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Ichnological analysis of ancient contourites: scientific and economic implications

Olmo Miguez Salas

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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 **Ichnological analysis of ancient contourites: scientific and economic implications** ha sido realizada bajo mi dirección y cumple las condiciones necesarias para que su autor, **Olmo Miguez Salas**, opte al grado de Doctor en Ciencias Geológicas por la Universidad de Granada.

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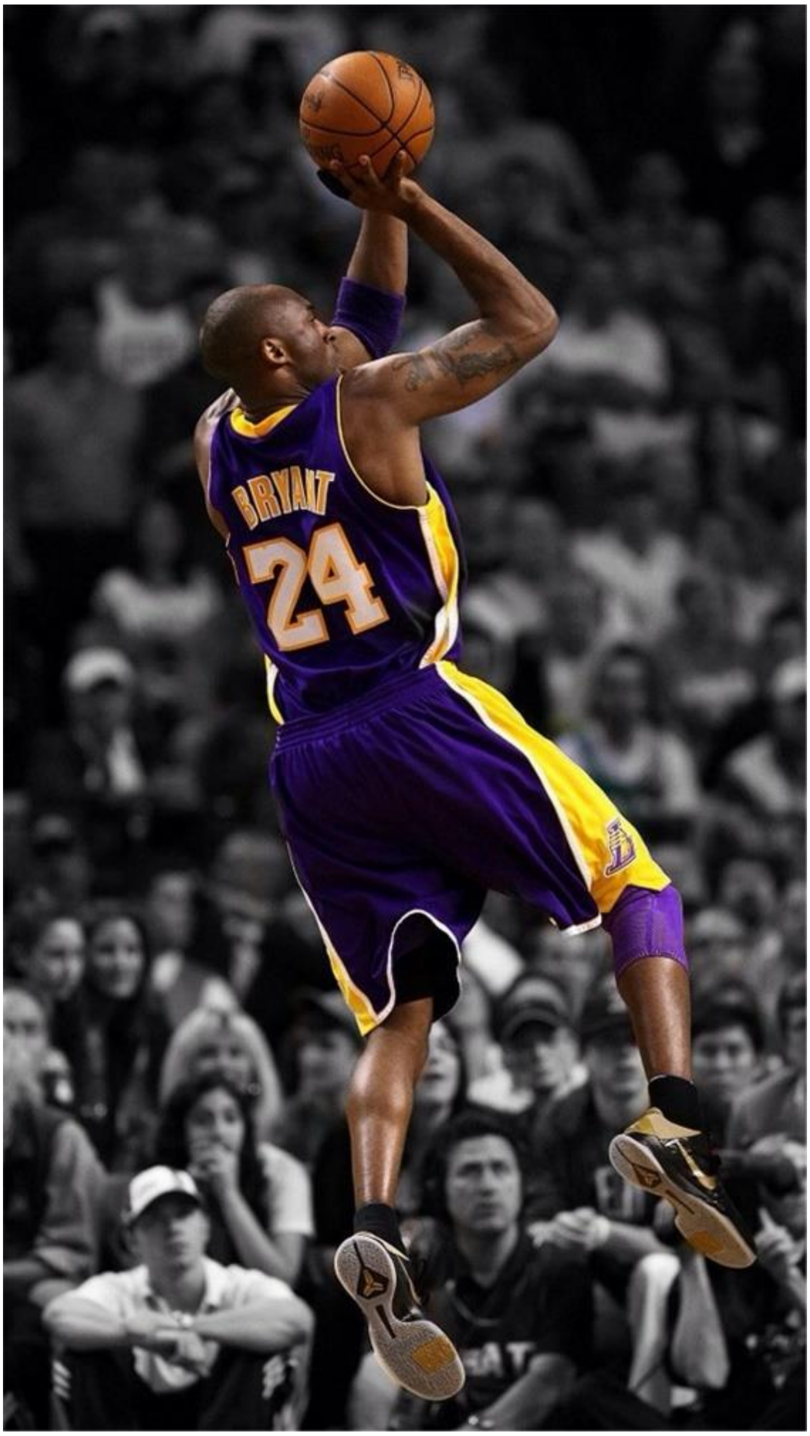
A todos aquellos que no pueden acceder a una educación

A todos aquellos que no disponen de los medios para investigar

“I've missed more than 9000 shots in my career. I've lost almost 300 games. 26 times, I've been trusted to take the game winning shot and missed. I've failed over and over and over again in my life. And that is why I succeed.”

— *Michael Jordan*

In memoriam of Kobe Bryant



"The important thing is to never stop questioning."

— Albert Einstein

"Reality is wrong. Dreams are for real."

— Tupac Amaru Shakur

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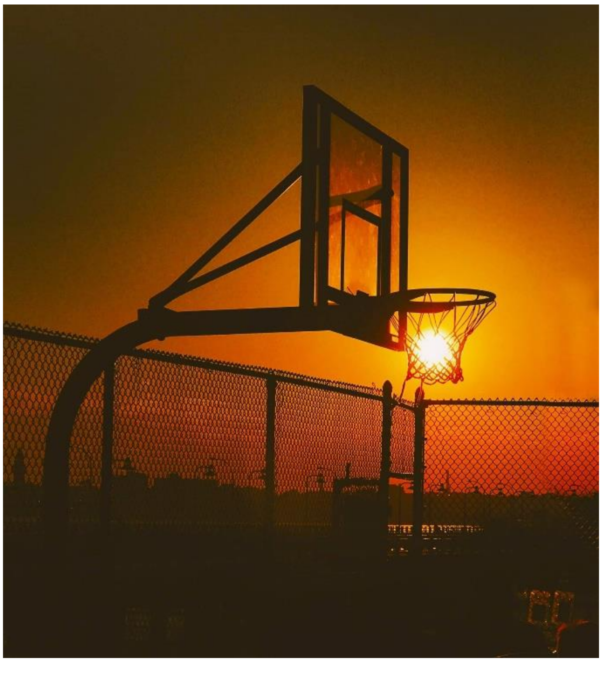

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ABSTRACT

Contourites, as deposits from thermohialine-induced geostrophic bottom currents, provide essential paleoenvironmental (i.e., ecological, depositional) information, especially on ocean circulation and climate change. Furthermore, the economic interest in contourite deposits has increased significantly during the last decades, being considered an important unconventional reservoir in hydrocarbon exploration. All of this determines the important advance in the knowledge of this facies, and in its application in paleoclimatology and paleoceanography research as well as in petroleum exploration. However, the recognition and characterization of ancient contourite deposits are not always an easy matter, being in most of the cases difficult to discriminate from other deep-sea facies (i.e., pelagites/hemipelagites, turbidites). Recently, ichnological approach has been revealed as a very useful tool in contourite research. On this base, this PhD Thesis focus on the ichnological analysis of ancient contourite outcrops, to advance in the characterization and differentiation of this facies, its use for palaeoenvironmental reconstructions, and its interest in reservoir characterization. With this purpose two main ancient contourite drift successions were selected: a) Late Miocene channelized clastic contourite deposits at Morocco and, b) Eocene-Miocene calcareous contourite drift deposits at Cyprus. Obtained ichnological information, including ichnofabrics and ichnofacies, allows characterization of different types of contourites, as well as its differentiation respect to hemipelagites and turbidites. In general contourites are usually characterized by high trace fossil abundance and low ichnodiversity, but significant differences occurs respect to the particular type. Specific palaeoenvironmental conditions during contourite deposition have been interpreted, showing that bottom currents played an important role on deep-sea macrobenthic community, specially providing a high nutrient supply to the seafloor. The bioturbation´s influence on petrophysical properties (i.e., porosity) of contourite deposits is also demonstrated, as exemplified with *Macaronichnus* trace fossil. Characterization of ichnological attributes may be a key factor for evaluating the real potential of these unconventional reservoirs. All these advances prove the usefulness of ichnology in the study of ancient contourites, supporting the ichnological approach as a tool in palaeoenvironmental, sedimentological and reservoir characterization of contourite facies.

RESUMEN

Las contornitas, entendidas como depósitos de corrientes geostróficas de fondo termohalinamente inducidas, proporcionan información paleoambiental esencial (ecológica, deposicional), especialmente sobre la circulación oceánica y el cambio climático. Además, el interés económico por los depósitos contorníticos se ha incrementado significativamente durante las últimas décadas, siendo considerado un importante reservorio (no convencional) en la exploración de hidrocarburos. Todo ello ha conllevado un importante avance en el conocimiento de estas facies, y en su aplicación en la investigación paleoclimatológica y paleoceanográfica, así como en la exploración petrolera. Sin embargo, el reconocimiento y caracterización de antiguos depósitos contorníticos no siempre es fácil, siendo en la mayoría de los casos difícil de diferenciar frente a otras facies marino profundas (pelagitas / hemipelagitas y turbiditas). Recientemente, el análisis icnológico se ha manifestado como una herramienta muy útil en la investigación de las contornitas. Sobre esta base, la presente Tesis Doctoral se centra en el análisis icnológico de afloramientos contorníticos con el fin de avanzar en: la caracterización y diferenciación de estas facies, su uso para reconstrucciones paleoambientales y su interés en la caracterización de reservorios. Con este propósito, se seleccionaron dos ejemplos contorníticos: a) depósitos de canales contorníticos clásticos del Mioceno Superior en Marruecos y, b) depósitos contorníticos calcáreos del Eoceno-Mioceno en Chipre. La información icnológica obtenida, incluyendo las icnofábricas e icnofacies, permite caracterizar los diferentes tipos de contornitas, así como su diferenciación respecto a hemipelagitas y turbiditas. En general, las contornitas se caracterizan por una alta abundancia de trazas de fósiles y una baja icnodiversidad, pero se reconocen diferencias significativas con respecto al tipo de contornita. Se han interpretado condiciones paleoambientales específicas durante el depósito de las contornitas, lo que demuestra que las corrientes de fondo desempeñaron un papel importante sobre la comunidad macrobentónica de aguas profundas, proporcionando altas cantidades de nutrientes al fondo marino. También se ha demostrado la influencia de la bioturbación en las propiedades petrofísicas (porosidad) de los depósitos contorníticos, como se ejemplifica con la traza fósil *Macaronichnus*. La caracterización de aspectos icnológicos puede ser un factor clave para evaluar el potencial real de estos reservorios no convencionales. Todos estos avances demuestran la utilidad de la icnología en el estudio de contornitas, apoyando el enfoque icnológico como herramienta en la caracterización paleoambiental, sedimentológica y petrolífera de facies contorníticas.

PART I

INTRODUCTION AND GENERAL POINTS

Chapter 1

INTRODUCTION

The deep-sea is a complex depositional system where multiple sedimentary processes co-exist. The three main deep-sea sedimentary processes are: i) downslope density currents (turbiditic flows), ii) predominantly alongslope bottom currents, and iii) settling of pelagic particles through the water column (vertical deposition) (Rebesco et al., 2014 and references therein). Accordingly, the most important deep-sea deposits are respectively turbidites, contourites, and pelagites (Fig. 1.1). As Rebesco et al. (2014) remarked, these deposits are simply extremes in a continuum of the deep-sea sedimentary facies, where pelagic deposition constitutes the background process and turbiditic flows represent a high energy episodic disturbance (see Fig. 1.1).

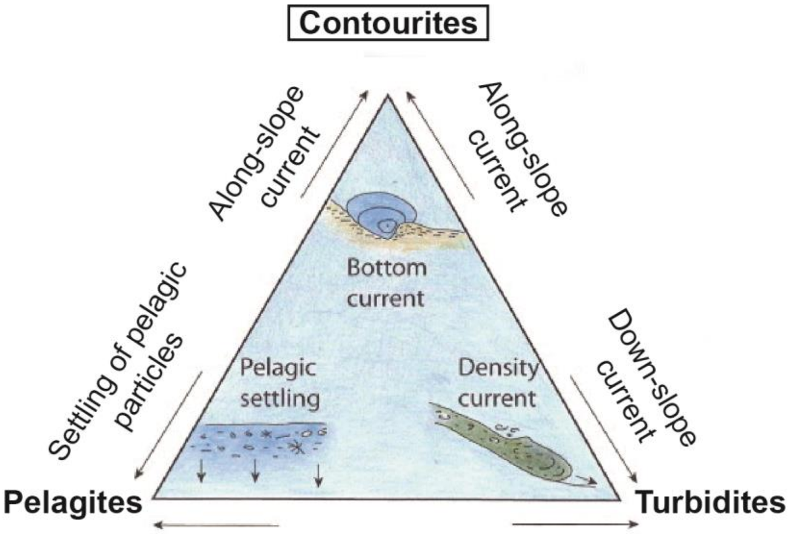


Fig. 1.1. Conceptual triangular diagram showing the three main types of sedimentary processes operating in the deep-sea and the associated deep-sea facies (modified from Rebesco et al., 2014).

During the 20th century, most of the deep-sea sedimentary studies were focused on turbidites, as they constitute one of the main hydrocarbon reservoirs (e.g., Bruhn et al., 2003; Morley et al., 2011). However, through the last decades, the importance and interest of contourites have increased notably, mainly due to its significance in: palaeoclimatology / palaeoceanography research and hydrocarbon exploration (unconventional reservoir) (Martín-Chivelet et al., 2008). Contourites, as deposits from contour currents, provide essential information about ocean circulation and climate change and are therefore of major importance in resolving the role of ocean circulation in modulating Earth's climate system (Knutz, 2008). Furthermore, contour currents can influence hydrocarbon systems, affecting reservoir geometry, quality, or distribution of sealing rocks (Viana and Rebesco, 2007); being coarse-grained contourites hydrocarbon reservoirs and fine-grained contourites sealing (and source) rocks (Rebesco, 2005). For this reason, the economic potential of contourite deposits has grown, becoming an important future reservoir target (Viana, 2008).

Contour currents strongly control deep-sea sedimentation (Rebesco et al., 2014). Contourite drifts (thick and extensive bottom currents accumulation of sediments) form at many different locations and water depths (Faugères and Stow, 2008) (Fig. 1.2), but contouritic facies are deposited mainly below 300 m deep under the action of along-slope semi-continuous bottom currents (Stow et al., 2008). Commonly, water depth influences the drift dimensions and the type of contourite deposits. That is, deeper areas have greater potential to develop larger drifts composed of finer-grained deposits (muddy contourites), while in shallower settings contouritic drifts show more reduced dimensions and may include coarser sediments (silty and sandy contourites) (Faugères and Stow, 2008). Over the last few years, knowledgement of the processes involved in contourite deposition and of the criteria for identification of bottom current associated deposits has significantly progressed (e.g., Stow and Faugères, 2008; Viana, 2008; Rebesco et al., 2014; Shanmugam, 2017). However, some important questions remain, as the role of biogenic structures as diagnostic features of contourites in respect to sedimentary ones. The near absence of detailed ichnological analyses on contourites favoured this hot topic. Moreover, this debate can be, in part, a consequence of two main unsolved aspects at this time: a) the influence of bottom currents on trace makers and thus on bioturbation features, and b) the relative importance of involved depositional and ecological conditions (e.g., rate of sedimentation, hydrodynamic energy, nutrients, oxygenation, etc.; Wetzel et al., 2008; Rodríguez-Tovar and Hernández-Molina, 2018; Miguez-Salas and Rodríguez-Tovar, 2019a, b; Miguez-Salas et al., 2019b; Miguez-Salas et al., 2020; Miguez-Salas and Rodríguez-Tovar, 2021a, b; Miguez-Salas et al., 2021a) during processes governing contourites. Consequently, the present research motivation arises from this debate, being the first Thesis focusing on the detailed ichnological analysis of contourites.

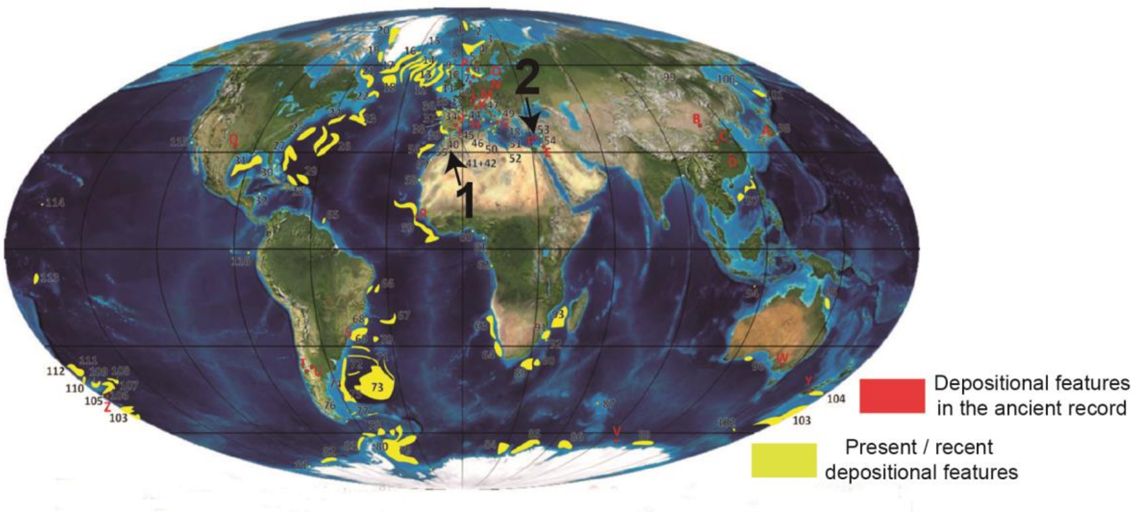


Fig. 1.2. Occurrence of large contourite deposits in the present / recent ocean basins (yellow areas) and in the ancient sedimentary record (red letters and points) (slightly modified from Rebesco et al., 2014). Note the location of the two studied areas (black arrows), Morocco (1), and Cyprus (2).

Ichnology is the science that studies structures produced by organisms on or within the substrate, including all issues related to bioturbation, bioerosion and biodeposition (Bromley, 1996). Ichnology considers processes (interaction between tracemakers and substrate) and their final products (resulting traces). This science can be divided in two main fields: neo-ichnology (study of modern traces / lebensspuren) and palaeoichnology (study of trace fossils). Ichnological studies have exponentially grown due to the definition and development of two main paradigms as the ichnofacies and ichnofabric concepts (Seilacher 1967a; Bromley and Ekdale, 1986; Pemberton et al., 1992; MacEachern et al., 2010; Buatois and Mángano, 2011). These two "tools" have proven to be very useful in palaeoenvironmental studies, especially in sedimentary basin analysis, and in the application of ichnology to reservoir characterization (Knaust and Bromley, 2012). Thus, nowadays ichnology has become a pivotal element not only in palaeoenvironmental reconstructions but also for hydrocarbon exploration (Pemberton, 1992).

The ichnofacies model was developed by Adolf Seilacher in the late 60's (Seilacher, 1967a), involving empirical trace fossil observations with proximal to distal marine trends. Thus, ichnofacies were used as palaeobathymeters during the early stages of the model (Seilacher, 1967a, b). Nevertheless, parallel to the advances of ichnological knowledge, the ichnofacies concept widely expanded to embrace the relationships between trace fossil associations and other palaeoenvironmental conditions, not just bathymetry; becoming a multidimensional framework (MacEachern et al., 2010, 2012). It includes hydrodynamic energy, grain size, rate of sedimentation, substrate consistency, oxygenation, and food, among others (MacEachern et al., 2005, 2012). Originally, there were just five archetypical sotfground marine ichnofacies (*Psilonichnus*, *Skolithos*, *Cruziana*, *Zoophycos*, and *Nereites*), clearly reflecting a proximal to distal distribution associated with the prevailing palaeoenvironmental conditions (Seilacher, 1967a, b, MacEachern et al., 2010, 2012). Nowadays, ichnofacies are characterized by recurring ethological groupings of trace fossils reflecting specific combinations of organism responses to environmental conditions; where invertebrate ichnofacies are defined, including marine and continental, as well as some vertebrate ichnofacies (Buatois and Mángano, 2011) (Figure 1.3). Thus, marine ichnofacies may be considered a first step in the here conducted sedimentary basin analysis at the regional scale, evidencing the relationship between ichnological features and dominant ecological and depositional conditions in bottom current affected environments.

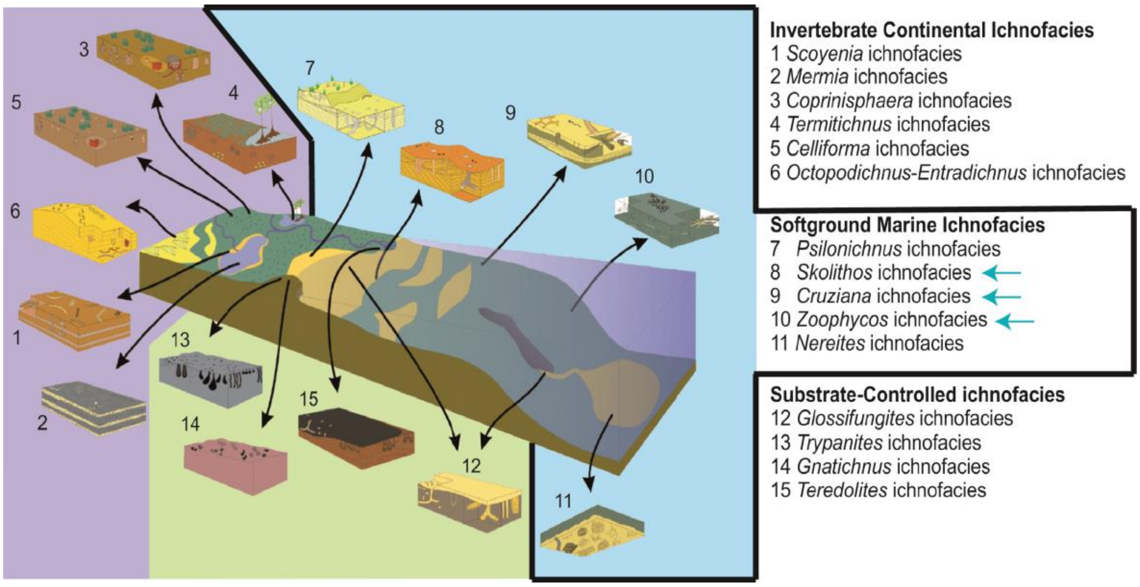


Fig. 1.3. Schematic diagram of invertebrate ichnofacies (modified from Buatois and Mángano, 2011). Surrounded in black marine ichnofacies; blue arrows indicate ichnofacies that have been identified at contourite deposits in this Thesis.

Later, during the 80's, Bromley and Ekdale proposed the ichnofabric concept (Bromley and Ekdale, 1986; Ekdale et al., 1991). Ichnofabrics refer to any textural and structural aspect of the substrate produced by bioturbation or bioerosion at any scale (Bromley and Ekdale, 1986). This approach considers more features than the ichnofacies model and takes into account both discrete trace fossils and poorly defined burrow mottling (Buatois and Mángano, 2011). These features include primary sedimentary structures, cross-cutting relationships, degree of bioturbation, diversity, tiering, and taphonomy. Characterization of the bioturbation degree is an important ichnological aspect in ichnofabric analysis. Traditionally semi-quatitative approaches have been applied, as the scheme proposed by Reineck (1963, 1967), laterly slightly modified by Taylor and Goldring (1993) differentiating seven grades of bioturbation (bioturbation index from 0, 0%; no bioturbation, to 6, 100%; complete bioturbation), and that of Droser and Bottjer (1989) using a series of flash cards on which five ichnofabric indices (ii) are illustrated, from ii 1 (0%) to 5 (60–100%), being ii 6 assigned to complete burrow homogenization (Fig. 1.4). Actually, quantitative methods have being developed, supporting a more objective evaluation of the degree of bioturbation (i.e., Dorador et al., 2014; Dorador and Rodríguez-Tovar, 2018; Miguez-Salas et al., 2019a; Casanova-Arenillas et al., 2020; Rodríguez-Tovar et al., 2020; Miguez-Salas et al., 2021b). Ichnofabrics are divided in simple ichnofabrics (associated to just one ichnotaxa), and composite ichnofabrics (characterized by different trace fossil suites) (Ekdale et al., 2012). In detail, composite ichnofabrics characterized by a single ichnocoenosis, self-generated by a particular assemblage of trace makers, are referred to autocomposite ichnofabrics (Savrda, 2012; Miguez-Salas and Rodríguez-Tovar, 2019a, 2021b), and those produced by two or more different ichnocoenoses to heterocomposite ichnofabrics (Savrda, 2012).

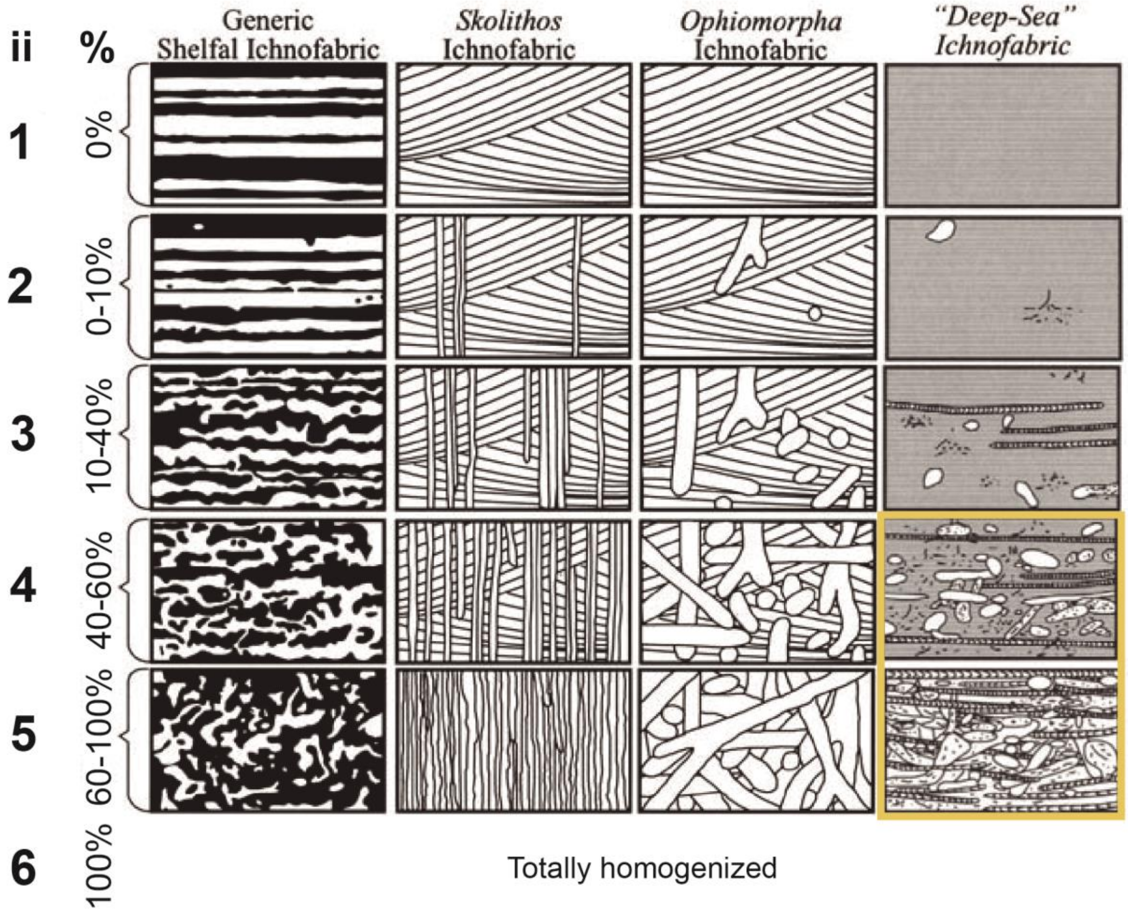


Fig. 1.4. Visual charts correlating ichnofabric indexes (ii; according to Droser and Bottjer, 1989), and percentages in different types of ichnofabrics (slightly modified from McIlroy, 2004). Note: Yellow rectangle exemplify ichnofabrics that have been recognized in muddy calcareous contourite and pelagite/hemipelagite deposits from Cyprus.

In short, integrative ichnological analysis considering both ichnofacies and ichnofabric tools has been proved to be the most useful approach in ichnological research (Knaust and Bromley, 2012). Thus, through this Thesis the conducted ichnological research has been based on an integrative ichnofacies and ichnofabric approach to be applied for the identification and characterization of bottom current associated deposits. Obtained results will offer some light on the debate about the role of biogenic structures as diagnostic features of contourites. Also, they will advance in their palaeoenvironmental reconstructions, and finally will approach the influence of bioturbation on petrophysical properties (i.e., porosity) of bottom current deposits as being important unconventional reservoirs.

Chapter 2

RESEARCH MOTIVATION, OBJECTIVES AND LAYOUT

The present PhD Thesis focuses on the ichnological analysis of ancient contourite outcrops, involving different types of contourites (clastic and calcareous), selected by the generalized presence of bioturbation. The main motivation of this PhD was to demonstrate the usefulness of ichnology in contourite recognition and characterization (sedimentological, palaeoenvironmental, economical), based on the detailed trace fossil analysis of ancient contouritic outcrops from Cyprus and Morocco. It is my belief that in the wake of the present thesis ichnology will be considered as a key tool to indetify and discriminate ancient contourites from other deep-sea facies (i.e., pelagites/hemipelagites, turbidites). Moreover, an essential aim of this PhD is to emphasize the importance of trace fossil analysis on palaeoenvironmental interpretations and reservoir characterization; hoping that it will be included as a significant proxy for future research.

In this sense and considering the usefulness of ichnological analysis, the proposed goals of this Thesis were:

1) To conduct a detailed ichnological analysis in ancient contourite deposits (clastic and calcareous), focusing on the study of ichnological aspects as ichnodiversity, ichnofabrics and ichnofacies.
2) To calibrate the usefulness of the conducted ichnological studies for recognition of contourites and discrimination respect to other deep-sea facies (i.e., pelagites/hemipelagites, turbidites).
3) To interpret the ichnological attributes on contourites, their variation and distribution, in relationship with the dominant palaeoenvironmental conditions at deep-sea settings affected by bottom currents.
4) To propose patterns relating the presence and distribution of ichnological attributes to particular environmental conditions at deep-sea bottom current affected settings, approaching the macrobenthic community response to deep-sea bottom current dynamics and associated palaeoenvironmental parameters (i.e., oxigenation, nutrients, and substrate consistency, among others).
5) To evaluate the incidence of bioturbation on petrophysical properties of contourite deposits; obtaining a more detailed and comprehensive model about trace fossils, porosity distribution and reservoir characterization.

Furthermore, together with the initial goals above mentioned, during the first steps of the PhD study we evidenced the difficulty for trace fossil recognition on contourite deposits, especially in the case of calcareous chalky deposits. Thus, considering that high resolution image treatment has been demonstrated as a useful methodology for ichnological analysis in marine cores (Dorador and Rodríguez-Tovar, 2018), we have tried to implement this approach by the development of a parallel methodology that can also be applied in outcrop, as an additional objective:

6) To develop a methodology which facilitates ichnological analysis in contourite outcrops based on image processing techniques that increase visibility of ichnological attributes.

The results of this PhD Thesis have been published in scientific journals (included in the Science Citation Index) as research papers. Thus, the content and structure of most chapters of this memory 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. Accordingly, the present PhD Thesis is organized as follow:

Part I Introduction, aim and setting

Chapter 1 Deep-sea deposits, contourites and trace fossils.

Chapter 2 Motivation and main objectives.

Chapter 3 Geological setting of selected outcrops in Cyprus (calcareous contourites) and Morocco (clastic contourites). As the geological setting is described in detail in most of the papers, here only a brief overview is shown.

Part II Workflow and methodology

Workflow and methodology used during the present PhD Thesis.

Chapter 4 Research paper about methodological techniques (software; ICY and Fiji) developed to facilitate trace fossil attributes recognition on contourite outcrops.

Supplementary paper of Part II Methodological paper focusing on improving characterization of autocomposite ichnofabrics in calcareous deep-sea deposits from Cyprus.

Part III Ichnological characterization of calcareous contourites

Chapter 5 Research paper showing ichnofacies analysis of one of the main calcareous contourite successions at Cyprus.

Chapter 6 Research paper about ichnofabric analysis of contourites, comparing calcareous contourites and calciturbidites at Cyprus.

Supplementary papers of Part III Ichnological and sedimentological papers on calcareous deep-sea deposits from Cyprus.

Part IV Ichnological characterization of clastic contourites

Chapter 7 Research paper showing a detailed analysis of the trace fossil *Macaronichnus*; as it is the first time described on contourites.

Chapter 8 Research paper focusing on ichnofacies analysis, comparing ichnofacies composition and distribution in ancient deep seaways (clastic contourites, turbidites) and shallow marine settings at Morocco.

Supplementary papers of Part IV Ichnological and sedimentological papers published on clastic deep-sea deposits from Morocco.

Part V Economic implications

Chapter 9 Research paper evaluating the relationship between bioturbation and petrophysical properties (porosity) on contourite deposits, based on the application of Micro-CT techniques.

Supplementary papers of Part V Ichnological papers addressing economic implications of bioturbation in contourites, based on the application of mercury porosimetry and blue epoxy resin techniques.

Part VI Next step: Coupling past and present

Chapter 10 Research paper about neo-ichnological attributes observed at an actual deep-sea environment affected by high energetic bottom current episodes. This chapter illustrates the line of research that I would like to continue in the future.

Part VII Conclusions

Finally, other topics addressed during the PhD (published papers) have been included as an **Appendix**.

Note that to obtain International Mention, the use of both English and Spanish languages is mandatory. For this reason, Abstract and Conclusions are included in both languages. Only the references not included in chapters associated to published papers are presented in the reference section.

Chapter 3

GEOLOGICAL SETTING

3.1. Eocene-Miocene carbonate drift of Cyprus: an example of calcareous contourite deposits.

Cyprus is located in the eastern part of the Mediterranean Sea, in a complex tectonic area — a broad zone of plate convergence between the African and Eurasian plates under the influence of subduction for at least the past 10–20 Myr (Edwards et al., 2010) (Fig. 3.1). The studied outcrops, Petra Tou Romiou and Agios Konstantinos, are located in the southern part of the island, and include both the Lefkara and Pakhna formations, which are part of the circum-Troodos sedimentary successions (Edwards et al., 2010) (Fig. 3.1). The contact between the Lefkara Fm. and the younger Pakhna Fm. is a diachronous sharp contact, either conformable or unconformable, depending upon location. It is a consequence of the onset of a rapid general uplifting of the Troodos Massif, resulting in a shallowing and coarsening upward trend within the sedimentary facies (Kinnaird, 2008).

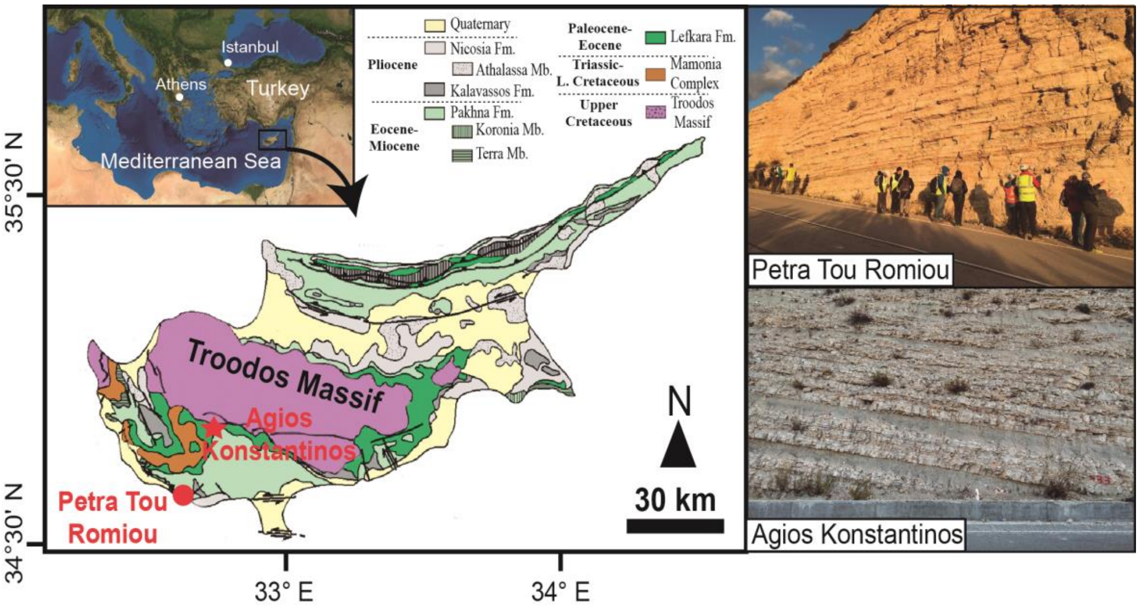


Fig. 3.1. Location of Cyprus in the eastern Mediterranean Sea (Google map) with geological map of Cyprus and the position of the studied outcrops, Petra Tou Romiou and Agios Konstantinos (modified from Kinnaird, 2008). On the right, photographs of the studied outcrops.

The Lefkara Fm. is characterized by deep-marine carbonate and siliceous sediments containing planktic foraminifera, calcareous nannofossils and subordinate radiolarians (Kinnaird, 2008). It mainly consists of chalks, marly chalks, thin calciturbidites, muddy contourites, radiolarian-rich calcilutites and cherts deposited from the Late Cretaceous to the Oligocene — Early Miocene at a paleodepth of 2000 to 3000 m (Kähler and Stow, 1998; Rodríguez-Tovar et al., 2019 a,b; Hüneke et al., 2020). The upper part of the Lefkara Fm. is characterized by the presence of contourites, which have been profusely studied (Kähler and Stow, 1998; Stow et al., 2002; Hüneke and Stow, 2008;

Hüneke et al., 2020), and at Petra Tou Romiou outcrop are even considered as type examples of fossil contourites in ancient successions exposed on land (Stow et al., 2002).

The overlying Pakhna Fm. was deposited during the Early to Late Miocene and shows an upwardly increased input of shallow water bioclastic and siliciclastic components supplied by gravitational processes (Hüneke et al., 2020); locally showing transition to reef and other shallow-water carbonates of the Terra and Koronia Members (Follows, 1992). Within the Pakhna Fm. significant bottom currents originated calcilutitic and calcarenitic bioclastic contourites of different thicknesses (Hüneke et al., 2020). Moreover, Pakhna Fm. was coeval with the uplift of the Troodos Massif during the Miocene, when several basins developed. Hemipelagic sediments were dominant in the basin centres, whereas closer to the margins turbidites and mass transport deposits were much more abundant. The intensity of the bottom current flows that affected the southern Cyprus paleoslope was essentially controlled by the Indian Gateway depth (de la Vara and Meijer, 2016).

3.2. Late Miocene Rifian Corridor (Morocco): an example of sandy clastic contourite deposits.

During the Late Miocene, the Atlantic Ocean and the Mediterranean Sea were connected through the Betic Corridor (southern Iberian Peninsula) and the Rifian Corridor (Morocco) (Krijgsman et al., 2018). The Rifian Corridor comprised two main channels, the North and South Rifian corridors (e.g., Capella et al., 2018 and references therein). Both channels were progressively sealed due to a tectonically induced uplifting process, leading to the commencement of the Mediterranean Salinity Crisis in the late Miocene (e.g., Flecker et al., 2015; Krijgsman et al., 2018); the South Rifian corridor was the last one to close, around 7 Ma ago (Krijgsman et al., 2018). Over this period, the bottom current pathways of the Miocene Mediterranean overflow, that came out into the Atlantic Ocean through the South Rifian corridor, formed the sandy clastic contourite drift exposed on land (Capella et al., 2017, 2018). The exclusive record of these deposits in the northern margin of the gateway is the mirror of ancient geostrophic processes that forced the thermohaline bottom currents northward (Capella et al., 2017, 2018).

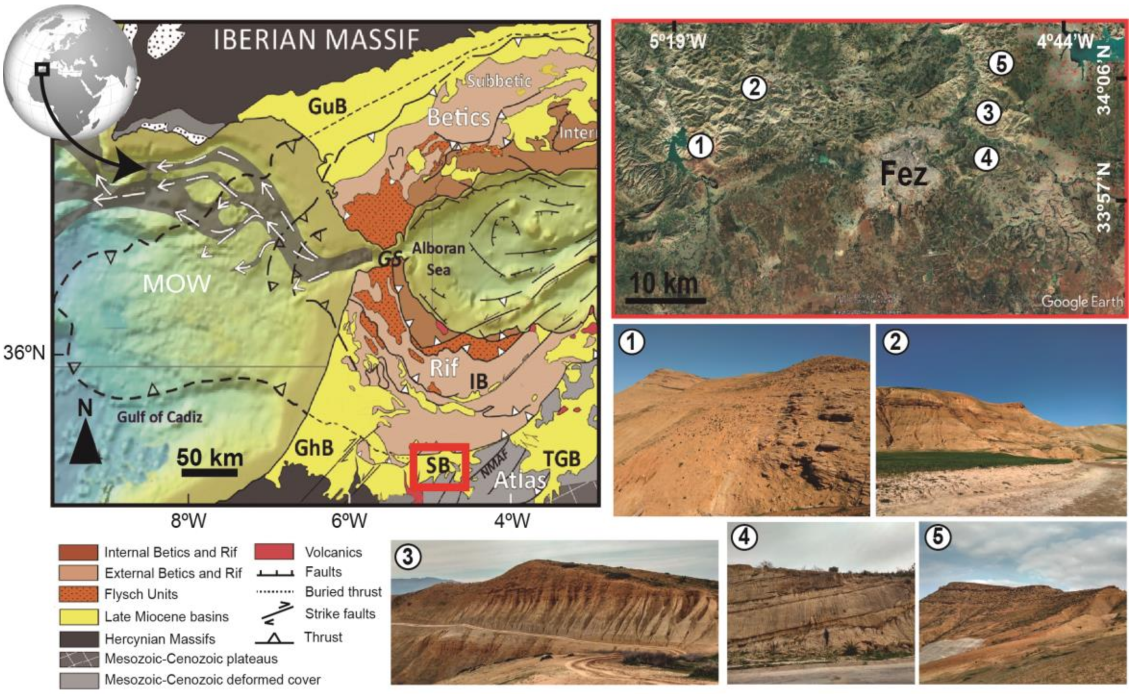


Fig. 3.2. Geological and tectonic map of the Betic-Rif arc with the main stratigraphical units. Note: GhB: Gharb Basin; GS: Gibraltar Straits; GuB: Guadalquivir Basin; MOW: Modified Outflow Water; NMAF: North-Middle-Atlas Fault; SB: Saiss Basin (studied area; red rectangle); TGB: Taza-Guercif Basin (modified from Capella et al., 2017). On the right, the studied outcrops and their location: 1) Sidi Chahed; 2) Kirmta; 3) El Adergha; 4) Sidi Harazem; and 5) Ain Kansera.

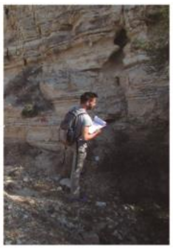
The study outcrops are emplaced in the Saiss Basin (Fig. 3.2): 1) Sidi Chahed (34°05′58.07″N, 5°18′15.12″W); 2) Kirmta (34°10′15.07″N, 5°14′21.43″W); 3) El Adergha (34°4′34.19″N, 4°51′33.43″W); 4) Sidi Harazem (34°01′52.67″N, 4°52′47.69″W); and 5) Ain Kansera (34°07′34.06″N, 4°51′20.04″W). The Saiss Basin is located by the western exit of the South Rifian Corridor and comprises middle to late Miocene foreland deposits (Flecker et al., 2015; Capella et al., 2017; de Weger et al., 2020). Sidi Chahed, Kirmta and El Adergha outcrops record contouritic sandstones from the Late Tortonian (between 7.8 and 7.25 Ma ago), deposited within a upper slope to the outer shelf environment (Capella et al., 2017; de Weger et al., 2020, 2021). Sidi Harazem outcrop consists mainly of upper Tortonian (between 7.80 and 7.51 Ma) sandstone and marlstone intercalations associated with a basinal turbidite system (Capella et al., 2017). Ain Kansera consists of upper Tortonian (between 7.51 and 7.31 Ma) sandstone and marlstone intercalations associated with an inner shelf environment and toward the top with a shallower wave-dominated infralittoral setting.

