range palaeoenvironmental changes, associated with sub-Milankovitch phenomena and involving variations in palaeoclimate and ocean/atmosphere dynamics. Highly detailed ichnological analyses, and correlations with other high-resolution proxies (i.e., geochemical data) hold promise in this aspect.

- In terms of contourites and gravity-flow deposits, the use of bioturbation for their characterization and differentiation has only slightly been approached, but the results thus far are of great interest (e.g., Alonso et al., 2016). On this topic, bioturbation could provide useful information to resolve several controversial points surrounding the characterization of contourites, turbidites or mixed deposits. The information obtained from future applications of the ichnological approach to these different deposits might lead to the proposal of new conceptual models. This prospect has both scientific and economic implications, as the differentiation of these deposits is a key point in reservoir characterization.

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APPENDIX

Another published paper of ichnological applications in IODP Expedition 339 cores as a coauthor

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Contourite vs gravity-flow deposits of the Pleistocene Faro Drift (Gulf of Cadiz): Sedimentological and mineralogical approaches

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ABSTRACT

Pleistocene succession at Sites U1386 and U1387 (IODP 339) from palaeo-moat and drift domains of the Faro Drift has been examined to characterize the lithofacies and to identify the most useful criteria for distinguishing between contourite and gravity-flow deposits. Three lithofacies, A, B, and C, are defined based on a combination of sedimentological and mineralogical analyses. The dominant lithofacies A corresponds to contourite deposits; lithofacies B and C comprise turbidites and debrites respectively. Three main criteria have been utilized to distinguish between these deposits: (i) the vertical trend of the grain-size and the sedimentary structures. The contourites show complete sequences (C1 to C5 divisions) and truncate sequences (basecut-out divisions, e.g., C3–C2–C1, and C3). The turbidites display mainly Td–Te divisions, although Tc division is also present to a lesser extent. The debrites display deformational and shearing structures; (ii) the modal frequency distribution. The contourite sequences show similar mode grain-size values in different textures suggesting that the steady conditions of supply are maintained over time. In contrast, turbidite and debrite sequences display different modes, primarily conditioned by mixing of components from allochthonous sources and their downslope gravitational transport; (iii) the sediment composition (clay mineral, bulk mineral and sand fraction) and provenance that reflect long- and short-distance transport modes. Most of the terrigenous components of the contourites come from the Guadalquivir drainage basin, whereas for the turbidites and debrites these are sourced from the neighbouring fluvial drainage basins (Guadiana, Tinto-Odiel). The biogenic components in the latter indicate shallow depositional environments prior to seafloor failure. The spatial and temporal distributions of the lithofacies reflect the different (palaeo) environments of the Faro Drift. Debrite and incomplete turbidite sequences characterize the palaeo-moat domain during the Early Pleistocene. Complete contourite sequences (C1 to C5) and basecut-out sequences (C3–C4–C5, and C3) characterize the proximal palaeo-drift domain during the Early and Middle Pleistocene and the complete contourite sequences represent the distal drift domain during the Late Pleistocene.

1. Introduction

The Integrated Ocean Drilling Program (IODP) Expedition 339 (November 2011 to January 2012) drilled five sites in the Gulf of Cadiz and two offshore in western Portugal, and recovered 5.5 km of sediment cores. This expedition provided the opportunity to interpret events (tectonic, climate, sea level changes) occurring around the Gulf of Cadiz in terms of their impacts on regional basin evolution, global ocean circulation, and climate (Hernández-Molina et al., 2016). Five sites, two of them (U1386 and U1387) are analysed in this work, were targeted within the contourite depositional system (CDS) for drilling as a key location for the investigation of Mediterranean Outflow Water (MOW) through the Strait of Gibraltar, and its evolution and environmental implications (Hernández-Molina et al., 2013; Stow et al., 2013). This CDS has developed at very high rates of sediment accumulation over past 5 M.a. as a direct result of MOW, providing an expanded sedimentary record of palaeocirculation linked to past environmental change. Preliminary results indicate a Pleistocene register made up of contourites and some interbedded turbidites (Stow et al., 2013; Hernández-Molina et al., 2014). One of the objectives of that expedition was to identify the sedimentary facies related to the MOW bottom current and the possible interaction between downslope and alongslope processes during the Pliocene and Quaternary (http://iodp.tamu.edu/scienceops/expeditions/mediterranean _outflow.

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html). This interplay of processes has been well illustrated on the westernmost part of the Gulf of Cadiz where numerous downslope channels deliver abundant terrigenous material to the continental slope. This region is swept by an active MOW that captures and reworks sediment delivered by downslope processes (Mulder et al., 2006; Marchès et al., 2007, 2010). It is clear that the interplay of downslope and alongslope processes is the rule rather than the exception for deep-water ocean-margin sedimentation, even in isolated drift settings far from a continental source (Faugères and Stow, 1993).

During the last 50 years there have been numerous studies and reviews of criteria for distinguishing between alongslope and downslope and processes (Hollister and Heezen, 1972; Stow, 1979; Stow and Shanmugam, 1980; Johnson and Rasmussen, 1984; Shor et al., 1984; Stanley, 1987, 1993; Locker and Laine, 1992; Faugères and Stow, 1993; McCave and Carter, 1997; Gonthier et al., 2003; Mulder et al., 2006, 2008, 2013). There is no general agreement on diagnostic criteria at a small scale (cores and outcrops) whereas the difference between them is very clear at large scale (depositional systems, on the basis of seismic facies) (Rebesco and Stow., 2001; Llave et al., 2002; Viana, 2001; Hernández-Molina et al., 2006; Roque et al., 2012; Rebesco et al., 2014). At a small scale, several quantitative and qualitative parameters have been used, individually or in combination: grain-size and statistical parameters of their granulometric distribution (e.g., sorting, modal frequency distribution), sedimentary structures, textural vertical trend, mineralogical composition, and magnetic fabric. Various studies (Stow, 1979; Stow et al., 2002; Stow and Faugères, 2008) have argued strongly that a definitive interpretation of contourite facies requires careful combination of small (sediment), medium (seismic) and large-scale (regional) evidence.

Few studies take into account the detailed mineralogical composition and characteristics of contourite and gravity-flow deposits, although this can provide important information about sediment provenance (Stow, 1979; Shor et al., 1984; Stanley, 1987, 1993; Alonso et al., 1999; Martínez-Ruíz et al., 1999). The mineral composition of shelf sediments of the Gulf of Cadiz has been related to the hinterland weathering and to the intensity and direction of the processes responsible for their distribution within the marine environment (Grousset et al., 1988; Gutiérrez-Mas et al., 1995, 1996; Moral Cardona et al., 1997; Machado et al., 2005). In addition, specific clay minerals (e.g., smectite and kaolinite) have been considered of interest for detecting the signal of MOW in the continental slope sediments of the Gulf of Cadiz (Grousset et al., 1988; Vergnaud-Grazzini et al., 1989). In particular, the smectite + kaolinite/illite + chlorite and smectite/illite ratios previously used in this area are seen to be useful for distinguishing particles transported back in the Atlantic Ocean by the MOW and deposited along the Faro Drift (Grousset et al., 1988; Vergnaud-Grazzini et al., 1989). Therefore, the combination of sedimentological and mineralogical criteria can be useful to discriminate between contourite and gravity-flow deposits (turbidites and debrites) in the core material from IODP Expedition 339. For the Gulf of Cadiz slope system, the seismic and regional evidence for contourite sedimentation already exists.

The focus of this study is the Pleistocene sedimentary record from Sites U1386 and U1387, which are located on the Faro Drift on the Algarve margin (Fig. 1). The principal aims are: i) to characterize Pleistocene lithofacies based on sedimentological and mineralogical properties; ii) to identify the main diagnostic features for distinguishing contourite and gravity-flow deposits by examining sedimentological and mineralogical criteria; and iii) to define a model of facies distribution for the depositional architecture of the Pleistocene Faro Drift deposits.

2. Regional settling

2.1. Geological and oceanographic setting

The Gulf of Cadiz, located on the African–Eurasian plate boundary forms a deeply concave indentation between the African and European continental plates (Zitellini et al., 2009; Fig. 1). Its northern margin (Iberian margin) extends off the coast of the SW Iberian Peninsula, from Cape of St Vicente in the west to the Strait of Gibraltar in the east. The Gulf of Cadiz margin can be divided into two sectors, east and west, based on physiographic and sedimentary architecture (Fig. 1A). The eastern sector extending from western Cadiz margin to Huelva margin is progradational. It is marked by the presence of several major tectonic features: the Cadiz and Guadalquivir ridges and the Guadalquivir Bank, and the presence of linear diapiric ridges that are perpendicular to the slope (Maldonado et al., 1999; Nelson et al., 1999; Llave et al., 2002; Garcia et al., 2009, 2015). Fluvial supply is high to the eastern sector. The main fluvial sources are, from east to west: the Barbate, Guadalete, Guadalquivir, Tinto-Odiel, and Guadiana rivers (Fig. 1A). The fluvial discharges of these rivers are very irregular, with significant seasonal and interannual variability (Borrego et al., 1995). The Guadalquivir River has the highest mean water discharge (164 m^3 s^{-1}) into the Gulf of Cadiz (Palanques et al., 1995) and the Guadiana River has the second highest. The mean annual discharges show considerable variability (80–140 m^3 s^{-1}) reaching peak discharge of 3000 m^3 s^{-1} in the winter. The Tinto-Odiel and Guadalate rivers have low mean annual discharges (1 and 10 m^3 s^{-1}).

The western sector of the Gulf of Cadiz, the Algarve margin, is relatively more narrow and steep margin. This margin is scoured by erosional features (including canyons and linear channels) and is interrupted by a marginal plateau between 600 and 800 m water depth (Mougenot, 1988; Marchès et al., 2007, 2010; Brackenridge et al., 2013). Fluvial supply is low to moderate with small fluvio-estuarine systems. The main sources of sediments to the margin are from cliffs erosion and river input with ephemeral discharges (e.g., Quarteira and Portimao rivers; Roque et al., 2010; Rosa et al., 2013).

The surficial shelf sediments of the Gulf of Cadiz are characterized as follows (Fig. 1A): i) a continuous belt of sandy deposits, in particular bioclastic quartzose sands, on the inner shelf of the easternmost sector (Cape of Trafalgar—Cadiz); this trend is interrupted in the proximity of the most important river mouths (Guadiana and Guadalquivir), in front of which more mud-rich patches occur; ii) mud on the mid-outer shelf, locally interrupted by sandy sediments off the Guadiana River; iii) clayey sand, sandy and silty clay, and large patches of relict sand and gravel on the shelf break (Gutiérrez-Mas et al., 1996; Fernández-Salas et al., 1999; López-Galindo et al., 1999; González et al., 2004; Lobo et al., 2014); and iv) reworked relict sand with a high content of ultra-stable heavy minerals and bioclastic particles over the Barbate continental shelf, SE of the Bay of Cadiz. Toward the Strait of Gibraltar, the surficial shelf sediments show an increase in gravel and local rock outcrops of Betic and flysch units from the Campo de Gibraltar complex (López-Galindo et al., 1999; Nelson et al., 1999).

On the middle continental slope of the Gulf of Cadiz, an extensive contourite depositional system (CDS) was generated during the Pliocene and Quaternary (Fig. 1B, C). This CDS extends in a generally E-W direction along the middle continental slope (e.g., Gonthier et al., 1984; Nelson et al., 1999; Stow et al., 2002; Alves et al., 2003; Habgood et al., 2003; Hernández-Molina et al., 2003, 2006, 2008; Mulder et al., 2003; Hanquiez et al., 2007; Llave et al., 2007a,b; Marchès et al., 2007; Roque et al., 2012; Brackenridge et al., 2013). One of the main depositional features of this CDS is the Faro Drift (Faugères et al., 1984; Gonthier et al., 1984; Llave et al., 2006), which is located at ~500–1100 m water depth (Fig. 1B). The Faro Drift has a total length of 100 km, a maximum width of 20 km, a relief of 200 m and a maximum thickness of ~700 m and comprises both erosive (moat) and depositional features (drift) (Fig. 1C). It is limited by the Faro and Portimao canyons to the west and a sinuous contouritic moat (Alvarez Cabral) to the north, and merges southward above the adjacent sheeted drift platform region, where it is deeply incised by the Diego Cao Channel (Stow et al., 2002; Fig. 1B).

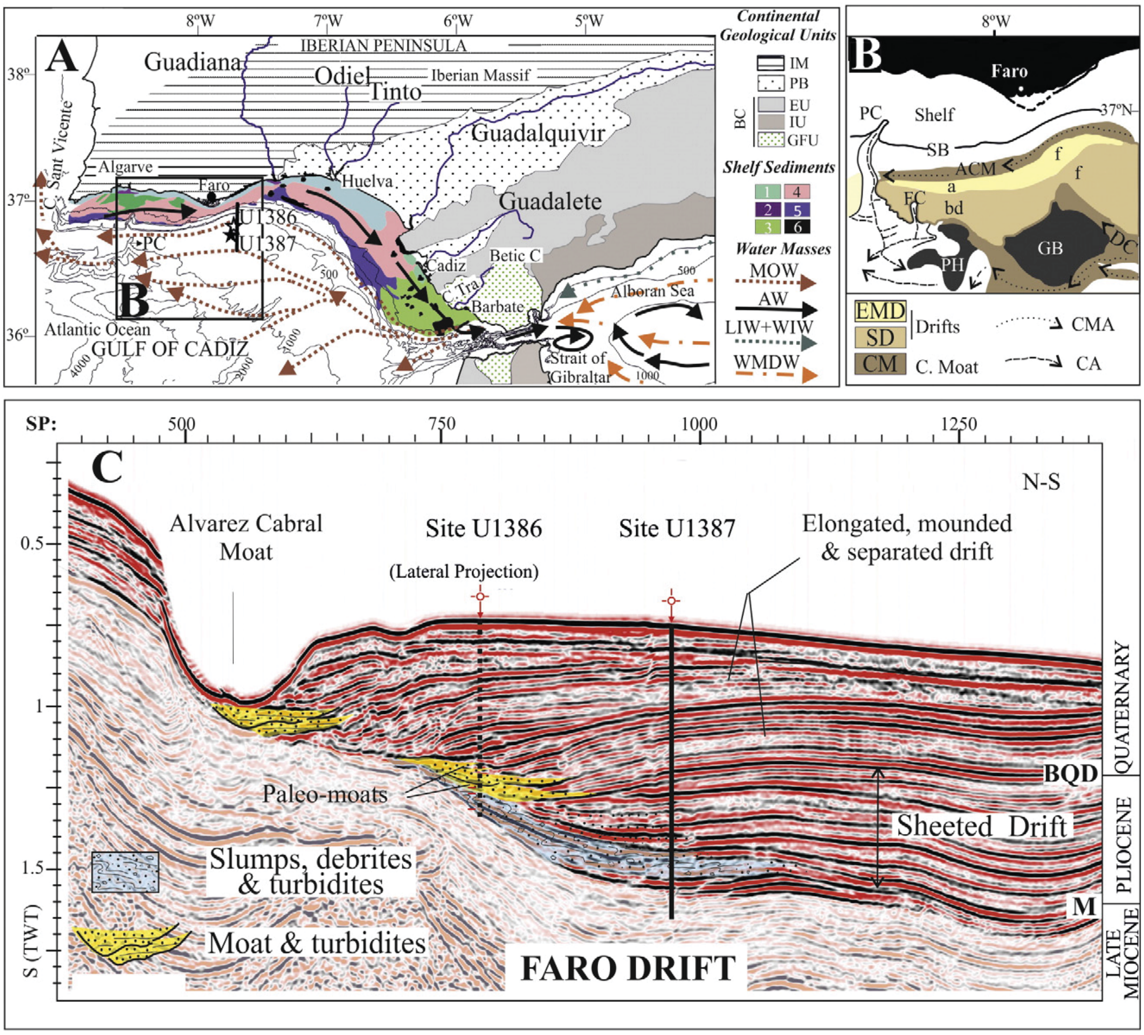

Fig. 1. General setting of the study area in the Gulf of Cadiz: A) geological map showing the river basin drainage with the main continental geological units (modified from Gutiérrez-Mas et al., 2003), shelf sediments (modified from Lobo et al., 2014) with regional bathymetry and the general oceanographic circulation pattern (modified from Hernández-Molina et al., 2006), and the location of the study sites; B) morphosedimentary features of the Faro (f), Albuferia (a) and Bartolomeu Dias (bd) drifts; and C) stratigraphic section displaying the major sedimentary deposits from the Pliocene and Quaternary of the Faro Drift (modified from Hernández-Molina et al., 2014). Legend: IM, Iberian Massif; PB, Postorogenic Basins; BC, Betic Cordillera; EU, External Units; IU, Internal Units; GFU, Gibraltar Flysch Units. 1, coastal and inner shelf sands; 2, proximal prodeltaic muds; 3, middle shelf sands; 4, middle shelf muds; 5, outer shelf sands; and 6, rocky outcrops. MOW, Mediterranean Outflow Water; AW, Atlantic Superficial Water; WIW + LIW, Western Intermediate Water, and Levantine Intermediate Water; WMDW, Western Mediterranean Deep Water; C, Cape of; C. Tra. cape of Trafalgar; EMD, elongated mounded drift; SD, sheeted drift; CMA, contourite moat axis; CM, contourite moat; CA, canyon axis; SB, shelf break; GB, Guadalquivir Bank; PH, Portimao High; PC, Portimao Canyon; FC, Faro Canyon; DC, Diego Channel; ACM, Álvares Cabral Moat. The thick line in A refers to the seismic profile in Fig. 1C. Contours in metres.

The hinterland domain of the Gulf of Cadiz comprises several geological formations, including the Betic and Rif Cordillera, the Iberian Massif and the Guadalquivir Basin (Fig. 1A). The Betic and Rif Cordillera contain (Galindo-Zaldívar et al., 1997; Maldonado et al., 1999): i) the metamorphic complexes of the Internal Zones, ii) sedimentary units of the External Zones, and iii) the Flysch domain consisting of thick, mainly turbidite sequences (Didon et al., 1973). The Iberian Massif is formed of metasediments and greywackes which are drained mainly by the Guadiana River and to a lesser extent by the Guadalquivir River (Oliveira et al., 1979). Some metasediments (phyllite and quartzite and volcanic rocks) are found in the south Portuguese zone, although the majority of this region is covered by turbidite sequences (Galindo-Zaldívar et al., 1997). Between the Iberian Massif and the External Zones is situated the Neogene Guadalquivir Basin, which is filled with siliciclastic and carbonate sediments (clays, sands and conglomerates) with olistostromes emplaced from the External Zones on its southern edge (Perconig and Martínez-Díaz, 1977; Roldán-García and García-Cortés, 1988; Alves et al., 2003).

The present-day water masses in the Gulf of Cadiz are driven by the density contrast between the water masses of Atlantic (cold, normal salinity, less dense) and Mediterranean (warm, higher salinity, more dense; Levantine Intermediate Water, Western Intermediate Water and Western Mediterranean Deep Water) origin that flow through the Strait of Gibraltar (Mélières, 1974; Baringer and Price, 1997; Ercilla et al., 2015). This water exchange is characterized by the eastward upper layer of Atlantic Water into the Mediterranean Sea and a westward bottom layer of the MOW. It is the bottom current generated by the MOW that is responsible for forming the contourite deposits of the Faro Drift (Gonthier et al., 1984). Surface Atlantic Water flows (0–500 m water depth) eastward over the Gulf of Cadiz continental shelf (Lobo et al., 2001) into the Mediterranean and is responsible for distributing the fine sediments supplied by the main rivers to the continental shelf (Grousset et al., 1988; Gutiérrez-Mas et al., 1995). A SE-directed littoral drift, resulting from the predominant W and SW storms, is the dominant factor in moving sediment along the shoreline and across the shelf (Gutiérrez-Mas et al., 1996, 2003).

2.2. Faro Drift: stratigraphy and lithological units

Seismic-stratigraphic studies reveal that the Faro Drift has been constructed from Pliocene to the present day in different phases that show different stacking patterns (Stow et al., 2013; Hernández-Molina et al., 2014, 2016). The weakly reflective Miocene unit is of pre-contourite construction (Fig. 1C). The Pliocene deposits that overlie the Messinian discontinuity (M seismic reflector in Fig. 1C) have built upwards as a sheeted drift. The Quaternary deposits are separated from the Pliocene by the Base Quaternary Discontinuity (BQD in Fig. 1C) and appear as mounded, separated drift deposits with clear oblique alongslope progradation. A general lateral migration of the palaeo-moats found within the Pliocene and Quaternary indicates a steady lateral migration of the drift-moat system and progressively greater confinement of the moat against the slope (Stow et al., 2002; Roque et al., 2012; Hernández-Molina et al., 2014; Fig. 1C). Stratigraphic correlation and specific age constraints of the Sites U1386 and U1387 were established by IODP Expedition 339 using several approaches (lithostratigraphy, biostratigraphy, palaeomagnetic data, geochemical analysis, and borehole logs) (Expedition 339 Scientists, 2012). Age data were used to determine the ages of key seismic horizons (including several hiatuses and stratigraphic boundaries) and the sediment accumulation rates (Fig. 2).

At Site U1386 two lithological units (I and II) were identified (Fig. 2A): i) Unit I (~0–418 m below sea floor [mbsf]), Holocene–Pleistocene in age, is subdivided into three subunits (IA, IB, IC) and is dominated by classical contourite deposition with thin turbidite

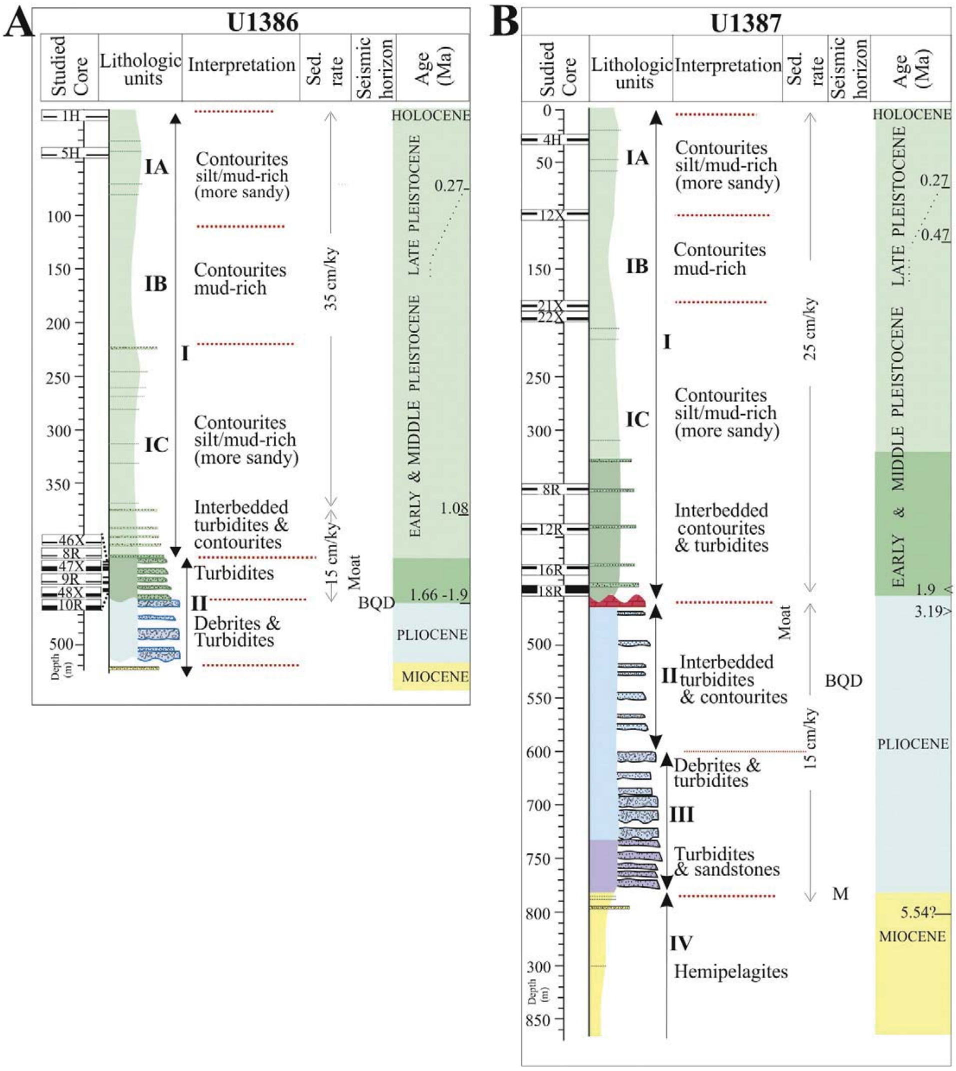

Fig. 2. Plio-Quaternary lithostratigraphic units from Sites U1386 (A) and U1387 (B) of the Faro Drift (based on Expedition 339 Scientists, 2012). The rectangle refers to the studied core and the thick black line corresponds to the studied core section. For more details of the studied holes and core sections, see Section 3. Legend: BQD, Lower Quaternary seismic reflector; M, Messinian seismic reflector.