PART II

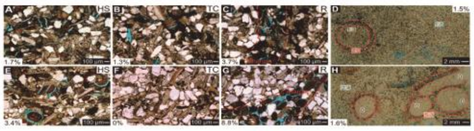
WORKFLOW AND METHODOLOGY

The workflow conducted in this Thesis can be summarized in the next diagram:

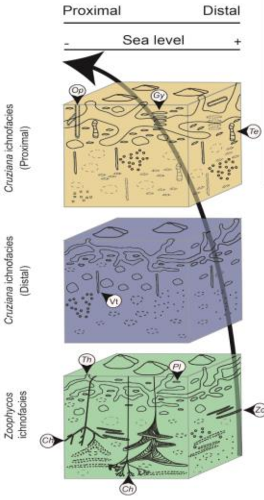
Outcrop
- -Log elaboration
  - -Stratigraphic features
    - -Facies
    - -Contourites
    - -Stacking patterns
  - -Ichnological features
    - -Taphonomy
    - -Tiering and cross-cuts
    - -Trace fossil distribution
    - -Trace fossil features (orientation, shape, length and diameter)
- -Photography

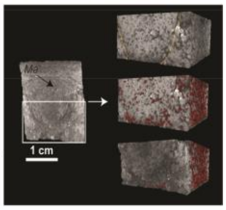


Laboratory
- -Software
  - -Visibility enhancement
  - -Bioturbation intensity
  - -Penetration depth
- -Degree of bioturbation
- -Tiering and cross-cuts
- -Trace fossil features (orientation, shape, length and diameter)
- -Ichnotaxonomy
- -Statistical data treatment (Excel)
- -Porosity
  - -Epoxy blue resine
  - -Mercury porosimetry
  - -Micro-CT

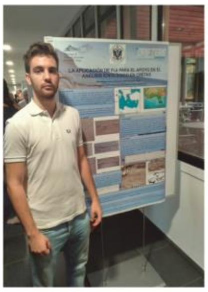


Results
- -Trace fossil assemblages of clastic and calcareous contourites
- -Ichnofacies characterization of contourites
- -Ichnofabrics of contourites, turbidites and pelagites
- -Bioturbation and porosity in contourites

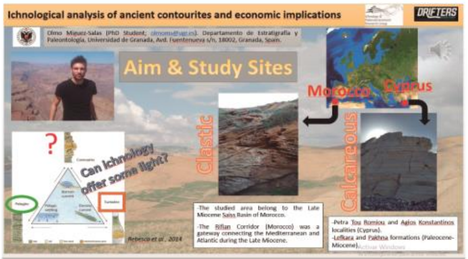




Interpretation & Discussion
- -Ichnofacies distribution
- -Trace fossil assemblage evolution
- -Ichnological features and sedimentary basin research (palaeoenvironmental)
- -Bioturbation and contourites (economic interest)



Dissemination
- -International meetings
  - -Oral communications
  - -Posters
- -Papers



Ichnological analysis of ancient contourites and economic implications

DRIFTERS

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Aim & Study Sites

Can ichnology offer some light?

Rebesco et al., 2014

Clastic

Morocco

Cyprus

Calcareous

-The studied area belong to the Late Miocene Sais Basin of Morocco.

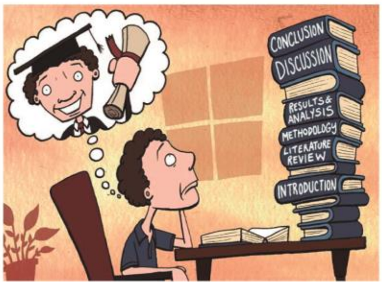
-The Rifian Corridor (Morocco) was a gateway connecting the Mediterranean and Atlantic during the Late Miocene.

-Petra Tou Romiou and Agios Konstantinos localities (Cyprus).

-Lefkara and Pakhna formations (Paleocene-Miocene).

and finally................

Writing
- -PhD Thesis elaboration



Conducted research can be clearly divided in several parts involving sampling (outcrop), samples analysis and obtained results (laboratory), and interpretation/discussion/dissemination (office). Because the outcrop methodology is extensively described in each of the published papers here, only a brief review is here presented.

Outcrop methodology includes a first step of log elaboration and photography. Respect to the ichnological research, macroscopic analysis of trace fossil features focused on: general composition, orientation, shape, length and diameter of individual burrow segments, configuration of burrow systems, and taphonomy. Special attention was paid to stratigraphic variations in ichnological features, and degree of bioturbation. Specimens were photographed to record their position within the bed and conduct an appropriate ichnofabric approach, and some of them were collected for laboratory analysis.

Collected specimens were studied in the laboratory, focusing on ichnotaxonomical features such as general shape, dimensions, horizontal/vertical arrangement, etc., allowing a detailed classification at ichnogenera/ichnospecies level. Detailed analysis was conducted focusing on the contact between traces and host sediment, and on the infilling material of burrows. Ichnological studies on whity calcareous deposits are difficult due to the poor visibility of biogenic structures. Thus, high-resolution images obtained from outcrop and laboratory samples were treated with software (Fiji, ICY, and Adobe Photoshop) techniques to improve visibility of ichnological attributes (e.g., crosscutting relationships, degree of bioturbation, penetration depth and tiering, among others) (see Chapter 4). Moreover, statistical studies were conducted on trace fossils features in order to describe stratigraphic trends (Microsoft Excel). Trace fossil specimens are housed at the Department of Stratigraphy and Palaeontology of the University of Granada, labeled as PT, AK, EA, KT, BA.

Laboratory methods used to evaluate the relationship between contourites porosity and bioturbation have been (see Part V):

1) Mercury Intrusion Porosimetry. This method is used to evaluate open porosity (interconnected pores) and pore-size distribution in the range from 0.003 to 350 μm. Since mercury is a non-wetting liquid; thus penetration into pores must be forced by external pressure, being the required pressure inversely proportional to the size of the pores. Mercury fills larger pores first and, as pressure increases, smaller ones. Pressure intrusion data are provided by the porosimeter, which determines volume and size distributions according to the Washburn equation (Pirard et al., 2002). Mercury intrusion porosimetry analysis allows evaluating both the porosity between the individual particles (interparticle porosity) and the porosity within the particles (intraparticle porosity).The equipment used in this study was a Micromeritics Autopore III apparatus (University of Alicante, Spain), model 9410, generating a maximum pressure of 414 MPa. Samples of approximately 2 cm^3 were freshly cut and oven-dried for 24 h at 110 °C before being analysed (see Rodríguez-Tovar et al., 2021).

2) Epoxy blue resin. Thin sections were prepared in the Department of Earth Sciences at Royal Holloway University of London and impregnated with blue dyed resin to highlight porosity. Struers EpoFix epoxy mixed with Sudan Blue II powder was used for the resin (see Dorador et al., 2021). Composition of all thin sections was described and modal analyses were conducted. Host rock and burrows (tube core and rim) were differentiated for these analyses. Eleven quantitative modal analyses were carried out by determining the composition at 300 points on each thin section using a stepping stage and associated PETROG software (Conwy Valley Systems Limited, UK). Porosity from all the thin sections was also obtained by blue pixels counting using Photoshop, obtaining a representative mean value for the whole samples and from every single part (i.e., host rock, tube core, and rim). Blue pixels were quantified using Color Range Selection Method (Dorador et al., 2014; Dorador and Rodríguez-Tovar, 2018). This method allows selecting all the blue pixels from an area of interest by clicking on some blue pixels and extending the selection to all the pixels with similar values. Once all the blue pixels are quantified, porosity can be calculated considering the number of pixels composing the area of interest. Degree of bioturbation was evaluated considering the bioturbated surface (BS), using Ichnological Digital Images Analysis Package (IDIAP) quantitative method (Dorador et al., 2014; Dorador and Rodríguez-Tovar, 2018).
3) Micro-Computed Tomography. Tomographic data were obtained using X-ray computerized axial microtomography (μ-CT, Zeiss Xradia 510 Versa) at the Scientific Instrumentation Center (CIC, University of Granada). Image reconstruction was done by means of Reconstructor Scout and ScanTM software (Zeiss) using a 0.5 Recon filter and 3201 projections. Dragonfly ProTM (Object Research System) was used for advanced post-processing analysis and 3D image porosity data. 2D analysis and quantitative pore distribution characterization were conducted using binary black and white CT images with the free software Fiji (Schindelin et al., 2012). Treatment to enhance 2D sample visibility was conducted by means of "Contrast Limited Adaptive Histogram Equalization (CLAHE)" of Fiji software (Miguez-Salas et al., 2019a). See Chapter 9 for a more detailed description.

Chapter 4

INTRODUCING FIJI AND ICY IMAGE PROCESSING TECHNIQUES IN ICHNOLOGICAL RESEARCH AS A TOOL FOR SEDIMENTARY BASIN ANALYSIS

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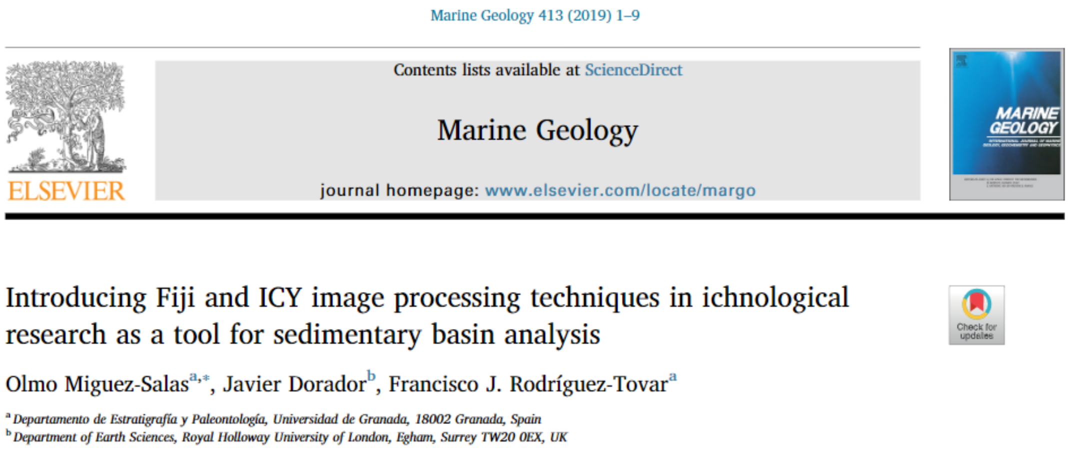

Marine Geology 413 (2019) 1–9

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Introducing Fiji and ICY image processing techniques in ichnological research as a tool for sedimentary basin analysis

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ABSTRACT

In recent years, image treatment has been appraised as a very powerful tool to facilitate ichnological analysis, especially in marine cores of modern sediments, supporting the determination of certain ichnological features. However, it is still a new approach and detailed research is necessary to encounter a faster and more efficient method. The present study focuses on two image processing techniques, Fiji and ICY, and their comparison with a refined version of the well-established high-resolution image treatment. Strengths and weaknesses of the methodologies for the determination of three main features were explored: i) visibility of trace fossils; ii) quantification of the percentage of bioturbated surface, and iii) penetration depth estimation. Refined high-resolution image treatment gives the best results for enhanced visibility of trace fossils, whereas Fiji is found to be a sound and rapid option. One disadvantage shared by Fiji and ICY is the binary character of the produced images, which may impede later ichnotaxonomical differentiation. Both Fiji and ICY (+ Fiji) are rapid alternatives for quantifying the bulk amount of bioturbated surface. The Magic Wand Method (+ RefineEdge), based on high-resolution image treatment, provides good results regardless of the contrast of the images, and it additionally allows for a more detailed quantification. The semi-automatic character of ICY favors quick estimation of penetration depth and facilitates differentiation between distinct tracemaker communities, based on a rapid quantification of pixel values. Thus, Fiji and ICY methods offer good results and are much less time-consuming than high-resolution image treatment. They are proposed as faster alternatives for the estimation of ichnological features, especially useful at the beginning stages of research, when a large number of samples must be analyzed.

Keywords: Image treatment methods, High-resolution images, Degree of bioturbation, Penetration depth, Basin research

4.1. Introduction

The study of trace fossils has been documented as a very useful tool in several Earth Sciences disciplines including palaeontology, sedimentology, marine geology or palaeoceanography, and proven key in sedimentary basin research (e.g., Buatois and Mángano, 2011; Knaust and Bromley, 2012). Trace fossils record the behavior of tracemakers in response to the environment, providing valuable information regarding paleoenvironmental conditions. Ecological and depositional parameters affecting the marine realm (i.e., oxygenation, nutrients, hydrodynamic energy, rate of sedimentation, etc.) can be addressed through a detailed ichnological analysis. Thus, ichnology is a valuable proxy for approaching marine processes or deposits. Most of these ichnological advances have entailed the application of two main paradigms: the ichnofabric approach (McIlroy, 2004; Buatois and Mángano, 2011; Ekdale et al., 2012) and the ichnofacies model (Buatois and Mángano, 2011; MacEachern et al., 2012), both based on a detailed characterization of ichnological properties (i.e., trace fossil assemblage, degree of bioturbation, among others). Occasionally, these properties are difficult to determine due to a poor visibility of the trace fossils in the studied samples. Against this background, in recent years, high-resolution image treatment has been successfully applied for the ichnological analysis of marine cores from modern deposits, proving useful for ichnofabric characterization and ichnofacies differentiation (see Dorador and Rodríguez-Tovar, 2018 for a recent review of the methodology).

Image treatment allows for a better visualization of biogenic structures, thereby making it easier to identify ichnological properties such as morphology, degree of bioturbation or penetration depth, which are of special relevance in applied ichnology (e.g., Bednarz and McIlroy, 2009; Dorador et al., 2014a, Dorador et al., 2014b; Rodríguez-Tovar and Dorador, 2014, Rodríguez-Tovar and Dorador, 2015; Timmer et al., 2016, among others). The use of high-resolution image treatment also contributes to studies surrounding paleoenvironmental developments (e.g., Rodríguez-Tovar and Dorador, 2014; Rodríguez-Tovar et al., 2015a, Rodríguez-Tovar et al., 2015b; Dorador and Rodríguez-Tovar, 2016a; Dorador et al., 2016) and provides information for sedimentary basin research (e.g., Alonso et al., 2016; Dorador and Rodríguez-Tovar, 2016b; Takashimizu et al., 2016), supported by the ichnological approach. So far, these techniques have been mainly applied on marine cores from modern deposits. However, Dorador and Rodríguez-Tovar (2018) recently showed that image treatment might be an adequate method for analyzing lithified cores and rock samples. While its usefulness has been clearly demonstrated, the application of high-resolution image treatment takes time, a plain fact that encourages further exploration of this approach to find the most efficient and less time-consuming methods. With this goal in mind, two software packages widely used in biological and medical research were selected to test and compare their performance: Fiji, as an extension of the ImageJ software; and ICY software.

Fiji software (Schindelin et al., 2012) is an extension of the well-known open-source software ImageJ, commonly but not exclusively applied in biological and medical studies (Schneider et al., 2012 and references therein), and less frequently in geological research (e.g., Grove and Jerram, 2011; Goldstein et al., 2017). ImageJ has been punctually used in ichnological analysis to enhance visibility of certain image attributes, to estimate bioturbated surface and to make shape/length measurements (Francus, 2001; Nicolo et al., 2010; Lauridsen et al., 2011; Curth et al., 2014). Fiji has already been applied in neoichnological analysis for format conversion in reconstructed volumes obtained by computed tomography of invertebrate burrow systems (Hale et al., 2015), and recently to estimate the degree of bioturbation (Miguez-Salas and Rodríguez-Tovar, 2019). This method holds great potential for ichnological studies because its toolbox features diverse tools and filters for the measurement of specific paleontological parameters (i.e., shape/length of bones; Iepure et al., 2012; Jarrett, 2016; O'Connor et al., 2018).

Whereas ICY software has been applied in cell biology studies for tracking, extracting or actively delimiting particles/cells (e.g., de Chaumont et al., 2011; Meijering et al., 2012; Montagnac et al., 2013), it has not been previously applied to geological research. The present research marks the first documented testing of its usefulness in the realm of ichnological aspects.

The aim of this paper is to examine two image processing techniques, Fiji and ICY, to approach a fast and useful method for the early research stages of ichnological studies in which numerous samples and images are examined. Then, the results obtained with the application of these two techniques are compared with a slightly modified version of a previously applied high-resolution image treatment (recent review in Dorador and Rodríguez-Tovar, 2018). In light of their comparison, the strengths and weaknesses of each procedure are characterized, outlining the most efficient approach for applied ichnology in sedimentary basin research.

4.2. Methods and materials

Two image treatment methods applied to ichnology—Fiji and ICY—plus the refined version of high-resolution image treatment were assessed for their usefulness in ichnological analysis. The focus was on: (1) enhanced trace fossil visualization; (2) quantification of bioturbated surface corresponding to discrete trace fossils; and (3) minimum penetration depth.

4.2.1. Fiji

Fiji software offers a wide range of plugins for enhancing image visibility, similar to the image adjustments of Adobe Photoshop (e.g., brightness, hue, saturation, levels). For the purposes of this study, to provide quick image visibility improvement, the Contrast Limited Adaptive Histogram Equalization (CLAHE) method was selected (Fig. 4.1A). This provides better visibility of ichnological features in a short time through the local contrast of an image based on modification of two main parameters: i) block size, controlling the size of the local region around a pixel for which the histogram is equalized; and ii) histogram bins, defining the number of bins used for histogram equalization, which should be smaller than the number of pixels in a block.

For the quantification of bioturbated surface, after applying CLAHE, the obtained image must be converted to an 8-bit grayscale image. Then, the threshold has to be defined to establish a differentiation range for black and white by means of the Image menu. The determination of this parameter is supported by a preview screen, where the potential image is observed, and the value can be modified to obtain a more appropriate bioturbated differentiation (black pixels were assigned to bioturbation). The enhanced black and white binary image can be used to quantify the amount of bioturbated surface (Fig. 4.1B left). The Fiji process menu offers a wide range of easy-to-use binary tools and filters (e.g., dilate, erode, fill holes and skeletonize, among others). After testing, the following ones were selected as the most suitable for ichnological analysis: a) Erode: it removes erratic black pixels from the edges of bioturbation, proving extremely useful to delete minor compounds of black pixels that do not correspond to trace fossils, and thereby more precisely discern the shape of the burrows; b) Fill holes: it fills white pixels located inside the trace fossils that are surrounded by black ones; and c) Minimum/Maximum filters: they perform binary erosion by replacing each pixel in the image with the smallest/largest pixel value in that pixel's neighborhood, helping one to remove small black pixels that conform background noise (Fig. 4.1B right). All these tools and filters present a preview option, which makes it easy, quick and intuitive to select the size of the neighborhood.

Finally, manual corrections can be conducted using eraser or painting tools, controlling that all the selected pixels belong to trace fossils. Afterwards, output measurement results are quickly obtained with the Fiji analyze menu, whose program measures the percentage of black pixels, hence offering a quantification of the bioturbated surface.

4.2.2. ICY

ICY software uses an adaptive histogram equalization to enhance trace fossil visibility (Fig. 4.2A). This plugin controls parameters similar to Fiji's, but through a distinctive automatic procedure, giving different results.

When it is used to quantify bioturbated surface, ICY software can extract part of the image according to pixel values via a thresholding menu. The pixel selection can be done through manual adjustment, where threshold values are defined to derive a binary image (Fig. 4.2B left). The selection may also be obtained automatically using the K-Means tool, whose algorithm calculates the threshold value after defining the number of “classes” (i.e., areas in the histogram) to be differentiated (value 2 for binary images). In the case of abundant background noise, a high threshold value should be chosen to ensure that bioturbation is well delimited and assigned to white pixels (Fig. 4.2B left). The derived image can then be exported and inverted by Fiji. A final filtering treatment and estimation of bioturbated surface should be conducted using Fiji, repeating the process, to arrive at improved yet rapid results (Fig. 4.2B right).

Finally, the Intensity Profile plugin was used here to characterize the penetration depth of trace fossils with passive filling (i.e., material that filled a burrow by physical sedimentation after its occupant departed; Bromley, 1990). This plugin calculates the intensity value of each pixel (obtaining three values per pixel, one for each channel) along a particular Region Of Interest (ROI). The values are plotted on intensity profile graphics from a given ROI (vertical line along the core), after which they must be manually checked and filtered to identify potential mistakes. The final graphs of intensity values along the ROI are used to compare intensity values from the infilling material with those from the host sediment. Similar values allow one to recognize the colonization horizon and then estimate the penetration depth of passively filled trace fossils from this horizon.

4.2.3. High-resolution image treatment

The tested high-resolution image treatment for enhancing trace fossil visualization is based on the method defined by Dorador et al., 2014a, Dorador et al., 2014b. This technique modifies some image adjustments (i.e., levels, brightness and vibrance) to increase the contrast between the host sediment and the infilling material. It was initially proposed in sediment core research, and later it was tested in rock samples after minor modification (see Dorador and Rodríguez-Tovar, 2018, for a review).

To characterize the percentage of bioturbated surface, Dorador et al. (2014b) presented a package consisting of three selection tools: Similar Pixel Selection Method (SPSM), Magic Wand Method (MWM) and Color Range Selection Method (CRSM). In the present study, to further enhance quantification, selections obtained from each of the above methods (Fig. 4.3B left) were slightly modified using a novel resource called RefineEdge (Fig. 4.3B right). It enables one to refine the selected area, corresponding to the biogenic structure, by modifying five parameters (Radius, Smooth, Feather, Contrast and Shift Edge), giving rise to a better characterization of the discrete trace fossil. The Radius parameter controls the size of the border in which refinement is applied. Once the size is defined, Smooth, Feather and Contrast are modified. Smooth makes it possible to remove hills and valleys, smoothing the border; Feather smudges the boundary between the selected area and surrounding pixels; and Contrast modifies transitions along the border. Finally, borders can be moved inward or outward by means of the Shift Edge parameter, controlling the final selected area.

Penetration depth is determined by high-resolution digital image treatment following quantitative pixel analysis, as was proposed by Dorador and Rodríguez-Tovar (2014). Host sediment pixels and those from the infilling material of trace fossils are quantified and plotted, and the comparison between pixel values allows the penetration depth to be evaluated (Dorador and Rodríguez-Tovar, 2014).

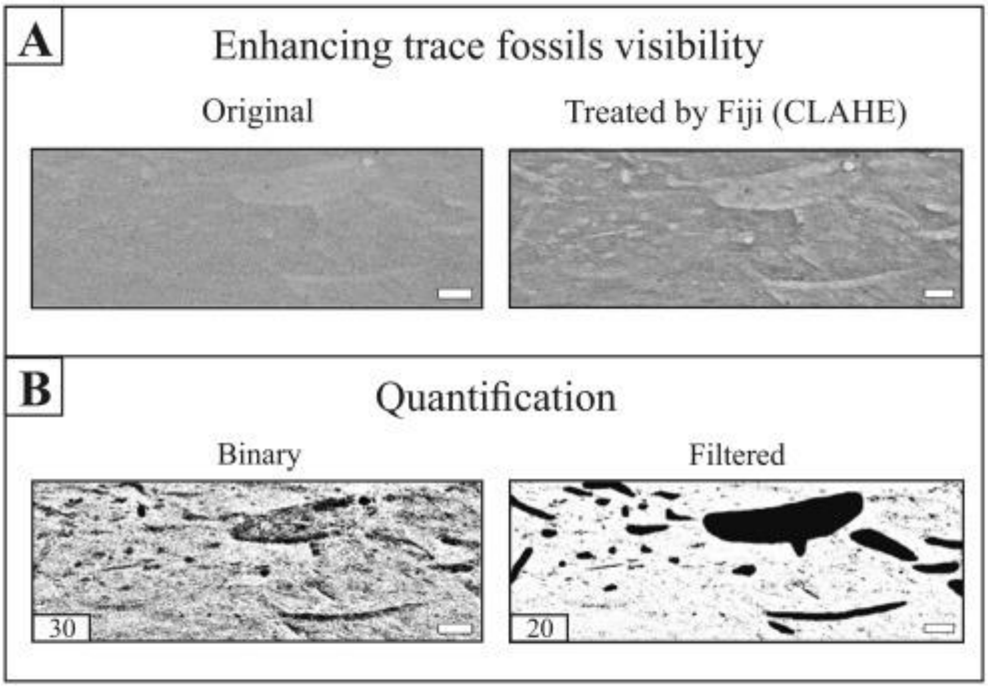

Fig. 4.1. Example of Fiji treatment stages to enhance trace fossil visualization (A) and quantify the bioturbated surface (B). Scale bars = 1 cm.

4.2.4. Data set

Numerous images from sediment cores and outcrops were considered in this study. For core samples, the data set consisted of high-resolution images from IODP Expedition 339, subjected to numerous ichnological studies during recent years (e.g., Rodríguez-Tovar and Dorador, 2014; Rodríguez-Tovar et al., 2015a, Rodríguez-Tovar et al., 2015b; Dorador and Rodríguez-Tovar, 2016a, Dorador and Rodríguez-Tovar, 2018). Core images were from 1.5 m sections split lengthwise and scanned (on the Section Half Imaging Logger) on board during the cruise (Expedition 339 Scientists, 2013a). Fifty-four of these core samples were selected, and 10–20 cm core intervals were cropped from every core section in view of potentially interesting ichnological content. Additionally, two core segments were selected from IODP Site U1385 corresponding to core depths of 40.05 to 40.20 m (U1385A-5H-CC) and 70.7 to 70.9 m (U1385-8H-5A) to analyze the penetration depth. They are mainly hemipelagic claystones, with no primary sedimentary structures, but many discrete trace fossils over a mottled background (Expedition 339 Scientists, 2013b; Rodríguez-Tovar and Dorador, 2014).

Several images of outcrop samples from the Cyprus carbonate contourite drift succession (Petra Tou Rominou section; see Stow et al., 2002) and Moroccan Miocene sandy contourite channels (Capella et al., 2017) were furthermore considered. Ichnological studies of these rocks reveal informative examples of variable relationships between trace fossils and host sediment. Before taking photographs (Canon ® PowerShot SX420), outcrops were sprayed with water to improve trace fossil visibility. More than 100 images corresponding to several lithologies (chalk, calcilutites, calcarenites) were treated to evaluate different cases (for chalk, see Miguez-Salas and Rodríguez-Tovar, 2019). Finally, based on the contrast between the trace fossils and the surrounded material, three images were selected as illustrative and representative examples: calcarenite (high contrast), chalk (medium contrast) and calcilutite (low contrast).

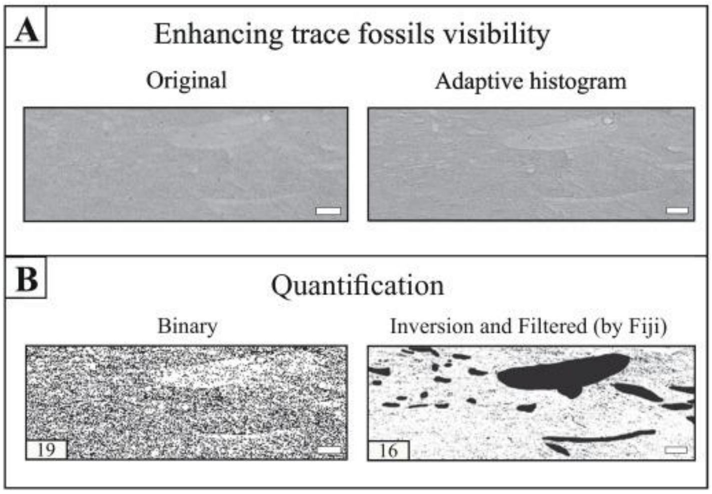

Fig. 4.2. Example of ICY treatment stages to enhance trace fossil visualization (A) and quantify the bioturbated surface (B). Note that bioturbation is assigned to white pixels and the last stages of filtering and inversion are assisted by Fiji. Scale bars = 1 cm.

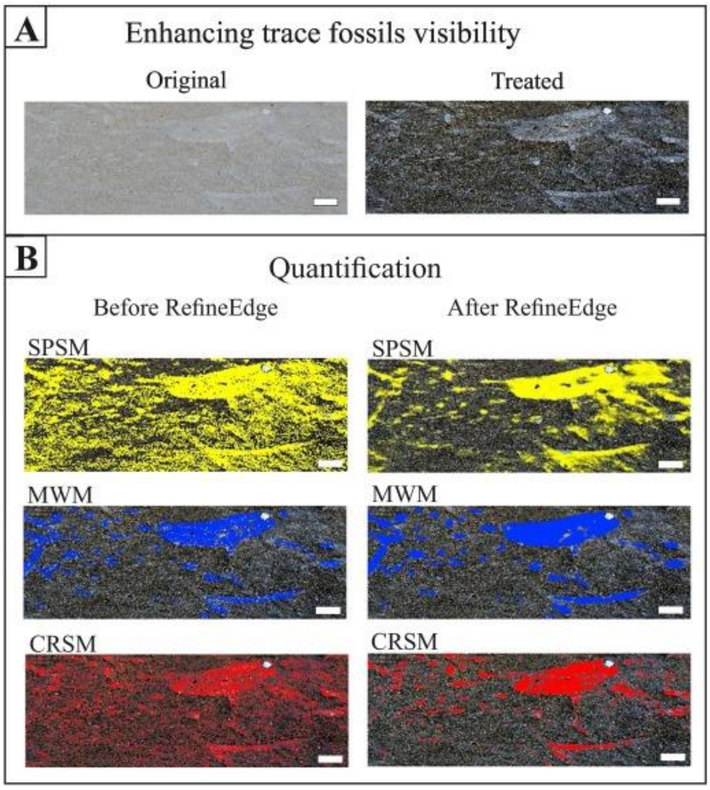

Fig. 4.3. Example of high-resolution image treatment application to enhance trace fossil visibility by the modification of image adjustments (A) and for quantification of bioturbated surface (B). SPSM, Similar Pixel Selection Method; MWM, Magic Wand Method; CRSM, Color Range Selection Method. Scale bars = 1 cm.

4.3. Comparative analysis

Comparison of the selected methods (i.e., Fiji, ICY and high-resolution image treatment) served to highlight the strengths and weaknesses of each in improving the visibility of trace fossils and quantification of bioturbated surface. In the case of high-resolution image treatment and ICY, we were able to compare the penetration depth as well.

4.3.1. Enhancing visibility of bioturbation

The techniques were applied on outcrop images to increase the visibility of trace fossils, and consequently facilitate ichnotaxonomical identification. For a detailed comparison, three examples were selected based on the original contrast (high, medium and low contrast) between trace fossils and the surrounding sediment (Fig. 4.4).

Application of the high-resolution image treatment served to enhance the visualization of trace fossils in the three examples, being particularly successful in low and medium contrast examples, where some ichnotaxa could not be identified in the original image. Reliable identification and characterization of some *Chondrites* was only possible after the treatment (Fig. 4.4).

The CLAHE methodology conducted with Fiji provides good results for medium to low contrast samples, especially for highlighting *Thalassinoides* and *Planolites* (Fig. 4.4). However, differentiation of *Chondrites* is still difficult after treatment. In the case of the high contrast example, visualization of traces such as *Chondrites* is aided by treatment (Fig. 4.4).

Adaptive histogram equalization in ICY gives excellent results for the reddish *Chondrites* of the high-contrast image (Fig. 4.4), although improvement in trace fossil visualization is relatively low in those images with medium to low contrast between trace fossils and surrounding sediment (Fig. 4.4).

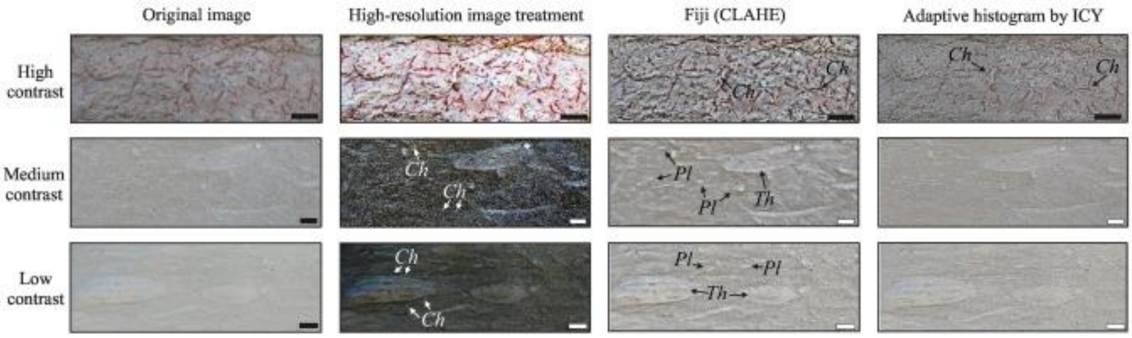

Fig. 4.4. Original images and obtained results after application of high-resolution image treatment, CLAHE extension by Fiji, and the adaptive histogram by ICY on high, medium and low contrast samples. Scale bars = 1 cm. Pl, *Planolites*; Th, *Thalassinoides*; Ch, *Chondrites*.

4.3.2. Quantification of bioturbated surface corresponding to discrete trace fossils

High-resolution image treatment entailed using the refined versions of Color Range Selection Method (CRSM), Magic Wand Method (MWM) and Similar Pixels Selection Method (SPSM) on high, medium and low contrast examples (Fig. 4.5). The three techniques provided similar values for bioturbated surface corresponding to discrete trace fossils in the high contrast example—from 9% to 12%—indicating a low degree of bioturbation (BI = 2, according to bioturbation index of Taylor and Goldring, 1993). These differences are higher in the medium contrast image, where quantification ranges from 10% to 19%, although both values correspond to the same bioturbation index (BI = 2). Finally, application on the low contrast example gives more variable values, from 19% to 47%; estimations obtained with CRSM and MWM represent a low index of bioturbation (BI = 2), while that from SPSM corresponds to a higher index (BI = 3).

In conjunction with Fiji and ICY methods, the amount of bioturbated surface corresponding to discrete trace fossils was calculated before and after filtering binary images (Fig. 4.1, Fig. 4.2, Fig. 4.5). Both techniques show similar results in the high contrast outcrop image (15% and 16%) pertaining to a low bioturbation index (BI = 2). The results obtained from medium (16% and 20%) and low (19% to 22%) contrast images are also similar, corresponding, at any rate, to a low bioturbation index (BI = 2 for all). Filtering was less complex in the case of binary images obtained with Fiji methodology. In the case of ICY method, the filtering was especially difficult due to the assignment of some host sediment areas as pixels belonging to trace fossils.

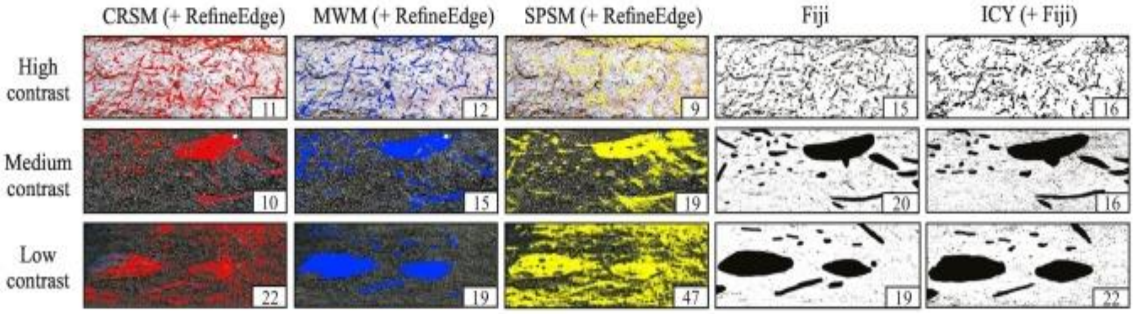

Fig. 4.5. Quantification of percentage of bioturbated surface by different methods of high-resolution image treatment, Fiji and ICY software. CRSM, Color Range Selection Method; MWM, Magic Wand Method; SPSM, Similar Pixel Selection Method. Scale bars = 1 cm.

4.3.3. Penetration depth

Penetration depth values were calculated, and then compared, using both the quantitative pixel analysis proposed by Dorador and Rodríguez-Tovar (2014), and the Intensity Profile plugin by ICY (IP-ICY). In both cases, images were previously treated with high-resolution image treatment and Fiji (CLAHE), respectively, to improve trace fossil visualization. As explained previously, we focus on passively filled trace fossils; comparison between data (mean pixel values in case of the high-resolution image treatment and intensity values in case of IP-ICY) from the infilling material with those of the host sediment enabled us to approach the colonization horizon and then estimate the penetration depth. Two core segments from IODP Site U1385 having different contrast between the fill material of trace fossils and the surrounding sediments were studied: a higher contrast image corresponding to U1385A-5H-CC, and a lower contrast image to U1385A-8H-5A (Fig. 4.6).

In general, the results of the two methods were similar, but some noteworthy differences should be pointed out (Fig. 4.6). For the higher contrast example, the high-resolution image treatment improved visualization of three *Thalassinoides* cross-sections and the quantitative pixel analysis allowed the identification of corresponding penetration depths of 2.8, 3.6 and 9.8 cm (Fig. 4.6A left). The IP-ICY shows two intensity value packages that can be linked to *Thalassinoides*; the first records penetration depths of 2.6, 3.5 and 5.5 cm, and the second shows lower intensity values, giving an estimated penetration depth of 9.5 cm (Fig. 4.6A right). For the low contrast core interval, according to quantitative pixel analysis, four *Thalassinoides* cross-sections showed penetration depths of 1.8, 6.3 and 10.0 (in two cases) cm (Fig. 4.6B left). Using IP-ICY it is more difficult to distinguish between the fill of trace fossils and the host sediment, although four different intensity value packages might be associated with the four *Thalassinoides* cross-sections, having penetration depths of 2, 9, 10 and 11 cm.

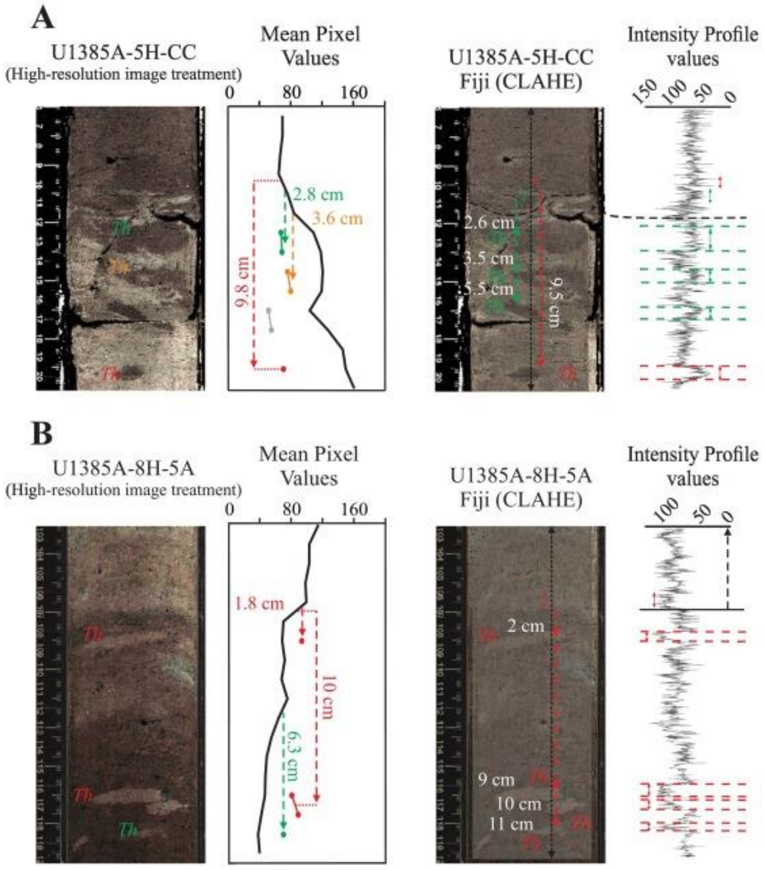

Fig. 4.6. Penetration depth of trace fossils obtained with quantitative pixel analysis (left) and IP-ICY (right) methodology in high (A) and low (B) contrast core examples. Note: left scale in cm.

4.4. Discussion

This study confirms that image processing techniques facilitate trace fossil analysis when applied to characterize particular ichnological features such as ichnodiversity, quantification of bioturbation, and penetration depth. Our comparative analysis furthermore served to evidence strengths and weaknesses of the three studied methodologies (Table 4.1).

Methods	Enhancing visibility of trace fossils	Quantification of bioturbated surface	Estimation of penetration depth
High-resolution image treatment (+ RefineEdge)	Good results for any image (high to low contrast), based on the modification of three image adjustments (levels, brightness and vibrance) Application of different colors facilitates ichnotaxonomy	CRSM and MWM provide reasonable values for high and medium contrast images. MWM is also useful in low contrast images, but it is time-consuming Application of different colors allows detailed quantification	Good estimation, but time-consuming
Fiji	It provides good results for any image in a rapid way Binary character makesichnotaxonomical differentiation difficult	Good for high and low contrast images, but after complex filtering Only for quantification of total bioturbated surface	Not possible
ICY	Successful for high contrast images Binary character makes ichnotaxonomical differentiation difficult	Good for high and medium contrast images, but it requires complex filtering. Note that the last stages have to be conducted with Fiji Only for quantification of total bioturbated surface	Good estimation in a very rapid way Facilitates differentiation between specimens

Table 4.1. Summary of strengths and weaknesses of each methodology depending on the purpose.

In terms of enhanced trace fossil visualization —facilitating trace fossil differentiation and therefore ichnotaxonomical classification— the three methods provide good results for high contrast images (Fig. 4.4). Results for mid and low contrast examples show some differences depending on the applied method, with better results after applying high-resolution image treatment and Fiji (CLAHE), and weaker visualization after adaptive histogram by ICY. Given the rapid processing of Fiji, this option may be seen as an alternative to the time-consuming high-resolution image treatment. This approach is especially promising for preliminary analyses, since the outstanding results on cores (Fig. 4.6) may be helpful when selecting the most appropriate core segments during the initial stages of a research study. In sum, the Fiji quick treatment facilitates decision-making in studies involving a great number of cores or outcrop samples. More detailed analysis can be conducted later through the application of high-resolution image treatment. Furthermore, whereas Fiji and ICY work with black and white binary images, the fact that high-resolution image treatment allows one to apply different colors according to the pixel values makes ichnotaxonomical classification easier.

All the applied methods quantify the abundance of bioturbation exclusively to discrete trace fossils (having differentiated outlines and characteristic shapes), without any evaluation of the biodeformational structures or bioturbated texture (undifferentiated outlines with no definitive geometry, a mottled background). However, after characterization of the presence/absence of a mottled background, quantification of the bioturbated surface corresponding to discrete trace fossils is indeed of interest, bearing a relationship with palaeoenviromental conditions.

The overall comparison of the different methodologies tested indicates that all of them provide good results for high contrast examples, ranging from 9% to 16% of bioturbated surface (Fig. 4.5), which belong to a low degree of bioturbation (BI = 2) (Fig. 4.5). Results are similar for medium contrast images (10%–20%), belonging to the same bioturbation index (BI = 2). At the opposite end, application on low contrast images shows very substantial differences, from 19% to 47%, though most values are around 20% (the exception being SPSM + RefineEdge). Accordingly, and taking into account that CRSM underestimates the amount of bioturbation, as some trace fossil pixels are not selected, the most successful selection tool would be Magic Wand Method (+ RefineEdge), providing very realistic results in all the studied examples. Since MWM is time-consuming, especially when working with small trace fossils (Dorador et al., 2014b), Fiji stands as an attractive alternative for low contrast samples, and ICY (+ Fiji) for medium contrast ones. For precise results both programs (Fiji and ICY) require complex filtering; however, the results of initial automatic estimation without filters are not very different from the final values (Fig. 4.1, Fig. 4.2), meaning they lend themselves to rapid initial appraisals. Finally, in high contrast images, any method can be applied—all three offer realistic results about the bioturbated surface corresponding to discrete trace fossils. Again, an important advantage of any high-resolution image treatment over Fiji and ICY resides in the possibility to estimate the percentage of area occupied for each ichnotaxon, the whole icnocoenosis, or the complete ichnofabric (Rodríguez-Tovar and Dorador, 2015). Fiji and ICY only allow for quantification of the whole bioturbated surface as they work with binary images.

In terms of penetration depth, good results were obtained for the core examples after either method, quantitative pixel analysis in the case of high-resolution image treatment or the intensity values in the case of IP-ICY. Still, the most appropriate procedure might be selected in light of the particular contrast of the images at hand. When dealing with a higher contrast image, both methods show similar values for penetration, supporting the obtained values; but the record of two intensity value packages with IP-ICY might indicate two different communities of *Thalassinoides* tracemaker, which could have paleoecological implications. For the low contrast core section, the scarce differentiation between the values associated with the fill of trace fossils and those from the host sediment in the IP-ICY analyses would impede a precise estimation, which can be obtained with the quantitative pixel analysis. Nonetheless, as in the previous case, data from IP-ICY allow discernment between two different communities of *Thalassinoides* tracemaker coming from two distinct horizons of colonization. Although both methods are valuable for estimating penetration depth, the semi-automatic character of IP-ICY favors faster calculation. In short, IP-ICY is a promising tool for characterizing the penetration depth of some trace fossils in a very rapid and intuitive way, especially for high contrast images, facilitating even the differentiation between distinct horizons of colonization. In any case, this approach must be supported by a precise ichnological analysis to avoid misinterpretation of the obtained pixel values, as those determined by reworking of biogenic structures (e.g., *Thalassinoides* reworked by other traces as *Chondrites*).