intercalations in the lowermost 30 m of subunit IC; ii) Unit II (~418–530 mbsf), Miocene–Pleistocene in age, is characterized by turbidites and debrites interbedded with contouritic and hemipelagic nannofossil muds. The Pleistocene units (Unit I and upper part of Unit II) were deposited at moderate sediment accumulation rate (15–35 cm/ky). At Site U1387 four lithological units (I–IV) were identified (Fig. 2B): i) Unit I (~0–450 mbslf), Holocene–Pleistocene in age, is subdivided into three subunits (IA, IB, and IC). It is dominated by classic contourite deposition with thin turbidite intercalations which are predominantly found in the lowermost section; ii) Unit II (~450–595 mbsf), Pliocene in age, is characterized by the same lithologies as in lower part of Unit IC; iii) Unit III (~600–746 mbsf) is mainly Early Pliocene in age, but may start in the latest Miocene. This unit comprises poorly sorted turbidites, chaotic debrites and slumps; and iv) Unit IV, Late Miocene in age, is dominated by hemipelagic sediments, mainly nannofossil muds and muddy oozes. The two studied sites (U1386 and U1387) have been projected on the seismic profile showed in Fig. 1C (Expedition 339 Scientists, 2012) providing information about the lithostratigraphy of palaeo-moat and drift domains (Fig. 1C). The lithostratigraphy of the palaeo-moat domain is recorded in the upper part of Unit II at Site U1386 and that of the drift domain is recorded in the subunit IA of Site U1386 and in the subunits IC, IB and IA of U1387 (Figs. 1C and 2).

3. Material and methods

3.1. Location

Two sites, U1386 and U1387, have been studied on the Faro Drift (Fig. 1A, C). Site U1386 (drilled over 526 mbsf) is located at 561 m water depth (36°49.685′N; 7°45.321′W) close to the Alvarez Cabral moat. Site U1387 (drilled over 820 mbsf) is located at ~559 m water depth (36°48.321′N; 7°43.1321′W), south-southeast of the Portuguese city of Faro, about 4 km from Site U1386, in the eastern part of the Faro Drift (Stow et al., 2013). We examined the following Pleistocene lithological units and subunits: IA (Holes U1386B and U1387A), IB (Hole U1387A), IC (Hole U1387C) and uppermost part of Unit II (Holes U1386B and U1386C). In particular, a total of 149 samples were selected from four holes basis onboard description, lithostratigraphy, and photos (U1386B, U1386C, U1387A and U1387C). The sections and age of sediments studied for each hole are as follows (Fig. 2):

i). Hole U1386B: sections 1H2 and 5H4 (subunit IA, Late Pleistocene); sections 46X5, 47X1, 47X2, 47XCC, 48X2, 48X3 (upper part of Unit II—Early Pleistocene).
ii). Hole U1386C: 8R2, 9R2, 10R3, 10R6 and 10RCC (upper part of Unit II—Early Pleistocene).
iii). Hole U1387A: section 4H5 (subunit IA–Late Pleistocene), section 12X4 (subunit IB, Middle Pleistocene), sections 21X4 and 22X6 (subunit IC—Middle Pleistocene).
iv). Hole U1387C: sections 8R5, 12R3, 16R3, 16R4, 18R2, 18R4, 18R5 and 18R7 (subunit IC—Early Pleistocene).

3.2. Methods

The grain-size was obtained using a Coulter LS 100 laser particle size analyser (CLS) that determines particle grain-sizes between 0.4 and 900 mm as volume percentages based on diffraction laws (McCave et al., 1986). Prior to measurement, we treated the ~10 g samples with hydrogen peroxide to remove organic matter. A cumulative curve and frequency histogram were plotted for the grain size distribution for each sample. Textural statistical parameters were established using the GRADISTAT software (Blott and Pye, 2001). These parameters were calculated using moments (geometric) methods on sample populations. The degree of sorting (standard deviation) was established using the Folk and Ward (1957) classification.

The carbonate content and sand fraction were analysed in terms of sediment composition. Total carbonate content was determined using a Bernard calcimeter (Alonso et al., 1996). For the sand fraction composition (320 grains per sample were counted) was examined using a binocular microscope. Terrigenous components were classified as quartz, mica, rock fragments, pyritized material and burrows, and glauconite. Biogenic components were classified as planktonic foraminifera (entire and fragments), benthic foraminifera, ostracods, bivalves, and gastropods. Quartz grains were examined by SEM.

Ichnological analysis was based on an integrative method using digitally treated high-resolution images from selected core intervals. Sections U1386B 46X5, 47X1, 47X2 and 48X2 and sections U1386C 10R3, 4H5 and 16R3 covering the main deposit types (contourite and gravity-flow deposits) as defined onboard during Leg 339 were selected for this purpose (Stow et al., 2013). The digital image treatment used here was recently developed and applied in cores from IODP Expedition 339 (Dorador and Rodríguez-Tovar, 2016; Rodríguez-Tovar et al., 2015a,b; Takashimizu et al., 2016). This integrative method improves ichnological investigation in soft sediment, enabling definition of ichnotaxa, differentiation between biogenic structures and host sediments (Dorador et al., 2014a), evaluation of the percentage of bioturbated structures (estimation of the amount of trace fossils produced by a particular ichnotaxon, by a whole ichnocoenosis or for a complete ichnofabric) (Dorador et al., 2014b), and characterization of ichnological features such as cross-cutting relationships and tiering patterns (Dorador and Rodríguez-Tovar, 2014; Rodríguez-Tovar and Dorador, 2015). Colour photos were taken from all the studied cores to complement the digital image treatment and the visual core descriptions undertaken on board Leg 339 in order to define sedimentary structures, type of sequence and thickness.

Bulk and clay mineral composition were analysed by X-ray diffraction (XRD) in order to identify mineral composition and help infer provenance. This mineralogical analysis was performed with a Bruker-AXS D8-A25 diffractometer equipped with a Cu tube (Lambda = 1.5405 Å) and an ultra-fast (Lynxeye) detector. For bulk mineralogy, a representative and homogenized part of each sample was used prior to the bulk mineralogic analysis; samples of about 3 g of bulk sediment were air-dried, ground and homogenized with an agate mortar. The relative abundance of the dominant clay fraction components including quartz, calcite, dolomite, and clay minerals was estimated using the intensity of their main diffraction peaks. For clay mineralogy, scans from 2° to 40° (2Θ) were performed on oriented clay fraction samples (untreated, glycolated, and heated to 550 °C). The samples were disaggregated obtaining a suspension of an amount of 500–1000 mg of sample in distilled water (10–15 ml) in a test tube, and softly shaken. After 60 s of natural sedimentation, we get the superior fraction with a pipette and put this on a glass slide that fits on the diffractometer sample holder. The first analysis is made without any treatment. The ethylene glycol solvation treatment involves placing the samples in a solvate vapor medium for not less than 48 h. The final treatment consists of placing the glass slides in a furnace at 550° for two hours. Diffraction profiles were visually interpreted with the help of a computerized search. The relative clay mineral proportion was estimated following the method of Chung (1974), and the peak heights for each mineral were considered as previously reported for sediments from southern Iberia (Algarve, Cadiz and Alboran; Grousset et al., 1988; Vergnaud-Grazzini et al., 1989; Heimhofer et al., 2008). The peak heights used were 10-Å (001) for illite, 7.17-Å (001) for kaolinite, 17-Å for smectite and 14-Å (001) for chlorite. Note that the main reason for the estimated semi-quantitative analysis is to show changes or gradients in mineral abundance rather than absolute values. In addition to clay mineral percentages, we systematically calculated the smectite/illite (S/I) ratio and smectite + kaolinite/illite + chlorite (S + K/I + C) ratio corresponding to the ratio of their peak heights.

We use the term lithofacies as the "sum total of lithological characteristics of a sedimentary rock" such as lithology, grain-size, mineralogy, petrology, physical and biogenic sedimentary structures, and stratification that bear a direct relationship to the depositional processes that produced them (Weller, 1958; Maldonado and Stanley, 1976; Jenner et al., 2007).

4. Results

4.1. Lithofacies

Three main lithofacies A, B and C, were defined based on a cluster of classic and fundamental qualitative and quantitative sedimentological, and mineralogical attributes that include assemblages of the following elements (Alonso et al., 2014): i) grain-size distribution; ii) structures and ichnofacies iii) carbonate content and sand fraction composition; and iv) bulk and clay mineralogical composition (Table 1).

4.1.1. Grain-size distribution

Lithofacies A consists of muddy and fine sandy sediments which are represented by three textures: (1) silty-clay (mean 4–6.2 μm), (2) clayey-silt (mean 9–17 μm), (3) clayey–sandy silt and silt (mean 19–54 μm), and sand (mean 72 μm, in only one sample). It has mainly bi-modal and tri-modal frequency distributions (Fig. 3). The modal frequency distributions of each textures are as follows (Fig. 3): (1) silty-clay: 4–11–26 μm, 4–10–66 μm (e.g., U1387A 21X4) and 4–9–24 μm, 10–26 μm (e.g. U1386A 4H5); (2) clayey silt: 61–26–4 μm, 55–11–4 μm (e.g., U1387A 21X4), and 66–10–4 μm and 55–10 μm (e.g., U1386A 4H5); (3) clayey–sandy silt and silt: 70–9-4 μm, 70–11–4 μm (e.g., U1387A 21X4), and 73–10–4 μm, and 73–10 μm (e.g., U1386A 4H5). This lithofacies is poorly sorted (>3 μm). The vertical succession of grain-size displays a progressive increase and then decrease of grain-size, referred to as a bi-gradational pattern (coarsening-up and fining-up). The complete vertical succession begins at the base with fine-grained mud (texture 1), passing upwards mottled to silt (texture 2), then sandy silt or very fine sand (texture 3), and then repeats these textures again but in the opposite order, passing to mottled silt (texture 2) and then homogeneous fine-grained mud (texture 1). The complete vertical succession of textures 1–2–3–2–1 is only observed in three sections (U1386B 1H2 and 5H4; U1387 4H5). Mostly, we observe partial bi-gradational succession of textures (1–3–2–1 or 1–3–1 (Fig. 4). The thicknesses of these successions are generally between 10 and 60 cm, with the exception of one thicker sequence (up to 90 cm) (section U1387C 16R3). Through a single vertical succession, the modal frequency distribution shows similar modal grain-size and only the relative abundance of the modes varies (Fig. 3).

Lithofacies B comprises fine-grained sediments and shows three textures: (1) clayey-silt, (2) silt and sandy-silt (mean 3–10 and 8–30 μm, respectively), and (3) silty-sand (mean 52–115 μm, reaching 142 μm only in two samples). This lithofacies has uni- bi- and tri-modal frequency distributions with variable mode values throughout the lithofacies. The modal frequency distribution of the different textures is as follows (Fig. 3): (1) clayey-silt: 7–19–50 μm (U1386B 46X5), 10–46 μm (U1386B 47X2), (2) silt and sandy silt: 154–20–7 μm (U1386B 46X5), 154–20–7 μm (U1386B 46X5), 60–16 μm (U1386B 47X2), and (3) silty-sand: 169–38 μm, and 245–127–30 μm. This lithofacies is poorly sorted (>3 μm). The vertical succession of grain-size shows normal grading from silt to mud with a sharp contact at the base. The thicknesses of individual succession vary from 1 cm to at least 95 cm (Fig. 4).