4.4.1. The applied techniques: consequences for paleoenvironmental research

Conducted research supports the usefulness of the image processing techniques evaluated here when characterizing particular ichnological features: ichnodiversity, quantification of bioturbation, and penetration depth. All these features are of major interest in any ichnological study, and especially under the ichnofabric approach (McIlroy, 2004; Buatois and Mángano, 2011; Ekdale et al., 2012) and the ichnofacies model (Buatois and Mángano, 2011; MacEachern et al., 2012). Both these paradigms in ichnological analysis have become consolidated as significant proxies to interpret sedimentary environments (Knaust and Bromley, 2012), based on the characterization of ecological and depositional conditions.

The ichnofabric approach has been successfully used as a tool in a range of Earth Science disciplines, but particularly for paleoenvironmental research and sedimentary basin analysis, and recently for reservoir characterization (McIlroy, 2004; Buatois and Mángano, 2011; Ekdale et al., 2012). Detailed ichnofabric analysis calls for integrating ichnofabric attributes, including ichnotaxa diversity, ichnological features (i.e., dimensions of ichnotaxa), amount of bioturbation, cross-cutting relationships, and/or tiering structures (Taylor et al., 2003). Such ichnofabric attributes are controlled by depositional and ecological conditions: grain size, nature of substrate, oxygenation, nutrient levels, salinity, and sedimentation rate, among others, determined by particular depositional processes (Taylor et al., 2003). On this basis, the applied image processing techniques would facilitate ichnofabric characterization, hence environmental interpretations.

Because the ichnofacies model looks into groups of trace fossils that reflect animal responses (ethology) to paleoenvironmental conditions (Buatois and Mángano, 2011; MacEachern et al., 2012), a detailed ichnofacies characterization proves essential for paleoenvironmental analysis and sedimentary basin research. Means of improving ichnotaxonomic analysis is important not only for the recognition and differentiation of ichnofacies; it becomes fundamental when working with cores from modern marine sediments showing a comparatively weak differentiation of discrete trace fossils.

Therefore, we strive to demonstrate the utility of the applied methods in the case of modern marine sediments that are mainly retrieved from deep-marine settings (Dorador et al., 2014a, Dorador et al., 2014b; Rodríguez-Tovar and Dorador, 2015) and ichnofacies (Dorador and Tovar, 2015). Depositional processes (i.e., pelagic, gravitational and bottom-current) determining variations in environmental conditions (i.e., organic matter deposition, oxygenation of the pore water, etc.) can be approached through deep-sea ichnological research (Wetzel, 2010; Uchman and Wetzel, 2011; Wetzel and Uchman, 2012), and facilitated by novel applications.

Image processing techniques should therefore be considered as an essential tool for sedimentary basin research, supported by ichnological information, and not only when working with marine cores from modern deposits, but also based on outcrop studies.

4.5. Conclusions

The usefulness of Fiji and ICY methods for ichnological studies has been tested and compared with high-resolution image treatment. Concretely, their efficiency in the enhancing of trace fossils visibility, quantification of the bioturbation and estimation of penetration depth were tested.

High-resolution image treatment (+ RefineEdge) is revealed as the best option to increase visibility of trace fossils. However, Fiji (CLAHE) proved to be a rapid alternative for preliminary analysis of cores when selecting the most appropriate segments in the initial stages of research.

Regarding the quantification of the bioturbation, the Magic Wand Method (+ RefineEdge) provides good results regardless of image contrast, allowing for quantification of the area occupied by each ichnotaxon, the whole icnocoenosis, or the complete ichnofabric. Notwithstanding, Fiji and ICY (+ Fiji) stand as faster alternatives to quantify the whole of the bioturbated surface, especially recommended in early research stages.

Quantitative pixel analysis and IP-ICY are useful for estimating penetration depth, but the semi-automatic character of IP-ICY favors speedy calculation.

Therefore, use of the newly tested techniques (Fiji and ICY) is highly recommended during early stages of research as an initial approach or to filter the adequate representative samples. The great potential of these techniques should be further explored in the realms of ichnological analysis, and particularly for sedimentary basin research, as ichnological information reported thus far is well supported and quite promising.

Acknowledgements

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Supplementary Paper of

PART II

- Image processing techniques to improve characterization of composite ichnofabrics (Ichnos, 2020)

ICHNOS
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Image processing techniques to improve characterization of composite ichnofabrics

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ABSTRACT

Image processing techniques, including the *Analyze Particles* tool offered by Fiji software and the *Intensity Profile* by ICY (IP-ICY), were applied in core and outcrop examples to improve characterization of autocomposite ichnofabrics. *Analyze Particles* gives information about particle shape and size in the studied image. This tool was applied to *Chondrites* assemblages in composite ichnofabrics in view of selected images of modern marine hemipelagic cores from Site U1385 of IODP Expedition 339. Differences in size, relative abundance, density and distribution of *Chondrites* were interpreted as related to variations within the population of *Chondrites* tracemakers. *Intensity Profile* quantifies pixel values of the infilling material of traces, proving helpful to discriminate between specimens, evaluate the horizon of colonization, and approach the penetration depth. Its application to the analysis of *Zoophycos* improves characterization of composite ichnofabrics from deep-sea pelagic calcilutites of the Petra Tou Romiou section (Eocene Lefkara Formation; southern Cyprus). Some suites of *Zoophycos* were interpreted as associated with different phases of colonization from several horizons. Moreover, it was possible to discriminate structures pertaining to different specimens, as opposed to those from the same specimen.

PART III

ICHNOLOGICAL CHARACTERIZATION OF CALCAREOUS CONTOURITES

Chapter 5

ICHNOFACIES DISTRIBUTION IN THE EOCENE-EARLY MIOCENE PETRA TOU ROMIOU OUTCROP, CYPRUS: SEA LEVEL DYNAMICS AND PALAEOENVIRONMENTAL IMPLICATIONS IN A CONTOURITE ENVIRONMENT

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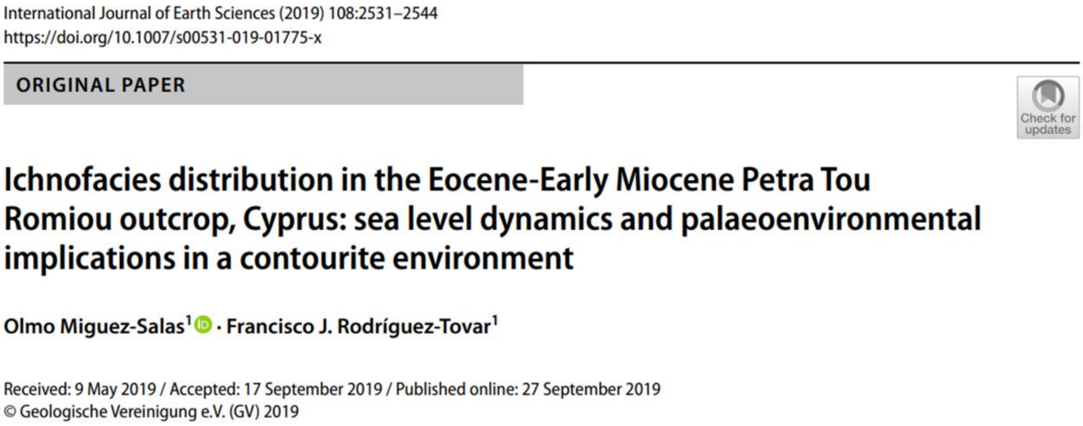

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ORIGINAL PAPER

Ichnofacies distribution in the Eocene-Early Miocene Petra Tou Romiou outcrop, Cyprus: sea level dynamics and palaeoenvironmental implications in a contourite environment

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ABSTRACT

Ichnological analysis of the carbonate contourite drift at the Petra Tou Romiou outcrop (southern Cyprus) reveals a relationship between sea level dynamics, shoreline position, sedimentation rate, flow hydrodynamics and trace fossil assemblages. The base of the outcrop is composed of chalky deposits showing the *Zoophycos* ichnofacies attributes. The transition to the first contouritic interval beds is marked by the gradual disappearance of *Zoophycos* and dominance of horizontal traces. This change is caused by a gradual sea level fall determining an increase in proximity and energy conditions in the environment that favoured the development of distal *Cruziana* ichnofacies. Upper contouritic interval beds contain abundant burrow systems with vertical components. Increased ichnodiversity, particularly among vertical morphologies, coincides with the appearance of *Teichichnus*, *Gyrolithes* and rare *Ophiomorpha*, revealing a transition to the proximal *Cruziana* ichnofacies, related with the maintenance of the previous trend toward more proximal and higher energy settings. The differentiated ichnofacies in the Petra Tou Roumiou carbonate drifts are controlled by complex interactions between variable environmental factors with sea level dynamics playing a major role.

Keywords: Ichnology, Contourites, Carbonate drift, *Cruziana* ichnofacies, *Zoophycos* ichnofacies, Sea level dynamics, Cyprus

5.1. Introduction

Trace fossil analysis has emerged during the past decades as a powerful indicator of palaeoenvironmental evolution and associated changes, becoming a pivotal element which supports sedimentological and stratigraphic interpretations, hence being key in sedimentary basin research (Knaust and Bromley 2012). The strength of ichnological studies resides in the relationship between trace fossils and palaeoenvironmental conditions: tracemaker behaviour records the response to biotic and abiotic factors (e.g. salinity, oxygen, nutrients, hydrodynamic energy, rate of sedimentation, and substrate, among others), offering invaluable information that cannot be obtained exclusively from stratigraphic and sedimentological analysis (Buatois and Mángano 2011). In light of new developments and paradigms in sedimentary basin research, changes in ichnofossil assemblages are studied to approach fluctuations in relative sea level, deepening and shallowing trends, genetically related sedimentary packages, and discontinuity surfaces of sequence stratigraphy significance. Ichnology holds heightened interest as well in sequence stratigraphy (allostratigraphy, genetic stratigraphy), especially given the role of the ichnofacies analysis (e.g. Frey and Howard 1990; Pemberton et al. 1992; Ghibaudo et al. 1996; Olóriz and Rodríguez-Tovar 2000; Malpas et al. 2005; MacEachern et al. 2007b, 2012b; Rodríguez-Tovar et al. 2007, 2010; Rodríguez-Tovar and Pérez-Valera 2008; Buatois and Mángano 2011).

Ichnofacies are characterized by recurring ethological groupings of trace fossils reflecting specific combinations of organism responses to environmental conditions (Seilacher 1967; MacEachern et al. 2007a, 2012a). The ichnofacies model has become a multidimensional framework. Marine ichnofacies may be seen as the logical first step in sedimentary basin analysis based on the relationship between ichnological features and ecological and depositional conditions, which are mainly related to the evolution from proximal to distal environments and changes in the relative sea level (MacEachern et al. 2007a, 2010, 2012a; Buatois and Mángano 2011). Ichnofacies depend on the interplay of numerous parameters (i.e. hydrodynamic energy, rate of sedimentation, substrate, oxygenation, food, among others) determining the behaviour and distribution of tracemakers. Integrating ichnological, stratigraphic, sedimentological and taphonomic information is essential for ichnofacies characterization, to refine interpretations based exclusively on individual approaches.

Deep-water bottom currents can build thick and extensive accumulations of sediments, known as contourite drifts (Rebesco et al. 2014). Carbonate drifts, corresponding to carbonate depositional environments, are extremely sensitive; they record palaeoenvironmental changes at a higher resolution than in typical pelagic areas where sedimentation mainly occurs as ooze rain (e.g. Lauridsen et al. 2011; Rasmussen and Surlyk 2012; Savrda 2012; Rebesco et al. 2014; Reolid and Betzler 2019). However, the recognition of dominant palaeoenvironmental conditions is often difficult due to variable interaction of processes taking place in complex deep marine setting, including pelagic, gravitational and bottom-current phenomena. On a small scale, the contourite facies model comprises a coarsening-up/fining-up cycle that defines the standard bi-gradational sequence (Rebesco et al. 2014), with certain variations in the ichnological features (e.g. Hüneke and Stow 2008; Stow and Faugères 2008; Rodríguez-Tovar and Hernández-Molina 2018). On this basis, ichnological information is acknowledged as a useful proxy to characterize contourites and differentiate them from associated facies (i.e. turbidites, debrites, mixed sediments), but at present, detailed ichnological analyses are scarce (Wetzel et al. 2008; Rodríguez-Tovar and Hernández-Molina 2018; Miguez-Salas and Rodríguez-Tovar 2019; Rodríguez-Tovar et al. 2019a, b). At the outcrop scale, ichnological features such as the intensity of bioturbation, ichnodiversity, or size and type of burrows can be applied to interpret palaeoenvironmental parameters during contourite deposition (Rodríguez-Tovar and Hernández-Molina 2018 and references therein).

Continental margin sedimentation has been commonly described as a mixture of gravitational currents, overflows and deep-water bottom currents (Sansom 2018). This statement is true at the Petra Tou Romiou outcrop (southern Cyprus), featuring a mixed/hybrid sedimentary system where dominant contourite deposition coexists along with pelagic sedimentation and punctual turbiditic events (Stow et al. 2002; Rodríguez-Tovar et al. 2019a, b; Hüneke et al. 2019). Yet discrimination of the influencing depositional processes is a difficult matter. In this context, we present a study of the vertical change of the trace fossil assemblage and ichnofacies characterization at the Petra Tou Romiou outcrop, one of the most complete carbonate contourite drift successions on land to address palaeoenvironmental changes in an affected bottom-current setting.

5.2. Geological setting

Cyprus lies in a complex tectonic area at the easternmost part of the Mediterranean Sea (Fig. 5.1a). Subduction between the African—Eurasian plates and associated tectonic structures has largely controlled the Circum Troodos sedimentary successions that surround the Troodos Massif (Kinnaird 2008; Edwards et al. 2010). Two essential constituents of the Circum Troodos sedimentary succession are the Lefkara and Pakhna formations (Edwards et al. 2010), both of them deposited in a deep-water Eocene-Middle Miocene palaeoslope system (Kähler and Stow 1998; Hüneke et al. 2019). The Lefkara Formation is primarily formed by pelagic or hemipelagic chalky sediment accumulation, with a significant influence of bottom currents and punctual distal turbiditic episodes (Kähler and Stow 1998; Stow et al. 2002; Miguez-Salas and Rodríguez-Tovar 2019; Hüneke et al. 2019). The Pakhna Formation was deposited during the early to late Miocene and shows an upwardly increased input of shallow water bioclastic and siliciclastic components supplied by gravitational processes (Lord et al. 2009; Rodríguez-Tovar et al. 2019c; Hüneke et al. 2019). Within the Pakhna

Formation, significant bottom currents originated calcilutitic and calcarenitic bioclastic contourites of different thicknesses (Hernández-Molina et al. 2018). The intensity of the bottom-current flows that affected the southern Cyprus paleoslope was essentially controlled by the Indian Gateway depth (see de la Vara and Meijer 2016).

The Petra Tou Romiou outcrop is located in the southern part of Cyprus, 30 km west of Limassol and near Aphrodite's Rock (Fig. 5.1b). The outcrop is constituted by a 150-m-thick carbonate-dominated succession that records the middle-upper Lefkara Formation and the Pakhna Formation (Fig. 5.2) (Hüneke et al. 2019). Based on a bed-scale analysis of sedimentary and carbonate microfacies, nine facies distributed in sections A–D (Fig. 5.1b) from the Lefkara and Pakhna formations could be differentiated (Hüneke et al. 2019). Thus, the Lefkara Formation consists of chalky calcilutites, marls, individual thin calcarenite beds and chert layers, including the beach section (PTb) of Miguez-Salas and Rodríguez-Tovar (2019) and section A of Hüneke et al. (2019), while the Pakhna Formation, made up of chalky calcilutites and thick calcarenite beds, corresponds to sections B and C of Hüneke et al. (2019) (Figs. 5.1, 5.2). A poorly exposed 15-m-thick marl interval separates the two formations with an indistinct unconformity (Fig. 5.2) (Hüneke et al. 2019).

Previous studies on trace fossils in the Lefkara and Pakhna formations are scarce. Eaton and Robertson (1993) indicated the presence of *Chondrites*, *Planolites*, *Teichichnus*, *Thalassinoides*, and *Zoophycos* in the Pakhna Formation, but without precise ichnological information. Only recently detailed ichnological analyses have been conducted in the chalky pelagic sediments from the Lefkara Formation at the lower part of the Petra Tou Romiou outcrop (PTb section; Fig. 5.1b) (Miguez-Salas and Rodríguez-Tovar, 2019), in the type contouritic bi-gradational sequence at the middle part of the Petra Tou Romiou outcrop (Rodríguez-Tovar et al. 2019a), and in the turbiditic beds from the Pakhna Formation in the Agios Konstantinos section (Rodríguez-Tovar et al. 2019c). The analysis by Miguez-Salas and Rodríguez-Tovar (2019) in section PTb showed the typical *Zoophycos* ichnofacies with *Chondrites* isp. (including *C. intricatus* and *C. targionii*), *Planolites* isp., *Thalassinoides* isp., *Taenidium* isp., and *Zoophycos* isp.

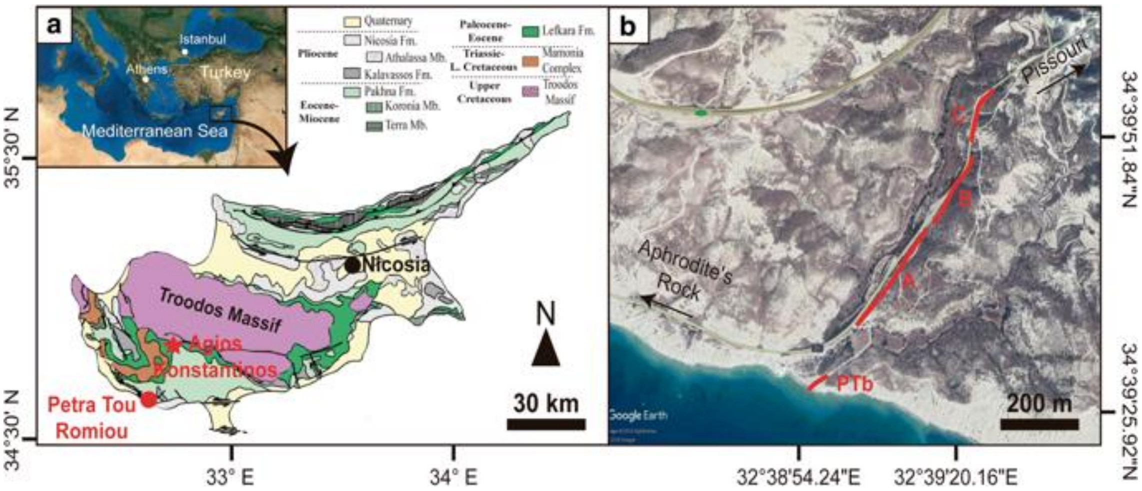

Fig. 5.1. a Location of Cyprus in the eastern Mediterranean Sea with geological map of Cyprus (Petra Tou Romiou outcrop, red dot; modified from Kinnaird 2008). **b** Geographical location of the Petra Tou Romiou outcrop with schematic allocation of each section along B6 road to Pissouri village (PTb Petra Tou Romiou beach section).

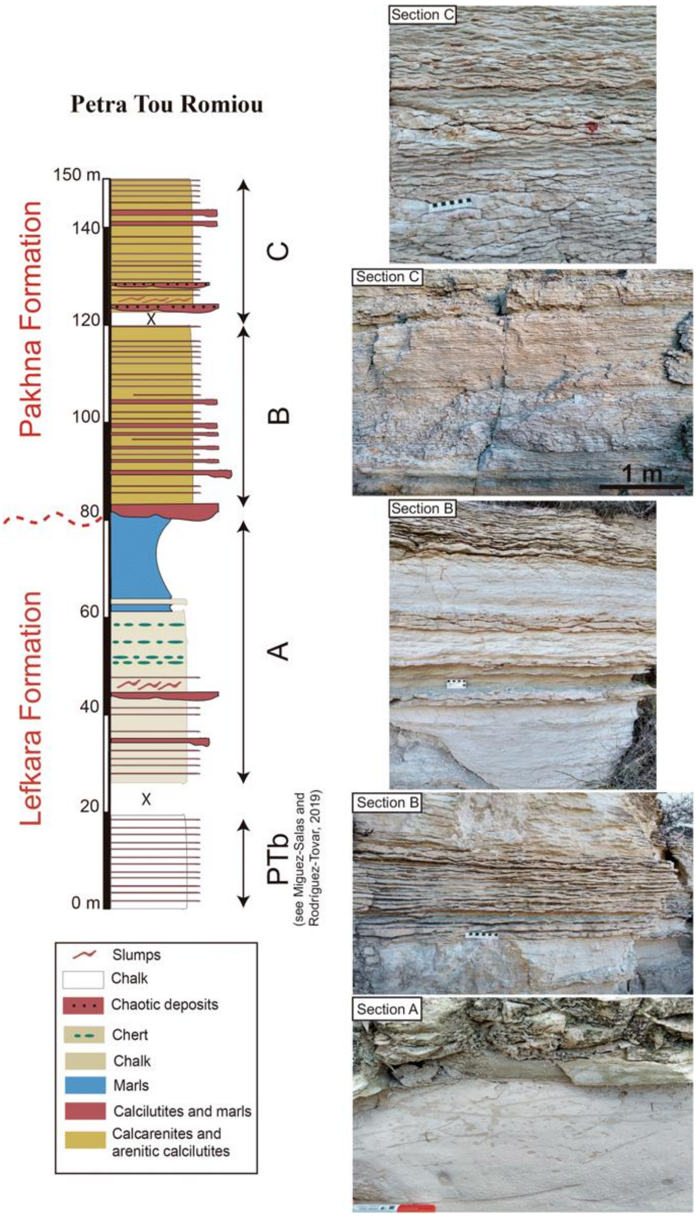

Fig. 5.2. Schematic stratigraphic column of Petra Tou Romiou outcrop (modified from Hüneke et al. 2019). PTb Petra Tou Romiou beach section in Miguez-Salas and Rodríguez-Tovar (2019).

5.3. Methods

Ichnological research has been conducted in sections A–C of Hüneke et al. (2019) of the Petra Tou Romiou outcrop, pertaining to the middle-upper Lefkara Formation and the Pakhna Formation, characterized by the presence of pelagic, contouritic, turbiditic and mixed sediments (Figs. 5.1, 5.2). The trace fossils were systematically studied bed-by-bed, paying special attention to their distribution and abundance along the outcrop, and their relationship with the differentiated facies. Morphological ichnological features were studied at the outcrop for a detailed ichnotaxonomical assignation, with special attention to ichnotaxobases (Bertling et al. 2006; e.g. orientation, configuration, shape). Trace fossils were meticulously photographed. Some specimens were collected for ichnological analysis at the laboratory, mainly focusing on the study of internal features and infilling material. The collected specimens are housed in the

Departamento de Estratigrafía y Paleontología at the Universidad de Granada, Spain (labelled PT).

5.4. Ichnological analysis

5.4.1. Trace fossil assemblage

The trace fossil assemblage is poorly diversified, consisting of seven ichnotaxa, most of them differentiated at the ichnogenus level, together with undifferentiated vertical structures (Figs. 5.3, 5.4). In general, at the outcrop, *Chondrites*, *Planolites* and *Thalassinoides* are abundant, *Zoophycos* common, and *Gyrolithes*, *Ophiomorpha* and *Teichichnus* are rare. Most of the specimens are observed in vertical cross-section, though epireliefs and hyporelief are also quite common. In addition, some traces are preserved as full reliefs.

Chondrites isp. is observed in variably oriented vertical cross-sections as oval or circular spots, bedding-plane views being less common. Branches are difficult to discern. Two morphological types of *Chondrites* are recognized: large *Chondrites*, ca. 2–5 mm-wide burrow, and small *Chondrites*, 1–2 mm-wide burrow. The smaller forms could correspond to *Chondrites intricatus* (Brongniart 1823) and the larger forms to *Chondrites targionii* (Brongniart 1828) (Uchman 1998; Uchman et al. 2012). Locally, *Chondrites* occurs in high densities and occasionally cross-cutting other traces (Fig. 5.4a, b). *Chondrites* is traditionally interpreted as a deposit-feeding structure (fodinichnion) constructed by an endobenthic, vermiform animal of unknown taxonomic affinity (Bromley and Ekdale 1984), yet other interpretations—as a chemichnion or as a cache structure—have been also proposed (Bromley 1996). *Chondrites* is recorded in a wide range of marine settings, whereas the tracemaker is considered to be a low-oxygen tolerance organism (Bromley and Ekdale 1984).

Gyrolithes isp. consists of unbranched helicoidal burrows, passively infilled, surrounded by dextral, sinistral or reversing coils, which are not in contact (Fig. 5.4g, h). No diagenetic halo is observed. Burrows are circular to oblate in vertical cross-section. Whorl diameter ranges from 10 to 40 mm with an average of 25 mm. Height between whorls is less than 10 mm. More complete specimens show up to seven whorls, with a minimum of four. *Gyrolithes* is essentially a shallow-marine trace fossil (Laing et al. 2018), in cases related to salinity fluctuations (Netto et al. 2007; Wetzel et al. 2010). *Gyrolithes* has been assigned to various ethologies, including feeding, dwelling, and farming, probably produced by decapod crustaceans exploiting nutrient-rich localized areas of the substrate (Netto et al. 2007; Gingras et al. 2008; Wetzel et al. 2010; de Gibert et al. 2012; Uchman and Hanken 2013; Laing et al. 2018).

Ophiomorpha isp. appears as sub-horizontal and slightly curved cylindrical burrow segments up to 100 mm long and 10 mm in diameter (Fig. 5.4f). Peloids of agglutinated sediment that form the wall are oxidized. *Ophiomorpha* is interpreted as a dwelling structure (domichnion), commonly attributed to suspension- and/or deposit-feeding decapod crustaceans, which construct linings to limit the collapse of burrow in relatively unstable substrates (Frey et al. 1978; Pemberton et al. 1992; Uchman 2009). Although not exclusive, *Ophiomorpha* is typical of high-energy environments (Knaust 2017), and may be used to differentiate between sandy shoreline sedimentary environments (Pollard et al. 1993). In terms of sequence stratigraphy analysis, even *Ophiomorpha* is associated with different types of system tracts, it was interpreted to be more common in lowstand system tracts than in transgressive system tracts (Anderson and Droser 1998; Knaust 2017).

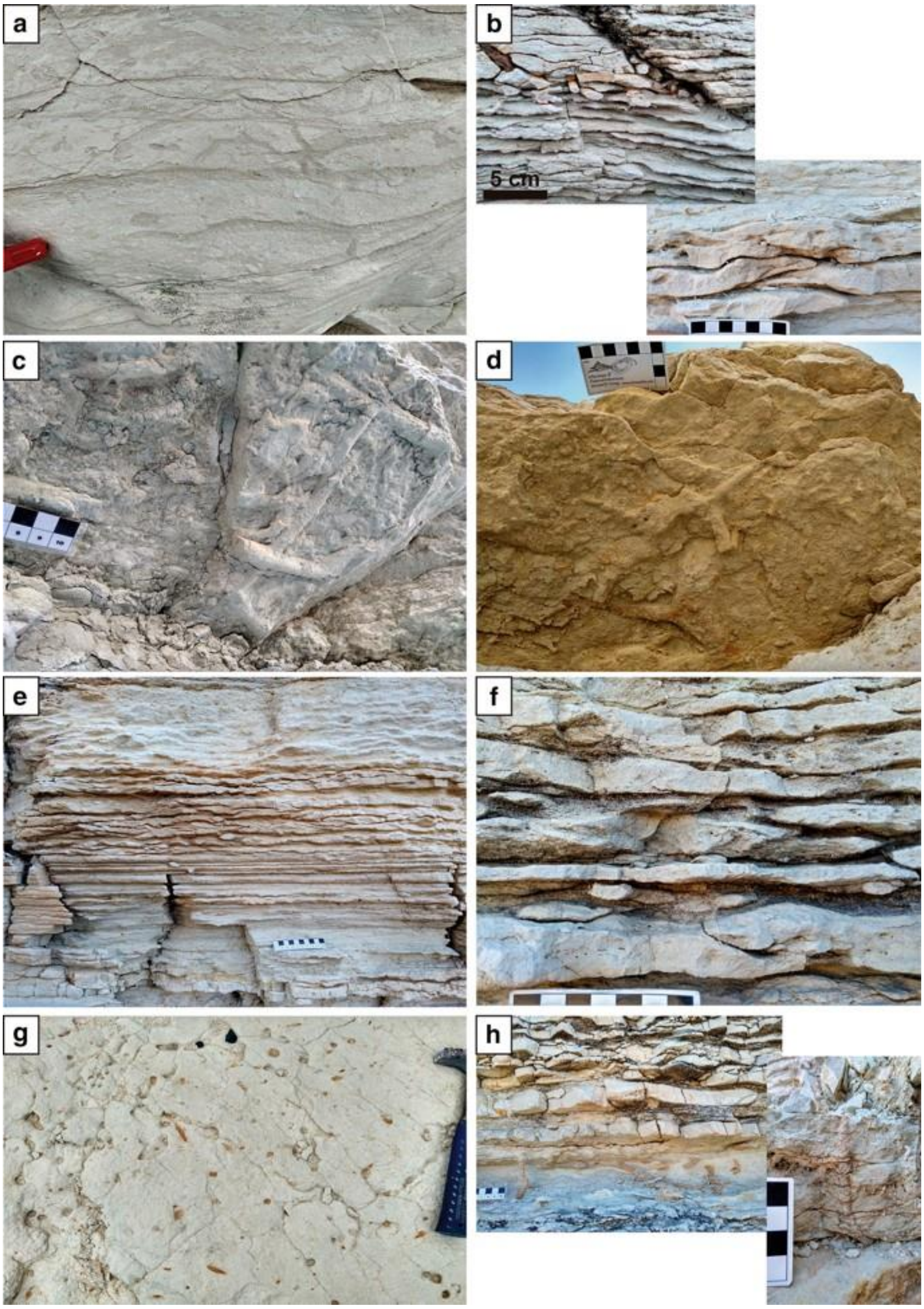

Fig. 5.3. a Interval I ichnoassembalge with *Chondrites*, *Planolites*, *Thalassinoides* and *Zoophycos*. **b–f** Close-up outcrop examples of the calcarenitic contourite facies (Interval II), showing *Planolites* isp. in the non-compacted layers and *Thalassinoides* isp. at the base of the beds (Y-shaped bifurcation). **g** Calcarenitic bed surface with profuse vertical burrowing (Interval III). **h** Vertical burrows penetrating from the calcarenitic to the calcilutitic intervals (Interval III).

Planolites isp. presents unlined, not branched, straight to tortuous, smooth to striated burrows with structureless fill that is lithologically different from the host sediment. Specimens that appear inside the non-compacted layers within the contouritic beds may record striae-walled burrows (Rodríguez-Tovar et al. 2019a; Fig. 5.3b, e, f). This feature is typical of *Planolites reinecki* (see Rodríguez-Tovar et al. 2019a for a recent example). Burrow diameter ranges from 2 to 10 mm, and length can reach 100 mm. The contrasting burrow fill was processed by the tracemaker which can include a wide range of organisms (Pemberton et al. 1992; Keighley and Pickerill 1995). *Planolites* is a ubiquitous trace fossil in marine and non-marine settings, being a common element of shallow-tier ichnofabrics (Rodríguez-Tovar and Uchman 2004, 2017, Rodríguez-Tovar et al. 2009; Knaust 2017).

Thalassinoides isp. consists of systems of branched, smooth, straight to slightly curved, unlined cylindrical burrows, shows both T-shaped and Y-shaped branches, resulting in horizontal networks (Figs. 5.3, 5.4). Diameter runs from 10 to 60 mm. T-shaped burrows record enlarged junctions up to ~ 50 mm wide (Fig. 5.4c). According to the dimensions, type of bifurcation and enlargement at the branching point, the specimens can be assigned to *T. suevicus* Rieth and *T. paradoxicus* Woodward (see Rodríguez-Tovar et al. 2017 for a recent review). *Thalassinoides* is a facies-crossing form, occurring in a great variety of marine environments, but commonly found in shallow-marine oxygenated environments (Bromley 1996; Monaco et al. 2007; Rodríguez-Tovar et al. 2008; Buatois and Mángano 2011). This ichnogenus is attributed to dwelling and feeding activities of decapod crustaceans, mainly deposit feeding (Frey et al. 1984), although filter feeding is also plausible (Rodríguez-Tovar et al. 2017).

Teichichnus isp. presents vertical stacks of horizontal to subhorizontal tubes forming straight retrusive spreiten (Fig. 5.4i). Burrow diameters and spreite heights range from 10 to 20 mm and from 20 to 50 mm, respectively. The morphological features allow a plausible assignation to *Teichichnus rectus*. *Teichichnus* is interpreted as a deposit-feeding structure (fodinichnion) constructed by a worm-like organism (Howard and Frey 1984; Pemberton et al. 1992). The spreite forms in response to upward migration of the causative burrow and may reflect, at least partly, an equilibrium response of the tracemaker (Knaust 2017, 2018). *Teichichnus* occurs in a variety of environments, being a characteristic element of estuarine, lagoon and lower shoreface to offshore (shelf) deposits (Pemberton et al. 2012; Knaust 2017).

Zoophycos isp. is visible as horizontal to subhorizontal, planar and helical spreite structures, and marginal tubes are diffuse (Fig. 5.3a). The marginal tube is from 10 to 40 mm wide. *Zoophycos* is a complex trace fossil of a sediment deposit-feeder and has been broadly interpreted as a strip mine, refuse dump, cache or cesspit structure, produced by marine worm organisms, possibly sipunculids, echiurids and/or polychaetes (e.g. Kotake 1989; Bromley 1991; Löwemark 2012, 2015; Zhang et al. 2015; Dorador et al. 2016; Monaco et al. 2017).

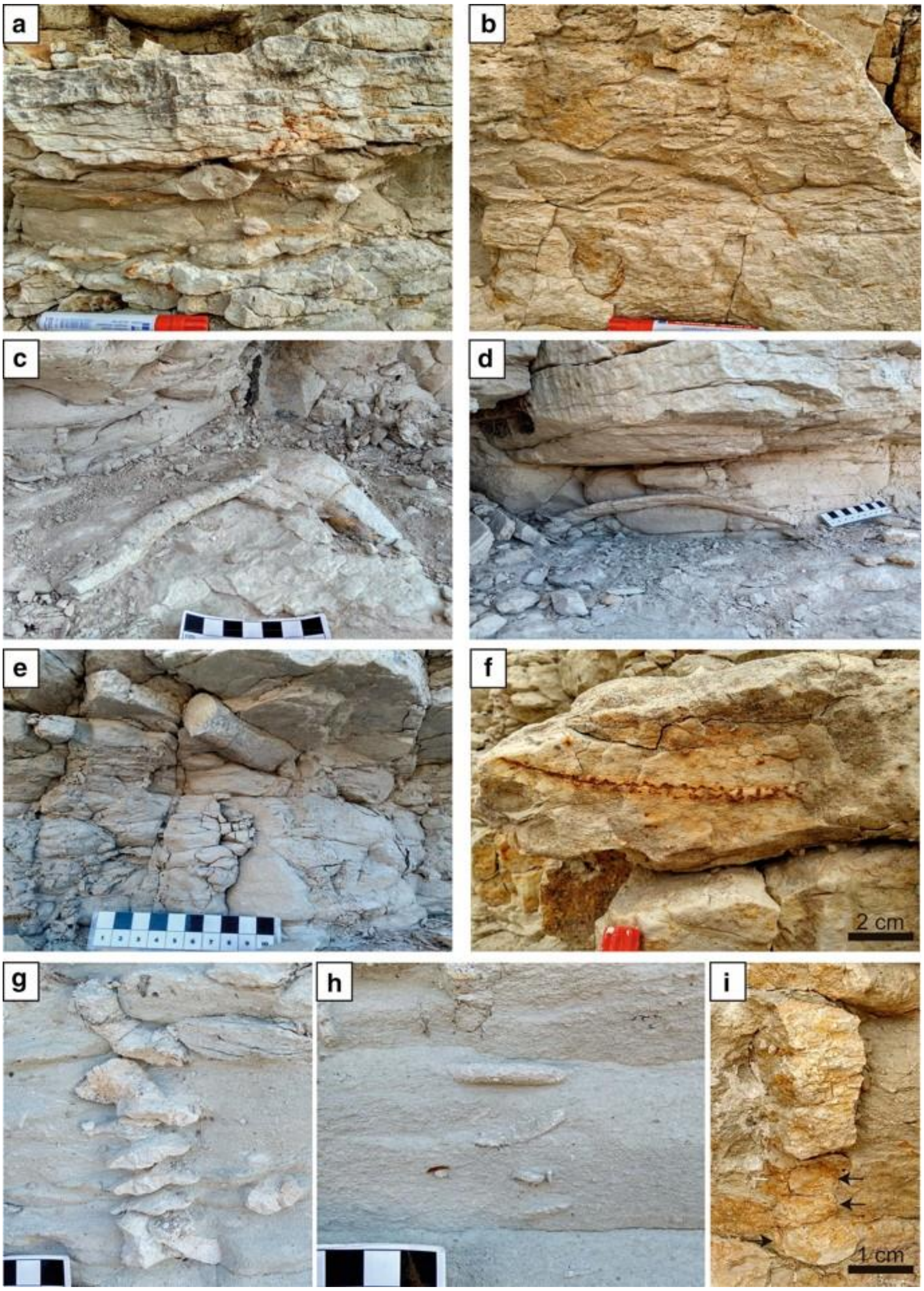

Fig. 5.4. Outcrop examples of the carbonate contourite facies (Interval IV). **a**, **b** Calcarenitic and calcilutitic successions with *Chondrites*, *Planolites* and *Thalassinoides*. Note the increase in size with respect to the previous intervals. **c–e** *Thalassinoides* specimens with different morphologies and T-shaped bifurcation. **f** *Ophiomorpha* isp. **g, h** *Gyrolithes* isp. **i** *Teichichnus* isp

Apart from these differentiated ichnotaxa, vertical passively filled burrows penetrating from calcarenitic beds can be observed (Fig. 5.3g, h). The surfaces are smooth and usually ferrugenized, and occasionally simple down-orientated branching is recognized.

Ichnotaxonomical assignation is difficult, since in most cases, only vertical tubes are seen without any particular ichnotaxobase.

5.4.2. Distribution of ichnological features

Trace fossil composition, their diversity, size and abundance fluctuate significantly throughout the outcrop (Fig. 5.5). The diversity is low/moderate (four ichnotaxa), except for the upper part of section C of Hüneke et al. (2019) which contain seven ichnotaxa. In the highly bioturbated chalk (section A of Hüneke et al. 2019), the presence of a mottled texture evidences intense activity of tracemakers in soupgrounds to softgrounds, determining biodeformational structures with indistinct outlines, though some ichnotaxa can be clearly distinguished as *Chondrites*, *Planolites* and *Zoophycos*. *Chondrites*, and *Planolites*, and less frequently *Thalassinoides*, moreover, vertical traces can be found more or less continuously throughout the outcrop, representing the permanent background ichnoassemblage. *Thalassinoides* and vertical traces are more abundant toward the top of the outcrop. *Zoophycos* occurs discontinuously, being mainly located in the lower part of the outcrop, at section A. In contrast, *Teichichnus*, *Gyrolithes* and *Ophiomorpha* are registered exclusively in the upper part (section C). According to stratigraphic variations in the ichnological features, four main intervals can be established, partly correlating with the facies distribution at sections A–C of Hüneke et al. (2019) (Figs. 5.2, 5.5).

Interval I, in the lower part of the outcrop, corresponds to the hemipelagic chalk calcilutites with intercalated green chert levels (section A of Hüneke et al. 2019) (Fig. 5.2). This interval shows a low/moderate diversity, with *Chondrites*, *Planolites*, *Thalassinoides* and *Zoophycos*, together with the discontinuous record of the vertical structures. This interval records the highest abundance in discrete trace fossils, including discrete trace fossils and biodeformational structures. Deposit feeder behaviour dominates.

Interval II is discerned in the middle part of the outcrop and corresponds to different scale sandy contourite successions and calcilutites (section B of Hüneke et al. 2019) (Fig. 5.2). Interval II is characterized by a decrease in trace fossil diversity and abundance, its main highlights being the gradual disappearance of *Zoophycos*. *Planolites* is located in the non-compacted layers of the calcarenitic contourite beds (Fig. 5.3f). *Thalassinoides* can appear in the non-compacted layers, but also cutting successive calcarenitic beds. The calcilutitic deposits that constitute the fine fraction of the bi-gradational sequences present an abundance of *Chondrites*, *Planolites*, *Thalassinoides* and a more or less continuous record of vertical trace fossils. Deposit feeder behaviour dominates.

Interval III corresponds to the upper part of section B and the lower part of section C of Hüneke et al. (2019). It refers to thicker calcilutitic deposits, which contain *Chondrites*, *Planolites*, and *Thalassinoides*. This interval shows a significant increase in the abundance of vertical trace fossils (Fig. 5.3g, h). As previously, deposit feeder behaviour dominates.

Interval IV corresponds to the upper part of the outcrop (upper part of section C of Hüneke et al. 2019), and records different scale sandy contourite successions and calcilutites, as in Interval II but with thicker calcarenitic deposits (Fig. 5.2). This interval is characterized by a major increase in diversity and abundance. Besides the previous background assemblage, *Teichichnus*, *Gyrolithes* and *Ophiomorpha* occur, determining a dominance of vertical burrow components. Moreover, Interval IV records larger specimens: among the *Thalassinoides*; diameters of over 30 mm are common. Trophic behaviour comprises filter and deposit feeding strategies.

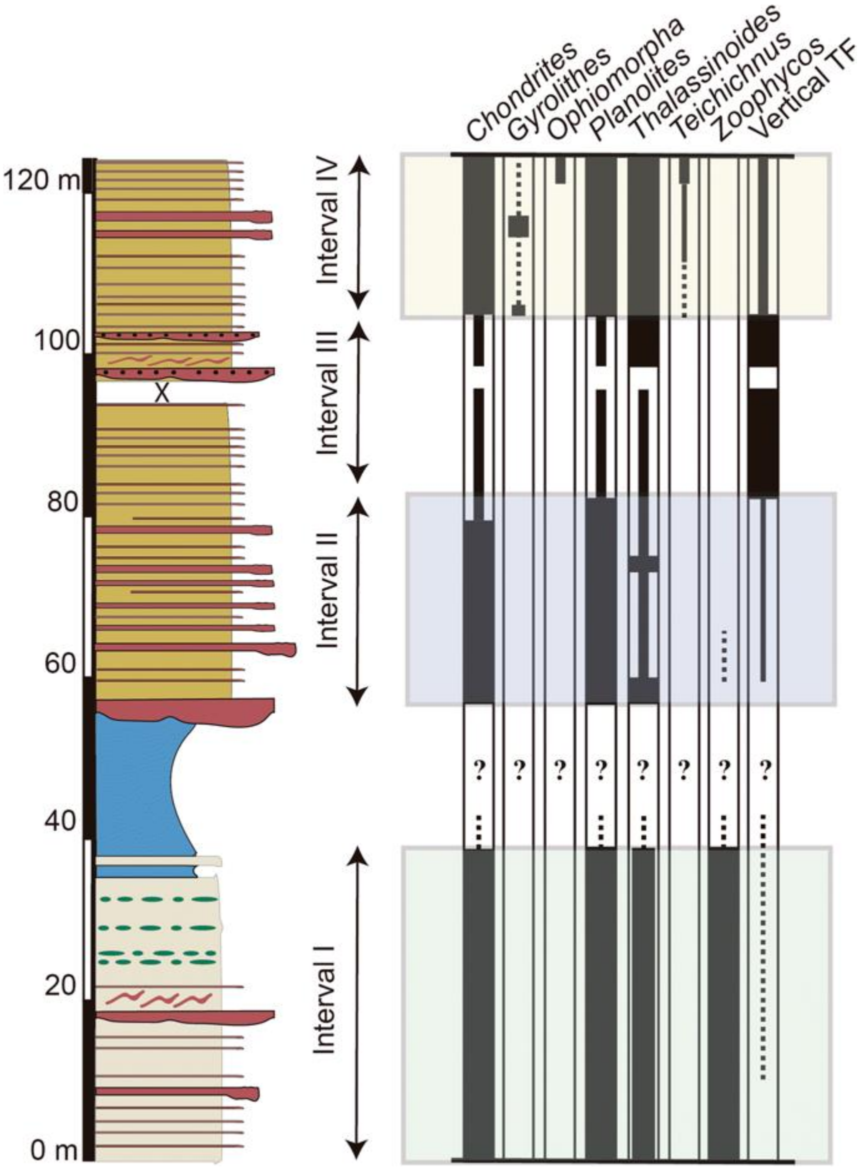

Fig. 5.5. Vertical abundance distribution of trace fossils in Petra Tou Romiou outcrop. Continuous lines and rectangles sizes for more or less abundant and continuous record. Legend as in Fig. 5.2

5.5. Discussion

5.5.1. Ichnofacies at the Petra Tou Romiou outcrop: the record of sea level evolution

Ichnofacies stands as a most useful ichnological tool for sedimentary basin research. The five archetypal sotfground marine ichnofacies of *Psilonichnus, Skolithos, Cruziana, Zoophycos* and *Nereites* clearly reflect a proximal to distal distribution associated with the prevailing palaeoenvironmental conditions (Seilacher 1967; Frey and Pemberton 1987; MacEachern et al. 2012a).