Lithofacies C consists of finer-grained sediments represented by two textures: (1) clayey-silt, and (2) clayey–sandy silt and silt (mean 4–9 μm, 9–16 μm, and 7–10 μm, respectively). It has bi- and tri-modal patterns of modal frequency distribution similar to that defined for lithofacies B. The modal frequency distribution of each texture is as follows (Fig. 3): (1) clayey-silt: 4–11–26–55 μm (U1386C 10R6), and (2) clayey–sandy silt and silt: 11–47 μm, 20–66 μm (U1385C 10R3) and silt: 50–11 μm, and 73–6–21 μm. This lithofacies is poorly sorted sediments (>3 μm). There are no distinct vertical trends of grain-size displaying matrix-supported mud-clast beds (Fig. 4). The thickness of individual beds is from 50 to 100 cm.

4.1.2. Structures and ichnofacies

Lithofacies A is moderately to intensively bioturbated. Two ichnofabric types are recognised (numbers 1 and 2 in Fig. 5): 1) a well-developed mottled silt background, mainly consisting on biodeformational structures overprinted by scarce trace fossils (*Planolites, Thalassinoides-like and Ophiomorpha-like*) especially in mottled silts and silts; 2) homogeneous muds with some trace fossils infilled by relatively coarser sediments (silts) from the overlying lithofacies (yellow stars in Fig. 5). Lithofacies B displays two ichnofabric types (numbers 3 and 4 in Fig. 5): 3) a well-developed

Table 1
Summary of the main characteristics of muddy contourite (LA), turbidite (LB) and debrite (LC) lithofacies of Pleistocene Faro Drift deposits. Legend: Carb. Cont., carbonate content; Sand Frac., sand fraction composition; XRD., X-ray diffraction; and S. Seq., sedimentary sequence.

		Muddy contourites (LA)	Turbidites (LB)	Debrites (LC)
Texture	✓	Fine-grained sediments (4–54 and 72 μm)	Fine-grained sediments (3–52, and 52–142 μm)	Fine-grained sediments (4–16 μm)
	✓	Silty muds alternate with fine-grained sands and silts	Clayey silts alternate with sandy silts and silty sands	Clayey silts alternate with sandy silts and clayey–sandy silts
	✓	Poorly and very poorly sorted	Poorly sorted	Poorly and very poorly sorted
	✓	Similar mode values throughout the core and nearby cores. Common bi- and tri- modal values	Different mode values. Common uni- and bi-modal values	Different mode values. Common bi- and tri-modal values
Carb. Cont.	✓	Rich in carbonate content	Low carbonate content	Low to medium carbonate content
Sand Frac.	✓	Siliciclastic-bioclastic nature	Terrigenous nature	Terrigenous with presence of shell fragments
	✓	Shiny-angular and subangular quartz grains	Shiny-angular and subangular quartz grains	Matt, rounded and shiny subangular quartz grains
Ichnofabric	✓	Well-developed mottled silt background with fossil traces (C2, C3, C4)	Mottled background (Td) Lack of mottled background and trace fossils (Te)	Alternation of poorly-developed mottled and unmottled facies with a few trace fossils
	✓	Some trace fossils in homogenous muds infilled by silts from the overlying lithofacies (C1, C5)		
Bulk XRD	✓	Rich in calcite	Rich in quartz	Rich in quartz
Clay XRD	✓	Rich in smectite with high S/I ratio values	Rich in illite with low S/I ratio values	Rich in illite with low S/I ratio values
S. Seq.	✓	Complete Stow & Faugères sequence (C1 to C5), common in Unit IA	Truncated Bouma sequence (Tc, Td, Te), common Td and Te divisions in upper part of Unit II	No specific textural vertical trend. Matrix-supported sediment with mud clasts and deformed beds
	✓	Truncated sequences (basecut-out) common in subunit IC	Grading toward top of sequence common in Tc	
	✓	Similar sequence thickness with internal gradational boundaries	Different thicknesses (thin to thicker) with sharp lower boundaries	Different thicknesses (thin to thicker)

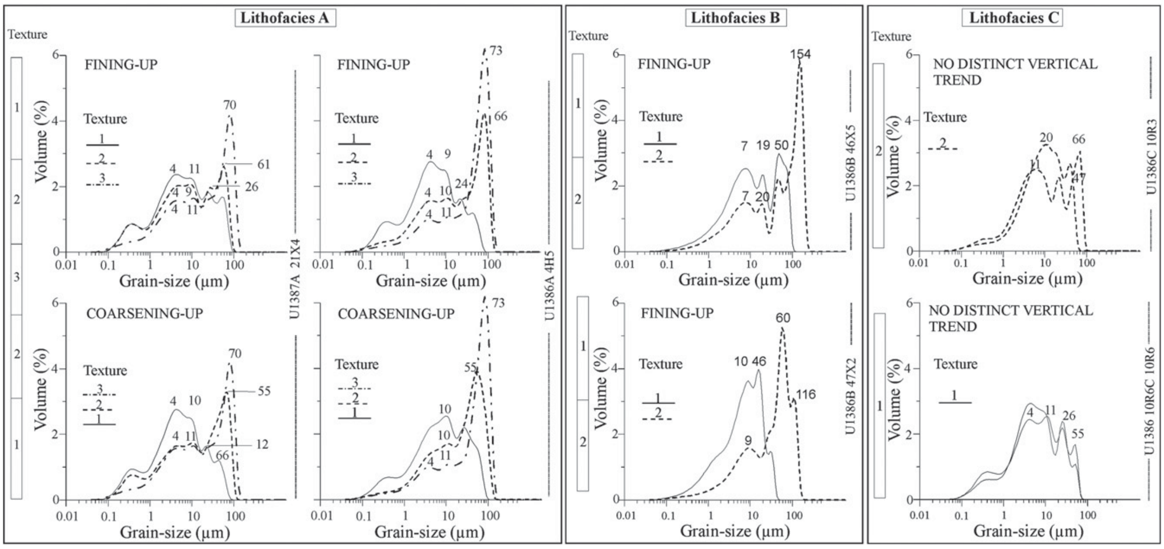

Fig. 3. Sedimentological description showing the granulometric parameter distribution and modes of lithofacies A (U1387A 21X4 and 4H5), lithofacies B (U1386B 46X5 and 47X2) and lithofacies C (U1386C 10R3 80 and 88 cm and 10R6 70 and 77 cm).

mottled background sediment with intercalations of unmottled sediments, generally found at the top of the very fine clayey-silt succession of textures (mean 3–10 μm), and also showing a few distinct trace fossils (green stars in Fig. 5 for traces infilled from host lithofacies); and 4) a lack of mottled background and trace fossils, typical in the homogeneous very fine clayey-silt (mean 6 μm) beds. Lithofacies C shows distorted stratified sediments and homogeneous sediments with mud clasts. The first is characterized by highly convoluted folded with colour-banded alternations of dark greenish-grey and greenish-black muds and the contacts between these beds are marked by truncations and zones of intense shearing (Fig. 4). The homogeneous mud appears as uniform mud matrix with small, soft mud and sand clasts. This lithofacies shows an alternation of poorly developed mottled and unmottled facies (number 5 in Fig. 5) with a few trace fossils (yellow and green stars for traces infilled from overlying and host lithofacies, respectively).

4.1.3. Carbonate content and sand fraction composition

Lithofacies A, with high carbonate content (18%–45%), is characterized by a mixed siliciclastic-bioclastic sand fraction composition. This fraction is dominated by biogenic components, mostly planktonic foraminifers (entire and fragments) with lesser quantities of others (e.g., benthonic foraminifers and ostracods), and quartz as a terrigenous component. The quartz grains are angular and subangular in shape (Fig. 6A). Lithofacies B, with low carbonate content (4%–19%), is characterized by a terrigenous sand fraction (80%–100%), mostly quartz (Fig. 6A). Some samples (e.g., intervals U1386B 47X1 99, 103, 108 and 115 cm; 48X2 13, 21 and 32 cm) also contain significant amounts of mica (up to 50%) and low percentages (<5%) of other components (e.g., glauconite, hornblende, and rock fragments). The quartz grains are angular and subangular in shape and show a prevalence of shiny surfaces (letters a and b in Fig. 6B). Lithofacies C displays low and moderate carbonate contents (4%–26%) and a heterogeneous sand fraction composition, being dominated by terrigenous components, particularly quartz (up to 95%) and also heterometric fragments of gastropods and other molluscs (Fig. 6A). The quartz grains are spherical and rounded and show prevalent matt faces with a polished surface (letters c and d in Fig. 6B).

4.1.4. Bulk mineral composition

The XRD analysis of the bulk fraction indicates that sediments are mainly composed of quartz, clay minerals, calcite and dolomite, with trace amounts of aragonite, microcline, albite, paragonite, and haematite. Lithofacies A, B and C show distinct variations between the major components of the bulk mineralogy, except for dolomite contents, which is more uniform (Fig. 7). Lithofacies A is richer in calcite (14%–32%), with highly variable quartz (9%–41%) and clay mineral (12%–41%) content, and a lower percentage of dolomite (5%–16%; Fig. 7A). There are two bulk mineral assemblages: i) quartz > calcite > clay minerals > dolomite, and ii) quartz > clay minerals > calcite > dolomite. In contrast, lithofacies B and C are richer in quartz (up to 58%) and have lower percentages of calcite (<19%; Fig. 7B). Specifically, lithofacies B is richer in quartz (22%–68%) and poorer in calcite (2%–20%), with a variable percentage of clay minerals (10%–46%) and a low dolomite content (2%–11%). Lithofacies C is also richer in quartz (22%–60%) and poorer in calcite (10%–18%), with great variations in the clay mineral content (18%–41%) and minor percentages of dolomite (5%–15%; Fig. 7B). Both lithofacies, B and C, show a quartz > clay minerals > calcite > dolomite bulk mineral assemblage.

4.1.5. Clay mineral composition

The XRD analysis of the clay fraction indicates that the sediments are mainly composed of illite, chlorite, kaolinite and smectite (Fig. 8). Lithofacies A, B, and C show variations in their major components, with the most significant clay mineral variations being between illite and smectite. Lithofacies A is poorer in illite (<39%) and richer in smectite (18%–33%), with higher values for the S + K/I + C (>0.8) and S/I (>0.6) ratios (Figs. 8 and 9). The dominant mineral assemblage is illite> > kaolinite > smectite > chlorite. Lithofacies B and C exhibit quite similar percentages of clay minerals. Both are richer in illite (37%–60%), reaching 73% in Lithofacies C, and poorer in smectite (0%–21%) with lower S + K/I + C (<0.8) and S/I (<0.6) ratios (Figs. 8 and 9). The mineral assemblage is illite ≫ kaolinite ≫ chlorite > smectite for Lithofacies B, and illite ≫ kaolinite > chlorite for lithofacies C. In addition to these clay minerals, several beds of lithofacies B contain two further minerals: i) magnesium-hornblende (intervals U1386B 47X2 23, 38, 56 and 64 cm; U1387B 47CC 3 cm, 48X2 129 and 147 cm, 48X3 9 and 14 cm); and ii) gypsum (intervals U1386B 47X1 115 and 117 cm).