From proximal to distal environments: *Psilonichnus* ichnofacies present permanent vertical to inclined dwelling burrows. They appear in mixed marine, quasi-marine and continental conditions, linked to intense variations in substrate types and energetic conditions (Frey and Pemberton 1987; MacEachern et al. 2007a). *Skolithos* ichnofacies record predominant vertical, cylindrical or U-shaped dwelling burrows of suspension feeders and passive predators. Spreiten and equilibrium burrows are also common. This ichnofacies is typical of high-energy sandy substrates in foreshore to middle shoreface settings (MacEachern et al. 2012a). *Cruziana* ichnofacies are dominated by horizontal traces with deposit and detritus-feeding strategies. This ichnofacies occurs from moderate- to low-energy sandy to silty substrates in lower shoreface to offshore settings (MacEachern et al. 2012a). *Zoophycos* ichnofacies present relatively simple–to-complex feeding structures with spreiten and deep-tier structures of deposit feeders or farmers. This ichnofacies is associated with low energy, abundant food supply and poor oxygenation, in slope to shelf domains (Buatois and Mángano 2011; Uchman and Wetzel 2012; Wetzel and Uchman 2012). The *Nereites* ichnofacies records a dominance of complex graphoglyptids produced by organisms that farm bacteria and trap microorganisms. This ichnofacies is related to low energy and food supply, good oxygenation, and periodic disruption by gravity flows in slope areas (Buatois and Mángano 2011; Wetzel and Uchman 2012).

The integration of ichnologic, sedimentological and stratigraphic data from the Petra Tou Romiou outcrop makes it possible to differentiate ichnofacies from bottom to top (Fig. 5.6) and derive interpretations regarding sea level variations and proximal–distal gradient changes. The base of the outcrop (Interval I) is characterized by low ichnodiversity and a high abundance of traces, the dominance of deposit feeder tracemakers, and complex feeding structures signaled by the presence of spreiten (e.g. *Zoophycos*). A multi-tiered assemblage is discerned, the uppermost tier characterized by highly bioturbated substrates determining its mottled background, the upper/middle tier mainly composed by *Planolites* and *Thalassinoides*, and the deep tier with *Zoophycos* and *Chondrites*. The continuous presence of *Zoophycos* in Interval I, locally as the dominant ichnotaxa, together with profuse bioturbation structures and regular low ichnodiversity of deposit feeder structures, allow assignation to the *Zoophycos* ichnofacies. A similar trace fossil assemblage and the corresponding *Zoophycos* ichnofacies could be recognized from the sediments registered below Interval I, corresponding to the PTb section (see Miguez-Salas and Rodríguez-Tovar 2019).

The Interval II is marked by some ichnological changes: (1) an increase in abundance of horizontal and inclined burrows linked to deposit feeder behaviour; (2) a more or less continuous record of vertical trace fossils; and iii) the gradual disappearance of previous *Zoophycos*. These ichnological features point to the distal *Cruziana* ichnofacies, mainly reflecting the transition between the *Zoophycos* ichnofacies and the archetypal *Cruziana* ichnofacies (MacEachern et al. 2007a, 2012a; Buatois and Mángano 2011). This shift could express a progressive and continuous transition to proximal and shallower depositional settings. Such an interpretation would agree with the facies changes entailing diminution of the pelagic/hemipelagic components and increased calcarenitic facies (Hüneke et al. 2019).

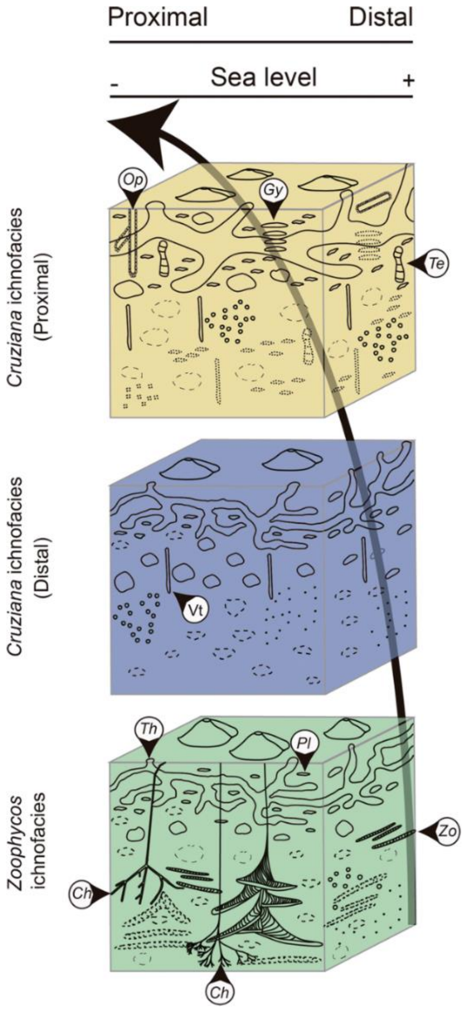

Fig. 5.6. Schematic ichnofacies evolution proposed for the carbonate contourite drift in the Petra Tou Romiou outcrop and relationship with sea level dynamics and proximal–distal gradient. Note: *Gyrolithes* (*Gy*), *Ophiomorpha* (*Op*), *Teichichnus* (*Te*), *Chondrites* (*Ch*), *Planolites* (*Pl*), *Thalassinoides* (*Th*), Vertical trace fossils (Vt) and *Zoophycos* (*Zo*).

Interval III largely maintains the trace fossil assemblage observed in Interval II, but with an increase in abundance of vertical structures. According to this minor change, the transition between the distal and the archetypal *Cruziana* ichnofacies can be interpreted in comparable environmental conditions.

Interval IV reveals the most significant ichnological changes, with a higher abundance of vertical burrow systems, including the appearance of new ichnotaxa as *Teichichnus*, *Gyrolithes* and *Ophiomorpha*, and a generalized increase in diversity and abundance of vertical structures. *Gyrolithes* is fundamentally a shallow-marine trace fossil (Laing et al. 2018) and, together with *Ophiomorpha*, it is common in the *Skolithos* ichnofacies (MacEachern et al. 2012a). Nevertheless, the frequent record of horizontal burrows (e.g. corresponding to *Planolites*) and the presence of *Chondrites* would discard the *Skolithos* ichofacies, favouring assignation to the proximal *Cruziana* ichnofacies. The proximal *Cruziana* ichnofacies is transitional between the archetypal *Cruziana* ichnofacies (basin-ward) and the *Skolithos* ichnofacies (landward); and although assemblages are dominated by deposit feeding structures, they contain more dwelling traces of suspension feeders and passive predators (MacEachern et al. 2007a; MacEachern and Bann 2008; Buatois and Mángano 2011). Thus, the change toward proximal and shallower depositional settings previously surmised is clearly evidenced in Interval IV. It is supported by the registered facies and sedimentary structures (e.g., cross lamination), characteristic of increased sandy intervals and thicker beds (Hüneke et al. 2019).

5.5.2. Depositional environment: influence of bottom currents

Bioturbation in carbonate drifts is the result of the complex interaction of diverse factors affecting the depositional environment (Wetzel et al. 2008). Nutrient availability and oxygenation are two of the most important ones, both closely dependent on the bottom-current hydraulic regime and sea level dynamics, in turn related to bottom-current processes (Rodríguez-Tovar and Hernández-Molina 2018). Petra Tou Romiou outcrop shows a carbonate-dominated succession formed by pelagic and hemipelagic sediment accumulation, temporarily influenced by weak bottom currents, and punctuated by distal turbidity flows (Stow et al. 2002; Hüneke et al. 2019). Thus, the tracemaker community in the studied setting would respond to the complex interactions between pelagic, gravitational, and bottom-current processes. In this context, environmental conditions such as hydrodynamic energy and sedimentation rate are of special significance. The record of a continuous moderately to highly bioturbated sediment in the studied outcrop points to generalized good sea floor oxygenation and nutrient availability for the macrobenthic tracemaker community. Previous studies report that along slope flow, bottom currents can input oxygen and amounts of fresh organic matter into deep marine environments (e.g. Thistle et al. 1985; Lucchi and Rebesco 2007;

Wetzel et al. 2008; Rebesco et al. 2014). The trace fossil assemblage along the Petra Tou Romiou outcrop corroborates these assumptions. Thus, further environmental factors tied to the changes in proximal–distal gradient and sea level dynamics would have affected the distribution of the different trace fossil assemblages.

Chalky interval I, where *Zoophycos* ichnofacies is developed, may be related with a continuous pelagic/hemipelagic sedimentation of conspicuous ooze rain, under low-energy conditions. Such depositional conditions favoured the establishment of a stable and abundant tracemaker community in pace with deposition. The generalized mottled texture can be related with soupgrounds to softgrounds. In view of this continuous pelagic/hemipelagic sedimentation, the local presence of sandy beds reveals punctual deposition of coarser material during highly energetic events (e.g. gravity and bottom-current processes; Miguez-Salas and Rodríguez-Tovar 2019). A similar interpretation is proposed for the underlying PTb section (Miguez-Salas and Rodríguez-Tovar 2019).

As mentioned above, the Petra Tou Romiou outcrop records an ichnofacies replacement, from *Zoophycos* ichnofacies (interval I) to *Cruziana* ichnofacies (intervals II–IV), a trend that suggests a drop in relative sea level determining a change toward proximal and shallower depositional settings. The *Cruziana* ichnofacies occurs from slightly above the fair-weather wave base up to the storm wave base, in a zone that goes from the lower shoreface to the lower offshore in wave dominated seas (Buatois and Mángano 2011). The abundant trace fossils in Interval III with vertical burrows that penetrate from the calcarenitic materials into the calcilutitic levels could tentatively indicate exhumed omission suites during minor erosions due to higher bottom-current flow velocity and following colonization by burrowers (MacEachern et al. 2007a). Interval IV is marked by thicker calcarenitic levels, together with the appearance of *Teichichnus*, *Gyrolithes* and rare *Ophiomorpha*. Trace fossils produced by predominant filter feeding organisms (e.g. *Gyrolithes* and *Ophiomorpha*) are absent in the calcarenite beds, reflecting comparatively worse conditions for colonization. The flow velocity and sedimentation rate were probably too high for these organisms, and suspension feeding would have been impaired, because the filter apparatus can easily be plugged by a high concentration of particles in suspension (Thistle et al. 1991). Instead, larger deposit feeders as those producing *Thalassinoides*, together with *Teichichnus*, are associated with the calcarenitic levels when the flow velocity is high. *Teichichnus* spreite structures may indicate an upward migration and, at least partly, equilibrium feedback of the tracemaker to an environment with considerable sedimentation rate (Knaust 2018).

5.6. Conclussions

Ichnological analysis of the carbonate contourite drift at the Petra Tou Romiou outcrop (Cyprus) reveals the ichnofacies replacement from the *Zoophycos* ichnofacies to the distal-archetypal-proximal *Cruziana* ichnofacies. This ichnofacies trend is traced to a complex relationship between sea level dynamics and bottom-current conditions. *Zoophycos* ichnofacies are associated with chalky calcilutite sediments deposited during low-energy conditions. Increased energy in the environment led to a shift towards the first sandy contouritic facies and the establishment of the distal *Cruziana* ichnofacies with predominant horizontal components. The increase in ichnodiversity, particularly in vertical morphologies, is related with more energetic and proximal environments, as revealed by the transition from archetypal to proximal *Cruziana* ichnofacies. Within this interval, filter feeding organisms (e.g. *Gyrolithes*, *Ophiomorpha* tracemakers) exclusively occupied the fine grain levels, whereas the calcarenitic intervals were colonized by deposit feeders. Although environmental features such as nutrient availability and oxygenation of the sea floor also play a role, the bottom current hydrodynamics and sedimentation rate are determinant in the distribution of the macrobenthic tracemaker community along the Petra Tou Romiou carbonate contourite drift.

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Chapter 6

ICHNOFABRIC ANALYSIS AS A TOOL FOR CHARACTERIZATION AND DIFFERENTIATION BETWEEN CALCAREOUS CONTOURITES AND CALCITURBIDITES

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ABSTRACT

The Eocene – Miocene Cyprus paleoslope system records complex deep-marine sedimentation comprising background vertical settling of autochthonous pelagic-hemipelagic particles (chalks) which were punctuated by calcareous bottom currents (contourites) and gravity-flows (calciturbidites). The Eocene Lefkara Formation at the Petra Tou Romiou beach section (Cyprus) shows the incidence of deep-marine bottom currents and distal turbiditic episodes in a context of pelagic-hemipelagic sedimentation. Trace fossil analysis of this section, utilizing an ichnofabric approach (i.e., ichnodiversity, Bioturbation Index, Bedding Plane Horizontal Index and cross-cutting relationships), was conducted to precisely describe the paleoenvironmental conditions of this complex setting. Ichnofabric analysis allowed for the characterization and differentiation of sporadic turbiditic events that disrupted both pelagic/hemipelagic and contourite deposition. Calciturbidite intervals show ichnofabrics consisting of post-depositional U-shaped traces (i.e., *Arenicolites* isp., ?*Diplocraterion* isp.,) and vertical borings typical of consolidated substrates. High energy sandy contourite deposits are dominated by horizontal deposit-feeder traces and the development of ichnofabrics with *Planolites* isp., and *Thalassinoides* isp. The record of ichnofabrics with slightly deformed *Planolites* in the interbeds of sandy contourites or in the transition between the facies reveals variations in sedimentation within the bi-gradational contourite succession, and can potentially act as an indicator of depositional hiatus.

6.1. Introduction

Deep-marine carbonate deposits have been extensively studied (e.g., Jenkyns 1986; Tucker and Wright 2009; Flügel 2010; Wilson 2012; Pickering and Hiscott 2015). Ichnological analysis has been revealed as a powerful tool for interpreting paleoenviromental (i.e., depositional and ecological) conditions in deep-marine carbonate deposits (e.g., Bromley 1967; Bromley and Ekdale 1984; Ekdale and Bromley 1984; Frey and Bromley 1985; Ekdale and Bromley 1991; Savrda 2012, 2014). Commonly, deep-sea carbonate facies slowly accumulate through pelagic rain (Savrda 2012; Pickering and Hiscott 2015). Yet in some cases, pelagic deposition is punctuated by bottom currents (i.e., contour currents) or gravity flow processes (i.e., turbidity currents), resulting in a complex environmental setting that gives rise to variable trace fossil assemblages (Wetzel 1984; Bromley and Ekdale 1987; Surlyk and Lykke-Andersen 2007; Uchman 2007; Uchman and Wetzel 2012).

Turbiditic deposits have been studied, discussed, and addressed from many points of view in different deep-sea environments (e.g., Mutti and Normak 1987; Mulder and Syvitski 1995; McCaffrey and Kneller 2001; Piper and Normark 2009; Mulder 2011; Brackenridge et al. 2013). However, from a paleoenvironmental perspective, understanding the short term ecological impact of transient episodes of increased sediment supply remains relatively poorly understood (Gage and Tyler 1991; Bromley 1996; Levin et al. 2001; Walker 2001). With regard to trace fossil analysis, siliciclastic or mixed siliciclastic/carbonate gravity systems have been intensively studied (e.g., Seilacher 1962; Crimes 1973; Crimes and Crossley 1980; Uchman 1999; Heard et al. 2008; Rodríguez-Tovar et al. 2010; Cummings and Hodgson, 2011; Phillips et al. 2011; Uchman and Wetzel 2012). Detailed ichnological analyses of calcareous turbidites (commonly referred to as calciturbidites in the literature) are comparatively scarce (Miller et al. 2004; Savary et al. 2004; Uchman 2007; Giannetti and McCann 2010; Monaco and Checconi 2010; Mohseni et al. 2011; Savrda 2012; Uchman and Wetzel 2012).

Contourite deposits, resulting from thermohaline-induced geostrophic bottom-currents, tend to be under-represented in the literature, as most deep-marine studies focus on pelagic and turbiditic deposits (Rebesco et al. 2014; Pickering and Hiscott 2015). In the past two decades, research covering contourite deposits have increased significantly, refining the bi-gradational sequence model (negative to positive grading) which is found to be the dominant expression of contourite sedimentation (Rebesco et al. 2014; De Castro et al. 2020; Miguez-Salas et al. 2021). This increase runs parallel to the importance of contourites as unconventional reservoirs in hydrocarbon exploration (Viana 2008). Meanwhile, trace fossil analysis has become a very helpful tool for characterizing contour current deposits, including the bi-gradational character (i.e., Rebesco et al. 2014), as well as the paleoenvironmental conditions prevailing during their deposition (e.g., Wetzel et al. 2008; Rodríguez-Tovar and Hernández-Molina 2018; Miguez-Salas and Rodríguez-Tovar 2019a, b, 2020; Rodríguez-Tovar et al. 2019a; Miguez-Salas et al. 2020). Recently, based on the application of different techniques, detailed ichnological analyses have been conducted on contourites to approach the impact of ichnological features on rock properties, evidencing the influence of bioturbation in the reservoir quality of this facies (Dorador et al., 2021; Miguez-Salas et al., 2021b; Rodríguez-Tovar et al., 2021).

The deep-sea environment is a very complex depositional setting in which pelagic/hemipelagic, turbiditic and contouritic processes are usually interconnected in a variable manner. In most cases the involved facies —pelagites/hemipelagites, turbidites and contourites— are registered in the same section, and can be characterized as mixed deposits. For this reason, integrative analysis can be key for successful characterization and discrimination of deep-sea deposits (de Castro et al. 2021), with ichnological information being a powerful proxy. However, using ichnological properties to characterize and compare calciturbidites and bottom currents is still in its infancy (Rodríguez-Tovar et al. 2019b, 2020a).

Given this framework, the aim of the present research is to improve our knowledge about calciturbidite and calcareous contourite trace fossil assemblages in a deep-sea environment affected by downslope and alongslope currents with a dominant vertical settling pelagic deposition. We selected the Petra Tou Romiou outcrop, proposed as a type example of ancient contourites exposed on land (Kähler and Stow 1998; Stow et al. 2002; Hüneke et al. 2020) in which turbidite, contourite and pelagite-hemipelagite facies have been clearly differentiated using sedimentological data (Hüneke et al. 2020). Recently, ichnofacies characterization was conducted in Petra Tou Romiou at outcrop scale (Miguez-Salas and Rodríguez-Tovar 2019b). However, a detailed ichnological analysis, allowing depositional characterization into the recognized ichnofacies was not performed. Here, ichnofabric analysis is presented to differentiate between bottom current and calciturbidite facies registered in the same depositional setting. This ichnofabric approach could be a reference to similar research on worldwide carbonate contourite settings.

6.2. Geological context: Petra Tou Romiou outcrop

Cyprus lies in the eastern part of the Mediterranean Sea (Fig. 6.1 A). Tectonic processes, especially subduction between the African - Eurasian plates, has broadly restrained the Circum Troodos sedimentary successions that encircle the Troodos Massif (Kinnaird 2008; Edwards et al. 2010). From the Eocene until the middle Miocene, the Circum Troodos sedimentary succession is essentially composed of the Lefkara and Pakhna formations (Edwards et al. 2010). Both formations were deposited in a deep-water paleoslope system and experienced an upward-increasing input of shallow-water material (Kähler and Stow 1998; Stow et al. 2002; Hüneke et al. 2020). The Lefkara and Pakhna formations are primarily formed by pelagic or hemipelagic sedimentation, with significant bottom-current deposition resulting in calcilutitic and calcarenitic bioclastic contourites of variable thickness (Hernández-Molina et al. 2018). Distal turbiditic episodes are also common (Rodríguez-Tovar et al. 2019b, 2020a; Hüneke et al. 2020). The bottom-current flow velocity that affected the Cyprus paleoslope was mainly controlled by Indian Gateway depth (see de la Vara and Meijer 2016).

The Petra Tou Romiou outcrop is located in the southern part of Cyprus, where it runs along road B-6 near Aphrodite's Rock (Fig. 6.1 B). The outcrop is constituted by a 150-m-thick carbonate-dominated succession from the middle-upper Lefkara Formation to the base of the Pakhna Formation (Hüneke et al. 2020). The outcrop can be divided into a lower part consisting of chalky limestones, marls, individual thin calcarenite beds and nodular chert belonging to the Lefkara Formation (Petra Tou Romiou beach and A sections in Fig. 6.1 B) (Kähler and Stow 1998), and an upper part made up of chalky calcilutites and thick calcarenite beds assigned to the Pakhna Formation (B, C and D sections in Fig. 6.1 B) (Hüneke et al. 2020). A poorly exposed 15-m-thick marl interval separates the two formations by an indistinct unconformity (Hüneke et al. 2020). This carbonate-dominated succession was deposited in a paleoslope system developed in the southern verge of Cyprus (Kähler and Stow 1998; Stow et al. 2002; Hüneke et al. 2020). The Petra Tou Romiou outcrop records a shallowing trend, with background pelagic and hemipelagic sedimentation mainly influenced by bottom-currents, and punctuated by distal turbidity flows (Hüneke et al. 2020).

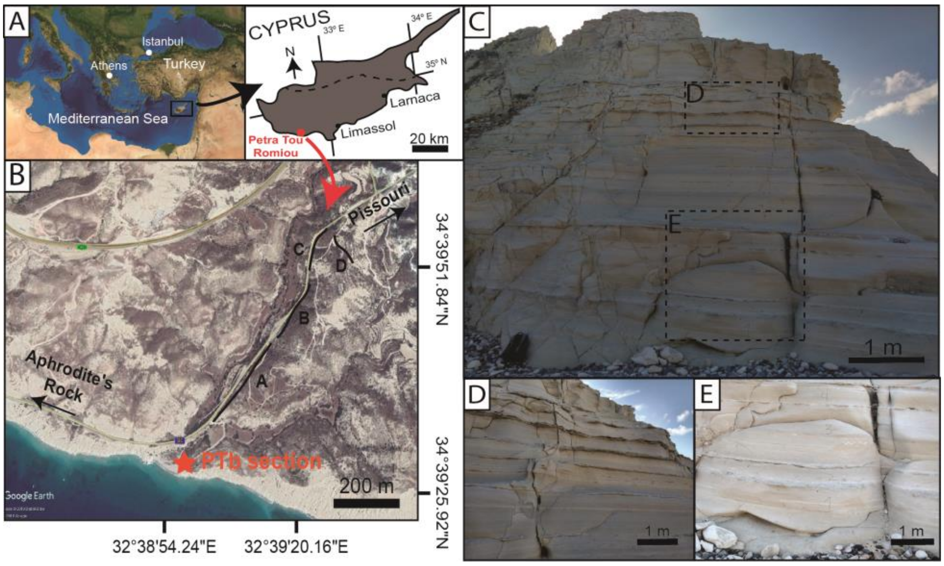

Fig. 6.1. A) Geographical location of Cyprus in the eastern Mediterranean Sea and the studied outcrop (red dot - Petra Tou Romiou; modified from Miguez-Salas and Rodríguez-Tovar, 2019a); B) Location of the differentiated PTb (Petra Tou Romiou beach), A, B, C and D sections in the outcrop (based on Hüneke et al. 2020 differentiation); C) General outcrop view of the PTb section; D-F) Detailed outcrop views with calcilutite/calcarenite intervals and discrete calcarenitic beds.

The Petra Tou Romiou beach section (PTb) (Fig. 6.1 C-E) constitutes the base of the Petra Tou Romiou outcrop and is located near the sea cliff at the end of the valley (34°39'27.52"N, 32°38'56.31"E). PTb is a 20m-thick dominant whitish chalk succession (Fig. 6.2) that records deposition of the Eocene Lefkara Formation (Miguez-Salas and Rodríguez-Tovar 2019a; Hüneke et al. 2020), in which three main facies have been characterized based on microfacies and sedimentological criteria (Table 6.1): a) Whitish calcilutites (facies F2a in Hüneke et al. 2020) interpreted as pelagic carbonate mud or calcareous muddy contourites associated with the fine grain part of the characteristic bi-gradational sequence (Hüneke et al. 2020). This facies records an autocomposite ichnofabric -single ichnocoenosis form by gradual upward migration of vertically partitioned benthic communities in pace with sedimentation, reflecting paleoenvironmental stasis *sensu* Savrda (2016)- typical of the *Zoophycos* ichnofacies (Fig. 6.2) (see Miguez-Salas and Rodríguez-Tovar 2019a for a detailed description of this ichnofabric); b) thin calcarenite beds with gradational boundaries and wavy lamination (facies F3a in Hüneke et al. 2020) interpreted as bioclastic sandy bottom-current deposits associated with the central part of the characteristic bi-gradational sequence (Hüneke et al. 2020); and c) thin sharp-based calcarenite beds (facies F3d in Hüneke et al. 2020) interpreted as fine-grained turbidites (Hüneke et al. 2020).

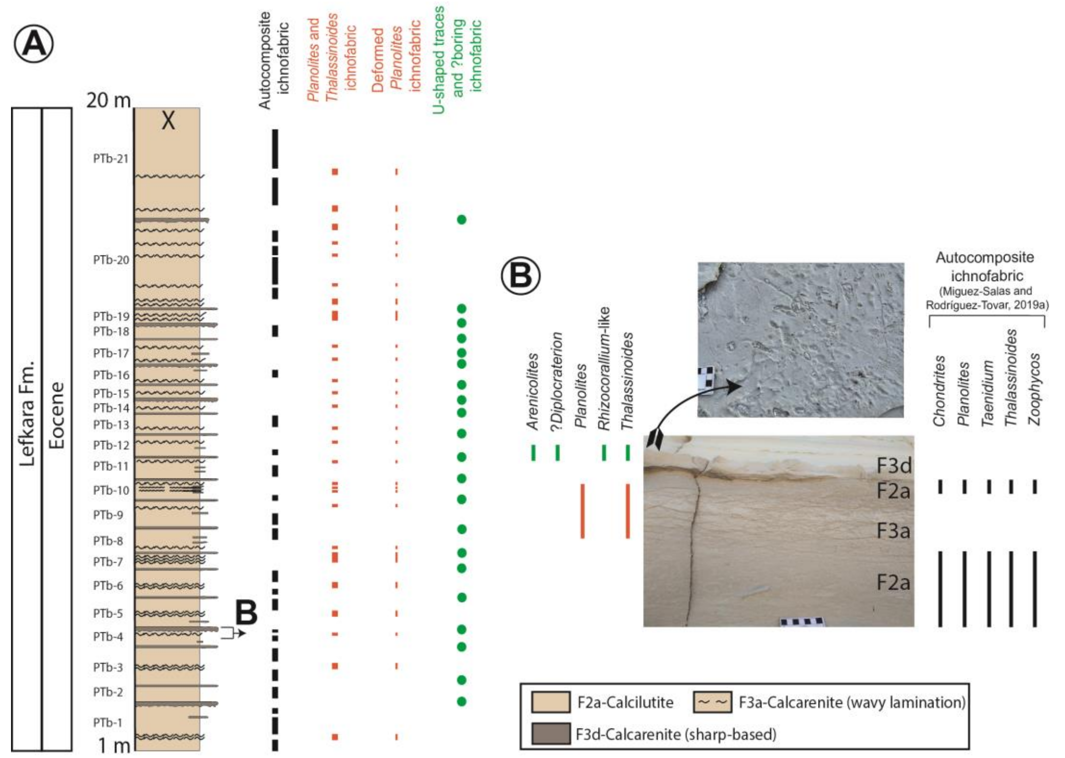

Fig. 6.2. A) Detailed lithologic log of the PTb section with indication of studied beds from PTb-1 to PTB-21 (modified from Miguez-Salas and Rodríguez-Tovar 2019a), and vertical ichnofabric distribution (facies type F2a, F3a and F3d according to Hüneke et al., 2020); B) Detailed bed-by-bed example of vertical trace fossil distribution through a bi-gradational sequence and a calciturbidite bed (line colors are

correlated with the ichnofabrics). Note the profuse presence of borings at the bedding plane of the calciturbidite bed (see details in Fig. 6.5).

6.3. Methodology

A high resolution, bed-by-bed ichnofabric analysis was conducted in the PTb section, focusing on stratigraphic features of beds, with special attention paid to the relationship between calcilutite (chalk), calcarenite and sandy calciturbidite levels, bed thickness and bed surfaces. The ichnofabrics were differentiated based on the integration of microfacies features (Huneke et al. 2020), primary sedimentary structures (i.e., lamination), ichnological properties as degree of bioturbation, density of trace fossils, ichnodiversity, size of ichnotaxa, cross-cutting relationships and tiering structure and taphonomic aspects. The degree of bioturbation for each ichnofabric was quantified by the application of Fiji (see Miguez-Salas et al. 2019). For vertical cross-sections we follow the "Bioturbation Index" (BI) of Taylor and Goldring (1993), from 0 (no bioturbation) to 6 (completely bioturbated). Additionally, for the degree of bioturbation on horizontal planes the "Bedding Plane Horizontal Index" (BPHI) proposed by Miller and Smail (1997) was used (0 no bioturbation and 5 completely bioturbated).

Together with stratigraphic observations, a detailed ichnological study was conducted based on outcrop observations and laboratory analysis. Outcrop analysis was focused on ichnological features such as orientation, deformation, shape, size, infilling material, cross-cutting relationships, stratigraphic distribution into beds, taphonomy, and the relationship between trace fossils and type of facies. Moreover, trace fossils were precisely photographed. Rock samples and trace fossil specimens were collected to be studied in the laboratory. Polished sections were prepared for a more detailed ichnological analysis, including ichnofabric characterization. In addition to taking close-up photographs, high-resolution images (outcrop and laboratory photographs) were obtained and treated with Adobe Photoshop CS6 (using adjustments for brightness, hue/saturation and color balance, among others; see Rodríguez-Tovar and Dorador 2015; Dorador and Rodríguez-Tovar 2018) and Fiji (CLAHE; Miguez-Salas et al. 2019) in order to enhance the visibility of trace fossils. All samples are housed in the Department of Stratigraphy and Palaeontology at the University of Granada (collection labelled PTb).

6.4. Results

Trace fossil assemblages and ichnofabric features were examined in calcarenitic levels (F3a and F3d in Hüneke et al. 2020), from bottom to top of the Petra Tou Romiou beach section (PTb-1 to PTb-21 in Fig. 6.2 A). Trace fossils were identified mostly in vertical cross-section and in some cases parallel to the bedding plane, recording a relatively abundant and moderately diverse ichnoassemblage (Fig. 6.2 B). Five ichnotaxa were recognized at the ichnogenus level, including *Arenicolites*, ?*Diplocraterion*, *Planolites*, *Rhizocorallium*-like, and *Thalassinoides*, together with probable borings (Table 6.2; Figs. 6.3 and 6.4). Trace fossils show no significant variations in abundance or composition at section scale, but significant differences at shorter scale, between facies, are noted (Fig. 6.2 B); facies F3d records *Arenicolites*, ?*Diplocraterion*, *Rhizocorallium*-like, *Thalassinoides*, and borings, facies F3a includes *Planolites* and *Thalassinoides*. Three ichnofabrics has been differentiated in the calcarenitic beds.

6.4.1. *Planolites* and *Thalassinoides* ichnofabric

The *Planolites* and *Thalassinoides* ichnofabric occurs in calcarenitic intervals with wavy lamination; F3a *sensu* Hüneke et al. (2020) (Fig. 6.3). This ichnofabric appears above calcilutitic chalk intervals (F2a), contacts range between gradational to erosive (Figs. 6.3 A, B). A similar composition between the host sediment and the infilling material of most of the trace fossils impedes the visualization of burrows in outcrop. Trace fossil characterization and ichnofabric analysis was therefore conducted in laboratory, based on the study of polished sections and high-resolution image treatment. Packed biomicrites and biosparites microfacies, which characterize the host sediment, are observed indistinctly in the trace fossil infillings. Thus, the original depositional fabric was not modified by the trace makers. Only locally, infilling material of *Planolites* and *Thalassinoides* seems to include fragmented globigerinid shells. The *Planolites* and *Thalassinoides* ichnofabric displays a high abundance, occupying the 50-85% of the wavy calcarenitic beds (BI=3-4), and a low diversity of traces (dominant *Planolites* and some *Thalassinoides*) (Figs. 6.3 E and F). Primary depositional structures are generally absent probably due to the abundance of bioturbation. Moreover, some of the traces are slightly deformed, thus primary sedimentary structures may have also been secondarily modified. The size of the traces is centimetrical (Table 6.2); significantly lower than in the adjacent calcilutitic ichnoassemblage (autocomposite ichnofabric of Miguez-Salas and Rodríguez-Tovar 2019a). Many of the traces are poorly preserved and the crosscutting relationships are difficult to observe.

Table 6.1. Mai
characteristic w
PTb section in
differentiation).

Facies type (Hüneke et al. 2020)	**Lithology and sedimentary structures**	**Depositional process**	**Ichnofabric**
F2a	Whitish calcilutite (globigerinid wackestone). No primary sedimentary structures.	Pelagic carbonate mud/calcareous muddy contourites (reworking of pelagic sediments)	Autocomposite ichnofabric
F3a	Whitish calcarenite (globigerinid wackestone–packstone). Thin beds with gradational boundaries and wavy lamination. Related with the central part of a bi-gradational sequence.	Bioclastic sandy bottom-current deposits (reworking of pelagic sediments)	*Planolites* and *Thalassinoides* ichnofabric Deformed *Planolites* ichnofabric
F3d	Greyish calcarenite (globigerinid grainstone to wackestone). Thin sharp-based/gradual top boundary into calcilutites (F2a). Fining-upward sequences (normal grading). Primary traction structures (parallel and low-angle cross lamination)	Fine-grained turbidites sourced from slope settings. Reworked and dislocated pelagic sediments only	U-shaped traces and ?boring ichnofabric

Table 6.
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Trace fossils	Morphological features	Sedimentary environments	Ethology	Facies (*sensu* Hüneke et al. 2020)	References
Arenicolites	*Arenicolites* isp. is abundant, appearing as simple, vertical U-shaped tubes with more or less parallel trend; the burrows extend upward to two apertures at the surface of the calciturbidites (Fig. 6.5E). Burrow diameters are about 1 or 2 cm and the horizontal distance between the tunnels is between 2 and 5 cm, with a vertical depth of some 6 to 10 cm.	Continental to deep marine. Commonly associated with high-energy deposition in shorefaces.	Dwelling-burrow (domichnial), suspension feeding.	F3d	Chamberlain 1977; Rindsberg and Kopaska-Merkel 2005
Rhizocorallium-like	*Rhizocorallium* appears occasionally in the bedding plane of calciturbiditic levels as a horizontal, actively-filled internal spreiten structure with a curved path (Fig. 6.4A). No fully U-shaped burrow structure is recorded. The width of the spreiten elements is about 1–2 mm. As the full structure is not preserved, we use the *Rhizocorallium*-like nomenclature for our specimens due to their morphological similarities.	Wide variety of depositional settings, often in shallow marine depositional systems (shelf and nearshore environments).	Combined suspension and deposit feeding strategies. Gardening and storage may also occur.	F3d	Jensen 1997; Kowal-Linka and Bodzioch 2011; Rodríguez-Tovar et al. 2012; Knaust 2013
?*Diplocraterion*	*Diplocraterion* occurs in the calciturbiditic beds, as a vertical U-shaped tube with parallel cylindrical limbs and marked spreiten (Figs. 6.5 D and F). Burrow diameter is about 1 cm and the horizontal distance between the external margins of the limbs is usually between 2 and 3 cm, the vertical depth being some 6 to 9 cm. The burrows are passively filled.	Marginal marine environments (e.g., tidal and estuarine settings). May also occur in shoreface and offshore environments.	Dwelling-burrow (domichnial), suspension feeding.	F3d	Fürsich 1974; Fillion and Pickerill 1990; Bromley and Hanken 1991; Šimo and Olšavskỳ 2007; Rodríguez-Tovar and Pérez-Valera 2013

Planolites	*Planolites* is the most abundant ichnogenus of the section and appears in the sandy bottom-current deposits (Fig. 6.3). Specimens are represented by horizontal straight to gently curved cylinders (diameter range from 0.5 to 1.5 cm). The specimens are unlined and commonly present smooth walls. The burrows are filled with fine to medium grained sediment from upper layers.	All aquatic environments (marine and non-marine).	Deposit feeders with active filling. Passive filling is plausible.	F3a	Pemberton and Frey 1982; Keighley and Pickerill 1995; Locklair and Savrda 1998
Thalassinoides	*Thalassinoides* are recorded mostly in vertical cross-sections of sandy bottom-current deposits (Figs. 6.3 D and E); and sometimes in the bedding plane of calciturbidites (Figs. 6.4 C and D). Specimens present unlined cylindrical or sub-cylindrical horizontal burrows with diameters from 1.5 to 3 cm. They are passively filled with above calcarenitic sediments. Burrow margins are predominantly smooth, but occasionally irregular margins were recognized in the specimens that appear below calciturbidites.	Wide variety of depositional settings, most common in shallow marine environments.	Combined suspension and deposit feeding strategies.	F3a and F3d	Frey et al. 1984; Ekdale et al. 1984; Monaco et al. 2007; Wetzel 2008; Rodríguez-Tovar et al. 2017
Vertical or sub-vertical boring	Abundant in the calciturbiditic levels, representing 20% to 30% of the bedding-plane surfaces occupied by spaced heterogeneous borings (Figs. 6.2 A to C). Their diameter ranges from 0.5 to 3 cm and the perforation depth can reach 10 cm. Burrows commonly present passive filling without structure. However, spreiten structures are sometimes seen (Fig. 6.5 C). The shape of the borings is diverse, vertical tubes being the more usual pattern, though J-shaped or sub-vertical borings are also recorded (Fig. 6.4 E).	Wide variety of depositional settings. It depends on the existence of hardground surfaces suitable for colonization	Dwelling (domichnia), mechanical or chemical bioerosion	F3d	

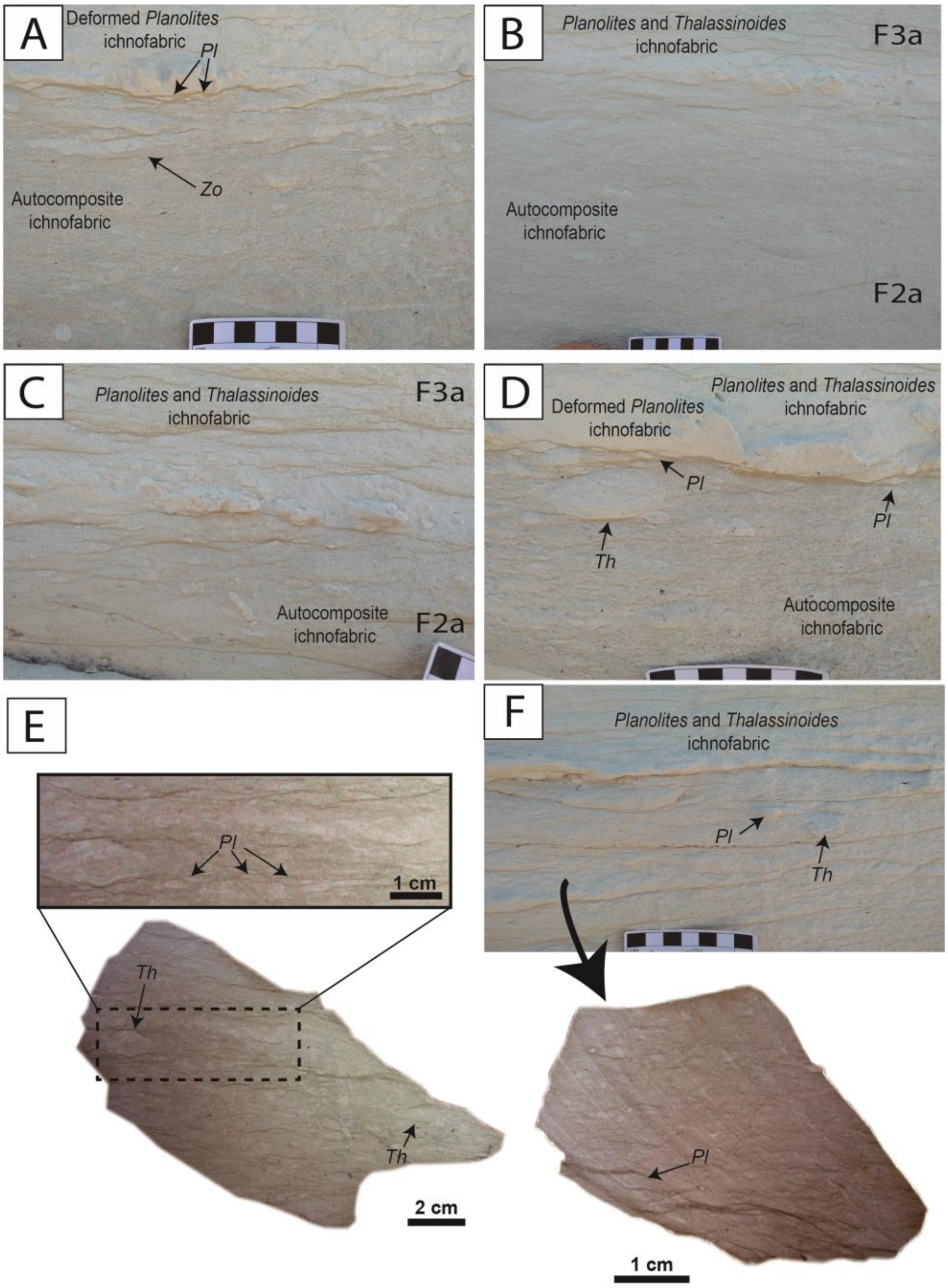

Fig. 6.3. A-D) Detailed outcrop views of the autocomposite ichnofabric, *Planolites* and *Thalassinoides* ichnofabric and deformed *Planolites* ichnofabric associated with facies F2a and F3a. Note: presence of calcilutitic *Zoophycos* in the upper part of the autocomposite ichnofabric in contact with *Planolites* and *Thalassinoides* ichnofabric; E) Polished section of the *Planolites* and *Thalassinoides* ichnofabric and deformed *Planolites* ichnofabric (zoom rectangle); F) Outcrop views of the *Planolites* and *Thalassinoides* ichnofabric with polished section where deformed *Planolites* ichnofabric is recognized. Note the presence of deformed *Planolites* in brown calcilutitic horizons. *Planolites* (*Pl*), *Zoophycos* (*Zo*) and *Thalassinoides* (*Th*).

6.4.2. Deformed *Planolites* ichnofabric

The deformed *Planolites* ichnofabric appears in the interbeds of the wavy calcarenitic packages of F3a (Fig. 6.3 C) or in the contact between calcarenitic and calcilutitic intervals (Figs. 6.3 A and D), associated with thin brown calcilutitic horizons. These thin wackestone layers consist of homogeneous microfacies, showing punctual diffuse mottling texture resulting from intensive bioturbation. The biogenic disturbance originates unevenly distribution of planktonic foraminifera. This ichnofabric is characterized by an occasional record of small deformed *Planolites* (Figs. 6.3 A and D). Infilling material of *Planolites* shows a white globigerinid packstone texture (Fig. 6.3 F) corresponding to the actively introduced calcarenitic material. The deformed *Planolites* occupy the 20-40% of the brown calcilutitic horizons (BI=2-3).

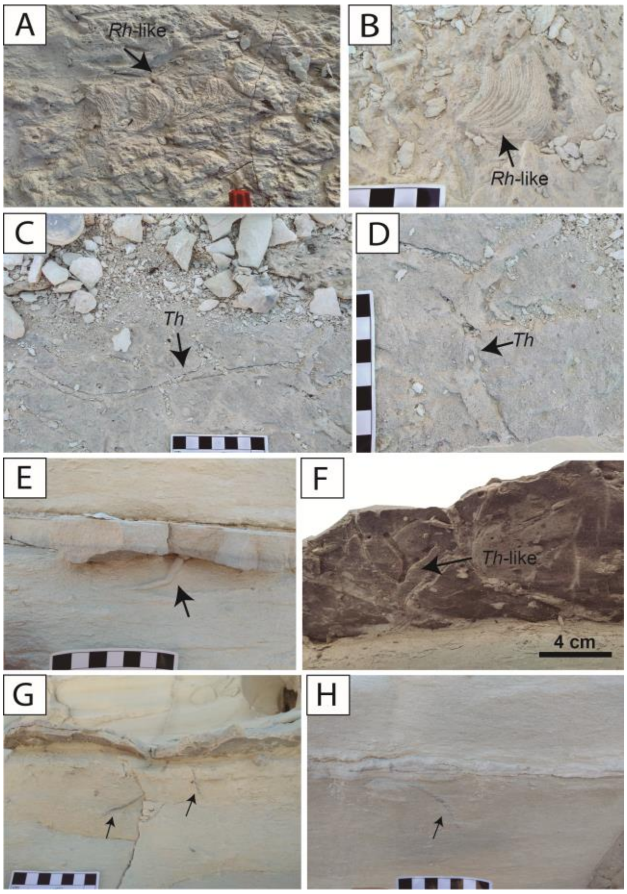

Fig. 6.4. U-shaped traces and ?boring ichnofabric. *Rhizocorallium*-like (A-B) and *Thalassinoides* (C-D) at the upper surface of the sharp-based calcarenite beds; E) Sub-vertical biogenic structures with J-shape; F) Calciturbiditic sole with hypichnia concave *Thalassinoides*-like; G-H) Calciturbiditic beds with vertical or sub-vertical biogenic structures (black arrows) located in the calcilutic interval below. *Rhizocorallium*-like (*Rh*-like) and *Thalassinoides* (*Th*).

6.4.3. U-shaped traces and ?boring ichnofabric

The U-shaped traces and ?boring ichnofabric can be differentiated in the calciturbiditic beds with an erosive sharp base (F3d, Figs. 6.4 and 6.5). This ichnofabric is characterized by the presence of *Arenicolites*, ?*Diplocraterion* and many vertical or sub-vertical biogenic structures (probable borings) mainly registered on the upper bedding surfaces (Figs. 6.2, 6.5). The vertical biogenic burrows and borings occupy 20-30% of the horizontal planes (BPHI =3). Sometimes *Thalassinoides* and *Rhizocorallium*-like burrows also appear in the bedding plane (Figs. 6.4 A-D). Many of the traces are observed in the facies below facies F3d, clearly distinguished by their passive calcarenite filling contrasting with the host calcilutitic sediment. Moreover, the boring structures included in this ichnofabric cross-cut the upper tier traces of the underlying ichnofabrics, reaching a maximum of 12 cm below the calciturbiditic bed. Planar parallel lamination (occasionally laterally replaced by a low-angle cross-lamination) is well-preserved at the lower part of the calciturbidites. However, the upper part of the calcaciturbidite beds, characterized by abundant bioturbation from the U-shaped traces and ?boring ichnofabric and the *Planolites* and *Thalassinoides* ichnofabric, reveals the absence of primary sedimentary structures. Calciturbiditic soles may preserve hypichnia concave traces (Fig. 6.4 F) corresponding to structures produced at the top of the chalky calcilutitic intervals (Miguez-Salas and Rodríguez-Tovar 2019a).

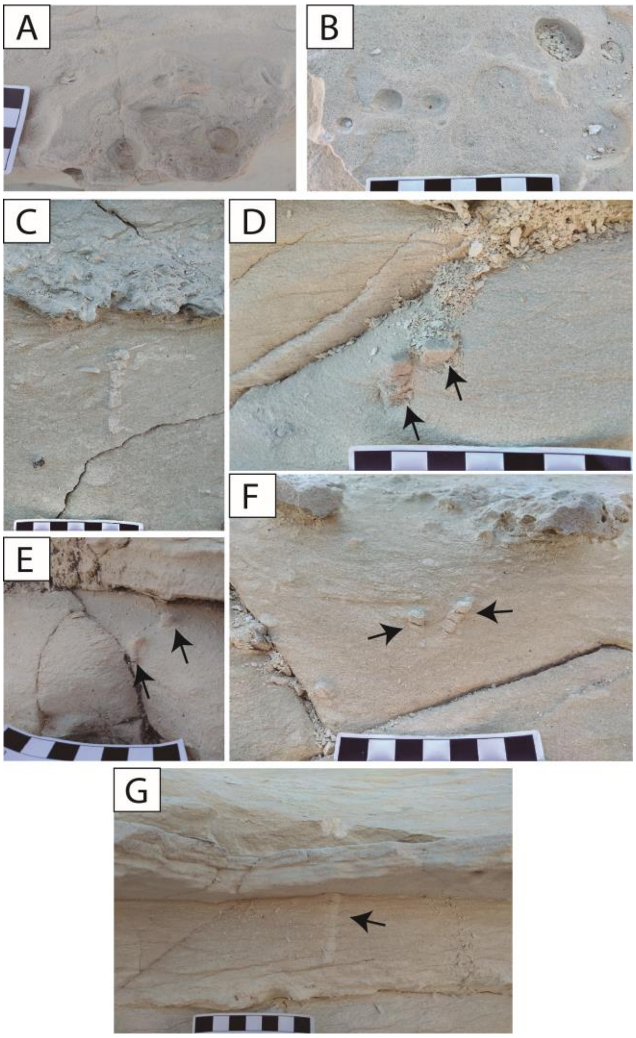

Fig. 6.5. U-shaped traces and ?boring ichnofabric. A-B) Calciturbiditic upper surface with paired holes; C) Vertical biogenic structure; D-F) U-shaped traces (?*Diplocraterion* isp., *Arenicolites* isp); G) Vertical biogenic structures. Note in C to G that biogenic structures coming from the sharp-based calcarenite beds are located in the calcilutic interval below.

6.5. Discussion

Deep-marine sediments (e.g., contourites, hemipelagites and pelagites) commonly record profuse bioturbation (Wetzel and Uchman 2012). In this framework, ichnological analysis —in particular the ichnofabric approach— of deep-marine carbonate successions is highly useful for paleoenvironmental and depositional reconstructions in complex deep-marine environments (Ekdale et al. 2012; Savrda 2012). The paleoenvironmental conditions prevailing in the carbonate basin during bottom currents are unlike those briefly predominant during and immediately after turbiditic events (Levin et al. 2001; Miller et al. 2004; Savary et al. 2004; Uchman 2007; Savrda 2012). Thus, in the carbonate depositional context corresponding to the deep marine PTb section, detailed ichnofabric analysis reveals significant differences between pelagites/hemipelagites, contourites and distal turbidites.

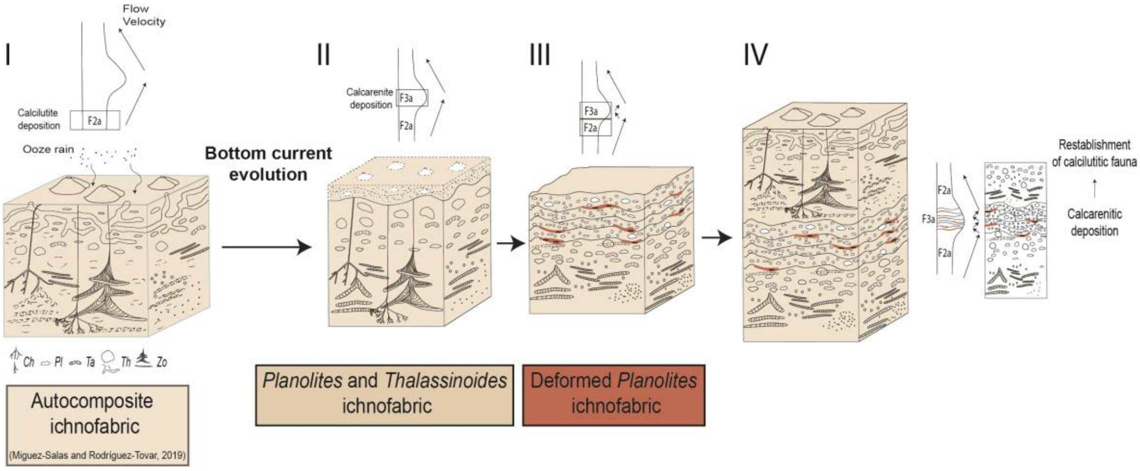

Fig. 6.6. Schematic diagram showing the development of the autocomposite ichnofabric (I), *Planolites* and *Thalassinoides* ichnofabric (II), and deformed *Planolites* ichnofabric (III) according to bottom current evolution and flow velocity (IV). Note the relationship with bigradational contourite models and facies F2a and F3a of Hüneke et al. (2020). *Chondrites* (*Ch*), *Planolites* (*Pl*), *Taenidium* (*Ta*), *Thalassinoides* (*Th*), and *Zoophycos* (*Zo*).

6.5.1. Calcareous sandy contourite ichnofabric approach

In recent years, the contourite facies model has been significantly improved due to a rise in the number and detail of contourite studies (Hsü 2008; Shanmugam 2017; see Rodríguez-Tovar and Hernández-Molina 2018). The current model comprises internal subdivisions and a wide range of sequences and partial sequences (Rebesco et al. 2014; Shanmugam 2017). Analyses conducted in bi-gradational contourites from the middle part of the Petra Tou Romiou outcrop reveal the intermittent sedimentary processes determining contourite deposition, rather than the continuous model traditionally proposed (Rodríguez-Tovar and Hernández-Molina 2018; Rodríguez-Tovar et al.

2019a; Hüneke et al. 2020). On this basis, ichnofabric analysis provides new improvements for the characterization of calcareous contourites.

In the PTb section, muddy contourite deposits indicates a pelagic setting or low bottom-current flow energy, associated with steady deep-marine carbonate basin conditions and the development of an autocomposite ichnofabric (see Miguez-Salas and Rodríguez-Tovar 2019a) (Fig. 6.6 I). In this context, a progressive increase in bottom-current flow energy induces a gradual transition from the autocomposite ichnofabric to the *Planolites* and *Thalassinoides* ichnofabric associated with BI= 3-4 (Fig. 6.6 II). This ichnofabric replacement, i.e. calcilutitic autocomposite ichnofabric - *Planolites* and *Thalassinoides* ichnofabric - calcilutitic autocomposite ichnofabric (Fig. 6.6 IV), runs parallel with the bi-gradational contourite facies model traditionally proposed (Stow and Faugères 2008). First, a negatively graded transition (calcilutite F2a - calcarenite F3a) is correlated with calcilutitic autocomposite ichnofabric to the *Planolites* and *Thalassinoides* ichnofabric, and then positively graded (calcarenite F3a - calcilutite F2a) with *Planolites* and *Thalassinoides* ichnofabric to calcilutitic autocomposite ichnofabric.

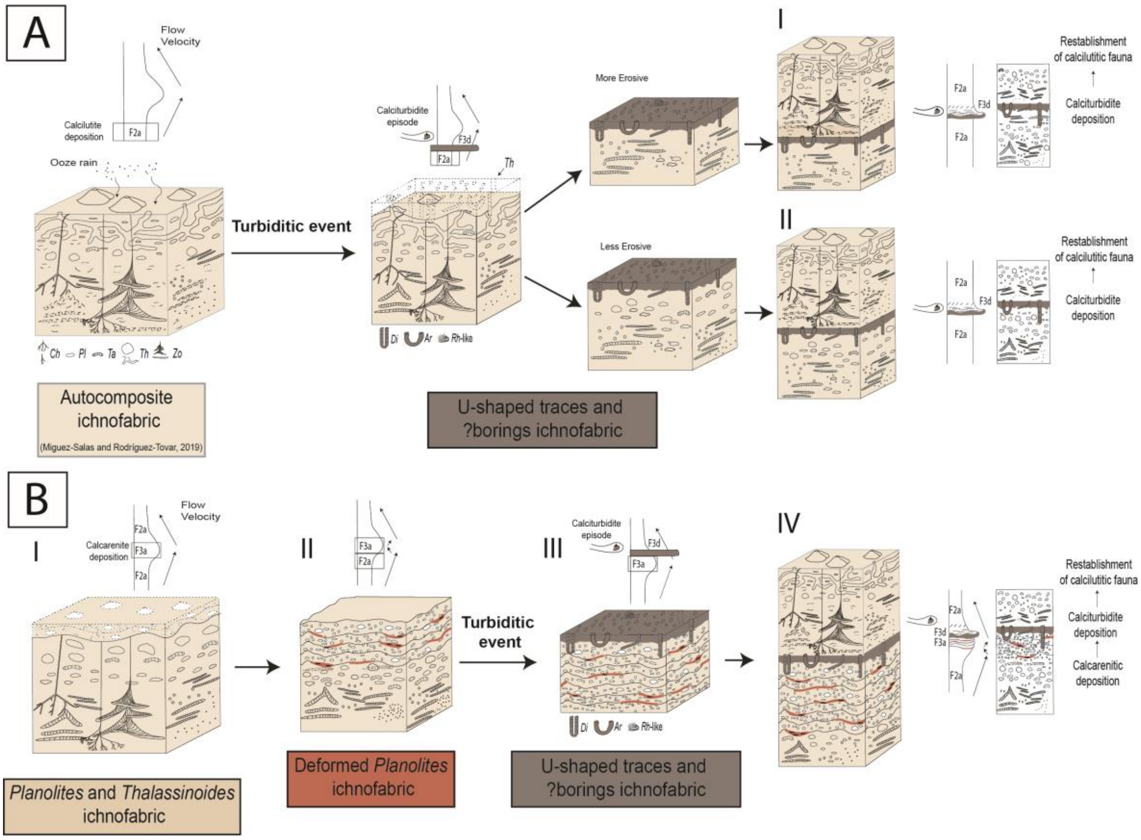

Fig. 6.7. Schematic diagram showing the development of U-shaped traces and ?boring ichnofabrics; displaying variable relationships with autocomposite ichnofabric, *Planolites* and *Thalassinoides* ichnofabric and deformed *Planolites* ichnofabric according to calciturbidite episodes and the prevailing bottom current regime. A) During calcilutitic depositionand low flow velocity (note the different results in function of the erosive power of the turbidite episode; I and II); B) During calcarenitic deposition and high flow velocity (cases I to IV). Note relationship with bigradational contourite models and facies F2a, F3a and F3d of Hüneke et al. (2020). *Arenicolites* (*Ar*), *Chondrites* (*Ch*), ?*Diplocraterion* (*Di*), *Planolites* (*Pl*), *Rhizocorallium*-like (*Rh*-like), *Taenidium* (*Ta*), *Thalassinoides* (*Th*), and *Zoophycos* (*Zo*).

As mentioned above, new ichnological data documents sedimentation pauses or even erosion inside the bi-gradational model (Rodríguez-Tovar et al. 2019a; De Castro et al. 2021). In the study case, specific ichnofabric features supporting this interpretation are (see Fig. 6.6 III); i) the occasional presence of *Zoophycos* in the upper part of the calcilutitic autocomposite ichnofabric in contact with the *Planolites* and *Thalassinoides* ichnofabric, and ii) the development of deformed *Planolites* ichnofabric (BI= 2-3) within the *Planolites* and *Thalassinoides* ichnofabric or in between the calcilutitic autocomposite ichnofabric and the *Planolites* and *Thalassinoides* ichnofabric.

The record of *Zoophycos*, a typical deep tier structure, in the upper part of the calcilutitic autocomposite ichnofabric, documents disappearance of the upper and middle tiers in the original autocomposite ichnofabric. A punctual increase in energy could determine erosion of these tiers (see Savary et al. 2004) before the development of *Planolites* and *Thalassinoides* ichnofabric, corresponding to the central part of a bi-gradational sequence. On the other hand, the record of the deformed *Planolites* ichnofabric within the *Planolites* and *Thalassinoides* ichnofabric suggest minor-scale decreases in energy during the high flow velocity regime (Fig. 6.6 III). These short-time diminutions/pauses allowed for exclusive bioturbation of soft upper tiers by *Planolites* trace makers (Rodríguez-Tovar and Hernández-Molina 2018; Rodríguez-Tovar et al. 2019a).

6.5.2. Calciturbidite ichnofabric approach

The calcarenitic sharp-based beds with planar parallel lamination are best interpreted as bioclastic sandy calciturbidite deposits (F3d in Hüneke et al. 2020). In the present study, U-shaped traces and ?boring ichnofabric records some features that could support the sedimentological interpretation: a) the record in the upper bed surface of U-shaped traces (mainly ?*Diplocraterion* and *Arenicolites*), b) some horizontal firmground burrows (i.e., *Thalassinoides*), and c) vertical or subvertical biogenic structures of probable borings, BPHI =3 (Fig. 6.7). This ichnofabric might be related to pauses in sedimentation, or minor erosion after the calciturbidite deposition. This may have resulted in the generation of firmground to hardground conditions, following colonization from the upper surface to deeper in the bed (Fig. 6.7). At the PTb section, calciturbidite deposits may occur punctuating pelagic-hemipelagic background sedimentation (Fig. 6.7 A) or calcareous sandy contourite deposition (Fig. 6.7 B). The record of deep tier traces (i.e., *Zoophycos*) in contact with the calciturbidite facies evidences disappearance of the upper and middle tiers, indicating a higher erosive power of the turbiditic flow (Fig. 6.7 A I). During the deposition of calcareous sandy contourites (and associated ichnofabrics; Fig. 6.7 B I-II), U-shaped traces and vertical ?borings ichnofabric sharply overlie the *Planolites* and *Thalassinoides* ichnofabric (Fig. 6.7 B III).

The absence of the typical pre-depositional graphoglyptid trace fossils from turbiditic settings does not suffice to reject this interpretation. Although these traces are common in siliciclastic turbidites, they are absent in other calciturbiditic examples, given the less erosive power of muddy turbiditc currents (e.g., Miller et al. 2004; Savary et al. 2004; Uchman 2007; Monaco and Checconi 2010; Cummings and Hodgson 2011; Wetzel and Uchman 2012). Yet in the Agios Konstantinos outcrop, close to Petra Tou Romiou and corresponding to the proximal settings of this turbiditic system, graphoglyptids have been documented (see Rodríguez-Tovar et al. 2020a). However, the PTb section is located in a distal part of the turbiditic system and may not present the erosive conditions needed to print out such traces, as reported in the aforementioned calciturbidite literature. Notwithstanding, the existence of graphoglytids in the PTb section cannot be totally discarded. Outcrop conditions (i.e., poor and limited calciturbiditic sole exposure) may impede their recognition.

Comparison of the PTb section with one of the best examples of deep-water calciturbidite trace fossil assemblages (Scaglia Rossa successions; Miller et al. 2004) highlights some differences. The ichnoassemblage differentiation proposed by Miller et al. (2004) for Tb and Tc Bouma sequence divisions, with *Thalassinoides*, *Teichichnus*, *Phycodes*, and *Ancorichnus*? is not recognized in the studied PTb section. Moreover, the distinction of upper heavily bioturbated wackestone (divisions Td and Te with common *Planolites* and *Chondrites*) observed by Miller et al. (2004) is hard to discern in the PTb section due to the similarity of these divisions (Td and Te) within the calcilutitic autocomposite ichnofabric. Moreover, pauses in sedimentation —even erosion— interpreted after the calciturbidite deposition could determine the absence of Td and Te intervals.

6.5.3. Paleocological and ethological implications

As demonstrated in modern analogues, an increase in bottom current flow velocity does not necessarily lead to decreased population density; but in some cases this change does indeed result in the establishment of higher density communities than in quiescent adjacent areas due to the remobilization and transportation of organic matter particulates (e.g., McCave 1985; Thistle et al. 1985; Thomsen et al. 2002; Wetzel et al. 2008; Wetzel and Uchman 2012). The replacement from calcilutitic autocomposite ichnofabric to *Planolites* and *Thalassinoides* ichnofabric marks a significant decrease in ichnodiversity, with the disappearance of *Zoophycos*, *Chondrites* and *Taenidium*, and the exclusive record of *Planolites* and *Thalassinoides*. An absence of middle to deep tier traces (e.g., *Zoophycos* and *Chondrites*) might be related to an increase in flow velocity and energy conditions, inducing comparatively rapid deposition. The rapid increase in deposition would have allowed bioturbation of shallow tiers, while restricting the ability of deeper tier trace makers (such as those in the *Planolites* and *Thalassinoides* ichnofabric) to successfully colonize the substrate.

Modern analogues in affected contour-current environments reveal that ordinary suspension feeders are not abundant, probably because their filter apparatus can be plugged when the suspended sediment concentration is very high (Thistle et al. 1991). Accordingly, organisms that passively extract drifting particles by maintaining a relief on the sea floor are dominant (Aller and Aller 1986). Yet Wetzel et al. (2008) suggested that a high flow velocity regime could be exploited by abundant trace makers if filter feeding takes place through water circulating in burrows or by interface feeding (Fig. 11.10 in Wetzel et al. 2008). In the present study, *Planolites* and *Thalassinoides* ichnofabric and deformed *Planolites* ichnofabric are registered in the context of a high flow velocity regime. *Planolites* and *Thalassinoides* are commonly interpreted as produced by shallow to middle tier deposit feeders (Pemberton and Frey 1982; Frey et al. 1984; Keighley and Pickerill 1995). Suspension feeding strategies have occasionally been assigned in the case of *Thalassinoides* (Rodríguez-Tovar et al. 2017). A deposit feeding behavior should therefore override in the sandy contourites of the PTb section, supporting a dominance of deposit feeding organisms in high energy settings. Still, this is a tentative interpretation, clear ichnological evidence of trophic mode changes within the contourite model must be pursued.

6.6. Conclusions

Detailed ichnofabric approach at the deep marine Petra Tou beach section (Cyprus) reveals significant differences between pelagites/hemipelagites, contourites and distal turbidites, evidencing variable relationships between vertical settling, alongslope and downslope sedimentation.

Microfacies features, primary sedimentary structures (i.e., lamination), ichnological properties and taphonomic aspects, allow characterization of the three different ichnofabric such as the *Planolites* and *Thalassinoides* ichnofabric, the deformed *Planolites* ichnofabric and the U-shaped traces and ?boring ichnofabric.

The previously defined autocomposite ichnofabric with *Chondrites* isp., *Planolites* isp., *Taenidium* isp., *Thalassinoides* isp. and *Zoophycos* isp., registered in calcilutites, is related to a low energy environment with pelagic carbonate mud and calcareous muddy contourites.

Increasing flow velocity is associated with the development of the *Planolites* and *Thalassinoides* ichnofabric in calcareous sandy bottom current deposits. These intervals record a similar trace fossil density, though a lower ichnodiversity suggests an overall low energy flux regime and the dominance of horizontal shallow deposit feeders. The development of the deformed *Planolites* ichnofabric inside calcareous sandy contourite deposits or in the transition between the facies points to variations or pauses in sedimentation rates, hence discontinuities, during the development of the bi-gradational sandy contourite sequence.

Calciturbidite episodes associated with thin sharp-based calcarenite beds are represented by the U-shaped traces and ?boring ichnofabric, revealing pauses in sedimentation, even minor erosion, after the calciturbidite deposition.

Depositional conditions as hydrodynamic energy, rate of sedimentation and continuity/discontinuity in deposition, reveal as major factors determining changes in ichnofabrics differentiated in pelagites/hemipelagites, contourites and distal turbidites.

The ichnofabric approach conducted in this type example of ancient contourite outcrop could be a reference for similar research on worldwide carbonate contourite settings, allowing characterization of contourite facies and differentiation respect to associated deep-sea deposits (i.e., pelagites / hemipelagites, turbidites).

Acknowledgments

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Supplementary Papers of PART III

- Stable deep-sea macrobenthic trace maker associations in disturbed environments from the Eocene Lefkara Formation, Cyprus (Geobios, 2019)

- A new teichichnoid trace fossil *Syringomorpha Cyprensis* from the Miocene of Cyprus (PALAIOS, 2019)

- First record of graphoglyptids in Cyprus: indicative presence of turbidite deposits at the Pakhna Formation (Ichnos, 2020)

- Key evidence for distal turbiditic- and bottom-current interactions from tubular turbidite infills (Palaeogeography, Palaeoclimatology, Palaeoecology, 2019)


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Original article

Stable deep-sea macrobenthic trace maker associations in disturbed environments from the Eocene Lefkara Formation, Cyprus☆

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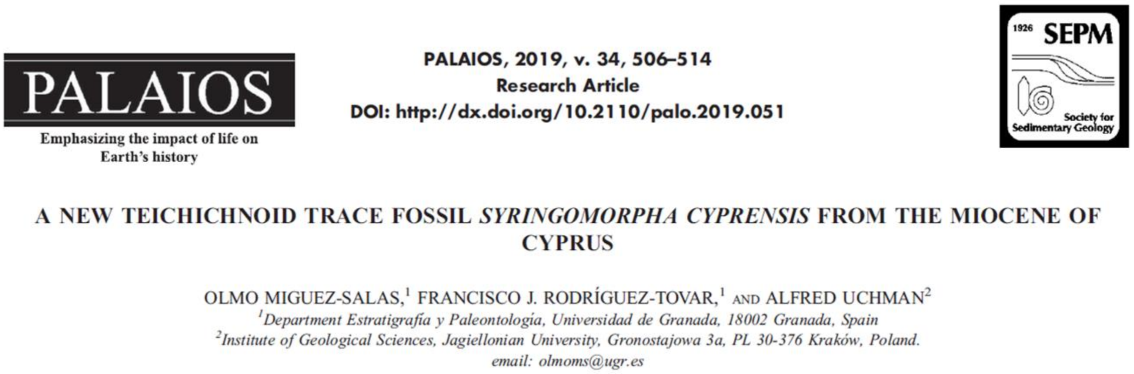
ABSTRACT

Ichnological analysis of Eocene deep-pelagic whitish chalky calcilutites interstratified with high-energy calcarenite beds in the lower part of the Petra Tou Romiou section (southern Cyprus) was conducted to interpret the development and evolution of the trace maker associations during calcilutite deposition after high-energy episodes. The trace fossil assemblage from the chalky calcilutites consists of *Chondrites* isp. (*Chondrites intricatus* and *Chondrites targionii*), *Planolites* isp., *Taenidium* isp., *Thalassinoides* isp., and *Zoophycos* isp., typical of the *Zoophycos* ichnofacies. A composite chalky ichnofabric reveals a multi-tiered association of burrowing animals: the uppermost tier determines a mottled background, the upper tier shows the highest trace fossil abundance and diversity (*Planolites*, *Taenidium* and *Thalassinoides*), the middle tier features *Zoophycos* and large *Chondrites*, and the deepest tier consists mainly/exclusively of small *Chondrites*. This ichnofabric has an autocomposite character, associated with bioturbation by a single ichnocoenosis and gradual upward migration of the tiered macrobenthic community as the pelagic calcilutite sedimentation slowly progresses. There are no changes in the trace fossil assemblage between or within calcilutite intervals, regardless of the associated calcarenite beds. This supports a stable, mature, background calcilutite trace maker association, which recovers shortly after the deposition of high-energy calcarenites. In turn, there would have been a rapid re-establishment of paleoenvironmental conditions during pelagic calcilutite accumulation after episodic deposition of any calcarenitic material.



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A NEW TEICHICHNOID TRACE FOSSIL *SYRINGOMORPHA CYPRENSIS* FROM THE MIOCENE OF CYPRUS

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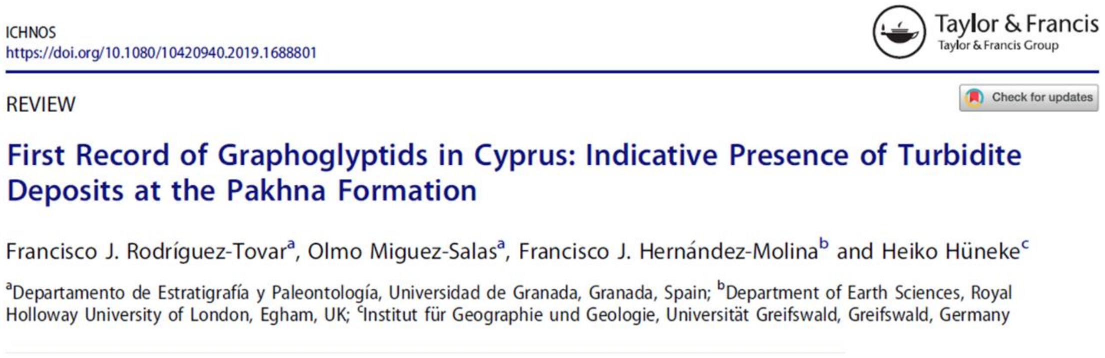
ABSTRACT

A new teichichnoid trace fossil, *Syringomorpha cyprensis* from the Miocene of Cyprus, is proposed as a vertical burrow composed of an arcuate-like tube with horizontal parts to subhorizontal distally and vertical to subvertical parts proximally and triangular spreiten in the inner corner of the tube. Previously, this ichnogenus was represented only by the lower Paleozoic, shallow marine *S. nilssoni*, which disappeared after the Cambrian. *Syringomorpha cyprensis* marks the reappearance of similar behavior, in a deep-sea environment with pelagic, contouritic, and turbiditic sedimentation, influenced by frequent turbiditic and bottom current flows. Both ichnospecies of *Syringomorpha* could be produced by the same taxonomic group of probable worm like organisms (polychaetes?). Energy conditions were a stronger influence on the distribution of *S. cyprensis* tracemaker rather depth.



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REVIEW

First Record of Graphoglyptids in Cyprus: Indicative Presence of Turbidite Deposits at the Pakhna Formation

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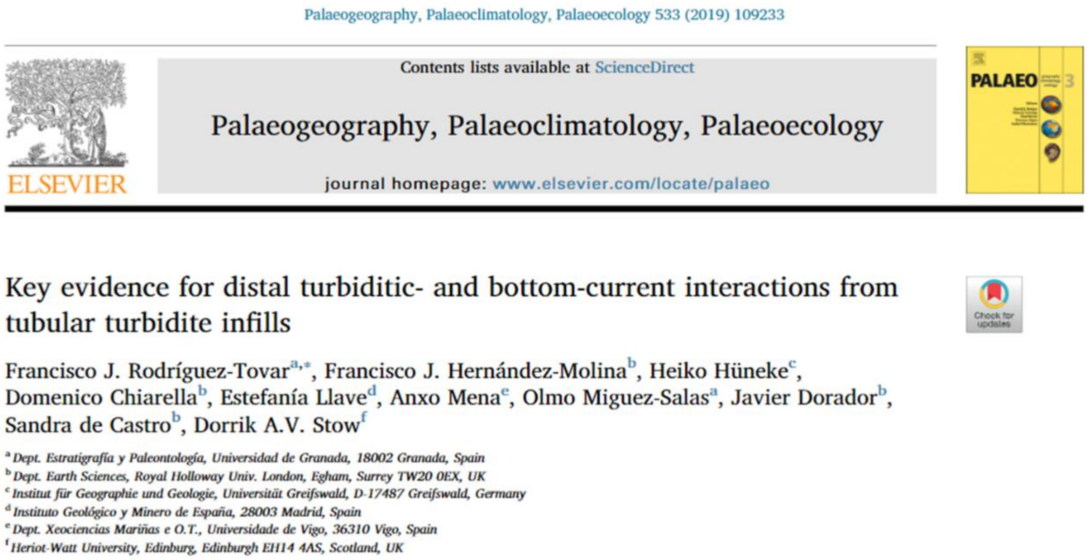
ABSTRACT

Ichnological analysis at the Pakhna Formation (Miocene, Cyprus) reveals, for the first time, the presence of graphoglyptid structures. The Pakhna Formation is dominated by pelagic/hemipelagic sediments, together with contourite, reworked turbidite and turbidite facies. Thus, a complex interaction between pelagic, bottom-current and gravitational sedimentation is envisaged. The discernment of facies is sometimes difficult, based principally on stratigraphic and microfacies features. The record of *Helminthorhaphe* as a component of the graphoglytid group supports the presence of turbidites, facilitating their differentiation from the other facies. *Nereites* ichnofacies, punctuating a dominant/background *Zoophycos* ichnofacies, would reflect changes in paleoenvironmental conditions. This record offers significant perspectives to advance in the study of bottom-current and gravitational processes through outcrop examples.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Key evidence for distal turbiditic- and bottom-current interactions from tubular turbidite infills

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ABSTRACT

Infilling of trace fossils can serve as a proxy for sediment otherwise missing from basin deposits. The Petra Tou Romiou section (southern Cyprus) includes calcilutite/calcarenite material that represents deep-marine deposits of Eocene age. Lateral and vertical variation indicates pelagic, gravitational, and bottom-current processes simultaneously influencing sedimentation. Detailed ichnological analysis resolved interactions between these deep-marine sedimentary processes in this distal marine setting. Calcarenite turbiditic beds occur as well-preserved and continuous tabular beds that disappear laterally. In some cases, trace fossils infilled with calcarenitic material are termed *tubular turbidites*. These structures correspond to actively filled *Planolites* formed in softground conditions and infilled by calcarenitic sediment interpreted as the record of missing turbiditic deposits when calcarenite turbiditic beds disappeared due to erosion. The variable preservation of calcarenite turbidite beds along with the presences of *tubular turbidites* indicate rapid erosion following turbidite deposition and post-depositional reworking of turbidites by bottom-currents. A refined interpretation of *tubular turbidites* can help constrain sedimentary processes that form deep-marine deposits and as such, has considerable paleoceanographic and economic implications.

PART IV

ICHNOLOGICAL CHARACTERIZATION OF CLASTIC CONTOURITES

Chapter 7

MACARONICHNUS AND CONTOURITE DEPOSITIONAL SETTINGS: BOTTOM CURRENTS AND NUTRIENTS AS COUPLING FACTORS

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Macaronichnus and contourite depositional settings: Bottom currents and nutrients as coupling factors

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ABSTRACT

The trace fossil *Macaronichnus segregatis degiberti* (7–15 mm in diameter) is recorded for the first time in deep-marine contourites which were deposited in a Late Miocene outer-shelf to upper slope of the Rifian Corridor (Morocco). *Macaronichnus* is typical of shallow-marine, mainly foreshore environments. It is produced by deposit feeding opheliid polychaetes in high to intermediate latitudes. This record supports the significance of bottom current processes on environmental conditions as a major limiting factor affecting the macrobenthic trace maker community. Mediterranean overflow water during the Late Miocene enabled a high nutrient supply to the seafloor, favouring colonization by *Macaronichnus* producers. Thus, *M. s. degiberti* should be used as an indicator for nutrient availability instead of mainly a palaeodepth indicator. This finding provides significant information for oceanographic and environmental reconstructions related to contouritic processes, as well as to contourite characterization.

Keywords: Trace fossils, Deep-sea; Contourites, Food supply, Morocco

7.1. Introduction

7.1.1. Bottom-currents and contouritic deposits

The deep sea is a complex depositional system affected by four main types of deep-water bottom currents, such as: (1) thermohaline-induced geostrophic bottom currents (i.e., contour currents), (2) wind-driven bottom currents, (3) deep-marine tidal bottom currents, and (4) internal waves and tides (baroclinic currents) (Shanmugam, 2008). In recent years, the role of contour currents in forging and shaping continental margins has been globally confirmed (Viana and Rebesco, 2007; Rebesco et al., 2014). Contourites, as deposits from contour currents, provide essential information about ocean circulation and climate change and are therefore of major importance in resolving the role of ocean circulation in modulating Earth's climate system (Knutz, 2008). Furthermore, contour currents can influence hydrocarbon systems, affecting reservoir geometry, quality, or distribution of sealing rocks (Viana and Rebesco, 2007). For this reason, the economic interest in contourite deposits has increased significantly (Viana, 2008).

Contourite drifts form at many different locations and water depths (Faugères and Stow, 2008), but contouritic facies are deposited mainly below 300 m deep under the action of along-slope semi-continuous bottom currents (Stow et al., 2008). Commonly, water depth influences the drift dimensions and the type of contourite deposits. That is, deeper areas have greater potential to develop larger drifts composed of finer-grain deposits (muddy contourites), while in shallower settings contouritic drifts show more reduced dimensions and may include coarser sediments (silty and sandy contourites) (Faugères and Stow, 2008).

Contour currents strongly control deep-sea sedimentation (Rebesco et al., 2014). Contourites and associated sediments are significantly affected by the physio- and oceanographic setting, but inversely, they modify the continental slope and rise morphology (Rebesco et al., 2014). Over the last few years, the understanding of the processes involved and the identification criteria of bottom-current-associated deposits has significantly progressed (e.g., Stow and Faugères, 2008; Viana, 2008; Rebesco et al., 2014; Shanmugam, 2017). However, an important debate exists about the role of biogenic structures (e.g., bioturbation structures) as diagnostic features in respect to sedimentary ones. This debate can be a consequence of two main unsolved aspects at this moment; a) the influence of bottom currents on trace makers and thus on bioturbation distribution, and b) the relative importance of involved depositional and ecological conditions on the contourite depositional settings (e.g., rate of sedimentation, hydrodynamic energy, nutrients, oxygenation, etc.; Wetzel et al., 2008; Rodríguez-Tovar and Hernández-Molina, 2018; Miguez-Salas and Rodríguez-Tovar, 2019a, Miguez-Salas and Rodríguez-Tovar, 2019b).

7.1.2. The trace fossil *Macaronichnus*

Macaronichnus segregatis (Clifton and Thompson, 1978) is a usually non-branching cylindrical structure, 3–5 mm in diameter, showing mineralogical segregation between the tube core and the surrounding rim. This trace typically occurs in sand-rich shallow-marine (up to foreshore) high-energy settings from medium to high latitudes, parallel to the bedding plane and perpendicular to the shoreline (e.g., Clifton and Thompson, 1978; Nara, 1994; Bromley, 1996; Pemberton et al., 2001; Nara and Seike, 2004; Seike, 2007; Bromley et al., 2009; Seike et al., 2011; Nara and Seike, 2019). However, vertical orientations can occur too (see Uchman et al., 2016). Burrows of opheliid polychaetes, including *Ophelia limacina*, *Travisia japonica* or *Thoracophelia* (formerly genus *Euzonus*) have been proposed as reliable modern counterparts.

Recent studies have shown specimens of *M. s. degiberti* from the middle to outer shelf (Rodríguez-Tovar and Aguirre, 2014), as well as local appearances of *M. segregatis* in deep-sea environments (Knaust, 2017; Giannetti et al., 2018). However, *Macaronichnus* has never before been associated with deep-sea contourite deposits. Seike et al. (2011) proposed a size-distribution model for *Macaronichnus* where open-platform specimens are larger than their shallow-water counterparts, the latter with a standard diameter of 3–5 mm. Therefore, larger specimens would be indicative of comparative deeper marine environments. However, *Macaronichnus* with smaller diameters, within the standard range, have been also punctually registered in deep-marine channel systems and neritic to upper bathyal environments (Knaust, 2017; Giannetti et al., 2018). Moreover, the ichnosubspecies *M. s. degiberti*, with diameters up to 15 mm (Rodríguez-Tovar and Aguirre, 2014), has been associated with a wide environmental distribution from tidal channels to shelf sand ridges; even based on neoichnological data, this ichnosubspecies can be related to deeper marine environments (Nara and Seike, 2019). According to this, there is not a clear relationship between *Macaronichnus* size and bathymetry. Thus, some key questions arise concerning this trace fossil: Is depth a major parameter controlling *Macaronichnus* trace maker? Can be used the record of *Macaronichnus* as an indicator of sedimentary environments? What environmental factors control the distribution of *Macaronichnus*?

The record of shallow marine traces such as *Macaronichnus* in deep-marine sediments is not impossible, but is unexpected in the fossil record. Here, we present the first record of large and abundant *Macaronichnus* in deep-marine settings affected by bottom currents. These large traces are recognized in contourite deposits from the Late Miocene Rifian Corridor (Morocco). This finding indicates that depth is not the major limiting factor for *Macaronichnus* trace makers, with other palaeoenvironmental conditions having greater importance (i.e., oxygenation, currents, nutrients). Observations on actual benthic communities in deep-sea environments affected by bottom currents allow comparisons with the ancient record, enabling interpretations of the limiting parameters. This research improves the understanding of sedimentary processes and bottom-current pathway interactions with benthic communities occurring during the past in a complex deep-marine setting.

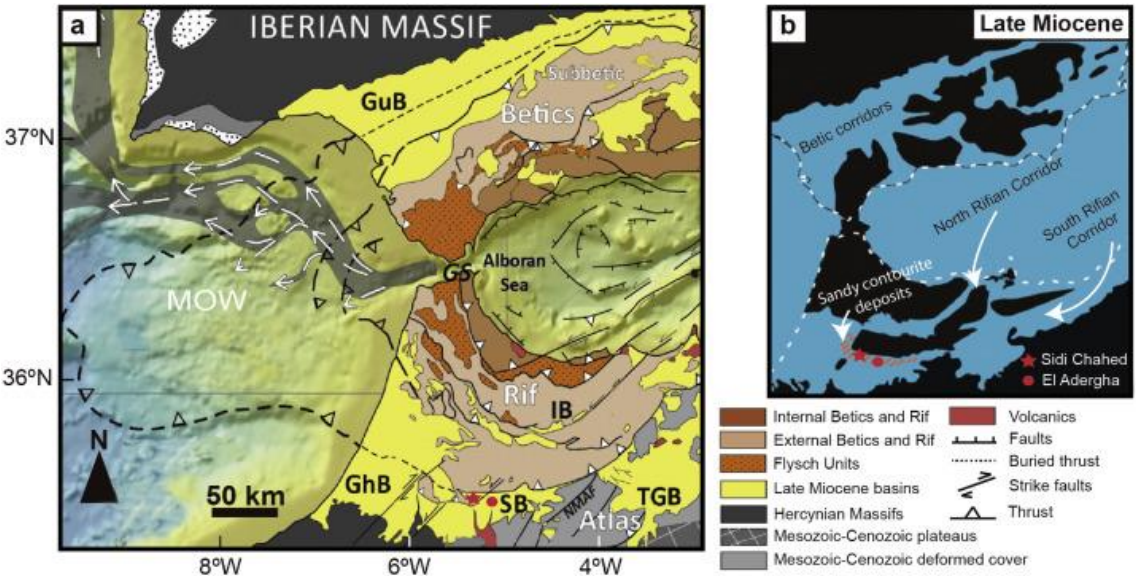

Fig. 7.1. Geological and palaeogeographic maps. a) Geological and tectonic map of the Betic-Rif arc with the main stratigraphical units. Note: GhB: Gharb Basin; GS: Gibraltar Straits; GuB: Guadalquivir Basin; MOW: Modified Outflow Water; NMAF: North-Middle-Atlas Fault; SB: Saiss Basin; TGB: Taza-Guercif Basin (modified from Capella et al., 2017). b) Approximate palaeogeography of the Betic and Rifian Corridor during the Late Miocene (adapted from Capella et al., 2017). White dotted lines are the present-day coastline. Light-brown grated area is the sandy contourite drift deposits. Location of the sections studied in the palaeogeographic context (red star: Sidi Chahed; red dot: El Adergha). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

7.2. Geological context and the studied sections

The studied sections are related to the Rifian Corridor in northern Morocco. This corridor evolved as a south-westward migrating foreland basin of the Rif-Betic Cordillera during the Late Miocene (Sani et al., 2007). The Rifian Corridor (Morocco) was a gateway connecting the Mediterranean and Atlantic during the Late Miocene (Fig. 7.1). This gateway progressively closed due to tectonically induced uplift, leading to the onset of the Mediterranean Salinity Crisis in the Late Miocene (Capella et al., 2018 and references therein). The Rifian Corridor was composed of two gateways, the North and South Rifian corridors, the latter associated with deeper waters (Krijgsman et al., 1999; Flecker et al., 2015). The palaeogeography was controlled by two main features; the Pre-Rifian Ridges (Roldán et al., 2014) and the Pre-Rif Nappe (Capella et al., 2017). The North and South Rifian corridors were separated by these, but mainly by the Pre-Rif Nappe, which at times might have been submerged, connecting both corridors (Capella et al., 2017). The study area of the present research is located in the South Rifian corridor comprising the Saiss Basin that is filled with middle to upper Miocene foreland deposits (Flecker et al., 2015; Capella et al., 2017, Capella et al., 2018). The Upper Miocene record of exposed sandy contourite channels of the Sidi Chahed section, are found within the slope of the south-westward migrating Pre-Rif Nappe. The El Adergha section is located south of the Pre-Rifian Ridges more proximal to the Taza-Sill (Capella et al., 2017). Both sections reflect bottom-current pathways that formed under the influence of late Miocene Mediterranean water overflowing into the Atlantic Ocean along the South Rifian Corridor (Capella et al., 2017, Capella et al., 2018). The sandy contourite outcrops are found along the northern margin of the seaway, indicating that geostrophic processes forced the thermohaline bottom currents northwards (Capella et al., 2017). Deposits of the two outcrops studied were deposited within a palaeodepth range from upper slope to the outer shelf (150–400 m water depth; Capella et al., 2017): I) The Sidi Chahed outcrop (previously called Ben Allou; Capella et al., 2017) consists of three main sandstone units deposited in contouritic channels. These channels show unidirectional west to northwest directed palaeocurrent directions. This outcrop contains different orders of traction structures ranging from ripples to metre-scale compound dunes (Fig. 7.2); II). The El Adergha outcrop consists of two main sandstone units. The lowermost sand unit presents 4 m of sandy to silty planar bedding with ripple lamination (Fig. 7.2). The uppermost sand unit is up to 17 m thick and contains cross-stratified bedsets that are part of larger-order cross-sets (Fig. 7.2). These units are separated by a marl interval with gradual changes in sand content and contain a 1-m-thick bigradational sequence (Capella et al., 2017).