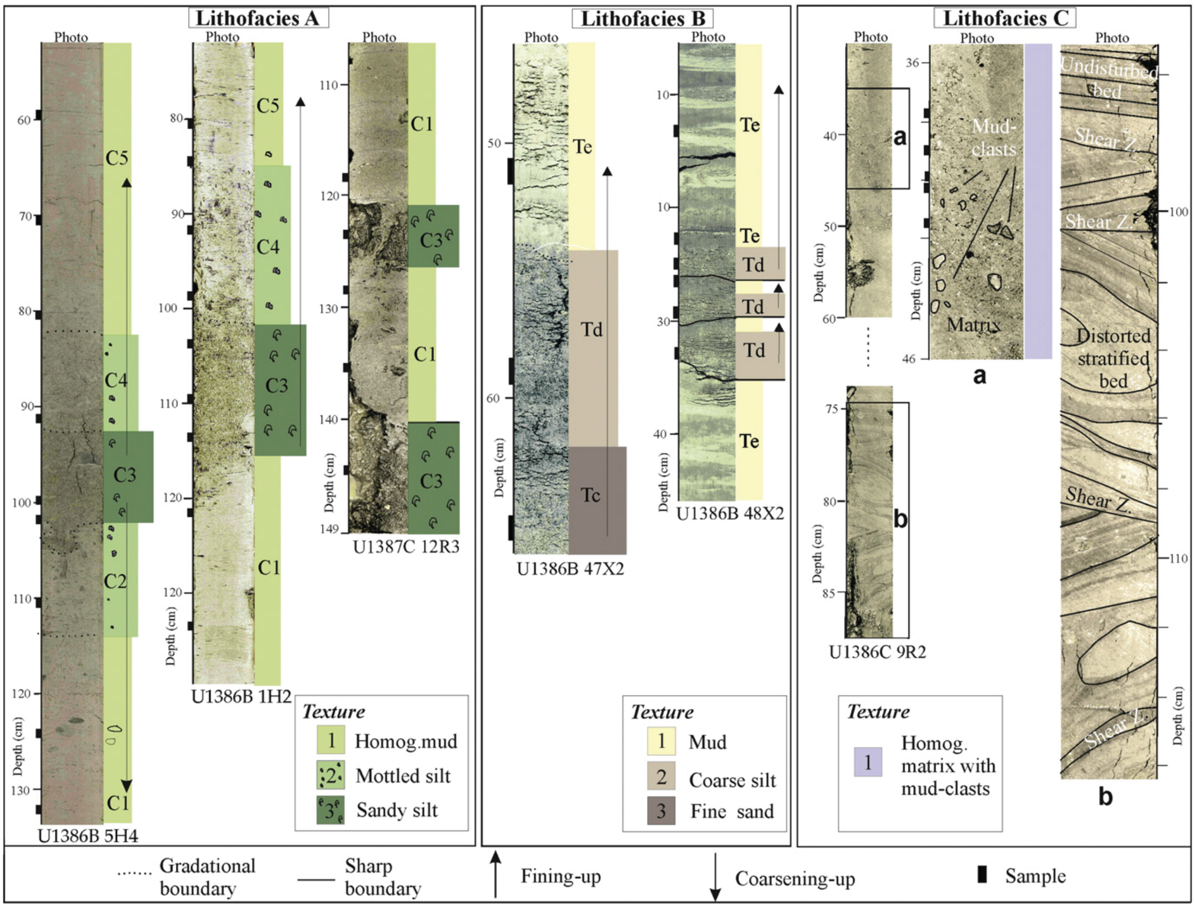

Fig. 4. Selected core photographs showing the main sedimentary sequences of the Pleistocene Faro Drift deposits. The sequences of lithofacies A display complete contourite sequence (C1 to C5) and truncated sequences (C3 to C5, and C3), the sequences of lithofacies B shows fining-up sequence; and the sequences of lithofacies C display a matrix with mud-clasts (a) and highly deformed beds (b). Legend: C1 to C5 refer to the contourite divisions of Stow and Faugères (2008); Tc, Td and Te are the turbidite divisions of the Bouma sequence; Homog. Homogeneous.

5. Discussion and conclusions

5.1. Genetic interpretation of lithofacies

The sedimentological and mineralogical attributes of lithofacies A, B and C making up the Pleistocene samples of Sites U1386 and U1387 provide significant clues for the genetic and environmental interpretations of the Faro Drift deposition. Each individual attribute is of little significance but when they are considered together interesting interpretative results are obtained. We are aware that the degree of accuracy is limited by the number of samples studied (149 samples), but dues to the great number of variables examined (~20) it is sufficient to discriminate between the principal sedimentary processes responsible for their deposition. Two major styles of sedimentary process are interpreted from Sites U1386 and U1387: i) alongslope processes controlled by bottom currents, and ii) downslope gravity-flow processes (turbidity currents, debris flows). Lithofacies A, dominant in Unit I, is the product of alongslope bottom currents. Lithofacies B, present in the upper part of Unit II, is interpreted as deposits originated by turbidity currents. Lithofacies C, presents also in the upper part of Unit II, is interpreted as a product of debris flows. We discuss below the principal criteria that have been most effective to distinguish between contourites and gravity-flow deposits.

5.2. Distinguishing criteria

5.2.1. Grain-size vertical trend and sedimentary structures

The classical contourite sequence was originally proposed by Gonthier et al. (1984) and Faugères et al. (1984) and it has been used as the standard facies model for interpreting deposition by alongslope processes in the deep sea (Viana et al., 1998; Toucanne et al., 2007; Mulder et al., 2013; Brackenridge, 2014). It comprises a bi-gradational sequence, with coarsening-up from homogeneous mud to mottled mud/silt to sandy silt/silty sand, followed by fining-up through the same facies succession in reverse order. This corresponds to the five sediment divisions (C1 to C5) of Stow and Faugères (2008). Facies sequences in lithofacies A are wholly consistent with the classical countourite sequence and partial sequences. Thus, the complete sequence formed by 1–2–3–2–1 textures corresponds to the five divisions C1 to C5. The truncated sequences formed mainly by 1–3–2–1 and 1–3–1 textures match to the divisions C1–C3–C4–C5 (fining upward), and C1–C3–C1 (Fig. 4). In addition, lithofacies A shows a general lack of primary sedimentary structures, poor and very poor sediment sorting and a relatively high level of mixing by bioturbation. Similar features have also been recognised as characteristic for other fine-grained contourite deposits (Stow et al., 1986, 2002; Brackenridge, 2014; Rebesco et al., 2014).

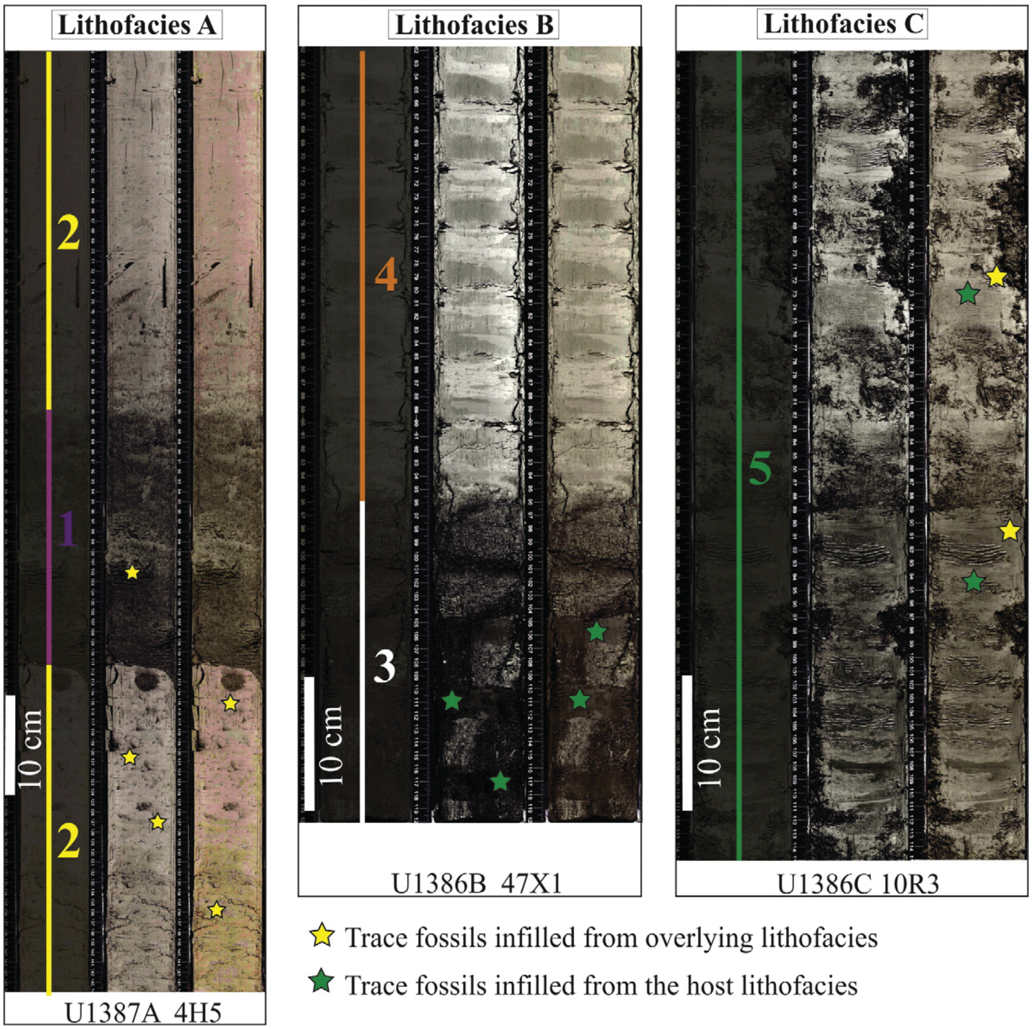

Fig. 5. Selected original core photographs and digital image treatment of lithofacies A, B, and C from the Pleistocene Faro Drift deposits showing five ichnofabric (1 to 5): 1) well-developed mottled background; 2) homogenous muds with some trace fossils infilled by relatively coarser sediments; 3) well-developed mottled background with unmottled intercalations and few trace fossils; 4) no mottling and no trace fossils, and 5) alternation of thick, poorly developed mottled and unmottled deposits with few trace fossils.

The grain-size variations noted (complete and partial bi-gradational sequences) can be broadly linked to variations in bottom current velocity (McCave and Carter 1997; Mulder et al., 2006; Toucanne et al., 2007; Stow and Faugères, 2008) and to changes in sediment provenance (Brackenridge, 2014; Rebesco et al., 2014). Bottom current variability of the MOW can be due to its interaction with local topography and/or different oceanographic processes (baroclinic and barotropic internal waves) (Kenyon and Belderson, 1973; Ambar and Howe, 1979; Baringer and Price, 1997; Llave et al., 2006; Stow et al., 2013), and also due to the upper and lower MOW core location changes. These latter changes may be linked to glacial and interglacial climate cycles and/or to millennial-scale oceanographic cycles (Llave et al., 2006; Toucanne et al., 2007; Hernández-Molina et al., 2014). Therefore, those sequences could be explained by the changing transport capacity of MOW and depositional mechanisms (suspended vs. bed load). The complete sequences (C1 to C5) are related to long-term changes in bottom-current velocity. The dominant middle-to-top sequences reflect the gradual onset in deposition after a period of erosion, according the model of Stow and Faugères (2008). With respect to grain-size variations linked to changes in sediment provenance, we discard this option because our sediment analysis results suggest the lack of changes during the Pleistocene, at least in the analysed samples, as will be discussed below (Section 5.2.3).

The classical turbidite sequence, was proposed by Bouma (1962) and has been commonly used as the standard interpretative facies model for the deposits of turbidity current (Shanmugam, 1997). A turbidite sequence is defined by five divisions (Ta to Te) and is the result of deposition from a single turbidity-current. Complete sequences are rare, and partial sequences are the norm (Walker, 1965; Alonso and Maldonado, 1990; Alonso et al., 1996, 1999, 2008; Talling et al., 2004; Gervais et al., 2006). In the lithofacies B, such sequences with normal grading and the presence of some sedimentary structures may be attributed to Tc, Td, Te divisions (Fig. 4). The beds fine upwards from sharp and erosional basal contacts. Also common are graded silt-laminated beds that show sharp and erosional basal contacts for the silt laminae, but relatively little grain-size difference between mud (mean 8 μm) and silt (mean 11 μm) laminae. This facies can be attributed to the standard sequence of fine-grained turbidites of Stow and Shanmugam (1980).

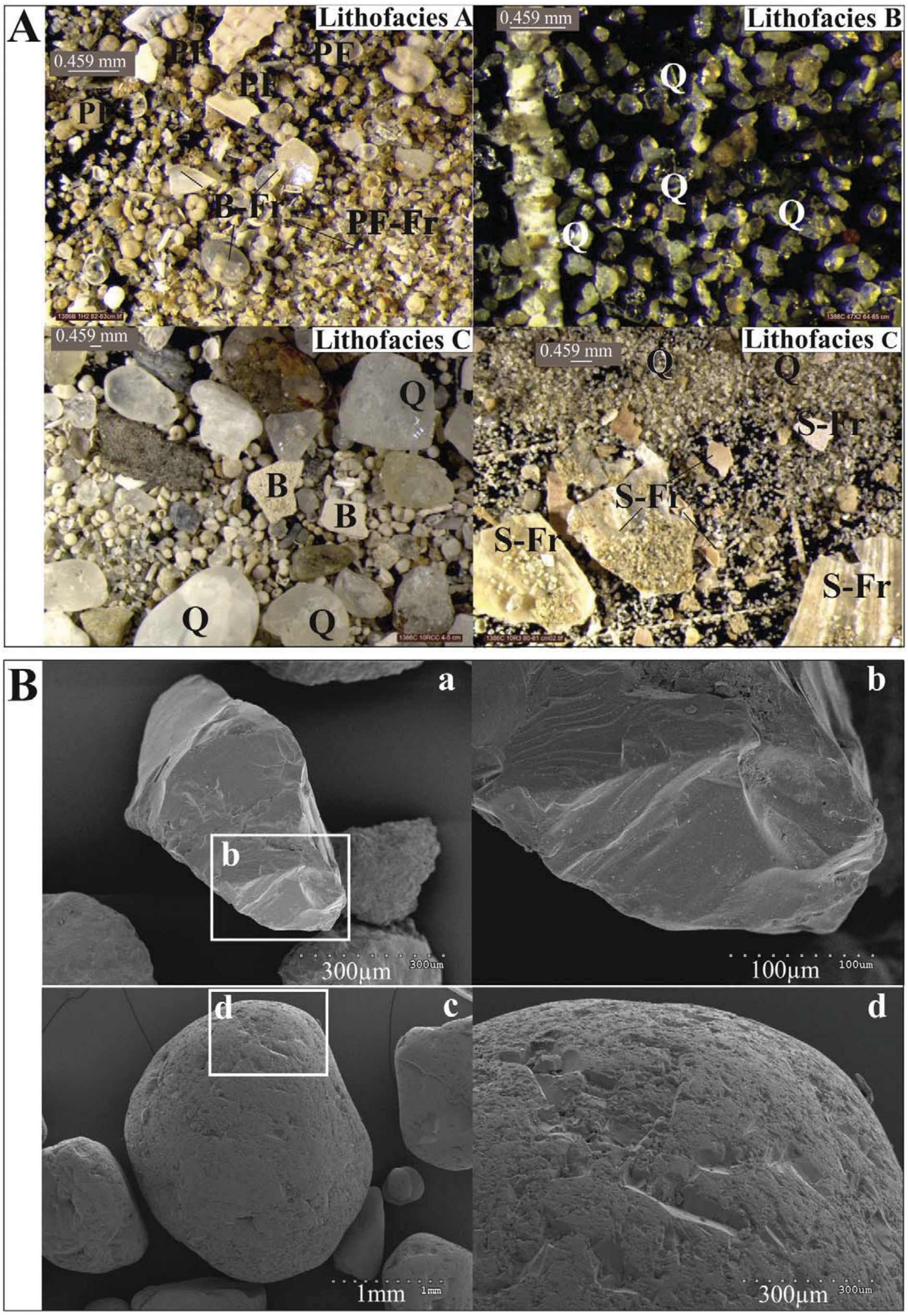

Fig. 6. Images of the sand fraction components of the Pleistocene Faro Drift deposits: A) binocular microscope photos showing the main components of lithofacies A, B and C; B) SEM microphotographs showing the morphoscopic features of quartz grains, in which a) and b) are shiny, angular and subangular quartz grains (e.g., interval U1386B 47X2, 38–39 cm) and c) and d) are matt, rounded and subrounded quartz grains (e.g., interval U1386C 10RCC, 4–5 cm). Legend: Q, quartz; B-Fr, biogenic fragments; PF, planktonic foraminifera; PF-Fr, planktonic foraminifera fragments; S-Fr, shell fragments.

Some turbidites show very poor sorting throughout. These have been recognised by various authors (e.g., Piper, 1973; Zaho et al., 2011). Piper (1973) explains the poor sorting of turbidites by deposition from rapid cohesion deposition of clay, trapping silt-size particles in the head of turbidity current. Although in a discrete beds, the poor sorting of Td division could be explained by the bioturbation structures sometimes found at their tops (Fig. 5). Bioturbation causes remobilization of the silt and its contamination with the finer overlying sediments as have also been observed in fine-grained turbidite sequences of African continental margin (Wetzel, 2007).

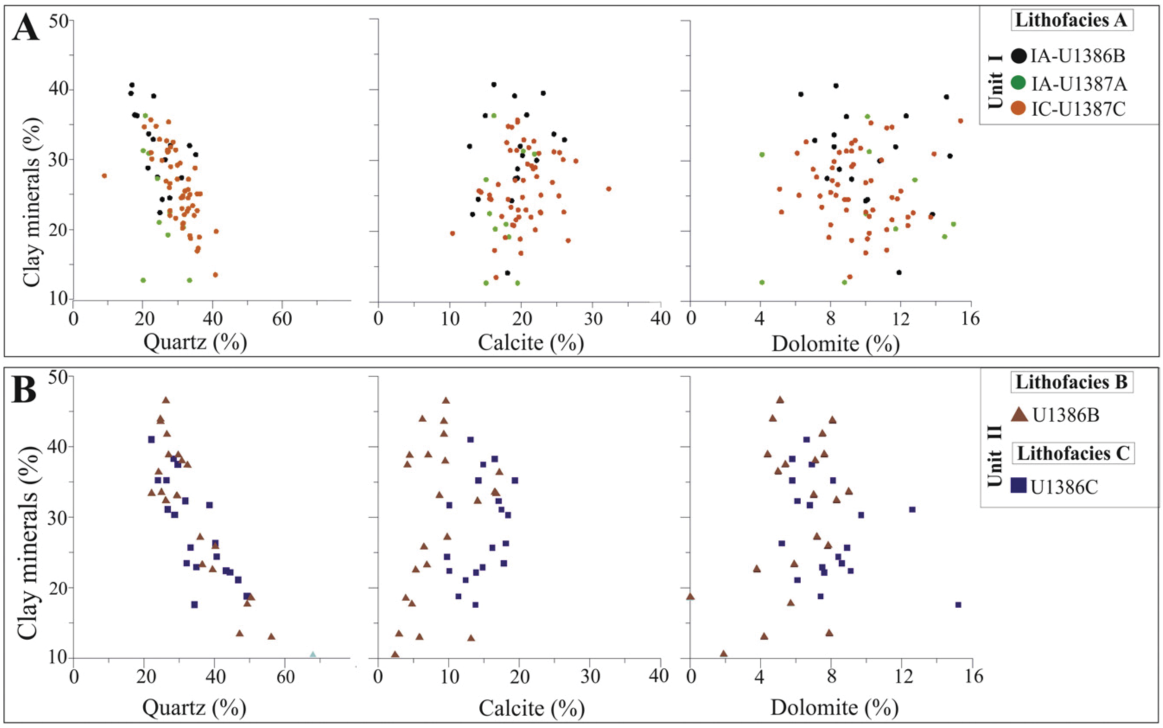

Fig. 7. Bulk mineralogy of the Pleistocene Faro Drift deposits showing the binary plots of clay minerals vs quartz, vs calcite, and vs dolomite for lithofacies A in Unit I from Hole U1386B and Holes U1387A,C and for lithofacies B and C in the upper part of Unit II from Holes U1386B,C.

Mass-transport deposits (slides, slumps and debrites) are recognised within cores on the basis of their disorganized and chaotic sedimentary structures (Almagor and Schilman, 1995; Nardin et al., 1979; Jenner et al., 2007; Tripsanas et al., 2008; Ratzov et al., 2010). In this study, we interpreted the occurrence of cohesive debris flows as explaining the deposition of those homogeneous matrix-supported mud-clast beds (U1386B 9R2-letter a in Fig. 4) and shear deformational structures (U1386B 9R2-letter b in Fig. 4) that characterize lithofacies C. Similar

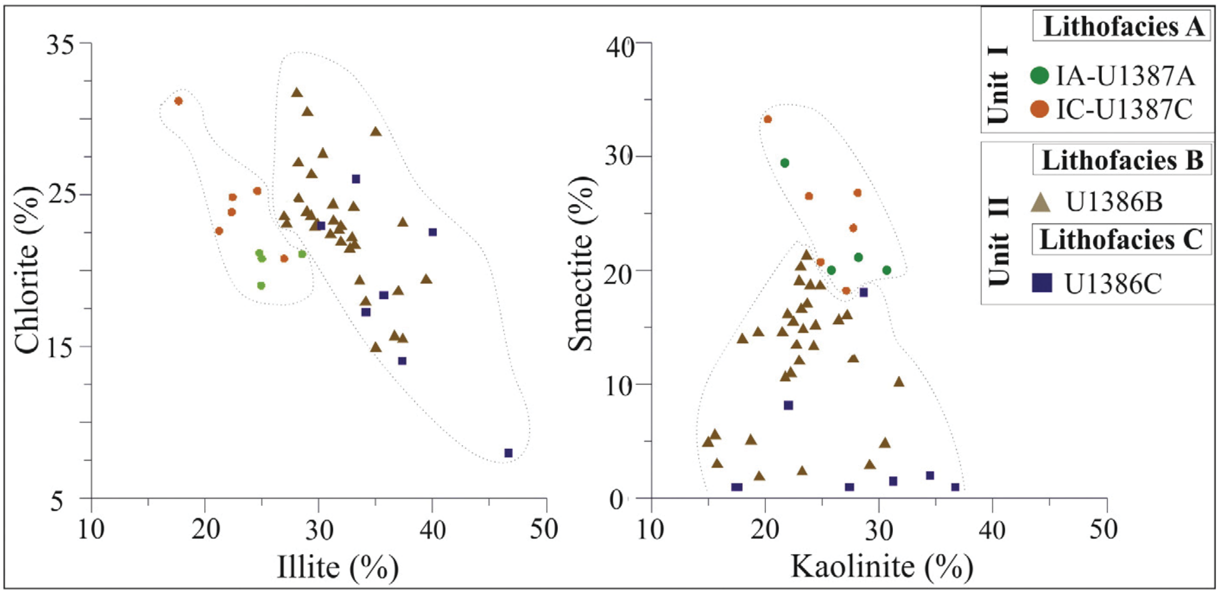

Fig. 8. Clay mineralogy of the Pleistocene Faro Drift deposits showing the binary plots of chlorite vs illite, and smectite vs kaolinite for the lithofacies A (Unit I, U1387A,C), and lithofacies B and C (upper part of Unit II — U1386B,C).

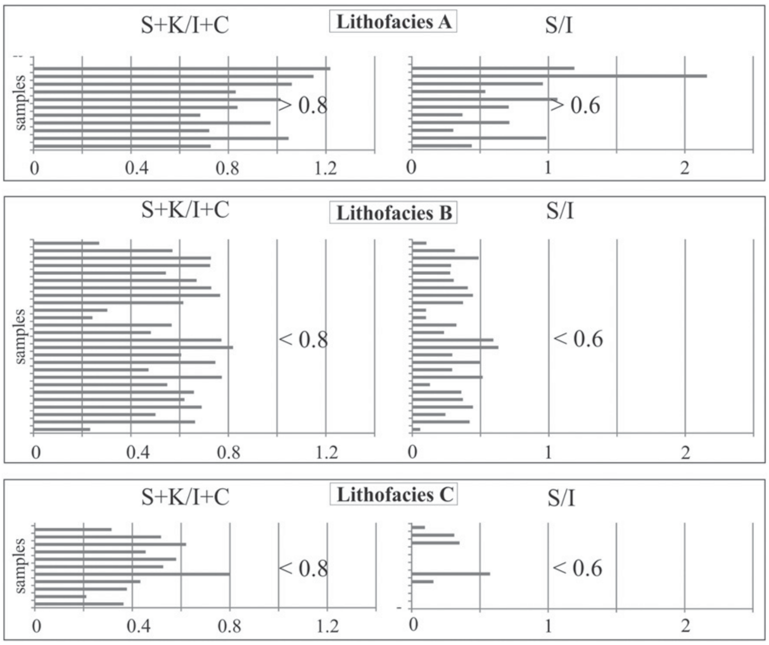

Fig. 9. Smectite + kaolinite/illite + chlorite ratio (S + K/I + C) and smectite/illite ratio (S/I) of the Pleistocene Faro Drift deposits for lithofacies A, B and C.

sedimentary structures, grain-size pattern and sand fraction composition were described by Ducassou et al. (2016) in debrites (D4) overlying the Early Pleistocene at Site U1386.