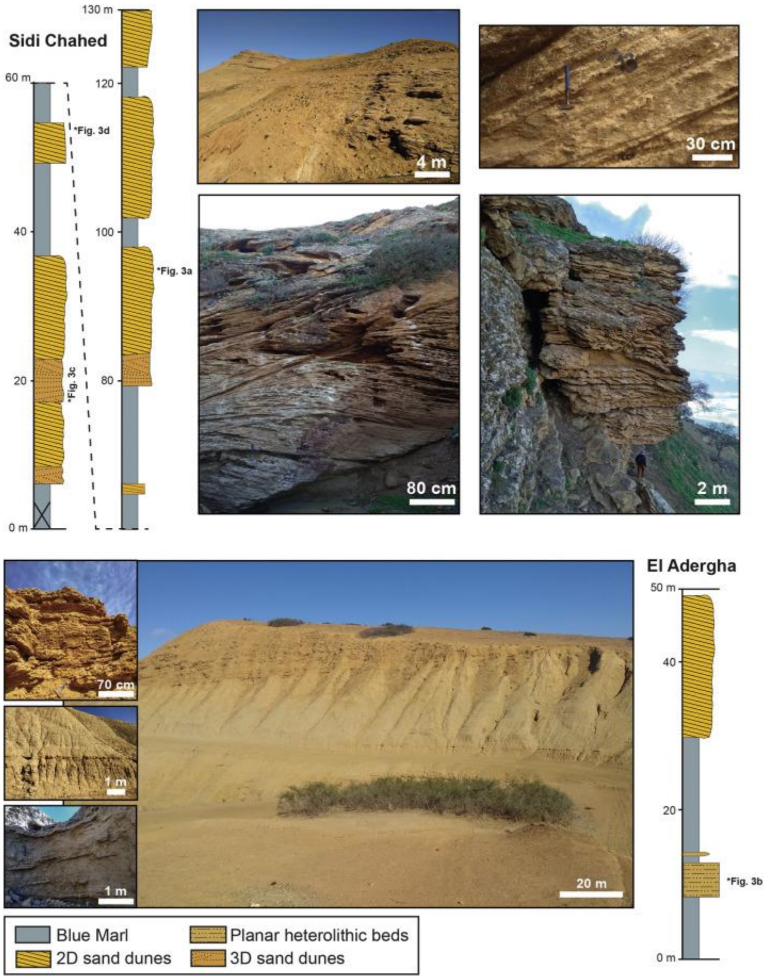

Fig. 7.2. Schematic logs of Sidi Chahed and El Adergha outcrops. General and detailed views of each outcrop with the sandy contourite deposits showing different orders of cross-stratification.

7.3. Methodology

The sandy bedsets of Sidi Chahed (34°5′53.81″N, 5°18′24.11″W) and El Adergha (34°4′34.19″N, 4°51′33.43″W) contouritic outcrops were studied bed-by-bed focusing on features and distribution of *Macaronichnus*. Ichnologic observations in outcrop (macroscopic morphological features) were focused on: orientation, shape, length and diameter of individual burrow segments, and taphonomy. Special attention was paid to stratigraphic variations and relationship with facies, bed surfaces and sedimentary structures, analysing ichnological features within and between sand bodies. Selected specimens were collected to study at the laboratory, focusing on the relationship between the host sediment and the infilling material of *Macaronichnus*, as well as on the sediment conforming the surrounding mantle of the burrow. The studied specimens are housed at the Department of Stratigraphy and Palaeontology, University of Granada. Some outcrop images were treated with Adobe Photoshop CS6 (using adjustments for brightness, hue/saturation and colour balance) to enhance visibility of certain ichnological features (Dorador and Rodríguez-Tovar, 2018).

7.4. Ichnological analysis

7.4.1. *Macaronichnus segregatis degiberti*

The *Macaronichnus segregatis degiberti* studied record consists of densely packed, endichnial, cylindrical, straight to slightly sinuous, variably oriented cylindrical cores, surrounded by a mantle, 7–15 mm in diameter (Fig. 7.3). The burrow is filled by slightly light-coloured sand (mainly quartz, occasional glauconite and rare feldspar) compared to the darker surrounding mantle (consisting of mica, brown glauconite pellets and heavy minerals) (Fig. 7.3). In most cases, the core is composed of structureless sand or coarse silt. Locally, a series of regularly spaced features occurs on both sides of the mantle, perpendicularly oriented to the burrow (Fig. 7.4). According to Nara and Seike (2019) we use the term "lobes" for these structures, instead of an alternative term such as "ribs", because they are slightly oblique, discontinuous, and in some cases (i.e., *Protovirgularia*) arranged in chevron-like biserial patterns (Uchman, 1998). The lobes are 5–10 mm wide, spacing from 7 to 20 mm apart (Fig. 7.4, Fig. 7.5a). Smooth, non-lobed mantles are predominant. Lamellae or meniscate structures have not been detected.

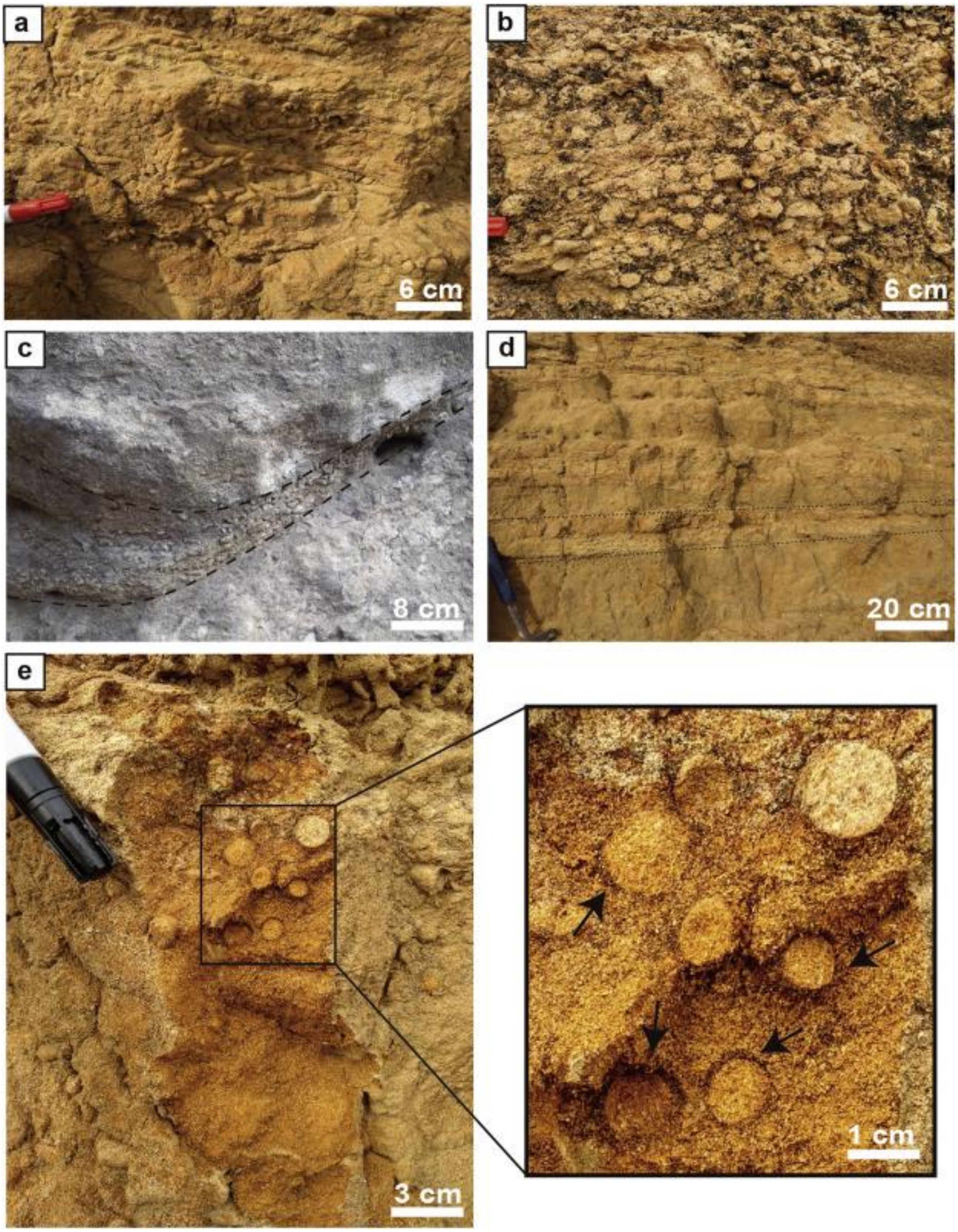

Fig. 7.3. *Macaronichnus* in outcrops of the sandy contourite drift (location in Fig. 7.2). a) General view with low-angle cross-stratification and pervasive bioturbation by *Macaronichnus* in Sidi Chahed. b) Close-up view of *Macaronichnus* inside sandy to coarse silty planar heterolithic cross-bedding packages in El Adergha. c) View of smaller *Macaronichnus* in the trough of a cross-stratified sandstone unit inside dune complex in Sidi Chahed. d) Low-angle cross-stratification with abundant *Macaronichnus* (dashed lines) and coarse silty beds (below) with less density in Sidi Chahed. e) *Macaronichnus* specimens showing circular shape and dark mantle.

The type of branching according to D'Alessandro and Bromley (1987) and Bromley (1996) is difficult to characterize on *Macaronichnus*, and actually is a controversial point (see discussion in Rodríguez-Tovar and Aguirre, 2014). False branching due to intersection of different burrows is relatively easy to be differentiated, but primary and secondary successive branching can be difficult to identify due to preservation (D'Alessandro and Bromley, 1987; Bromley, 1996). True branching has been only occasionally recognized (Rodríguez-Tovar and Aguirre, 2014 and references therein). In the studied specimens, branching of burrows is frequent, mainly consisting on false (Fig. 7.5a–c) and less frequently primary and secondary successive branching (Fig. 7.5d, e). Occasionally, true branching of the burrows may appear with predominant Y-shape and rare T-shape bifurcations (Fig. 7.5f). No significant enlargement is detected at the branching point.

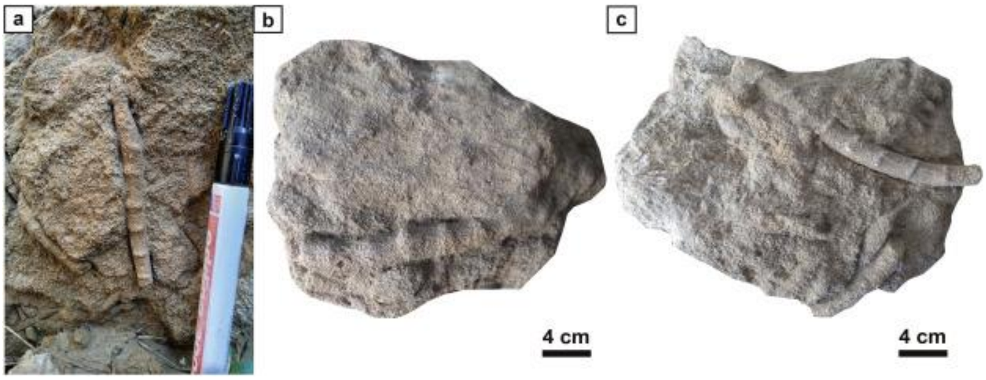

Fig. 7.4. Mantle lobes in large *Macaronichnus* specimens. a) With vertical orientation. b–c) With horizontal orientation.

The ichnogenus *Macaronichnus* is a relatively simple trace fossil and according to Knaust (2017) with high potential for confusion with similar ichnogenera as *Palaeophycus* and *Planolites*. The studied specimens record a morphology that could fit into the diagnosis of *Palaeophycus*, but the active fill allows us to discard this assignation (Pemberton and Frey, 1982). *Planolites* ichnogenus also records an active filling and similarities in the overall geometry of the burrow (Pemberton and Frey, 1982). Nevertheless, *Planolites* differs from *Macaronichnus* by the common absence of mantle (Knaust, 2017) and infrequent branching. The appearance of mantle lobes may be confusing and could be similar to the annulations of *Planolites annularis* Walcott (see Pickerill and Fyffe, 1999). Nevertheless, the annulations of *P. annularis* Walcott are much more closely spaced and slightly obliquely oriented to its long axis than the one observed in our specimens (Pickerill and Fyffe, 1999). Other features registered in *Planolites* as striae characterizing *P. reinecki* Książkiewicz, 1977 are not observed either.

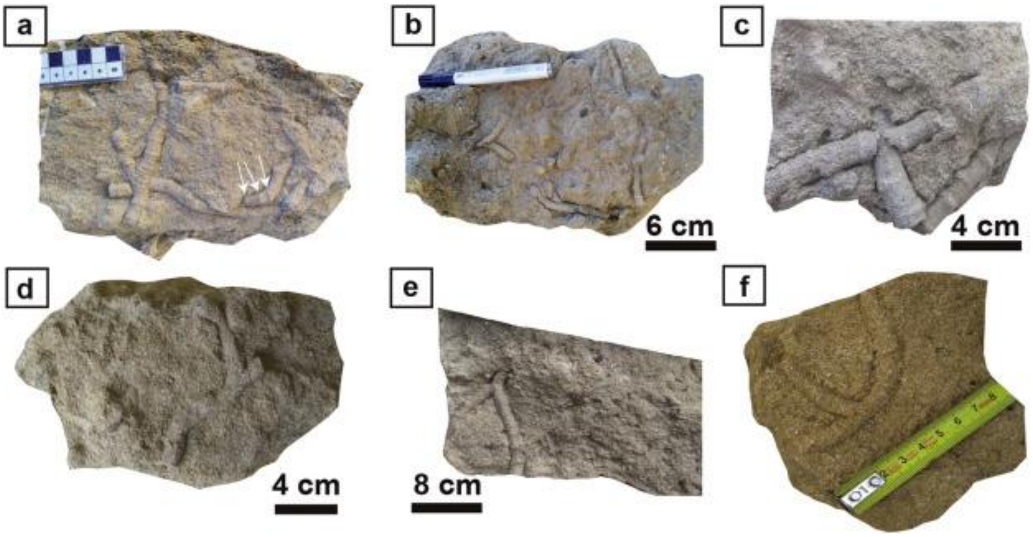

Fig. 7.5. Different branching type recorded in the large *Macaronichnus* specimens. a–c) False branching. d–e) Primary or secondary successive branching? f) True branching. Note: White arrows indicating closely spaced mantle lobes.

Initially, the ichnospecies *Macaronichnus segregatis* was proposed by Clifton and Thompson (1978) based on small specimens (3–5 mm in diameter), without establishing any diagnosis. Bromley et al. (2009) established a diagnosis and subdivided the ichnospecies into the four ichnosubspecies (*M. s. segregatis*, *M. s. lineiformins*, *M. s. meandriformis*, and *M. s. spiriformis*). Rodríguez-Tovar and Aguirre (2014) considered the large morphotypes with occasional true branching as ichnosubspecies of *M. segregatis*, and named them as *M. s. degiberti*. Nevertheless, recent studies consider that the formative process of the burrows indicated that true branching should be reconsidered as a diagnostic criterion (Nara and Seike, 2019). Even if size is not a recommended ichnotaxobase (Bertling et al., 2006), the most significant feature of *M. s. degiberti* can be its larger size (Rodríguez-Tovar and Aguirre, 2014; Nara and Seike, 2019). Therefore, the studied specimens exhibiting a large size (7–15 mm in diameter) have been assigned to the ichnosubspecies *M. s. degiberti*.

7.4.2. *Macaronichnus* at the contouritic facies: size, distribution and abundance

M. s. degiberti was found in coarser silts to medium-grained sandstones with planar to cross-bedded stratifications (Fig. 7.3a, b), interpreted as sandy drift complexes (Capella et al., 2017), and, less commonly, in the trough (lee side) of the cross-stratified medium- to coarse-grained sandstones accumulated inside the troughs formed by the migration of dune complexes (Fig. 7.3c). *Macaronichnus* density is greater near the sandstone units associated with contouritic channels (sides and axis). Abundance of *Macaronichnus* decreases progressively aside from the channels. Specimens located in high to low-angle cross-stratified sandstones are larger (10–15 mm) and record the highest densities with multiple cross-cutting relationships (Fig. 7.3a). Specimens in planar heterolithic sandstone beds are also large (9–13 mm) but more scattered (Fig. 7.3d). *Macaronichnus* inside the trough of cross-stratified sandstones near the channel-axis is slightly smaller (7–9 mm) but not abundant.

7.5. Discussion

7.5.1. Deep-sea benthic communities and bottom currents

The interaction between bottom currents of different hydraulic regimes and deep-sea benthos is ambiguous, in that effects can be either positive or negative (Levin et al., 2001). Previous studies suggest that macrofauna are more strongly impacted by bottom currents than meiofauna, but still involve local and regional mechanisms that are not well understood (see Levin et al., 2001 for a review). Generally, moderate currents can enhance the food supply, favouring the increase abundance and diversity of benthic fauna (Thistle et al., 1985; Aller and Aller, 1986). On the other hand, strong currents may decrease diversity directly by eroding surficial sediments and carrying away the organisms living in them (Aller, 1997). Nevertheless, a strong-current regime is not continuous, creating repeated breaks for opportunistic recolonization (Thistle et al., 1985, Thistle et al., 1991; Lambshead et al., 2001); during flow deceleration intervals, meio- and macrofauna can rapidly respond (Wetzel et al., 2008). Within these high hydrodynamic environments, active sedimentary ripples can generate heterogeneities in the seafloor by successively burying and exposing organic matter, which accumulates in the troughs, thereby determining the increase in benthic fauna with respect to steady areas (Thistle, 1998). Therefore, the redistribution of phytodetritus by bottom currents can establish topographic depressions as an organic-enrichment region, allowing a deposit-feeder community to exploit these localized food sources (Amaro et al., 2015). A similar response can be interpreted in the sandy contouritic drift with *M. s. degiberti* trace maker colonization associated with the periodic deceleration of bottom currents. Moreover, the trough between the sedimentary structures can act as topographic depressions where organic matter accumulates (Fig. 7.6).

The polychaetes, in which modern counterparts of *Macaronichnus* trace maker are included, show peculiar population dynamics with respect to hydrodynamic regimes. Gage (1997) demonstrated that diversity is highest at deep-marine calm sites, while Paterson and Lambshead (1995) observed a strong linear relationship between the frequencies of current velocities, with polychaete taxa generally being considered to be opportunists that predominate with high current speeds. Thistle et al. (1985) reported that in environments with high-energy currents abundance does not necessarily decrease; rather, increasing flow velocity favours the dominance of small and sexually immature polychaetes. Thus, there is no single response to different hydrodynamic regimes, but abundance, diversity, size, and behaviour of polychaete communities seem to be closely related to environmental energy stress, rather than with water depth. Tentatively, in the *M. s. degiberti* trace maker community from the sandy contouritic deposits studied, size, distribution, and abundance are related mainly to flow strength, seafloor heterogeneity, and food supply (Fig. 7.6a). Thus, low flow strength favoured the development of scattered *Macaronichnus* colonization due to comparatively scarce nutrient availability and then higher nutrient competitiveness on the seafloor (Fig. 7.6b-I). When flow accelerated and a moderate current was established, the food input increased, favouring the development of larger *Macaronichnus* inside the planar to low-angle cross-stratified sandstones (Fig. 7.6b-II). Similar actual environments record a scarcity of suspension feeder organisms (Thistle et al., 1991). This is probably due to the plugging of their filtering apparatus when the suspension concentration is periodically very high (Thistle et al., 1991), giving way to the dominance of deposit-feeding fauna. Moreover, during higher-energetic conditions, local areas as trough in cross-stratified sandstones near the main axis of the contouritic channel, can be colonized by smaller trace makers of *Macaronichnus* (3c and 6b-III), exhibiting an opportunistic behaviour similar to the one observed for actual benthos in topographic depressions with organic-enrichment due to bottom currents (Amaro et al., 2015).

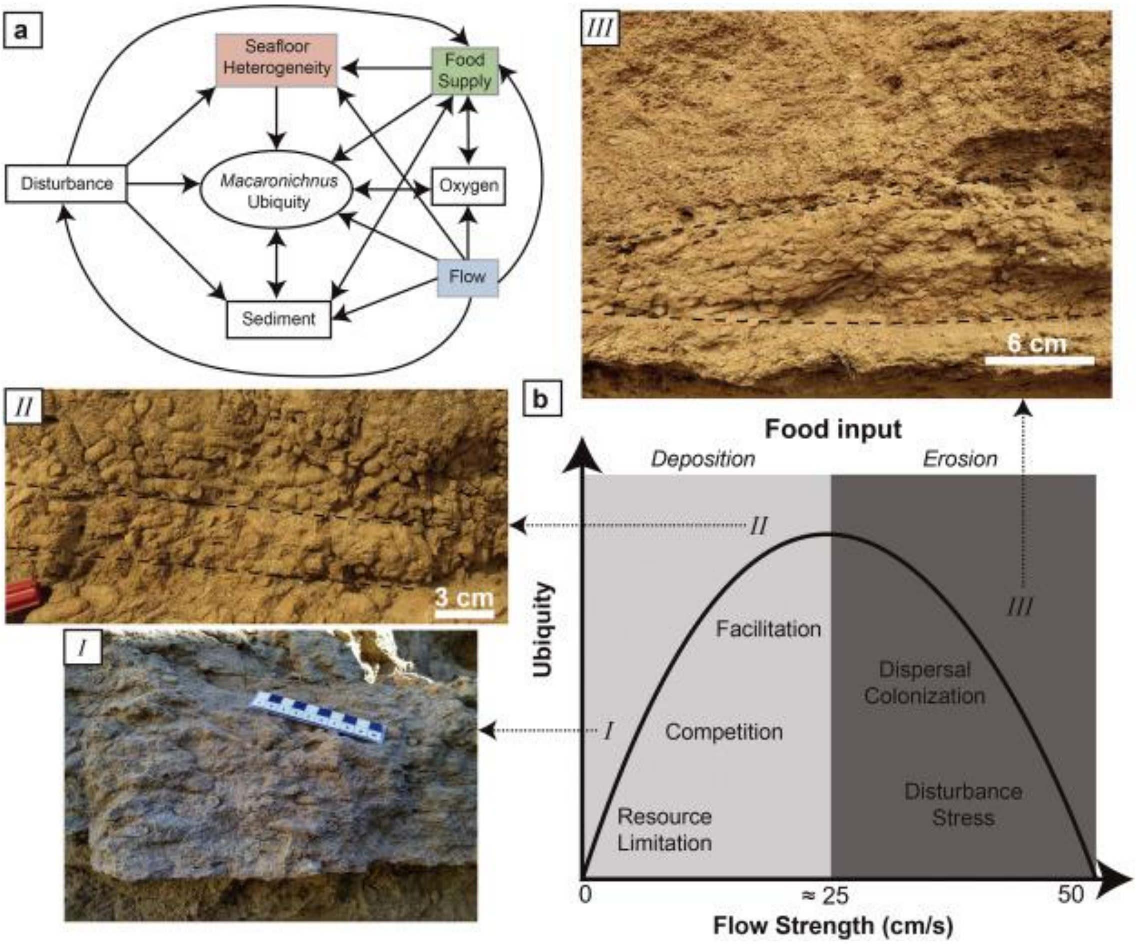

Fig. 7.6. Relationships between *Macaronichnus* ubiquity and palaeoenvironmental parameters. a) Conceptual model indicating direct and indirect effects of various environmental factors on *Macaronichnus* ubiquity, with different colours representing the most important in the study case (modified from Levin et al., 2001). b) Hypothesised food-input pattern and its relationship to the ubiquity of *Macaronichnus* in relation to flow velocity, showing three different cases (I to III) observed in the present study. Low flow strength associated with scarce food input determined higher nutrient competitiveness on the seafloor, inducing development of scattered *Macaronichnus* trace maker

communities (I); increase in food input associated with higher flow strength favoured the development of larger and abundant *Macaronichnus* in planar to low-angle cross-stratified sandstones (II); higher flow strength conditions determined lower deposition, even winnowing, of organic matter and thus the local record of smaller *Macaronichnus* in the trough of cross-stratified sandstones (III). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

7.5.2. Nutrients and bottom currents

The deep sea is a food-limited environment in which abundance and evolution of benthic fauna is in part controlled by the amount of organic matter that reaches the sediment surface (Suess, 1980; Lampitt, 1985; Gooday and Turley, 1990; Wetzel and Uchman, 2018). The interaction of bottom currents with ocean seafloor topography is most likely the mechanism by which organic-matter cover is controlled, in which bottom-current velocity and organic-matter cover resuspension may register different threshold speed values (Morris et al., 2016). Thus, bottom-current intensity would affect the amount of organic matter that is re-suspended, deposited or directly provided by the hemipelagic rain (Thomsen et al., 2002; McCave, 2008), changing the thickness of the nepheloid layer (McCave, 2008). Furthermore, the velocity fluctuations in deep bottom currents affect the transport of sediment, passing from depositional regimes to winnowing and erosional phases (Rebesco et al., 2014). Such changes in the energy regimes has implications for the benthic community, leading to different trace maker communities, variable burrowing rates, diverse bioturbation depths, and a specialized behaviour (Baldwin and McCave, 1999; Wetzel et al., 2008). Previous studies contended that bottom currents may carry a considerable amount of particulate organic matter in suspension (Thomsen et al., 2002; McCave, 2008; Wetzel et al., 2008), determining the abundance and diversity of trace makers across the continental slope, with 25 cm/s as the threshold value from which the organic matter is removed (Fig. 7.6b) (Aller, 1989, Aller, 1997; Wetzel et al., 2008). Also, high organic-matter flux related to bottom currents can enhance the production of bacterial biomass on the seafloor (Yingst and Aller, 1982). Therefore, profuse bioturbation is commonly associated with relatively abundant organic-matter contents in silty and sandy sediments affected by bottom currents, where moderate to high sedimentation rates facilitate the preservation of organic matter (Stow et al., 2013; Bahr et al., 2014).

In the sandy contouritic drift of the Rifian Corridor, conditions conducive to colonization by *M. s. degiberti* trace maker appear to have been generated in deeper environments, showing that depth is not a limiting factor for this producer; thus for *M. s. degiberti* trace maker occurrence other environmental (ecological and depositional) factors reveal of higher importance (Fig. 7.6a). From the involved factors (Fig. 7.6a) some of them could be totally discarded: i) Changes in the relative abundance of *M. s. degiberti* within the same lithology reveals that sediment was not a limiting factor; and ii) rapid ingestion of abundant organic matter by *M. s. degiberti* trace maker avoided degradation and then oxygen consumption, being this available for macrobenthos (see

Fig. 11 in Wetzel and Uchman, 2012 for relationship between organic matter deposition and oxygenation). The presence of *M. s. degiberti* only locally into studied bottom current deposits allows to discard the major incidence of flow. Thus, an interplay between food supply/flow/seafloor heterogeneity, being food supply the main limiting factor, could determine *M. s. degiberti* trace maker occurrence (Fig. 7.6a). Then, we suggest that environmental conditions (food supply/flow/seafloor heterogeneity) brought about by the ancient bottom currents favoured the development of opportunistic smaller *Macaronichnus* communities near the contouritic channel axis, and larger ones along the sandy drift with progressively density decrease aside from the channels. This finding is not unexpected. Lateral systematic variability of ichnological content across proximal to distal depocenters within a contourite drift has been recently proved, passing from *Zoophycos* and *Thalassinoides* (distal) to *Palaeophycus* (proximal) trace fossil assemblages (Dorador et al., 2019). This supports that tracemakers' behaviour as well as organic matter availability varies depending on the distance to the bottom current core (Dorador et al., 2019).

The main factor for *M. s. degiberti* occurrence may be the increasing of food supply carried through the Mediterranean-Atlantic gateway within the bottom current outflow. This agrees with the appearance of *M. segregatis* in tropical shallow-marine environments from low latitudes and in upper slope settings, both linked to coastal upwelling that replenishes the surface waters with nutrients (Quiroz et al., 2010; Knaust, 2017). Thus, *Macaronichnus* could be tentatively related to nutrient availability regardless of the particular setting, although different ichnosubspecies of *M. segregatis* could reveal distinct requirements.

7.6. Conclusions

The first record of exceptionally large and abundant *Macaronichnus* (*M. s. degiberti*) in deep marine sandy contourite deposits in the Late Miocene Rifian Corridor (Morocco) is presented, showing significant differences with all other documented occurrences from shallow to deep-marine settings. This study supports that *Macaronichnus* should not be considered an unequivocal indicator for shallow-marine depositional environments but as indicative of palaeoenvironmental conditions; i.e., indicator of nutrient availability on the seafloor, favouring the use of *Macaronichnus* in palaeoenvironmental reconstructions. In the study area, nutrient-rich Mediterranean overflow water associated with contouritic deposits provided suitable conditions for developing of *M. s. degiberti* community. This research further expands the implications of *Macaronichnus* in contouritic drift deposits, implying that bottom currents can enhance nutrient fluxes throughout deep-marine environments. An understanding of the relationship between bottom-current dynamics, seafloor topography, and organic-matter availability, enables an approach to the role of contouritic processes on macrobenthic trace maker community and thus the use of ichnology as a tool in contourite characterization and in sedimentary basin research.

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Chapter 8

THE LATE MIOCENE RIFIAN CORRIDOR AS A NATURAL LABORATORY TO EXPLORE A CASE OF ICHNOFACIES DISTRIBUTION IN ANCIENT GATEWAYS

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OPEN The Late Miocene Rifian corridor as a natural laboratory to explore a case of ichnofacies distribution in ancient gateways

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ABSTRACT

Oceanic gateways have modulated ocean circulation and have influenced climatic variations throughout the Earth´s history. During the late Miocene (7.8 - 7.35 Ma), the Atlantic Ocean and the Mediterranean Sea were connected through the Rifian Corridor (Morocco). This gateway is one of the few examples of deep ancient seaways with a semi-continuous sedimentary record. Deposits comprise turbidites intercalated between deep-sea mudstone (i.e., hemipelagites and drift deposits), channelized sandstone contourite facies, and shallow marine sandstone. Herein an ichnological analysis was conducted in these upper Miocene sediments to improve characterisation of palaeoenvironmental conditions. In addition, ichnofacies were analysed to elucidate how bottom currents control ichnofacies distribution and can modify their attributes. Turbidite deposits are typified by vertical trace fossils (i.e., *Ophiomorpha*), conforming the *Ophiomorpha rudis* ichnosubfacies. Contouritic sandstone exhibits high density and low diversity trace-fossil assemblage, with predominant *Macaronichnus* and *Scolicia*, resembling a proximal expression of the *Cruziana* ichnofacies. Shallow marine environments are dominated by vertical trace fossils (e.g., *Conichnus*, *Ophiomorpha*, *Skolithos*), allowing an assignation to the *Skolithos* ichnofacies. This study reveals for the first time a variability in ichnofacies attributes and distribution at the Rifian Corridor, associated with turbidites, contourite and shallow marine sediments. Hydrodynamic energy reveals as the major factor controlling trace maker communities in the studied seaway. Highly energetic conditions typical of shallower settings are present in deeper-water environments (i.e., slope), contributing to ichnodiversity impoverishment in ichnofacies.

8.1. Introduction

Oceanic gateways play a key role in controlling global ocean circulation and climate systems (Knutz, 2008). Ancient seaways are unique environments in which a complex interplay of processes may take place (i.e., oceanic-, tidal-, bottom-, turbiditic- and wind-currents) (de Weger et al., 2020, 2021). The constricted morphology of the seaway usually funnels and amplifies the currents that shape the seafloor (i.e., tidal currents) (Longhitano, 2013). Previous sedimentological studies of ancient seaways have been largely focussed on shallow counterparts (generally between 100–150 m of water depth) (Anastas et al., 2006; Olariu et al., 2012; Longhitano, 2013). Few published examples of deep ancient seaways (> 150 m) and associated deposits can be found. However, oceanographic studies have shown that deep seaways are different from shallow ones, with bottom-currents sometimes playing a dominant role (Legg et al., 2009; Hernández-Molina, et al., 2014; Rebesco et al., 2014). The Rifian Corridor is one of those few examples (Fig. 8.1) (Capella et al., 2017a, 2018; de Weger et al., 2020, 2021).

During the late Miocene, the Atlantic Ocean and the Mediterranean Sea were connected by two principal gateways, with a complex morphology, sills and channels through south Iberia and north Africa —the Betic and Rifian corridors, respectively (Flecker et al., 2015; Krijgsman et al., 2018). The Rifian Corridor was a main deep seaway of this network (Fig. 8.1). This gateway progressively closed (7.1-6.9 Ma) due to tectonically induced uplift, leading to the onset of the Mediterranean Salinity Crisis in the late Miocene (Capella et al., 2017b; Krijgsman et al., 2018). During the late Tortonian, the seaway evolved into a narrow, deep corridor hosting a complex interplay of processes (de Weger et al., 2020, 2021).

Ichnological analysis comprises a wide range of tools (e.g., ichnofabric approach, ichnofacies model) that prove very useful in sedimentary basin research (Knaust and Bromley, 2012). The ichnofacies model is of special interest for detailed palaeoenvironmental reconstructions and for recognizing, distinguishing, and interpreting sedimentary environments (Frey et al., 1990; MacEachern et al., 2007, 2012; Buatois and Mángano, 2011). Recent steps in ichnological research have established means of recognising and characterising contouritic processes, revealing the importance of ichnology as a proxy for discerning between contourites, turbidites, hemipelagites and pelagites (Wetzel et al., 2008; Rodríguez-Tovar and Hernández-Molina, 2018; Miguez-Salas and Rodríguez-Tovar, 2019a, b; Rodríguez-Tovar et al., 2019), but not without skepticism (Shanmugam, 2017). At any rate, the relationship between deep-sea settings and trace fossils is very complex, and depends highly upon the palaeonvironmental factors that affect trace makers (Wetzel and Uchman, 2012).

Trace-fossil research on seaway environments has been conducted mainly on shallow marine settings, including brackish-water ecosystems (i.e., estuarine complexes, resulting in the so-called “brackish-water model”; MacEachern and Gingras, 2007;

Angulo and Buatois, 2012), beach–shoreface complexes with evidence of tidal processes (Collela and d'Alessandro, 1988; Frey and Dashtgard, 2011), and compound dune fields (Desjardins et al., 2012). Still, detailed trace-fossil analysis and ichnofacies characterisation of ancient deep seaways has never been carried out. The aim of this research is to conduct a detailed ichnological analysis of selected outcrops of the Rifian Corridor (Ain Kansera, Sidi Chahed, Kirmta and Sidi Harazem), as a unique opportunity to assess trace-fossil variations to interpret an ancient deep-water seaway where shallow marine processes (i.e., tidal variations), pelagic/hemipelagic settling, turbiditic supplies and contouritic flows closely (less than 20 km) interact (de Weger et al., 2020, 2021). We evaluate the importance of palaeoenvironmental factors such as nutrients, oxygenation, and flow velocity in a setting dominated by bottom currents, and their incidence on the trace maker community. The utility of the ichnofacies approach is underlined within the framework of improving high-resolution palaeoenvironmental reconstructions in different depositional environments of ancient deep gateways.

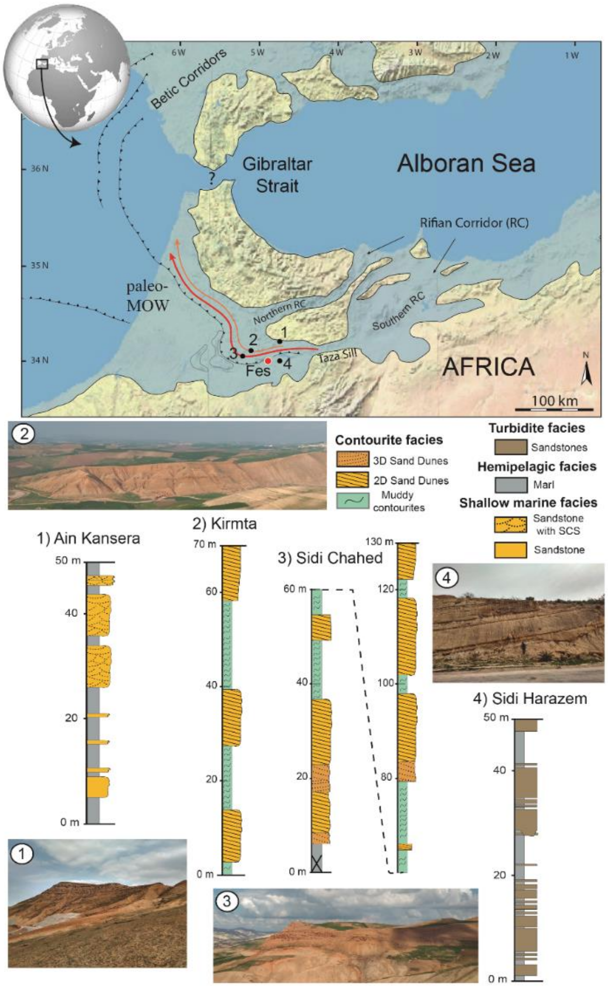

Fig. 8.1. Palaeogeographic reconstruction of the late Miocene western Mediterranean with the location of the studied outcrops; red (lower) and orange (upper) arrows show palaeo-Mediterranean Outflow Water (palaeo-MOW) branches (modified from de Weger et al., 2020). Below, schematic sedimentary logs of the studied outcrops. Map created with Adobe Illustrator, version 22.1.0 (https://www.adobe.com/products/illustrator.html).

8.2. Methods

8.2.1. Geological setting

The Rifian Corridor (Morocco) connected the Atlantic Ocean and the Mediterranean Sea during the late Miocene (Fig. 8.1). The outcrops studied herein are located on the northern flank of the Saiss Basin in the South Rifian Corridor, west of Taza-sill10 (Fig. 8.1). This basin comprises middle to upper Miocene foreland deposits (Sani et al., 2007) and records a unique contourite channel system related to the palaeo-Mediterranean Outflow Water (Palaeo-MOW; de Weger et al., 2020), which resulted from net evaporation in the Mediterranean leading to dense water formation. Regional tectonic activity favoured the development of turbiditic and gravity flows, inducing a complex deep system in which variable sedimentary processes interacted (de Weger et al., 2020).

Four outcrops (Fig. 8.1) from the Saiss Basin were selected for study: i) Sidi Harazem (34°01′52.67″N, 4°52′47.69″W), ii) Kirmta (34°10′15.07″N, 5°14′21.43″W) iii) Sidi Chahed (34°05′58.07″N, 5°18′15.12″W), and iv) Ain Kansera (34°07′34.06″N, 4°51′20.04″W). A brief facies description is included below, for more detailed information (see Capella et al., 2017a; de Weger et al., 2020).

The Sidi Harazem outcrop consists mainly of upper Tortonian (between 7.80 and 7.51 Ma) sandstone and marlstone intercalations10. The sandstone beds, up to 4 m thick, are commonly structureless, normally graded, and composed of poorly to moderately sorted, medium- to coarse-grained sand. Locally, channel-like features are observed. The deposits have been associated to a basinal turbidite system with benthic foraminiferal assemblages indicating water depths of 250–400 m (Capella et al., 2017a).

The Sidi Chahed sections, previously studied by Capella et al. 2017a and de Weger et al. 2020, and the Kirmta outcrop, previously studied by de Weger et al. 2020, consist of three main channelized upper Tortonian (7.8 – 7. 51 Ma) sandstone units encased in blue marls. Both outcrops contain different orders of unidirectional traction structures, ranging from ripples to m-scale 3D-dunes. Interbedded slump deposits have been identified within the main sandstone bodies, while turbidites have been recognized between the main sandstone bodies that are encased by marlstones (de Weger et al., 2020). In both outcrops, the blue marls have been most likely interpreted as muddy contourites (see Capella et al., 2017a; de Weger et al., 2020). Both outcrops were deposited within a palaeodepth range from the upper slope to the outer shelf (150–400 m water depth) (Capella et al., 2017a; de Weger et al., 2020).

The Ain Kansera outcrop consists of upper Tortonian (between 7.51 and 7.31 Ma) sandstone and marlstone intercalations (Capella et al., 2017a). Sandstone bed thicknesses range from 1 to 10 m, the beds containing medium- to coarse- and very coarse-grained sand. They consist of a compositional mix of siliciclastic and bioclastic sand, and regularly contain hummocky and swaley cross-stratification. Benthic foraminiferal assemblages and the presence of hummocky cross-stratification indicate an inner shelf environment (water depths of 50–100 m) (Capella et al., 2017a). Toward the top, the thick sandstone intervals probably represent a shallower (15–50 m water depth) wave-dominated infralittoral setting.

8.2.2. Methodology

Ichnological analysis from the selected sections at Sidi Harazem (50m), Sidi Chahed (130m), Kirmta (70m) and Ain Kansera (50m) was conducted first at the outcrop and then in laboratory. Special attention was pay to the correlation between ichnological attributes, facies and bed features (preservation within sedimentary beds and relationship with bottom and top surfaces). Outcrop analysis was performed bed-by-bed focusing on abundance, diversity and macroscopic morphological burrow features (e.g., orientation, shape, length / diameter, cross-cutting relationships, and taphonomy). Collected specimens were examined in the laboratory under microscope, with special attention to ichnotaxonomical features (e.g., infilling material, burrow wall). The images of some photographed specimens (outcrop and laboratory) were treated with image software to improve visibility of ichnological features (Miguez-Salas et al., 2019). Collected samples are housed in the Department of Stratigraphy and Palaeontology, University of Granada.

8.3. Trace fossil assemblages at the Rifian Corridor

In both contouritic and turbiditic deposits, ichnodiversity is low (4 and 5 ichnogenera, respectively), whereas trace-fossil abundance is high in the former and moderate in the latter. Shallow marine deposits from the southern Rifian Corridor feature an abundant and moderately diverse trace-fossil assemblage (9 ichnogenera). Within the selected outcrops, the clear ichnological variability can be attributed to the different facies.

The Sidi Harazem turbiditic ichnoassemblage consists of 5 ichnogenera — *Ophiomorpha* (*O. rudis*), *Planolites*, *Spirophyton*, *Thalassinoides*, and *Zoophycos* (Fig. 8.3 E-H)— and the thick sandstone beds are more bioturbated than the marly ones. *Ophiomorpha* is the most abundant ichnogenus, and appears in the thick turbiditic sandstone beds; *Thalassinoides* is common, *Planolites* rare, and *Zoophycos* and *Spirophyton* is occasionally found. The trace-fossil assemblage of marly pelagic and hemipelagic deposits from the Sidi Harazem consists of abundant undifferentiated structures and scarce *Planolites*-like and *Thalassinoides*-like trace fossils.