5.2.2. Modal frequency distribution

This criterion is useful to understand the pattern of sediment transport because it can help to decipher the complex interaction between the sediment source and MOW hydrodynamic flow behaviour along slope in the Gulf of Cadiz (Folk and Ward, 1957; Rea and Hovan, 1995). In the Faro Drift, the modal frequency distribution is significantly different between the contourites and gravity-flow facies (turbidites and debrites). For contourites, the bi- and tri-modal sediments have similar values and only the relative proportions of the modes vary through a contourite sequence, as well as in different locations across the drift. This means that the mode values are nearly constant through the different textures that make up the sequences, and that steady conditions of supply are maintained over time.

The dominant mode values are mostly in the silt grain-size range, which indicates that this is the dominant "background" component of the Faro Drift. The modal constancy between nearby contourite sequences must reflect the prevalence of a bottom current that is strong enough to move silt-sized particles and whose variations in energy levels produce variations in their relative proportions. On the other hand, the bi- and tri-modal signatures suggest two or three dominant sediment components as well as the break-up of clay flocs prior to grain-size analysis.

In contrast, turbidites and debrites have variable mode values throughout their sequences. We suggest that this fact is mainly controlled by the through mixing of components from allochthonous source areas and their transport by gravity-driven downslope processes. In most cases there appears to have been little interaction with the "background" bottom current conditions. The biogenic sand fraction of debrites (fragments of bivalves and gastropods) is consistent with a continental shelf origin of this part of the sediment. Likewise, the mode differences between nearby turbidite and debrite sequences would be explained because those turbidity and debris flow processes originated from different areas and/or had different rheology.

5.2.3. Sediment composition and provenance

Literature shows examples of the inferences derived by sedimentologists from the present day position of continental sediment sources to the mineral composition (clay and bulk mineralogy) in the sea-floor and subbottom sediments of deep sea areas (Weaver and Rothwell, 1987; Chamley, 1989; Pearce and Jarvis, 1992; Martínez-Ruíz et al., 1999; Hoogakker et al., 2004; Frenz et al., 2009; Wynn et al., 2012), although their transport and deposition may have taken place in lowered sea-level conditions when river mouths were closer to the continental slope (Miall, 1991). In this work, we use mineralogical composition (clay and bulk mineralogy) as indicators to establish the potential source of sediments coming from the surrounding soils and geological formations of the fluvial drainage basins surrounding the Gulf of Cadiz (Guadalquivir, Tinto-Odiel and Guadiana rivers). Previous studies of surficial coastal and shelf deposits allowed the identification of different fluvial sources, the Guadiana plus Tinto-Odiel source on one side and the Guadalquivir source on the other side (Grousset et al., 1988; Vergnaud-Grazzini et al., 1989; Gutiérrez-Mas et al., 1995; López-Galindo et al., 1999; Lobo et al., 2001; Gutiérrez-Mas et al., 2003; Maldonado et al., 2003; González et al., 2004; Achab and Gutiérrez-Mas, 2005; Machado et al., 2005; Rosa et al., 2013). In addition, the submarine depositional bodies formed mostly by their sediment supply during the different stages of sea-level can be demarcated in the Quaternary sedimentary register (Lobo et al., 1999). In the Faro Drift, the clay minerals are detrital rather than authigenic in origin, as suggested by the young age (Pleistocene) of the sediments, precluding significant diagenetic change, as well as the fact that they typically contain a large amount of intermixed illite species in the continental shelf (Gutiérrez-Mas et al., 2003). Furthermore, we can assume that drainage areas and patterns did not vary greatly through the Quaternary and there has not been a significant mixing process masking the local mineral signatures during the glacio-eustatic sea-level changes, at least at scale of the two major sources noted above.

Although the mineral composition of the clay and bulk fractions alone can be used as indicative of provenance (Chamley, 1989; Martínez-Ruíz et al., 1999; Machado et al., 2005), here we complement it with sand fraction components. The amount and characteristics of the sand fraction components allow discrimination between contourites and gravity-facies and their sediment source. Grain-shape, roundness and surface texture analysis of quartz grains are also used to infer processes seen in modern coastal and shelf environments and hence can be indicative of provenance (Gutiérrez-Mas et al., 2003; Moral Cardona et al., 2005). Detrital muscovite mica is a common terrigenous component resistant to degradation during the transport. During the transport and deposition, only micas of smaller grain-size could have been degraded (Martínez-Ruíz et al., 1999). In our samples, degradation is not significant, and micas from all samples are very well preserved, which supports their origin by physical weathering of the outcropping metamorphic rocks.

5.2.3.1. Clay mineral approach. The differences in clay minerals between contourites and gravity-flows facies (turbidites and debrites) can be attributed to their different sources. For contourites, we propose that their clay mineral assemblage (illite ≫ kaolinite > smectite > chlorite) with the notable presence of smectite (18%–33%) and interstratified illite–smectite (I–S) has one primary potential source, the Guadalquivir River. This assemblage is similar to the association observed in the Neogene and Quaternary rocks of the Bay of Cadiz and Guadalquivir Basin, and in the terraces of the Guadalete River, as reported by Gutiérrez-Mas et al. (1995), who suggested the Guadalquivir River as the main source area for these clay minerals (Fig. 10). This interpretation is also supported by Mélières (1974); López-Galindo et al. (1999) and Machado et al. (2005), who obtained high contents of smectite and the presence of interstratified I-S, at the Guadalquivir river mouth and in its prodelta sediments, decreasing toward the shelf but increasing on the Cadiz upper continental slope. These higher smectite quantities contrast with the low values found in other nearby prodeltas of the eastern Gulf of Cadiz, which also decrease toward the shelf (Fernández-Caliani et al., 1997; López-Galindo et al., 1999; González et al., 2004; Machado et al., 2005). These high smectite quantities contrast with the low values found in other nearby prodeltas of the easternmost and western of Gulf of Cadiz (Machado et al., 2005).

In addition to the Guadalquivir River, we propose the nearby Alboran Sea in the Mediterranean Sea as a complementary source region and transport by the MOW (Fig. 10). In this case, the smectite would have been transported by the surficial AW eastward into the Alboran Sea and back again into the Atlantic by the MOW, being deposited along the Iberian continental slope and mimicking the trajectory of the MOW, as was already suggested by Grousset et al. (1988); Vergnaud-Grazzini et al. (1989) and López-Galindo et al. (1999). This mechanism could explain the otherwise anomalous increase of smectite on the Cadiz upper continental slope deposits (Mélières, 1974; López-Galindo et al., 1999) compared with lower values on the continental shelf. Our results (Fig. 8) with S + K/I + C (>0.80) and S/I (>0.5) ratio values are comparable to those (S + K/I + C ratio, 0.64–0.85; S/I ratio, >0.5) in the Gulf of Cadiz and even off the Cap St Vincent. In fact, mineralogical clay evidence of this complementary source may be found as far north as Lisbon where the presence of smectites (~20%) has been also detected (Vergnaud-Grazzini et al., 1989). The remarkable uniformity in clay mineralogy of contourites observed in Fig. 7 indicates a common and stable sediment source. This would be achieved by significant mixing and long-distance transport within the MOW. To confirm this interpretation we consider it necessary to examine, using the same approaches applied in this work, the other three sites (U1388, U1389, and U1390) drilled in the Gulf of Cadiz, and the two sites (U1385 and U1391) drilled off the West Iberian margin during Expedition 339.

For gravity-flow deposits a different sediment provenance is proposed. The clay mineral assemblage of both facies, turbidites and debrites (illite < <kaolinite > chlorite > smectite) with enrichment of illite (up to 73%) and impoverishment of smectite (0%–15%) point to the primary source being the Guadiana River and Tinto-Odiel rivers, which drain metamorphic and igneous rocks (Iberian Massif) and deposit their sediment load on the continental shelf (Morales, 1997; González et al., 2004). This interpretation is supported by the enrichment in illite, chlorite, and kaolinite, and the little or no smectite in the continental shelf sediments in front of these rivers. Additional clay mineralogical evidence, such as the occurrence hornblende in several turbidite samples (e.g., intervals U1386B 47X2, 56 and 64 cm; 47XCC, 3 cm; 48X2, 129 and 147 cm; 48X3, 9 and 12 cm), also supports this interpretation. The hornblende represents an amphibole coming from metamorphic rocks that outcrop in the Guadiana River drainage basin (Vidal et al., 1993). The presence of gypsum (intervals U1386B 47X1, 115 and 117 cm) that has also been detected in the overlaying debrite 4 of Ducassou et al. (2016), could be explained either as detrital, from the Tinto-Odiel river flood plains, or as an authigenic mineral formed on the shelf by the reaction of the carbonate biogenic material with acid sulphate water (Siesser and Rogers, 1976; Fernández-Caliani et al., 1997).

5.2.3.2. Bulk mineral composition and sand fraction approach. For the contourites, the greater abundance of calcite (28% on average) quantified on the bulk fraction is proportionate to the high carbonate content of the total sample (18%–45%). It can be linked to the presence of biogenic components, mainly nannofossils and planktonic foraminifera. A second and additional potential source of calcite would be related to the presence of detrital carbonate in the sand fraction sourced from the marl-rich diapirs of the eastern upper slope in the Gulf of

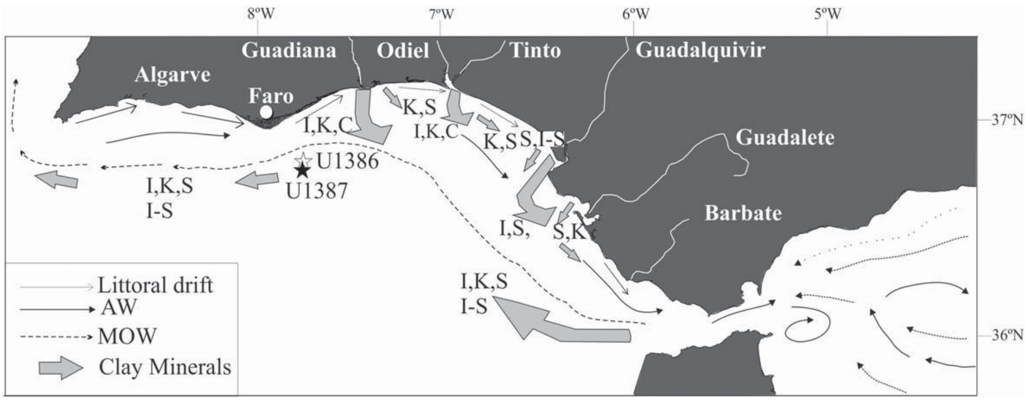

Fig. 10. Schematic map illustrating the main sedimentary sources of clay minerals and transport paths to the Faro continental slope. Characteristics are summarized from both previous works (López-Galindo et al., 1999; Machado et al., 2005) and the present work. Arrows size is proportional to the quantity of clay minerals (I, illite; S, smectite; K, kaolinite; C, chlorite, I-S interstratified illite-smectite). Legend of water masses in Fig.1.

Cadiz. These diapirs, which contain carbonate (15%–60%) (calcite, dolomite and aragonite) with variable proportions of quartz (17%–45%) and clay minerals (<35%) (Mhammedi et al., 2008), are eroded and the particles transported by the MOW (Nelson et al., 1999). The higher content of dolomite (>12%, Fig. 6A) in several samples of mud and sand-silt contourites versus samples of turbidites should support this hypothesis. The dominant source of quartz is most likely the Guadalquivir River, as this river drains metamorphic and sedimentary regions of the Betic Cordillera and Postorogenic Neogene materials supplying the greatest concentration of quartz detected near its mouth (López-Galindo et al., 1999), much of which is subangular with low sphericity and smooth surfaces (Figs. 1, 9). All these attributes are found in the sand fraction. Other possible sediment source could be in input from the Guadalete River, the mouth of which is situated within Cadiz Bay, and the Barbate River, located to the south of the study area. Even so, this source is not considered to have provided sediment for the contourites due to the different natures of quartz found in the contourites and the sediments supplied by this river. The Guadalete River injects sediment originating from erosion of the Aquitanian Numidic sandstone (Aljibe Sandstone), which contains very well-rounded quartz grains (Gutiérrez-Mas et al., 2003) contrasting to the angular-subangular quartz grains observed in the contourites.

For gravity-flow deposits the source area of quartz is probably the sequence of Palaeozoic metaschists and greywackes which are drained by the Guadiana River and Tinto-Odiel rivers which have very close drainage basin (Achab and Gutiérrez-Mas, 2005; Machado et al., 2005). This interpretation is supported by two clues given by the sand fraction: the shiny angular quartz in turbites, the dominant rounded shape displayed by quartz grains in debrites (Fig. 9B), and the abundance of micas in several turbidite samples. The shiny angular-subangular quartz of the turbidites may preferentially have come from the Guadiana shelf sediments based on the greater quantity of shiny angular-subangular quartz found in the river mouth there. In contrast, rounded matt quartz found in the debrites could be related to the Tinto-Odiel shelf sediments, considering the elevated content of round matt quartz grains in the Tinto-Odiel system. Mica particles of continental origin are linked to discharges from Guadiana, which give specific depositional imprint on the shelf sediments (González et al., 2004). The very high mica content (up to 70%) recognised in the sand fraction in some turbidite samples suggest that these components could be linked to discharge from the Guadiana and Tinto-Odiel rivers (Vidal et al., 1993). These rivers mainly drain metamorphic and igneous rocks and deposit their sediment load on the continental shelf. The high quantities of mica in front of these rivers contrast with its scarcity on the continental shelf off the Guadalquivir River (González et al., 2004; Achab and Gutiérrez-Mas, 2005). The traces of hornblende identified in the bulk mineralogy also support this interpretation because this mineral is present in the metamorphic rocks of the Guadiana River drainage basin (Vidal et al., 1993). In addition, the biogenous components of the sand fraction (ostracods, bivalves, gastropods) also suggest a shallow water environment deposition for the components of the debrites before the seafloor failure. A similar interpretation has also been suggested for the source of the overlying terrigenous debrites (D4) described by Ducassou et al. (2016).

To summarise, these approaches to interpretation of sediment provenance for the different lithofacies reflect different modes of long- and short-distance transport. According to the drainage basins here considered, most of the terrigenous sediment of contourites is coming from the distant Guadalquivir drainage basin whereas the terrigenous and biogenic components of turbidites and debrites are sourced more directly from vicinity fluvial drainage basins (Guadiana, Tinto-Odiel) close to the Faro Drift. Based on these observations and taking into account that mineral provenance is well constrained and lacks of significant mixing processes as it has been mentioned above, we therefore favour an interpretation that particles stripped off the distant Guadalquivir shelf margin delta by MOW fed primarily into the Faro Drift during the Pleistocene (Unit I-Holes U1386B, and U1387A,C); and the terrigenous particles of turbidites and debrites are injected downslope by gravitational processes especially during the Early Pleistocene (upper part of Unit II-Holes U1386B,C). The well preserved local mineralogical signature of their deposits also suggests that the gravity-flow processes are not significantly influenced by the MOW action. Alternatively, their fine suspended loads may be stripped off by the MOW and advected westward, away from the Faro Drift.

5.3. Depositional architecture of Pleistocene Faro Drift

The spatial and temporal distribution of the Pleistocene contourites, turbidites and debrites in combination with the seismic character and evolution of the Faro Drift (e.g., Hernández-Molina et al., 2014; Fig. 1C), allow us to define a preliminary model of the facies distribution. Further work will help confirm or refine this interpretation. Most authors have emphasised the role of geostrophic bottom currents in shaping the continental slope of Cadiz (e.g., Nelson et al., 1999; Mulder et al., 2003) but mass wasting and turbidity currents also occur locally, as was mentioned recently by Hernández-Molina et al. (2014) and Ducassou et al. (2016).

The lithofacies defined in this study characterize two drift domains, which were seismically defined by Stow et al. (2013) and Hernández-Molina et al. (2014): the palaeo-moat and drift domains (Figs. 1A and 10). The palaeo-moat deposits of the Early Pleistocene (1.66–1.9 to 1.24–1.27 Ma; Expedition 339 Scientists, 2012) are more strongly influenced by gravity-controlled deposition and ~50 m thick of gravity-flow deposits at Site U1386 could have been channelized by the palaeo-moat. Its duration should be strongly dependent of the sediment supply from the continental shelf as suggested by the stacked vertical succession of siliciclastic fine and coarse-grained turbidites interbedded with siliciclastic muddy debrites (number 2 in Fig. 11). Turbidite sequences are incomplete, mainly Td–Te sequences (fine-grained turbidites), and are characterized by their homogeneity in siliciclastic composition (mainly quartz), erosive lower boundary, lack of primary sedimentary structures, and mottled appearance in some beds. Based on palaeoenvironmental and sequence stratigraphy studies in the area (González et al., 2004; Roque et al., 2012; Hernández-Molina et al., 2013, 2014; Stow et al., 2013; pers. comm. P. Lobo), these gravity flows were probably funnelled by fluvial-fed small canyons related to the Guadiana and Tinto-Odiel rivers, as suggested by the bulk and clay mineralogical composition. Taking into account sequence stratigraphic (Llave et al., 2002; Hernández-Molina et al., 2002; Llave et al., 2007a, b; Roque et al., 2012) and structural (Medialdea et al., 2004) studies in the Gulf of Cadiz, gravitational processes took place primarily during sea-level fall and lowstand stages when the Guadiana plus Tinto-Odiel river mouths were located close to the shelf-break, and the occurrence of gravity-driven instability processes is significant because deposition occurs on the steeper continental slope (Chiocci et al., 1997), and/or could be triggered by tectonic pulses.

The drift deposits recorded from the Early to Late Pleistocene are quite different from those of the palaeo-moat domain (Fig. 11), here the contourite construction represents the largest part of the total volume of accumulated sediment on the Faro Drift during this time. There is also relatively high sedimentation rate (up to 35 cm/ky) of contourite deposits and enhanced permanent activity of the MOW (Expedition 339 Scientists, 2012). The drift deposits are defined by a vertical succession of sandy, silty and mud contourite sequences, with homogeneity in the mixed siliciclastic-bioclastic nature, gradational boundaries, mud with lenses of coarse material, and a well-developed mottled background with trace fossils (number 1, 3, and 4 in Fig. 11). By contrast, the sequences are heterogeneous: basecut-out contourite sequences predominate during the Early and Middle Pleistocene, whereas the complete sequences develop during the Late Pleistocene (U1387A 4H5, 12X4) (Fig. 11). This heterogeneity in the vertical successions is the consequence of the general lateral migration of the

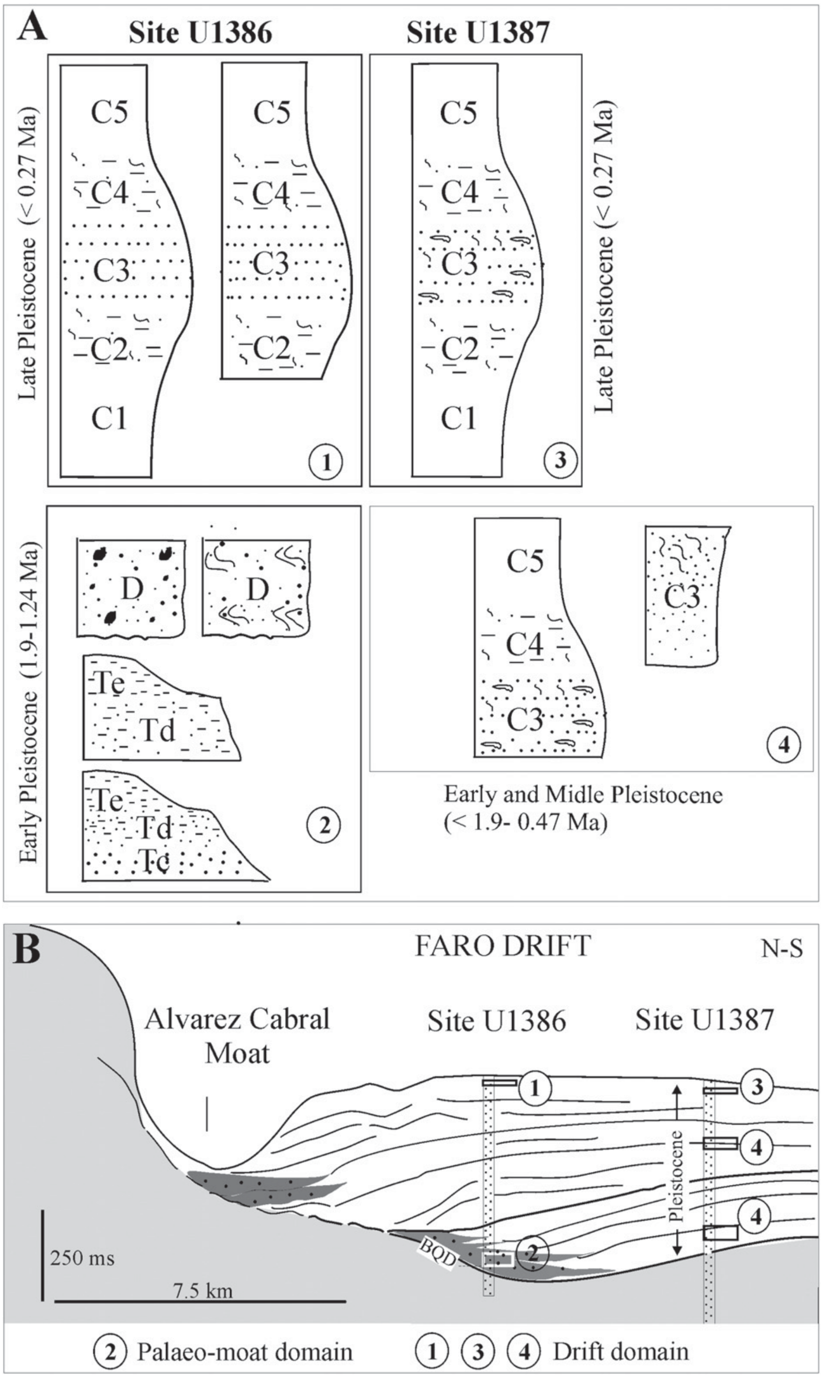

Fig. 11. Schematic representation of facies model for the depositional architecture of the Faro Drift deposits showing: A) the sedimentary sequences commonly encountered in palaeo-moat domain (number 2) and drift domain (numbers 1, 3, and 4) at Sites U1386 and U1387 during the Early, Middle and Late Pleistocene; and B) the Quaternary stratigraphic section showing the drift domains and the location of both studied sites and units based on the seismic profile of Fig. 1C. Legend: C1 to C5 refer to the contourite divisions. Tc, Td and Te correspond to the turbidite Bouma divisions; BQD, Lower Quaternary seismic reflector.

drift-moat system, as is reflected by its seismic architecture defined previously by Stow et al. (2013) and Hernández-Molina et al. (2014). The basecut-out contourite sequences occur in environments closer to the Alvarez Cabral moat (e.g., the internal side of the drift) and are being overlain by the complete contourite sequences deposited in a more distal drift environment (e.g., the external face of the drift). Therefore, basecut-out sequences occur where higher energy bottom currents and/or variations in sediment supply are more prevalent.

Acknowledgements

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