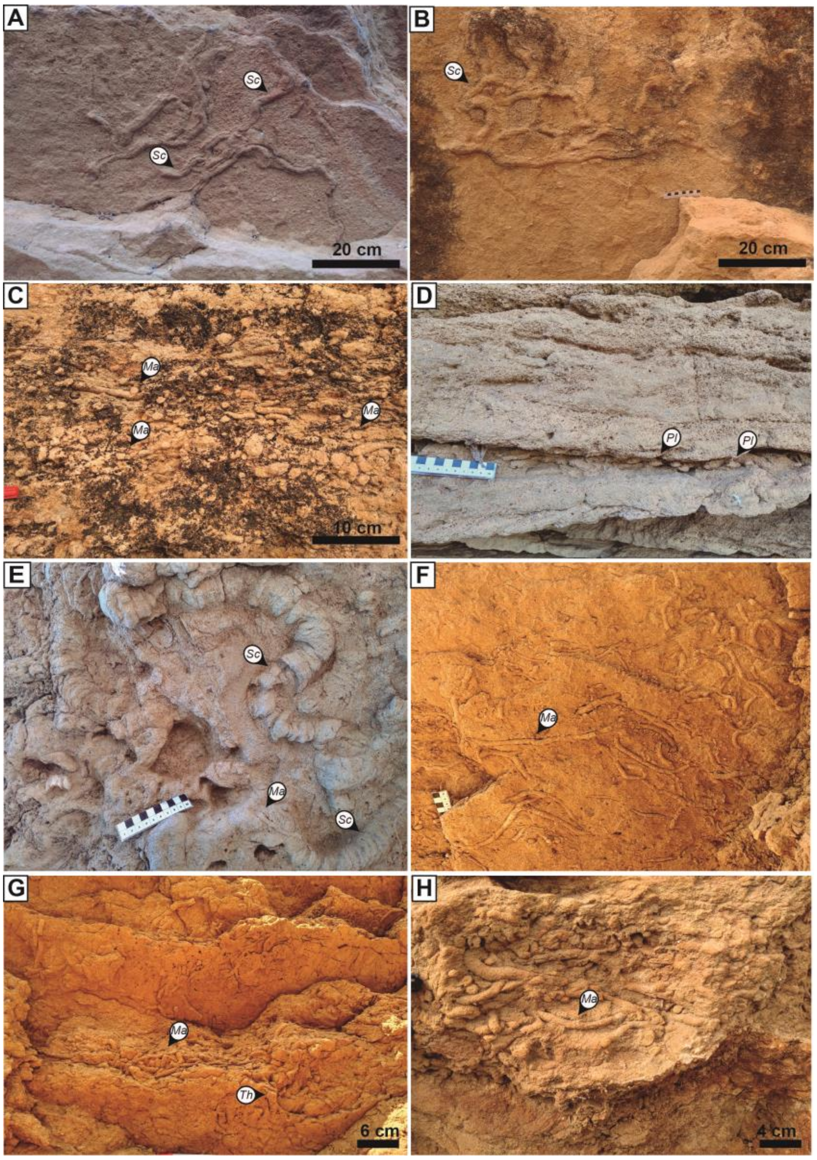

Fig. 8.2. Trace-fossil specimens from the sandy contourite deposits at Sidi Chahed (A-D) and Kirmta (E-H) outcrops. A-B) *Scolicia* in the sole of sandy clastic contouritic beds of Sidi Chahed; C) Close-up view of *Macaronichnus* at Sidi Chahed; D) *Planolites* within the interbedding of the foresets at Sidi Chahed. E) *Scolicia* and some *Macaronichnus* at Kirmta; F-G) *Macaronichnus* isp. and some *Thalassinoides* in the sole of sandy clastic contouritic beds at Kirmta; H) Close-up view of *Macaronichnus* at Kirmta. *Macaronichnus* (*Ma*), *Planolites* (*Pl*), *Scolicia* (*Sc*), and *Thalassinoides* (*Th*).

The sandy contourites in Kirmta and Sidi Chahed comprise a highly abundant and scarcely diverse trace-fossil assemblage (4 ichnogenera), dominated by *Macaronichnus* and *Scolicia*, and common *Planolites* and *Thalassinoides* (Fig. 8.2). Trace fossils were predominantly found in the planar-stratified and cross-bedded sandstone. Turbidites show an absence of discrete trace fossils. The trace=fossil assemblage of muddy contourite deposits from both outcrops consist of regular undifferentiated biogenic structures and scarce *Planolites*-like and *Thalassinoides*-like trace fossils.

The Ain Kansera section is characterised by a shallow marine ichnoassemblage with high ichnodiversity and an abundance of vertical structures, including 9 ichnogenera in the sandstone beds: *Conichnus*, *Diplocraterion*, *Macaronichnus*, *Ophiomorpha*, *Parahaentzschelinia*, *Planolites*, *Scolicia*, *Skolithos*, and *Thalassinoides* (Fig. 8.3 A-D). The sandstone beds with swaley cross-stratification show a change in the trace-fossil assemblage towards the top of the outcrop. The lower sandstone beds present dominant *Conichnus* and *Macaronichnus*, common *Parahaentzschelinia* and *Thalassinoides*, and rare *Diplocraterion*, *Planolites*, and *Scolicia*. The upper sandstone beds record the disappearance of *Conichnus* and *Parahaentzschelinia*, while *Ophiomorpha* and *Skolithos* become dominant.

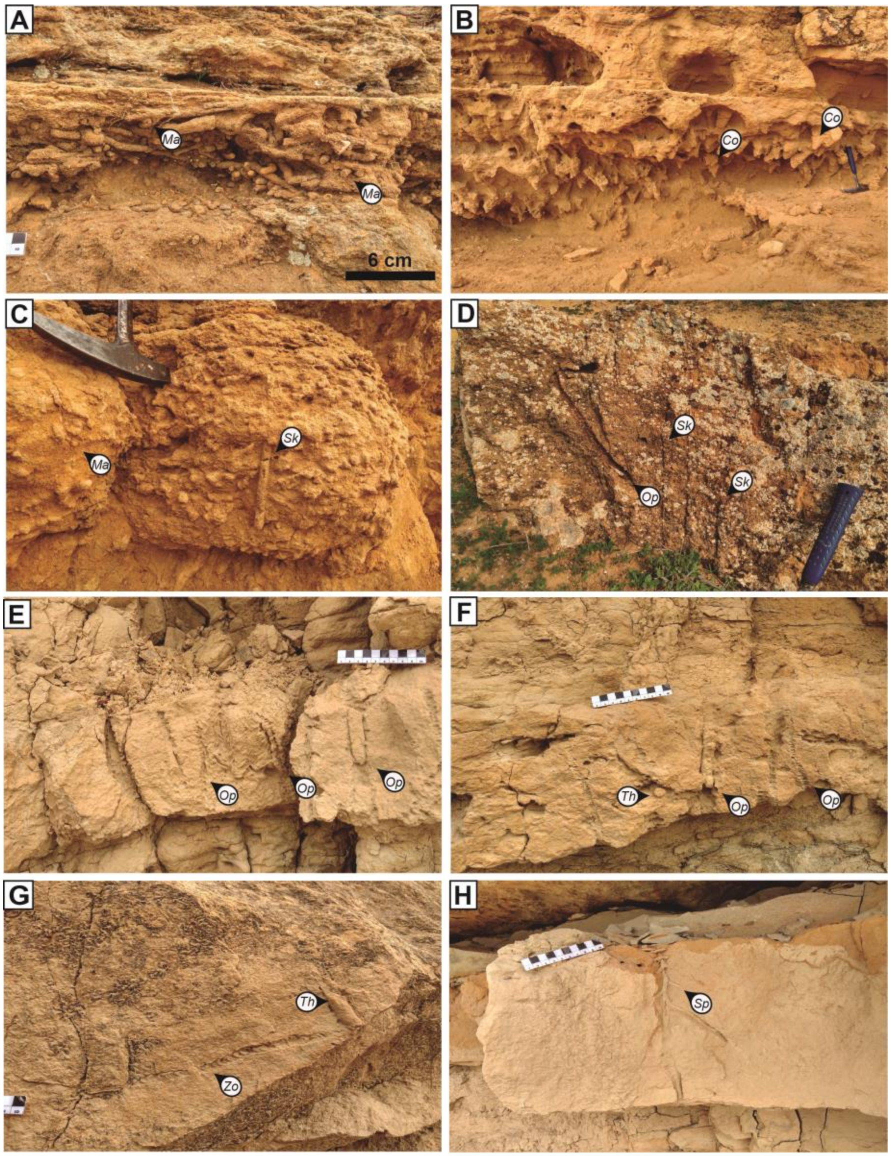

Fig. 8.3. Trace-fossil specimens from shallow marine deposits at Ain Kansera (A-D) and turbiditic deposits at Sidi Harazem (E-H). A) Close-up view of *Macaronichnus* at Ain Kansera; B) Densely *Conichnus* assemblage at Ain Kansera; C) *Macaronichnus* cross-cut by a *Skolithos* at Ain Kansera*;* D) *Skolithos* and *Ophiomorpha* at Ain Kansera; E-F) *Ophiomorpha* (*O. rudis*) at Sidi Harazem; G) *Zoophycos* cross-cut by a *Thalassinoides* at Sidi Harazem; H) Close-up view of *Spyrophyton* at Sidi Harazem. *Conichnus* (*Co*), *Macaronichnus* (*Ma*), *Ophiomorpha* (*Op*), *Skolithos* (*Sk*), *Spyrophyton* (*Sp*), *Thalassinoides* (*Th*), and *Zoophycos* (*Zo*).

8.4. Ichnofacies characterisation

The trace-fossil assemblage of Sidi Harazem is typified by vertical burrows of *Ophiomorpha rudis* and some *Thalassinoides*. *Ophiomorpha* is generally but not exclusively characteristic of high-energy environments (i.e., shoreface) in well-sorted, shifting sandy substrates, constituting a common element of the *Skolithos* and *Cruziana* ichnofacies (MacEachern et al., 2007, 2012). However, the appearance of *Ophiomorpha* in deep-sea environments is also recorded, and usually explained as an effect of transport of the trace makers by currents from shallow marine environments into the deep-sea (Wetzel, 1984; Föllmi and Grimm, 1990). Uchman (2001) proposed the *Ophiomorpha rudis* ichnosubfacies within the *Nereites* ichnofacies for the record of ichnoassemblages dominated by *Ophiomorpha rudis* in thick sandstone beds related with channels and proximal lobes in turbiditic systems (Uchman, 2009). Accordingly, the Sidi Harazem trace-fossil assemblage could be associated with the *Ophiomorpha rudis* ichnosubfacies. Ichnosubfacies/ichnofacies assignation is tentative due to the absence of other components of this ichnosubfacies (e.g., *Scolicia*, *Nereites*, graphoglyptids); this uncertainty is tied to outcrop limitations, e.g. the low exposure of turbiditic soles and difficulties in observing discrete trace fossils in the non-compact hemipelagic and pelagic deposits.

The trace-fossil assemblages of Kirmta and Sidi Chahed feature high abundance and low ichnodiversity, being dominated by horizontal trace fossils, such as *Macaronichnus* and *Scolicia*. *Macaronichnus* is usually interpreted as a shallow marine (up to foreshore) trace fossil (Seike, 2007) that occasionally appears in deeper water environments (Rodríguez-Tovar and Aguirre, 2014; Miguez-Salas et al., 2020) and is commonly associated with the *Skolithos* ichnofacies (Buatois and Mángano, 2011; MacEachern et al., 2007, 2012; Knaust, 2017). *Scolicia* presents a wide environmental range, but is a typical element of the deep-marine *Nereites* and the shelfal *Cruziana* ichnofacies (Knaust, 2017). The proximal expression of the *Cruziana* ichnofacies is dominated by deposit-feeding burrows, but also includes structures of passive carnivores, omnivores, suspension feeders, as well as grazing forms (MacEachern and Bann, 2008). This ichnofacies is defined as a transition between the distal expression of the *Skolithos* ichnofacies and the archetypal *Cruziana* ichnofacies (MacEachern and Bann, 2008). The low ichnodiversity observed within the contourite facies from Kirmta and Sidi Chahed outcrops, together with the ubiquity of the dominant trace fossils, hamper a conclusive ichnofacies assignation. Still, though *Macaronichnus* is typical from high energy shallow marine environments, it may locally appear in the proximal *Cruziana* ichnofacies (MacEachern and Bann, 2008). Considering the dominance of horizontal feeding trace fossils produced by deposit and detritus feeders over dwelling structures of suspension feeding structures, contourite ichnoassemblages at the Rifian Corridor, registered at Kirmta and Sidi Chahed outcrops, can therefore be tentatively assigned to an impoverished proximal *Cruziana* ichnofacies (MacEachern et al., 2012).

The trace-fossil assemblage of Ain Kansera is characterised by moderate ichnodiversity with a dominance of vertical (*Skolithos* and *Ophiomorpha*), cylindrical or conic-shaped (*Conichnus*) dwelling burrows of suspension feeders and passive predators. Horizontal trace fossils produced by a mobile fauna are scarce, mainly associated with *Macaronichnus* trace makers. According to these ichnological features, shallow marine facies at the Rifian Corridor —represented by Ain Kansera sediments— can be clearly assigned to the *Skolithos* ichnofacies, with predominant burrow systems having vertical, cylindrical, or U-shaped components of suspension feeders and passive predators, and a scarcity of horizontal trace fossils (Pemberton et al., 1992; Buatois and Mángano, 2011; MacEachern et al., 2007, 2012; Knaust, 2017).

8.5. Ichnofacies in the Rifian Corridor seaways: hydrodynamic energy and the incidence of bottom currents

Over the past years, detailed ichnological research has revealed the major incidence of particular environmental factors (e.g., organic-matter content, oxygenation, sedimentation rate) on ichnological attributes from deep-sea environments, including ichnofacies characterisation and distribution (Wetzel and Uchman, 2012). The deep sea is a complex environment where several depositional processes co-exist, including pelagic/hemipelagic settling, bottom currents and gravity flows (Rebesco et al., 2014). Trace-fossil analysis has proven useful for discerning and characterising such sedimentary environments and associated deposits (Rodríguez-Tovar and Hernández-Molina, 2018). Hydrodynamic conditions are a very significant limiting factor for trace makers, inducing variations in distribution and behaviour, hence in the preservation of trace fossils (Anderson, and Droser, 1998; Frey and Dashtgard, 2011; Buatois and Mángano, 2011; Dorador et al., 2019). Typically, ichnoassemblages related to high energy conditions are characterised by vertical dwelling structures of infaunal suspension feeders and/or passive predators, forming low-diversity suites; ichnoassemblages related to low energy conditions are dominated by horizontal feeding trace fossils of deposit and detritus feeders, as well as higher diversity (Buatois and Mángano, 2011). Ichnofacies identification is mainly based on the recognition of key features that connect biological structures with physical parameters (i.e., environmental conditions) (Buatois and Mángano, 2011; MacEachern et al., 2007, 2012). Accordingly, ichnofacies reflect specific combinations of organisms′ responses to a wide range of environmental conditions.

In the case of seaways, prevailing hydrodynamic conditions are a main environmental factor, along with controlling depositional processes and sedimentation regimes (Colella and d'Alessandro, 1988; Olariu et al., 2012). Even though the number of trace-fossil studies is considerably lower than in other clastic shallow or deep marine environments, ichnological analysis has proven to be useful to characterise waves, tides or storms in shallow seaways (Colella and d'Alessandro, 1988; Frey and Dashtgard, 2011) overlooking deep seaways and their implications. Deep seaways with narrow palaeogeographical configuration, as is the case of the Rifian Corridor (Capella et al., 2017a), would promote higher energetic conditions than those typical of deep-sea environments. In the study area, clearly distinct sedimentary environments —in terms of hydrodynamic conditions, bathymetry, rate of sedimentation, etc.— are closely spaced (de Weger et al., 2020), passing from shallow marine to turbiditic slope systems in less than 20 km (Fig. 8.4). Such variations in palaeoenvironmental conditions are supported by ichnofacies characterisation and distribution.

Turbidite deposits from Sidi Harazem, emplaced on the slope of the Rifian Corridor, are typified by vertical trace fossils, mainly by the record of *Ophiomorpha rudis*. These ichnological attributes are similar to those associated with particular sub-environments (e.g., channels and proximal trubiditic lobes) of the turbiditic systems, conforming the *Ophiomorpha rudis* ichnosubfacies inside the *Nereites* ichnofacies (Uchman, 2009).

Sandy contourite 2D- and 3D-dune facies (upper slope environment) (Fig. 8.4) from Sidi Chahed and Kirmta are related to high-energy deep-water environments. However, they are dominated by horizontal trace fossils (*Macaronichnus* and *Scolicia*) produced by mobile deposit- and detritus-feeders, discarding a direct assignation to the *Skolithos* ichnofacies. In this case, palaeoenvironmental conditions other than hydrodynamic energy must be considered to explain the dominance of horizontal forms and the absence of vertical biogenic structures. The record of densely *Macaronichnus* ichnoasemblages in these contourite sediments was recently linked to high nutrient supply provided by ancient bottom currents (Miguez-Salas et al., 2020; Miguez-Salas and Rodríguez-Tovar, 2021a). This agrees with the record of *Scolicia*: its abundance and size usually increase in conjunction with greater amounts and nutritious values of benthic food (Wetzel, 2008; Wetzel et al., 2008). Thus, the strong palaeo-MOW bottom currents that dominated the slope may have created well-oxygenated and nutrient-rich benthic environments, favouring colonisation by trace makers that could exploit such accumulations of organic matter inside the sediment. *Macaronichnus* and *Scolicia* producers could develop an opportunistic behaviour, determining rapid and complete bioturbation, avoiding colonisation by other trace makers —including suspension feeders—These ichnological features resemble the *Cruziana* ichnofacies attributes. Notwithstanding, the high ichnodiversity that is characteristic of the *Cruziana* ichnofacies is absent here. The great abundance and low ichnodiversity observed for the contourite facies appear to indicate the absence of an archetypal *Cruziana* ichnofacies, but the development of the proximal *Cruziana* ichnofacies. Bottom currents and their associated deposits (i.e., contourites) have been previously linked to both the *Cruziana* and *Zoophycos* ichnofacies in Cyprus Miocene carbonate contourite deposits (Miguez-Salas and Rodríguez-Tovar, 2019a, b), meaning that contourite deposits are not exclusively related to a single ichnofacies. The replacement from the *Zoophycos* to *Cruziana* ichnofacies was interpreted to be mainly controlled by sea level dynamics (Miguez-Salas and Rodríguez-Tovar, 2019b).

The shallow marine facies from Ain Kansera (shoreface environment) are dominated by vertical, cylindrical, or U-shaped dwelling burrows (*Conichnus*, *Ophiomorpha* and *Skolithos*) of suspension feeders (Fig. 8.4). These attributes are usually related to high energetic conditions developed in shallow marine environments conforming the *Skolithos* ichnofacies (MacEachern et al., 2012).

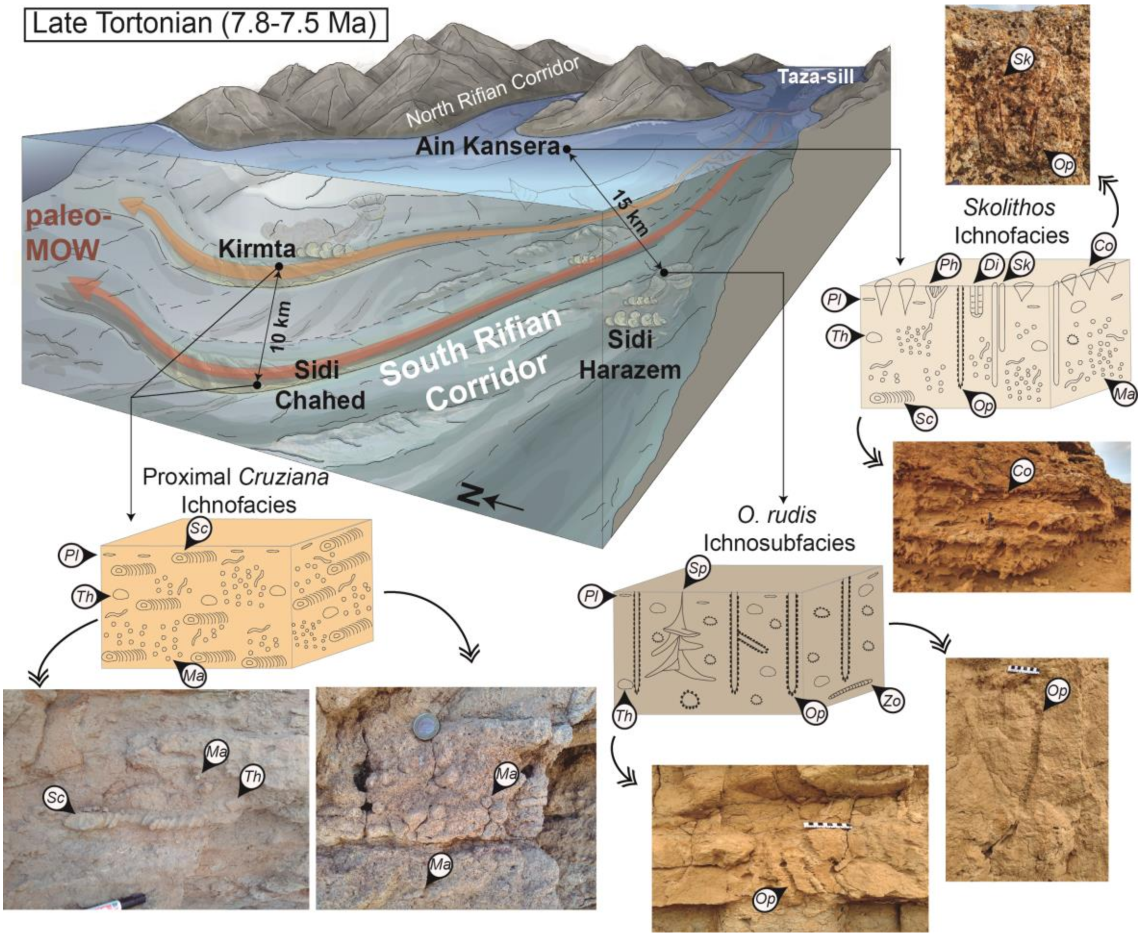

Fig. 8.4. Palaeogeographic model of the late Miocene Rifian Corridor (Morocco) with ichnofacies distribution (lower red and upper orange branches indicate palaeo-MOW location; modified from de Weger et al., 2020). *Conichnus* (*Co*), *Diplocraterion* (*Di*), *Macaronichnus* (*Ma*), *Ophiomorpha* (*Op*), *Parahaentzschelinia* (*Ph*), *Planolites* (*Pl*), *Scolicia* (*Sc*), *Skolithos* (*Sk*), *Spyrophyton* (*Sp*), *Thalassinoides* (*Th*), and *Zoophycos* (*Zo*).

In short, at the Rifian Corridor, ichnofacies distributions from proximal to distal settings are controlled by bottom currents (palaeo-MOW), with hydrodynamic conditions being the major palaeonvironmental limiting factor. Particularly noteworthy is the development of the proximal *Cruziana* ichnofacies in deeper settings from the slope environments; bottom currents generated high energetic conditions similar to those of shallow/proximal areas.

8.6. Conclusions

During the late Miocene, the Rifian Corridor (Morocco) connected the Atlantic Ocean and the Mediterranean Sea. The particular palaeogeographical configuration led this ancient deep seaway to be affected by variable palaeoceanographic processes and associated deposits (e.g., shallow marine sandstones, channelized sandstone contourite facies, and turbidites intercalated between deep-sea hemipelagites), inducing different ichnological features in terms of ichnofacies composition and distribution. Turbidite deposits are typified by vertical trace fossils (i.e., *Ophiomorpha*), with assignation to the *Ophiomorpha rudis* ichnosubfacies. Contourite deposits record ichnological assemblages dominated by *Scolicia* and *Macaronichnus*, with a plausible assignation to the impoverished proximal *Cruziana* ichnofacies. Shallow marine environments are dominated by vertical trace fossils (e.g., *Conichnus*, *Ophiomorpha, Skolithos*) conforming the *Skolithos* ichnofacies. This research evidenced that ichnofacies distribution in the studied ancient seaway (Rifian Corridor) is mainly controlled by the prevailing hydrodynamic regimes.

Acknowledgments

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Supplementary Papers of PART IV

- Trace fossil analysis of sandy clastic contouritic deposits in the late Miocene Rifian Corridor (Morocco): Ichnotaxonomical and palaeoenvironmental insights (Journal of African Earth Sciences, 2021)
- Contourite depositional system after the exit of a strait: case study from the late Miocene Rifian Corridor, Morocco (Sedimentology, 2021)

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Trace fossil analysis of sandy clastic contouritic deposits in the late Miocene Rifian Corridor (Morocco): Ichnotaxonomical and palaeoenvironmental insights

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ABSTRACT

Ichnological analysis was conducted in the late Miocene sandy clastic contouritic deposits from the Rifian Corridor (Morocco). The Rifian Corridor was a main gateway between the Mediterranean Sea and the Atlantic Ocean during the late Miocene. An initial detailed ichnological analysis of clastic contourite facies revealed trace fossil assemblages of high abundance (similar to that of calcareous contourites) and low ichnodiversity. *Parahaentzschelinia* and *Rosselia* were registered for the first time in contouritic facies. *Scolicia* and *Macaronichnus* were found to be the dominant ichnogenera in the studied sandy clastic contourites. Abundant *Macaronichnus*, *Parahaentzschelinia* and *Scolicia* evidence the adaptation of trace makers to "unfavourable" energetic conditions, food availability being a major parameter that favoured opportunistic colonization of the supposedly "un-inhabitable" high-energy contourite depositional setting. Similar ichnological studies conducted in selected outcrops will allow us to address the representative ichnoassemblage of coarser (silty/sandy) clastic contourites.

SEDIMENTOLOGY the journal of the International Association of Sedimentologists IAS
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Contourite depositional system after the exit of a strait: Case study from the late Miocene South Rifian Corridor, Morocco

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ABSTRACT

Idealized facies of bottom current deposits (contourites) have been established for fine-grained contourite drifts in modern deep-marine sedimentary environments. Their equivalent facies in the ancient record however are only scarcely recognized due to the weathered nature of most fine-grained deposits in outcrop. Facies related to the erosional elements (i.e. contourite channels) of contourite depositional systems have not yet been properly established and related deposits in outcrop appear non-existent. To better understand the sedimentary facies and facies sequences of contourites, the upper Miocene contourite depositional systems of the South Rifian Corridor (Morocco) is investigated. This contourite depositional system formed by the dense palaeo-Mediterranean Outflow Water. Foraminifera assemblages were used for age-constraints (7.51 to 7.35 Ma) and to determine the continental slope depositional domains. Nine sedimentary facies have been recognized based on lithology, grain-size, sedimentary structures and biogenic structures. These facies were subsequently grouped into five facies associations related to the main interpreted depositional processes (hemipelagic settling, contour currents and gravity flows). The vertical sedimentary facies succession records the tectonically induced, southward migration of the contourite depositional systems and the intermittent behaviour of the palaeo-Mediterranean Outflow Water, which is mainly driven by precession and millennial-scale climate variations. Tides substantially modulated the palaeo-Mediterranean Outflow Water on a sub-annual scale. This work shows exceptional examples of muddy and sandy contourite deposits in outcrop by which a facies distribution model from the proximal continental slope, the contourite channel to its adjacent contourite drift, is proposed. This model serves as a reference for contourite recognition both in modern environments and the ancient record. Furthermore, by establishing the hydrodynamics of overflow behaviour a framework is provided that improves process-based interpretation of deep-water bottom current deposits.

PART V

ECONOMIC IMPLICATIOS

Chapter 9

X-RAY MICROTOMOGRAPHY ANALYSIS TO APPROACH BIOTURBATION´S INFLUENCE ON MINOR-SCALE POROSITY DISTRIBUTION: A NOVEL APPROACH IN CONTOURITE DEPOSITS

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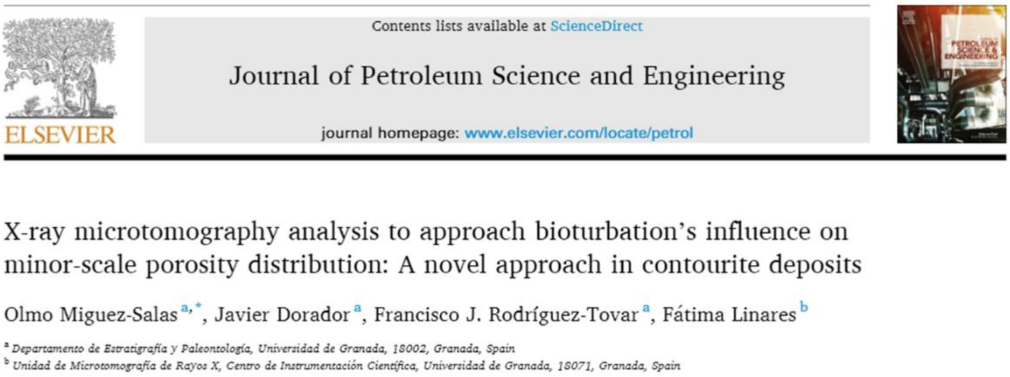

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X-ray microtomography analysis to approach bioturbation's influence on minor-scale porosity distribution: A novel approach in contourite deposits

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ABSTRACT

Micro-CT analysis is employed for the first time to evaluate the effects of bioturbation on porosity distribution in contourite facies, namely: i) sandy clastic contourites from the Late Miocene Moroccan Rifian Corridor; and ii) dominant-calcareous contourites from Eocene- Middle Miocene Cyprus paleoslope. Porosity distribution is affected by bioturbation due to trace maker behavior and burrow infilling, but there is no clear, single relationship. *Macaronichnus*, especially *M. segregatis*, located in sandy clastic contourite facies would have the greatest impact, increasing porosity due to the grain-selective deposit-feeding behavior of the trace maker. Porosity values are up to three times higher in the burrow rim than in the infilling material, which favors a dual-porosity flow medium. Samples with *M. s. degiberti* record higher porosity values in the host sediment than in the burrow fill, but any increase of porosity in the burrow rim is not certain. This variable influence on porosity distribution (*M. segregatis* vs. *M. s. degiberti*) might be associated with different trace maker behaviors during feeding activities, or even with variable producers. *Chondrites* located in muddy chalk contourite facies has a neutral effect on porosity distribution, porosity data of the host sediment and the filling material being similar, in agreement with a comparable grain size. *Thalassinoides* located inside calcarenitic contourite facies has a minor effect on porosity distribution, showing similarities between passively infilled material and the host sediment. Our results also reveal the importance of secondary diagenetic overprints when homogenizing primary differences. Accordingly, understanding the impact of bioturbation on porosity distribution in contourite facies appears to be a key factor for evaluating the real potential of these unconventional reservoirs. This study represents a first step forward in discerning the relationship between contourite facies, ichnological features, petrophysical properties and reservoir geology.

Keywords: Bioturbation, Contourites, Unconventional reservoir, Porosity, Pore structure.

9.1. Introduction

The deep-sea is a complex sedimentary mosaic ruled by deep-water bottom currents, including thermohaline-induced geostrophic bottom currents, deep-marine tidal bottom currents, wind-driven bottom currents and baroclinic currents (Shanmugam, 2008). The study of contourites —deposits associated with thermohaline-induced contour currents— has increased significantly in recent years, with a main focus on paleoclimatology and paleoceanography aspects, slope-stability/geological hazard assessment, and petroleum exploration (Rebesco et al., 2014). Regarding the latter topic, contourites may play an important role in hydrocarbon systems, influencing reservoir geometry, quality and distribution (see Rebesco et al., 2014). Some papers have corroborated and revitalized the significance of contouritic deposits in petroleum exploration (e.g., Viana and Rebesco, 2007; Viana et al., 2007; Viana, 2008; Shanmugam, 2012, 2013, 2017; Marsaglia and Nolasco, 2016; Yu et al., 2020). Analysis conducted on bottom-current reworked sands has shown that porosity and permeability characteristics may surpass turbiditic deposits, a well-recognized reservoir facies, in terms of indicating reservoir quality (see Shanmugam, 2017). Coarse-grained contourites can determine hydrocarbon reservoirs like the one described for offshore Brazil (Viana, 2008; Mutti et al., 2014). Fine-grained contourites may act as seals —as in the Santos Basin, where sealing rocks of bottom-current provenance have been found (Duarte and Viana, 2007)— and/or source rocks (Rebesco et al., 2014). Thus, given a better understanding of unconventional reservoirs and their economic value, contourites could play an important role in forthcoming petroleum exploration (Yu et al., 2020). Accordingly, there is rising interest in contourites as potential reservoirs, both conventional and unconventional, with some exploration researchers marking them as a main target of deep-water exploration in the next few years (Viana et al., 2007; Stow et al., 2011; Yu et al., 2020)

Contourite facies are so commonly characterized by abundant bioturbation that it may be considered as a diagnostic feature (Rebesco et al., 2014; Rodríguez-Tovar and Hernández-Molina, 2018), the latter authors affirming that “One aspect of contourites not yet addressed, however, is the influence of bioturbation in modifying porosity and permeability in sediment”, which can significantly invigorate the economic potential of this facies (Rodríguez-Tovar and Hernández-Molina, 2018). Biogenic structures and unconventional reservoirs are intimately connected (e.g., Schieber, 2003; Jans et al., 2012). Bioturbation impacts unconventional reservoirs by: developing bimodal distribution of pore throat size apertures, preserving intergranular porosity, or enhancing vertical permeability through the inhibition of calcite cementation (Moslow et al., 2021).

Bioturbation is the alteration/reworking of sediments due to the activity of organisms. This process leads to the modification of physical properties of the substrate, such as grain size, removal, compaction, porosity, and permeability, among others (Bromley, 1996). It is generally believed that bioturbation diminishes permeability, since burrowing organisms reduce sorting and can favor sediment homogenization (see Gingras et al., 2012). Nevertheless, during the past decade or so, several examples have shown that bioturbation may enhance bulk permeability, modify pore structure and affect reservoir fluid flow (e.g., Pemberton and Gingras, 2005; Gordon et al., 2010; Cunningham, 2012; La Croix et al., 2013; Eltom et al., 2019; Liu et al., 2019; Quaye et al., 2019; Knaust et al., 2020). Bioturbation is therefore a relevant feature for petroleum exploration. It can affect hydrocarbon reservoirs either positively or negatively, since it modifies their physical and chemical sediment properties (Knaust, 2017). Factors such as burrow morphology, impact of bioturbation on grain-size distribution, and the mineralogy of fossils and grains, together with post-depositional chemical processes, will determine the lateral and vertical distribution of porosity and permeability (Gingras et al., 2012).

The most widely used methodologies to calculate porosity in the context of contourite deposits involve thin section blue epoxy (Marsaglia and Nolasco, 2016), and moisture and density method equations (pore water/wet-bulk mass; see Yu et al., 2020). These methodologies are conducted on bulk contourites offering a general overview. The incidence of bioturbation on petrophysical properties (porosity and permeability) has not been addressed to date.

The novelty of our research lies in its detailed study, for the first time, of the porosity distribution of contouritic deposits, in order to evaluate the impact of bioturbation structures on reservoir-associated properties (i.e., porosity). To this end, X-ray Micro-CT analysis was conducted. This highly precise methodology allows for more exact porosity evaluation than traditional methods. Aiming at a more complete approach, two different types of contouritic facies were studied —clastic and calcareous-dominated contourite deposits— focusing on the matrix and the main bioturbation (i.e., ichnogenus) observed in these deposits. This preliminary research endeavor attempts to shed light on how bioturbation can influence the reservoir porosity of contourite deposits.

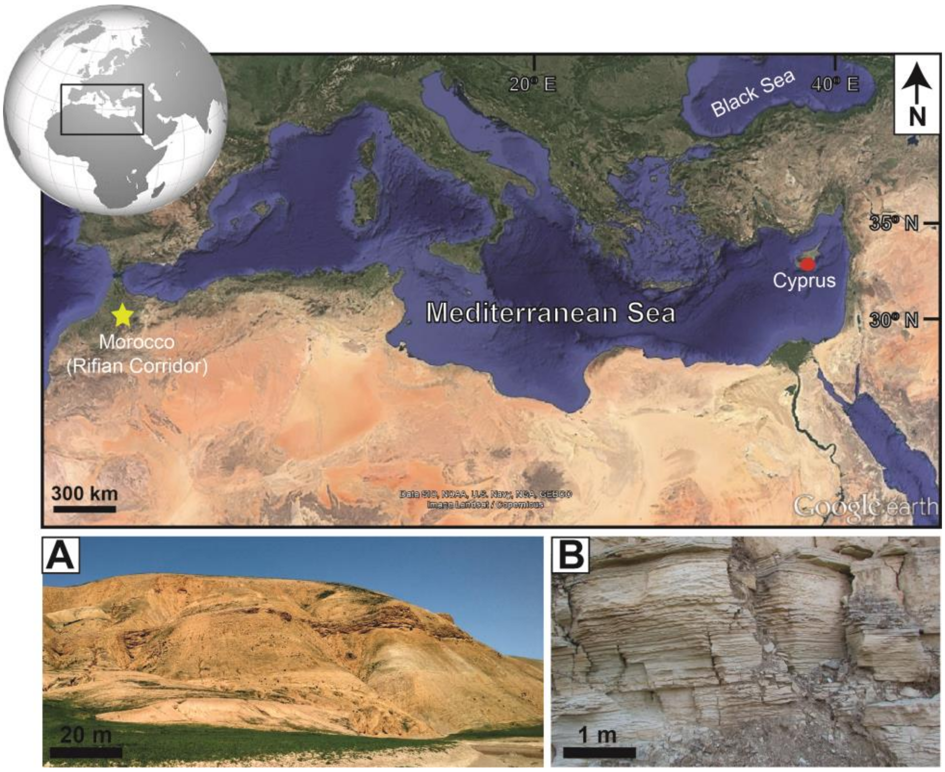

Fig. 9.1. Geographical location of the study areas at the Late Miocene Morocco Rifian Corridor and Eocene-Early Miocene Cyprus paleoslope. A) General view of Kirmta outcrop in Morocco; B) Detailed view of the middle part of Petra Tou Romiou outcrop, showing a bi-gradational contourite sequence.

9.2. Geological context

The research was conducted in two areas (Fig. 9.1): (1) sandy clastic contourite deposits from the Late Miocene Rifian Corridor in Morocco (Capella et al., 2017), and (2) dominant-calcareous contourite facies from the deep-water Eocene-Middle Miocene palaeoslope system in Cyprus (Stow et al., 2002) (Fig. 9.1).

During the Late Miocene, the Rifian Corridor was one of the main seaways that connected the Atlantic Ocean and the Mediterranean Sea (see Krijgsman et al., 2018, for a recent review). This gateway was progressively sealed owing to tectonical processes, leading to the onset of the Mediterranean Salinity Crisis in the Late Miocene (Flecker et al., 2015; Krijgsman et al., 2018). At this time, the bottom-current pathways of the Miocene Mediterranean overflow that went out into the Atlantic Ocean, across the Rifian Corridor, deposited extensive clastic-dominated sandy contouritic sediments (Capella et al., 2017; De Weger et al., submitted). Recent ichnological analyses of these clastic contouritic deposits revealed a trace fossil assemblage consisting of *Macaronichnus*, *Parahaentzschelinia*, *Planolites*, *Rosselia*, *Scolicia* and *Thalassinoides* (Miguez-Salas et al., 2020; Miguez-Salas and Rodríguez-Tovar, 2021a). The studied samples were obtained from the Sidi Chahed and Kirmta outcrops (Fig. 9.1A).

During the Early to Middle Miocene, the Mediterranean Sea was connected to the Indian Ocean through the Indian Gateway (see de la Vara and Meijer, 2016). On the western side of the gateway, the westward bottom-current pathways that came out into the Mediterranean Sea modulated the southern Cyprus paleoslope and associated deposits (de la Vara and Meijer, 2016). Eocene-Middle Miocene deep-water deposits in Cyprus are mainly represented by the Lefkara and Pakhna formations (Edwards et al., 2010). The Lefkara Formation contains an accumulation of pelagic or hemipelagic chalky sediments, with a significant influence of bottom currents and punctual distal turbiditic episodes determining the record of contourites and turbidites (Kähler and Stow, 1998; Stow et al., 2002; Rodríguez-Tovar et al., 2019a). The trace fossil assemblage of contourite deposits from the Lefkara Formation is composed of *Chondrites*, *Planolites*, *Taenidium*, *Thalassinoides*, and *Zoophycos* (Miguez-Salas and Rodríguez-Tovar, 2019a). The Pakhna Formation was deposited during the Early to Late Miocene, showing an upwardly increasing input of shallow water components. Significant bottom currents originated calcilutitic and calcarenitic bioclastic contourites of different thicknesses (Hernández-Molina et al., 2018; Rodríguez-Tovar et al., 2019a, b). The trace fossil assemblage from contourite deposits at the Pakhna Formation mainly consists of *Chondrites*, *Gyrolithes*, *Ophiomorpha*, *Planolites*, *Syringomorpha*, *Teichichnus* and *Thalassinoides* (Miguez-Salas and Rodríguez-Tovar, 2019b; Miguez-Salas et al., 2019a). The studied samples were obtained from the Petra Tou Romiou and Kalavasos outcrops (Fig. 9.1B).

9.3. Materials and Methodology

Samples from sandy clastic and dominant-calcareous contourites were selected in outcrops in view of trace fossil features. First, a detailed ichnological analysis was conducted in outcrop, with the focus on macroscopic ichnological features such as orientation, architecture, shape, length and diameter of individual burrow segments, density, and cross-cutting relationships. Numerous samples were collected to be studied in the laboratory. Polished and thin sections were studied by the naked eye and under the microscope with special attention to additional ichnological properties as infilling material, halos, internal textures, and deformation, among other features. Some of these thin sections have been previously studied for quantitative petrography characterization (see Dorador et al., 2021). Finally, several samples were selected, involving more than 30 specimens of *Chondrites*, *Macaronichnus* and *Thalassinoides*.

Chondrites burrows are complex, root-like, passively filled systems of vertically oriented branching tunnels (Baucon et al., 2020 and references therein). Selected samples feature different neighboring burrow systems, showing cross-cutting relationships as a common feature of *Chondrites* assemblages (Baucon et al., 2020). *Macaronichnus* are actively filled burrows associated with grain-selective deposit-feeding behavior, resulting in a slightly light-colored core and a darker surrounding mantle, with different petrographic features (Miguez-Salas et al., 2020). The size of both the core and the surrounding mantle, together with morphological features (i.e., true branching), differs considerably throughout this ichnogenus (i.e., *M. segregatis* vs *M. s. degiberti*). Selected samples include *Macaronichnus* of different size, with smaller *M. segregatis* (standard diameter of 3–5 mm) and larger *M. s. degiberti* (up to 15 mm). *Thalassinoides*, a dwelling and/or deposit-feeding structure with passive filling (Rodríguez-Tovar et al., 2017), is one of the most abundant ichnogenera in contourite facies (Rodríguez-Tovar and Hernández-Molina, 2018). Accordingly, selected samples consist of *Thalassinoides* with well-preserved passive infill.

Based on both field and laboratory observations, Micro-CT analysis was performed on representative and well-preserved specimens (see Table 9.1). Thus, out of the sandy clastic contourite facies from Morocco (Capella et al., 2017; De Weger et al., submitted), samples with *Macaronichnus* specimens (*M. segregatis* from Kirmta and *M. s. degiberti* from Sidi Chahed) were selected as the most abundant and best preserved biogenic structure in the studied outcrops. Out of the calcareous contourite facies from Cyprus, samples including *Chondrites* and *Thalassinoides* specimens were studied as the most abundant trace fossils, covering muddy and calcarenitic contouritic facies. In particular, we selected samples from muddy contourite chalk with *Chondrites* from Kalavasos, and from the calcarenitic bi-gradational contourite type succession with *Thalassinoides* of the Petra Tou Romiou outcrop (Stow et al., 2002).

Sample	**Technical acquisition parameter**	**Ichnological features**	**Notes** (Facies)	**Picture**
Sidi Chahed clastic contouritic sand (BA-36)	0.4X, 80kV, 87 µA, LE6, 6.22 µm, 50s, 3201 projections.	*M. s. degiberti* specimen inside a clastic contourite bed	Sandy clastic contourite deposits from channelized bedsets (Capella et al., 2017)	
Kirtma clastic contouritic sand (KT-Arr-2)	0.4X, 140kV, 72 µA, HE1, 14.66 µm, 4s, 3201 projections.	Three *M. segregatis* specimens with multiple crosscutting relationships	Sandy clastic contourite deposits from channelized bedsets (Capella et al., 2017)	
Petra Tou Romiou calcarenitic contourite (PT-P2-Co2)	0.4X, 140kV, 72 µA, HE1, 11.4 µm, 4s, 3201 projections.	*Thalassinoides* specimen inside a contourite bed	Calcarenitic contourite deposits (Hüneke et al., 2020)	
Kalavasos calcareous muddy contourite (KA-Ch-2)	0.4X, 80kV, 87 µA, LE6, 8.05 µm, 12s, 3201 projections.	*Chondrites* specimens with multiple cross-cutts	Calcareous muddy contourite (Stow et al., 2002)	

Table 9.2. Summary showing the acquisition parameters for each sample, the ichnological features and the dominant facies where they were located. Scale bar = 1cm.

Tomographic data were obtained using X-ray computerized axial microtomography (μ-CT, Zeiss Xradia 510 Versa) at the University of Granada, in the Scientific Instrumentation Center (Granada, Spain). The following common settings were established for the analyzed samples: 0.4X Magnification, bin 1 and 2334 images. Voltage, current, filter, distance and exposure time were adjusted according to particular features of each sample (summarized in Table 9.1). Then, image reconstruction was done by means of Reconstructor Scout and ScanTM software (Zeiss) using a 0.5 Recon filter and 3201 projections. Dragonfly ProTM (Object Research System) was used for advanced post-processing analysis and 3D image porosity data. For this purpose, we proceeded as follows: 1) Segmentation of the pores of the sample creating a region of interest (ROI) that is separated from the total volume by establishing differences in the gray level given to this component (threshold values). 2) Inclusion of a basic shape (cube) within the sample to delimit the interesting area (e.g., burrow infilling, lining with cross-cuts if possible, and the host sediment). 3) Intersection of the ROI pores with the shape established in the previous step. 4) Transformation of the pores in the selected area into a three-dimensional mesh (cube) that permits their visualization. The mesh offers a relative pore abundance visualization, wherein higher color intensity (red) indicates higher pore density.

2D analysis and quantitative pore distribution characterization were conducted using binary black and white CT images with the free software Fiji (Schindelin et al., 2012). Initially, treatment to enhance visibility was conducted by means of “Contrast Limited Adaptive Histogram Equalization (CLAHE)” of Fiji software (Miguez-Salas et al., 2019b). Each still image was then converted to an 8-bit grayscale where the threshold was defined to establish an appropriate differentiation range for black and white pixels, the black ones being assigned to pore structures (for expanded methodological explanation see Miguez-Salas et al., 2019b). The black and white images were improved using binary tools and filters (e.g., erode, fill holes and minimum/maximum filters). Minor manual corrections were also made with eraser or painting tools, making sure that all the selected black pixels belonged to pore structures. Finally, black pixel quantification provided the porosity value estimation. Within the same CT image, areas of interest (i.e., burrow walls) were selected to measure porosity percentage variation and distribution within the same sample. For each sample, a minimum of 50 still images was selected to analyze the porosity values.

9.4. Results

Results from micro-tomographic data and 2D image analyses conducted on selected samples from sandy clastic contourites with *Macaronichnus segregatis* (KT-Arr-2) and *Macaronichnus segregatis degiberti* (BA-36) specimens, and from calcarenitic contourites with *Thalassinoides* (PT-P2-Co2) and muddy contourites with *Chondrites*

(KA-Ch-2) specimens, reveal significant differences according to the type of facies and the ichnotaxa involved (Figs.9.2-9.9).

9.4.1. Sandy clastic contourites

9.4.1.1. *Macaronichnus segregatis*

A sample with *M. segregatis* specimens (KT-Arr-2) from the Late Miocene Rifian Corridor at the Kirmta outcrop was selected from sandy clastic contourite channelized deposits (De Weger et al., submitted). The sample, located in fine to medium sandstone inside 2D unidirectional dunes (De Weger et al., submitted), presents two parts with different degrees of diagenetic cementation (see left and right parts in Fig. 9.2B). Three close specimens of *M. segregatis* showed cylindrical to slightly oval shapes with diameters ranging from 0.5 to 0.8 cm and a burrow lining thickness of 0.1 to 0.2 cm (Figs. 9.2A and B). Micro-CT analysis was conducted on different cubes, covering the infilling material of the burrows, individual burrow lining, burrow linings belonging to several specimens with cross-cutting relationships, and the host sediment (Figs. 9.2B to F). As in the previous case, the porosity mesh shows higher density in the host sediment than in the burrow fill (Figs. 9.2C, D and F). The burrow lining records higher pore density (greater red intensity) than burrow fills, and also usually higher than the host sediment, the latter depending largely on the cementation degree (Figs. 9.2B to F). Some overlapped burrow linings originate a considerable increase in porosity, reaching the highest densities (see Fig. 9.2B and especially Fig. 9.2E). The 2D analysis confirms that the burrow lining has higher porosity values than the burrow fill, commonly reaching up to three orders of magnitude (12%-19% vs 6.3%, respectively) (Fig. 9.3A). Still images moreover support the existence of two degrees of diagenetic cementation inside the sample, showing considerable porosity contrast (5% vs 18%; Fig. 9.3B). Thus, in the case of the less cemented part, similarities between burrow lining and host sediment could reflect original values (Case I in Fig. 9.3B), while in the more cemented part a considerable increase with respect to the burrow lining is observed (Case II in Fig. 9.3B).

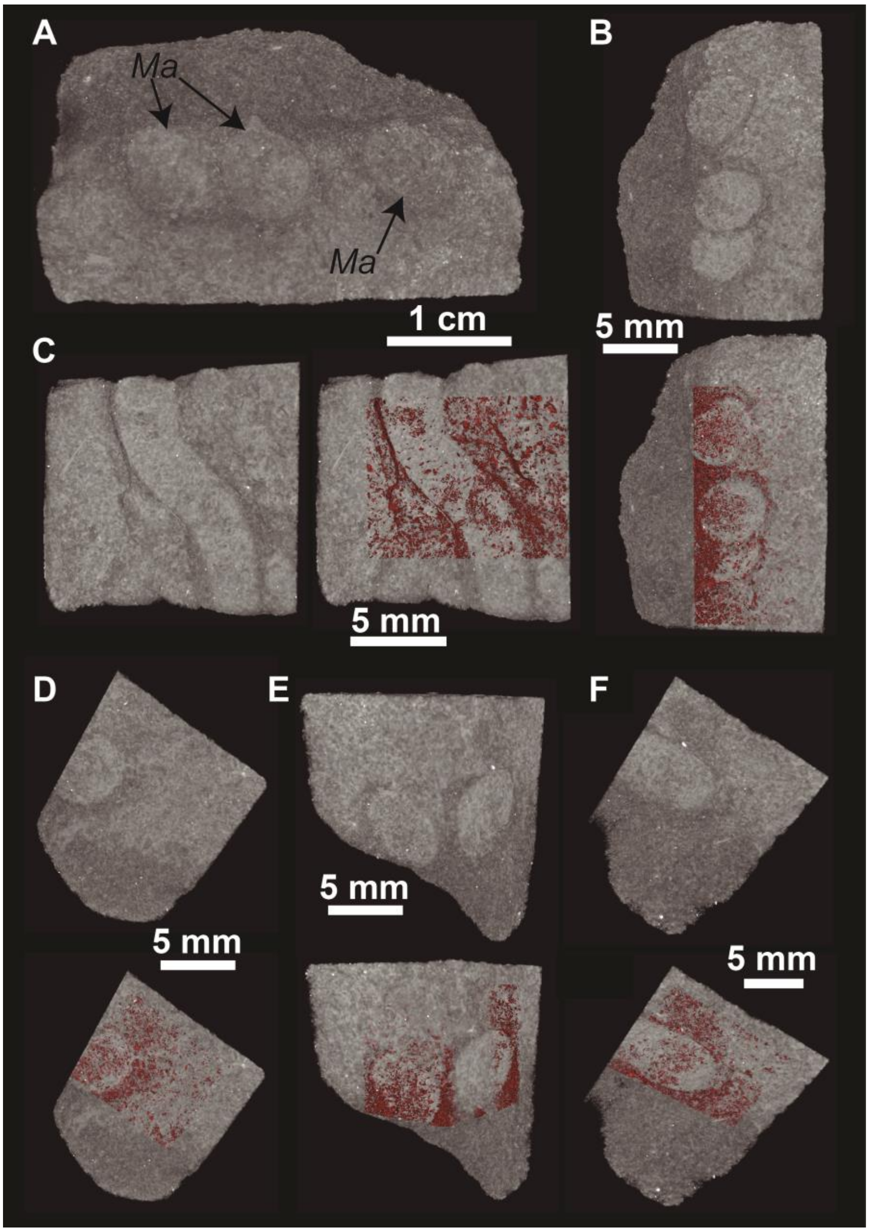

Fig. 9.2. Micro-CT illustrations of *M. segregatis* from Kirmta outcrop. A) General view of the sample with the three specimens of *M. segregatis*. Note that the sample has two parts with different degrees of diagenetic cementation (less cemented top part of the sample); B) Cropped sample with the implementation of the pore mesh where the intersection between different burrow linings can be observed. Note the porosity increase in these areas and; C) *M. segregatis* where porosity values inside the burrow fill are lower than in host sediment and burrow lining; D) *M. segregatis* crop section where higher porosity values in the burrow lining can be observed; E) *M. segregatis* crop section where the cross-cut between two specimens reveal a porosity increase inside the burrow linings. F) *M. segregatis* crop section where higher porosity values in the burrow lining can be observed.

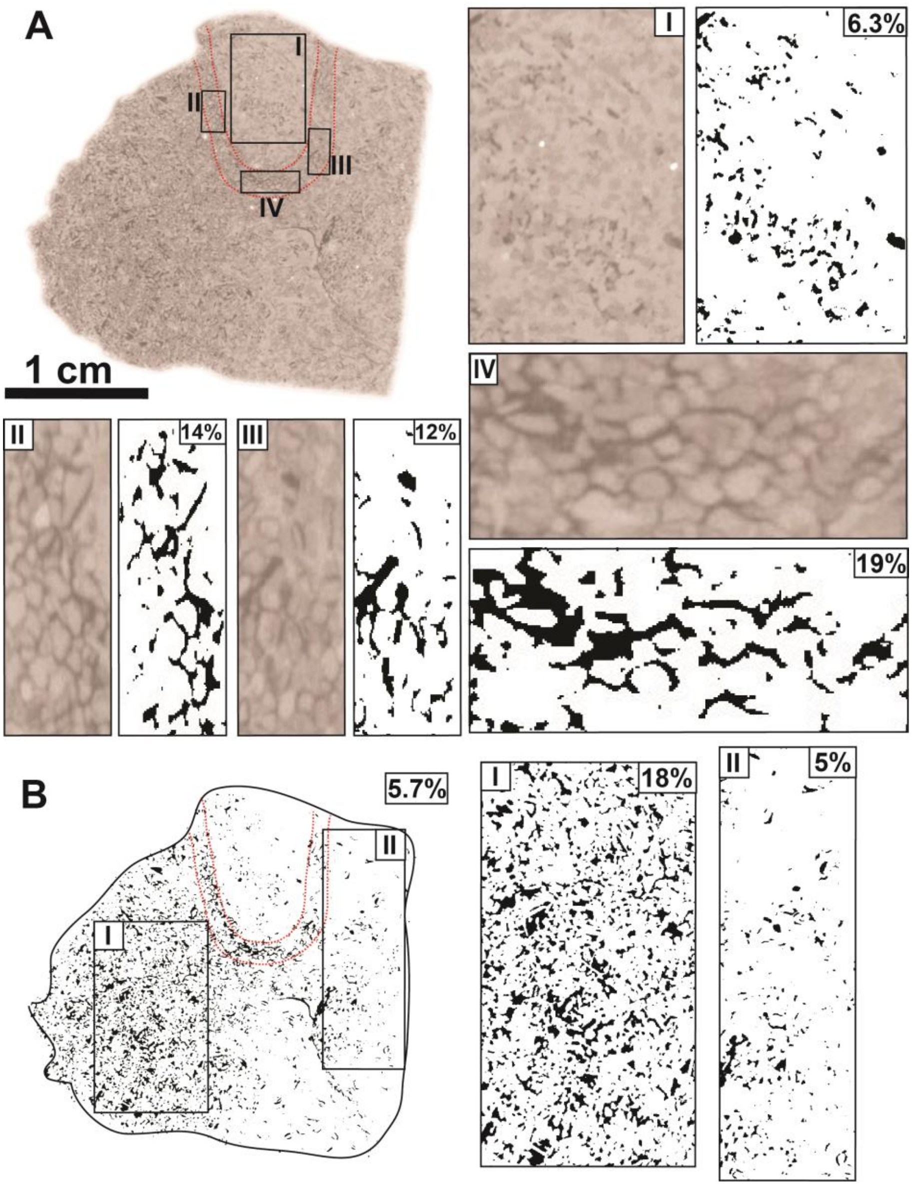

Fig. 9.3. Micro-CT image with associated binary black and white images (after Fiji treatment) from *M. segregatis*. A) Micro-CT image and binary crops from the burrow lining and fill. Note the porosity contrast between burrow lining and fill (two to three order of magnitude higher); B) Full sample binary black and white image where two areas of host sediment can be clearly distinguished, the left one with less cementation and high porosity, the right one with higher cementation and less porosity.

9.4.1.2. *Macaronichnus segregatis degiberti*

A sample with *M. s. degiberti* (BA-36) from the Late Miocene Rifian Corridor at Sidi Chahed outcrop was selected from those collected in sandy clastic contourite channel axe deposits (Capella et al., 2017). *M. s. degiberti* are emplaced in fine to coarse sandstones inside westward oriented foresets. The analyzed burrow presents a diameter of 1.1 cm and a lining thickness of 0.2 cm (Fig. 9.4A). The Micro-CT analysis shows the porosity mesh to be higher in the host sediment than in the burrow fill (Fig. 9.4B). Burrow lining observations reveal a high pore density with discontinuous distribution throughout the rim (Figs. 9.4C and D). The 2D analysis corroborates a generally higher porosity of the host sediment with respect to infilling materials, up to two orders of magnitude (6.5%/4.7% and 4%/2.3%, respectively, Figs. 9.5A, B). Increased porosity in the burrow rim, as registered for the *M. segregatis* examples (Figs. 9.2, 9.3), is not observed; punctual porosity increases seen in the Micro-CT data (Fig. 9.4) might be related to fractures during manipulation, as the burrow rims locally match the sample limits.

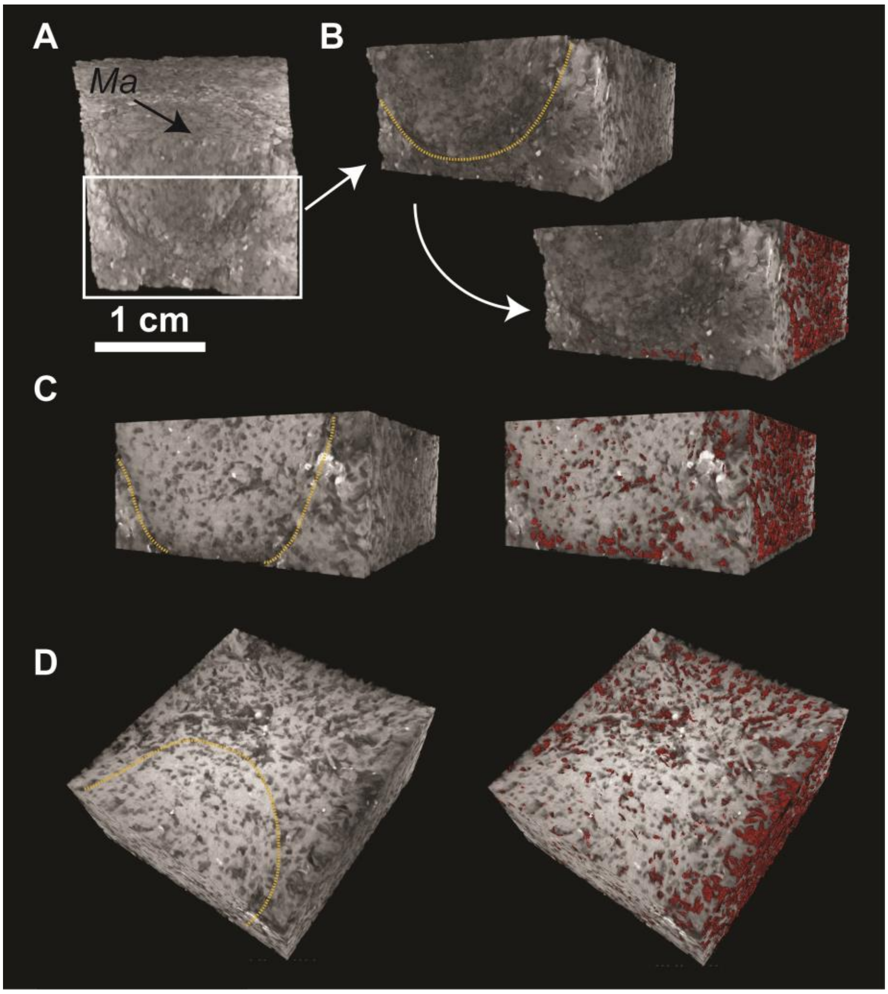

Fig. 9.4. Micro-CT illustrations of *M. s. degiberti* from Sidi Chahed outcrop. A) General view of the sample; B) Cropped sample with the implementation of the pore mesh (red) and the delimitation of the burrow lining (yellow dashed line); C and D) Lateral and top view of the specimen (without and with pore mesh; left and right, respectively). Note the significantly lesser porosity inside the burrow fill than in the host sediment.

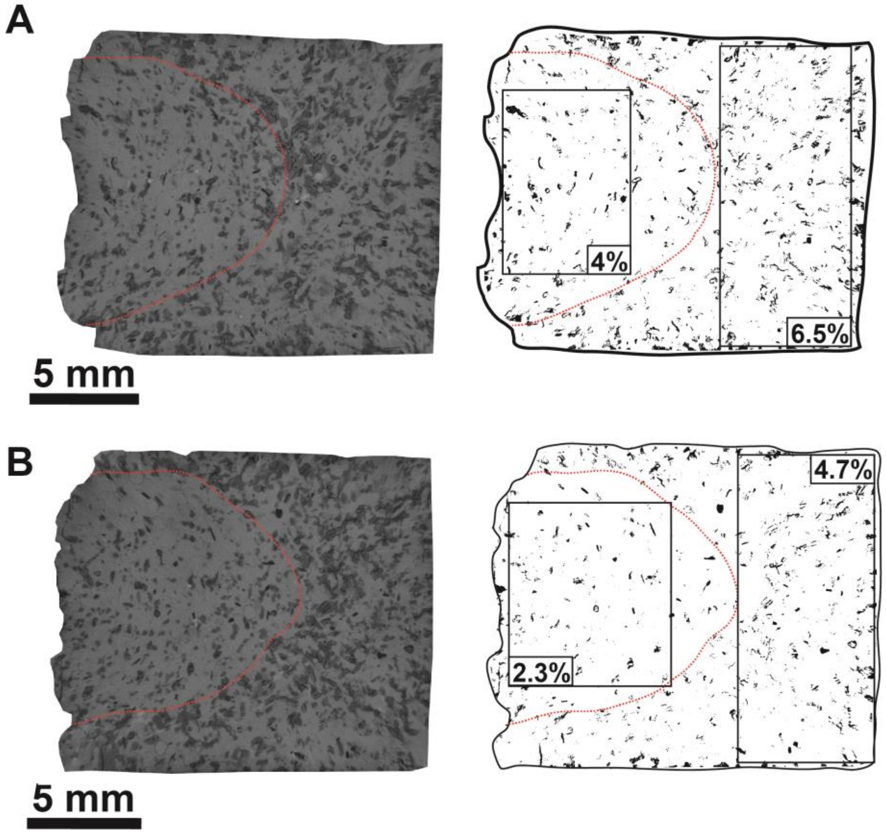

Fig. 9.5. A and B) Micro-CT images (left) with associated binary black and white images (right, after Fiji treatment) from *M. s. degiberti*. *M. s. degiberti* specimen showing lower porosity values in the burrow fill. Note that darker minerals conforming the burrow lining are not associated with pore concentration in the binary images.

9.4.2. Calcareous contourites

9.4.2.1. Calcarenitic contourite with *Thalassinoides*

A selected sample with *Thalassinoides* (PT-P2-Co2) from the Early Miocene Pakhna formation at Petra Tou Romiou outcrop (Stow et al., 2002) was obtained from the central part of a contourite bi-gradational sequence. The *Thalassinoides* specimen was found in a thin calcarenite bed (around 8 cm thick) displaying wavy lamination and lateral changes in thickness and gradational boundaries. These beds were recently interpreted as bioclastic sandy bottom-current deposits (see Hüneke et al., 2020). The burrow has a nearly cylindrical shape of 1.3 cm in diameter (Fig. 9.6A), supporting the absence of secondary deformation. Micro-CT analysis was conducted on a cube that covered the burrow infilling and the host sediment (Figs. 9.6B and C). The porosity mesh reveals the existence of vertical and horizontal fractures, including one surrounding the *Thalassinoides* burrow wall (Fig. 9.6B). Beyond these fractures, as observed in the sample, the highest porosity is related to the presence of planktic foraminifers (globigerinids), together with smaller pores whose origin is difficult to assign; the pores are unconnected and conform non-effective network porosity. Micro-CT data suggest a preferential location of larger pores inside the burrow, causing higher pore density (Fig. 9.6C). Nevertheless, 2D analysis does not show this porosity contrast (between host sediment and burrow infilling) so clearly as observed in the Micro-CT data (Fig. 9.7). The host sediment porosity values range from 7% to 12% (8% and 10% in the illustrated case, Fig. 9.7), while the infilling commonly reaches values higher than 12% (14% in the case illustrated in Fig. 9.7). The preferential occurrence of larger pores inside the burrow is detected in the still images (Fig. 9.7), although cases with opposite or random pore size distribution were also observed locally.

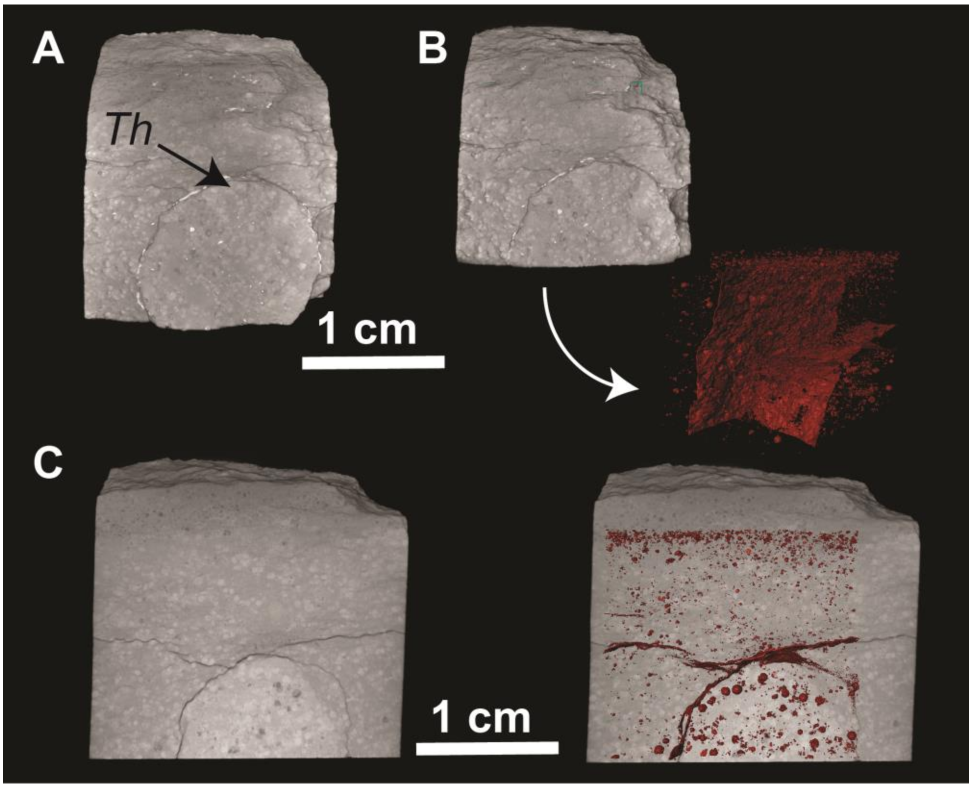

Fig. 9.6. Micro-CT illustrations of *Thalassinoides* from Petra Tou Romiou outcrop. A) General view of the sample with *Thalassinoides*; B) Cropped sample with the implementation of the pore mesh. Note the existence of two fractures, one of them following the *Thalassinoides* shape; C) *Thalassinoides* crop section where slightly higher porosity values in the burrow fill can be observed (without and with pore mesh; left and right, respectively). Note that the pores inside the burrow record larger sizes (associated with bigger globigerinids).

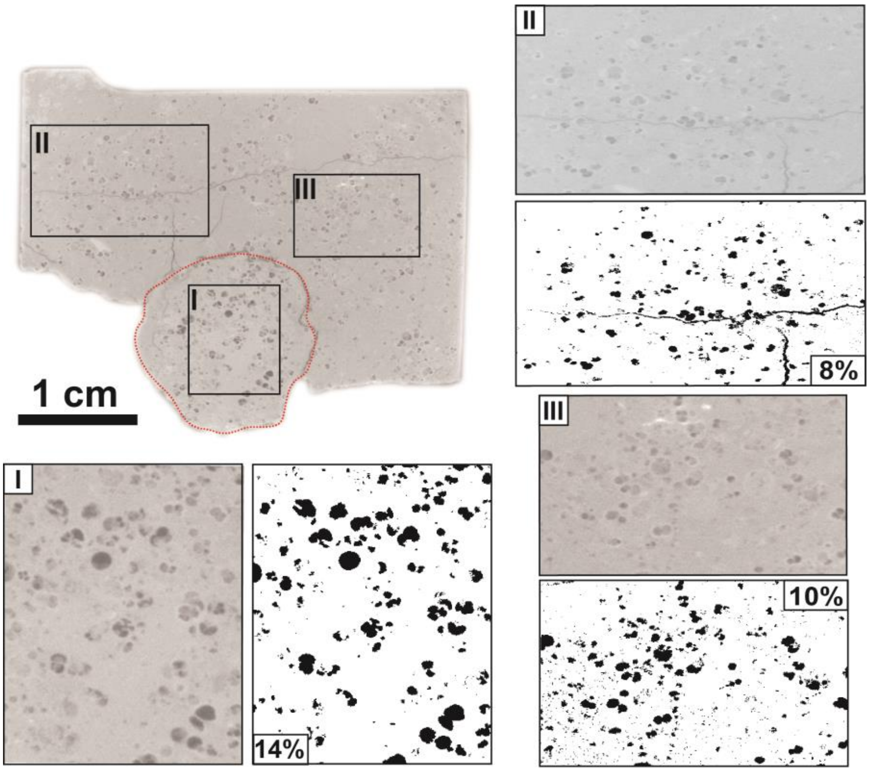

Fig. 9.7. Micro-CT image with associated binary black and white images (after Fiji treatment) from *Thalassinoides* with crops from the host sediment and the burrow fill. Note that porosity is slightly higher in the burrow fill and that globigerinids present larger sizes.

9.4.2.2. Calcareous muddy contourite with *Chondrites*

The sample with dense ferruginized *Chondrites* (KA-Ch-2) was selected from those collected at the Eocene Lefkara Formation at Kalavasos section, composed of white calcareous mud. The infilling of *Chondrites* burrows mainly consists of the same muddy material as the host sediment; only some specimens are filled by calcareous sediment with slightly differing grain size. The average diameter of the tunnels ranges between 0.5 and 2 mm. The Micro-CT analysis was conducted in a cube inside the sample where several specimens of *Chondrites* could be seen (Fig. 9.8). As observed in the sample, porosity is mainly related with empty chambers of globigerinid planktonic forams (intra-particle porosity). Planktic foraminifers and the associated porosity are randomly distributed (Fig. 9.8) —sometimes the burrow infilling seems to harbor smaller pores (see upper left *Chondrites* in Fig. 9.8), but this is not a common feature. The 2D analysis conducted on still images reveals low porosity values, always less than 2% (Fig. 9.9). No preferential porosity distribution was observed.

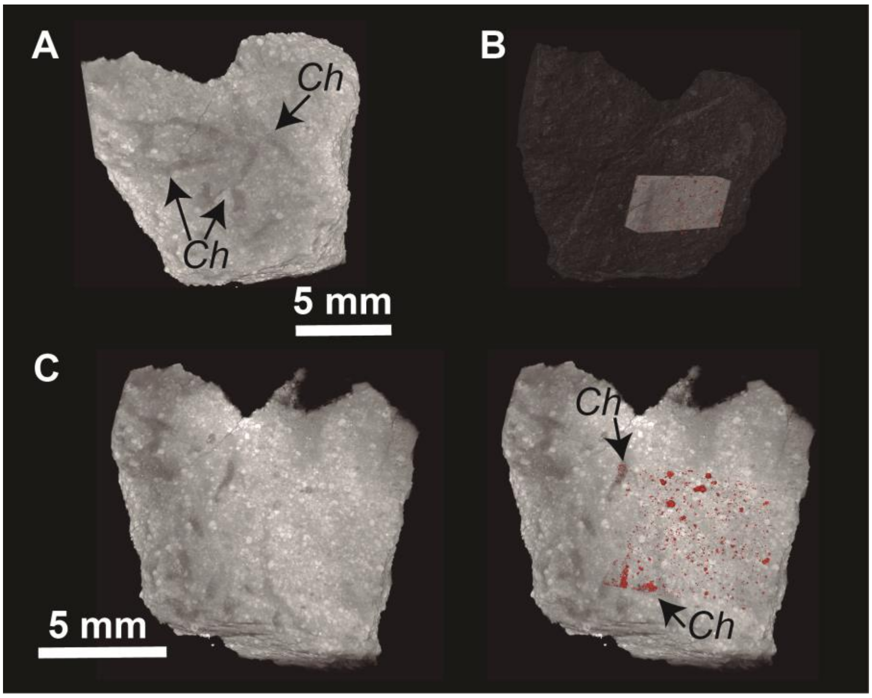

Fig. 9.8. Micro-CT illustrations of *Chondrites* from Kalavasos outcrop. A) General view of the sample with *Chondrites*; B) General view of the sample with modified transparency values in order to illustrate the cube where the pore mesh was implemented; C) *Chondrites* crop section where no preferential porosity distribution can be observed (without and with pore mesh; left and right, respectively).

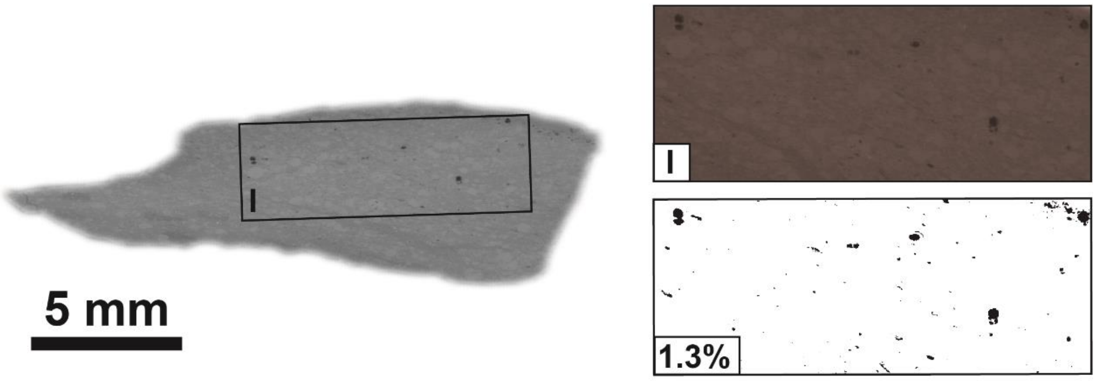

Fig. 9.9. Micro-CT image with associated binary black and white images (after Fiji treatment) from *Chondrites*. Binary crop shows low porosity values and none preferential distribution. Note that the recognition of *Chondrites* burrows is hard to evidence.

9.5. Discussion

The effect, positive or negative, of trace fossils on reservoir quality is mainly related with burrow connectivity, intensity, depth of penetration, and permeability contrast between matrix and burrow fill, affecting petrographic properties such as permeability/porosity (Gingras et al., 2012; Eltom, 2020). Several studies have corroborated that permeability can be notably enhanced when coarser-grain filled burrows are within a finer-grained and less permeable matrix (e.g., Cunningham et al., 2009; Gordon et al., 2010; Tonkin et al., 2010; La Croix et al., 2013, 2017). In such a scenario, bioturbation can produce dual-porosity or dual-permeability networks, depending on the permeability contrast (order of magnitude) between the burrow fills and matrix (Gingras et al., 2012; Knaust et al., 2020). Thus, dual-porosity generally refers to sediments showing two contrasting porosity regimes (Gingras et al., 2012). This contrast may be created by benthic fauna moving through the sediment, or dwelling animals that selectively ingest and rework the sediment (Gingras et al., 2012). Burrowing behavior (e.g., backfilling vs. passive filling; tunneling vs. sediment swimming) therefore plays an important role in the modification of petrographic features and, hence, in reservoir quality (Tonkin et al., 2010; Knaust et al., 2020). In the literature, dual-porosity is mostly associated with cryptic bioturbation (high abundance of small-size trace fossils resulting in a quasi-homogenization of the sediment; Pemberton et al., 2008) with the record of *Macaronichnus*, and with bioturbated sandstone that contains *Arenicolites*, *Ophiomorpha*, *Skolithos* or *Thalassinoides* (Gingras et al., 2012). In the studied specimens, results vary depending on the ichnogenus; each one is discussed separately below.

9.5.1. *Macaronichnus* from clastic contourite deposits

Macaronichnus burrows comprise two main architectural parts; the infilling material and the surrounding halo (Seike, 2007). The trace maker of *Macaronichnus* develops a grain-selective deposit-feeding behavior, avoiding dark-colored detrital fragments (mainly consisting of mica, brown glauconite pellets and heavy minerals), while exploiting the sediment for feeding (Seike, 2007). Thus, a re-sorting of the grains occurs as the dark-colored grains outline the burrows.

Several studies have demonstrated the subtle but positive effect of *Macaronichnus* ichnofabrics on enhancing reservoir quality, which is related to the sorting and cleaning effects of the trace makers (e.g., Gingras et al., 2002; Pemberton and Gingras, 2005; Knaust, 2009, 2014; Gordon et al., 2010; La Croix et al., 2013; Quaye et al., 2019). Gordon et al. (2010) studied in detail the petrophysical effects of *Macaronichnus* on reservoir quality. Primary porosity and permeability were preferentially preserved within the light-colored burrow fills. Permeability in *Macaronichnus*-burrowed zones was higher than in less bioturbated laminated sandstone of similar grain size, favoring a dual-porosity flow (Gordon et al., 2010). This trend has also been recently corroborated by Quaye et al. (2019) —local porosity in host sandstone is reduced by 33.28%, while permeability is increased by 41.36% in *Macaronichnus* burrow fills. In the case study, Micro-CT data and still images reveal a dual effect, either confirming or rejecting these findings. In the case of *M. segregatis* (Figs. 9.2, 9.3), the burrow rim records higher porosity values than both the burrow fillings and the host sediment. In some cases, the porosity contrast is up to three orders of magnitude higher than in the burrow infilling, but more often it is within two orders of magnitude. Accordingly, the record of *M.*

segregatis could promote a dual-porosity flow medium in the sandy clastic contourite deposits from the Late Miocene Rifian Corridor, hence a positive effect on reservoir quality. In the case of the studied sample with *M. s. degiberti* (Figs. 9.4, 9.5), however, the opposite result is observed: higher porosity values were registered in the host sediment with respect to the burrow fills, and only the lining shows local increases.

Porosity distribution within *Macaronichnus*-like burrows, differentiating between the infilling material and the surrounding halo, has rarely been studied (Greene et al., 2012; Quaye et al., 2019). Our findings contrast with those of Greene et al. (2012) in slope-channel massive sand deposits having cryptic bioturbation (most often linked to *Macaronichnus segregatis* trace fossil). These burrows fills are better sorted, less compacted, and contain high porosity values; meanwhile the linings are more compacted, less sorted, and present lower porosity than the burrow fills (Fig. 13 in Greene et al., 2012). Still, Greene et al. (2012) emphasize that even if such cryptic bioturbation resembles *Macaronichus segregatis*, the examples are smaller (burrow diameters are 200–800 μm) than typical *Macaronichnus* specimens and the mineral halos are commonly very diffuse or absent. Accordingly, this bioturbate texture would be better explained as resulting from hydraulic and gravitational separation (as the trace makers dig through the sediment), not from selective grain ingestion (Greene et al., 2012).

Recently, Quaye et al. (2019) indicated that burrow filling porosity in *Macaronichnus* specimens is enhanced by 23% with respect to the host sediment values, and by 51% with respect to the burrow lining. Furthermore, permeability values are 26.46% and 54.6% higher in the burrow fillings than in host sediment and burrow linings, respectively. *Macaronichnus* porosity distribution therefore appears to follow the trend observed by Greene et al. (2012) in cryptic bioturbation. Micro-CT data presented here reflect the opposite —the burrow lining records higher porosity values than the burrow infilling, at least in the case of *M. segregatis*.

In recent research conducted by Quaye et al. (2019), burrow lining porosity is considerably lower than that of burrow filling or host sediment. The different results could be attributed to the methodology applied. Quaye et al. (2019) addressed porosity by means of the Core Measurement System 300 (Stage 4.00) pressure decay porosimeter, where diameter cylindrical plugs are higher than 1 cm, implying less precise differentiation between burrow infilling and lining than that ensured by the X-ray microtomography applied here.

Another noteworthy aspect of our results is how the porosity data depend on the type of *Macaronichnus* (*M. segregatis* vs *M. s. degiberti*). This dual effect can be related to the ichnological features involved (i.e., behavior of the trace maker, size or type of producer) and the diagenetic effect on the host sediment. Recent studies suggest different behaviors between the trace makers of *M. segregatis* and *M. s. degiberti*; indeed, it cannot be discarded that these traces were produced by different trace makers of quite variable size (see discussion of *M. s. degiberti* in Rodríguez-Tovar and Aguirre, 2014; Nara and Seike, 2019). The disparity between burrow lining porosity values (higher in *M. segregatis*) could be linked to variations in the grain-selective deposit-feeding behavior. Thus, *M. s. degiberti* trace maker might have a specific behavior during feeding activities, with grain segregation determining more compaction, hence decreasing porosity values, at the burrow lining. In another recent study, a similar interpretation has been put forth based on blue epoxy resin analysis, showing different porosity values between the burrow infilling and surrounding rim (see Dorador et al., 2021). The specific trace maker´s behaviour would seem to be the main reason for the porosity increase at the burrow rim.

9.5.2. *Chondrites, Thalassinoides* from calcareous contourite deposits

Studies covering the impact of *Chondrites* on reservoir proprieties give diverse results (e.g., Tonkin et al., 2010; La Croix et al., 2013, 2017; Bednarz and McIlroy, 2015; Knaust, 2020). In several examples *Chondrites* induce a positive impact on porosity and permeability distribution, as they introduce grains coarser than the surrounding matrix, increasing heterogeneity (La Croix et al., 2013, 2017; Bednarz and McIlroy, 2015). However, Tonkin et al. (2010) found that the presence of *Chondrites* in the mud-rich facies of Ben Nevis Formation (Cretaceous, offshore Newfoundland, Canada) had a neutral effect in terms of permeability reduction. Knaust et al. (2020) recently reported that *Chondrites* observed in the Maastrichtian chalk of the Gullfaks Field (Norwegian North Sea) may either be filled with tight mud or porous grainy sediment, with contrasting effects on the resulting reservoir rock. *Chondrites* ichnofabrics in marly chalk and chalky marlstone could help create reservoir zones if burrow density is high enough and burrows are sand-filled (Knaust et al., 2020). On the other hand, if *Chondrites* colonization occurs in more consolidated, stiffer sediment, or in a hard substrate where the filling material is diagenetic cement (Fig. 7 in Knaust et al., 2020), *Chondrites* burrows would play a minor or neutral role in enhancing reservoir quality.

Hence, in the light of previous studies, *Chondrites* can induce variable changes in porosity, increasing or decreasing it, depending on the abundance, size and the nature of the filling material (Knaust et al., 2020). In this case study, *Chondrites* burrows are filled with the same muddy chalk as the hosting rock. Porosity distribution is not affected by these burrows, both the infilling material and the host sediment showing low porosity values (under 2%). These results were expected, since the burrow infilling is the same as the host sediment; but at the same time they reveal the minor influence of the trace maker in the redistribution of grains. In the studied examples of muddy chalk contourite deposits, *Chondrites* play a neutral role in reservoir quality, while diagenetical processes might have had an important effect on pore-filling cementation. Taking into account the complexity of *Chondrites* (see Baucon et al., 2020), however, a more detailed and comprehensive analyses of *Chondrites* burrows with the inclusion of sand-filled examples would be necessary for a widespread evaluation of this trace in contourite facies.

Thalassinoides is one of the most studied trace fossils when it comes to the relationship between ichnology and reservoir geology (e.g., Pemberton and Gingras, 2005; Cunningham, 2009; Tonkin et al., 2010; Golab et al., 2017; Eltom, 2020, among others). Several studies have proven the relevance of *Thalassinoides* for improving reservoir quality, even connecting isolated parts of a reservoir (e.g., Pemberton and Gingras, 2005; La Croix et al., 2013; Knaust et al., 2020). Knaust et al. (2020) affirmed that *Thalassinoides* ichnofabric in chalk deposits has the highest impact on improving reservoir quality. Tonkin et al. (2010) found that the presence of *Thalassinoides* increases isotropy and enhanced porosity and permeability up to 600%. Passively-filled *Thalassinoides* burrows having grain coarser than the surrounding matrix would therefore act as significant fluid pathways (Tonkin et al., 2010, Golab et al., 2017). Yet if *Thalassinoides* burrows are filled with mud or silt, the permeability of the facies tends to decrease significantly (Tonkin et al., 2010). In addition, the influence of fluid flows and mineral precipitation during subsequent diagenesis (i.e., calcite cementation) should not be underestimated (Knaust, 2013).

In the study case, the *Thalassinoides* infilling records slightly higher porosity values than the surrounding calcarenitic sediment, ranging 10%-15%. This minor porosity difference can be attributed to the similarity between the infilling material of *Thalassinoides* and the host sediment, in composition, grain distribution and grain size. Furthermore, secondary diagentic cementation (e.g., calcite) may have played an important role, homogenizing primary differences. *Thalassinoides* from the Miocene calcarenitic contourite facies of Cyprus therefore bear a minor impact on porosity reservoir quality. Positive or negative effects should not be discarded in other cases, however: the discontinuous deposition recently interpreted for contourite facies (see Rodríguez-Tovar et al., 2019c) allows for the passive infilling of open burrows with material having petrographic features different from those of the host sediment.

9.6. Conclusions

Micro-CT analysis performed, for the first time, as a novel approach on bioturbated contourite facies reveals that porosity distribution is clearly determined by bioturbation, a finding of great interest in the context of reservoir exploitation. The cases studied show a variable incidence of bioturbation —increasing, decreasing or maintaining porosity with respect to the host sediment. This effect is mainly controlled by trace maker behavior and burrow features (i.e., shape, size, architectural parts, and infilling material).

In the sandy clastic contourite deposits analyzed, *Macaronichnus* have the greatest impact on (modified) porosity distribution. In the case of *M. segregatis* specimens, porosity values are up to three times higher in the burrow rim than inside, generating a dual-porosity flow medium. Elsewise, *M. s. degiberti* shows a burrow fill with lower porosity values than the host sediment, with the burrow rim alone recording punctual high values. This variable influence on porosity distribution (*M. segregatis* vs. *M. s. degiberti*) could be associated with different behaviors of the trace maker during feeding activities, or even with different producers. In calcareous contourite deposits, *Chondrites* located in muddy contourite chalk have a neutral effect on porosity, given the similar grain size of the host sediment and the filling material. In calcarenitic contourite facies, *Thalassinoides* generate a minor effect on porosity, reaching slightly higher values in the burrow fill. Again, this minor effect is related to similarity between the passive infilling material and the host sediment, evidencing the scarce influence of the trace maker in the redistribution of grains. Moreover, a subsequent diagentic overprint may serve to homogenize primary differences.

Understanding the impact of bioturbation on porosity distribution in contourite facies could increase or decrease the potential of these unconventional reservoirs, thereby favoring more accurate estimations during petroleum explorations. Nonetheless, this is an early step towards comprehension of the relationship between contourite facies, ichnological features, petrophysical properties and reservoir geology. More studies are needed, covering distinct contourite facies and a wider range of trace fossils. At any rate, the application of precise techniques such as micro-CT analysis opens a new way to advance, through highly detailed characterizations.

Acknowledgments

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Supplementary Papers of PART V

- The complex case of *Macaronichnus* trace fossil affecting rock porosity (Scientific Reports, 2021)

- Mercury intrusion porosimetry to evaluate the incidence of bioturbation on porosity of contourites (Rivista Italiana di Paleontologia e Stratigrafia, 2021)

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The complex case of *Macaronichnus* trace fossil affecting rock porosity

Javier Dorador[1]✉, Francisco J. Rodríguez-Tovar[2] & Olmo Miguez-Salas[2]

ABSTRACT

Bioturbation is an important factor for reservoir quality due to the modification of host rock petrophysical properties (i.e., porosity, permeability, and connectivity). However, there is no predictable relationship between bioturbation and its effect on rock properties, due to the variability of the involved ichnological features. A detailed ichnological analysis is necessary to determine how bioturbation affects petrophysical properties in a bioturbated reservoir. Traditionally, ichnological features such as density, tiering, size, orientation, architecture, and fill, have been considered. However, other properties have been undervalued as is the case of lining. Here, we present a detailed study on the effects of *Macaronichnus* burrows, an ichnotaxon usually related to hydrocarbon exploration due to its high concentration in rock notably affecting petrophysical properties. *Macaronichnus*, a subhorizontal cylindrical burrow, is characterized by a well-defined and developed outer rim surrounding the tube core. Our data indicates a clear zonation in porosity according to burrow structure, with the lowest porosity in the tube core and higher values associated with the surrounded rim. This duality is determined by the tracemaker grain selective feeding activity and the consequent concentrated cementation. The organism concentrates the lighter minerals in the tube core fill during feeding, favoring post-depositional cementation during diagenesis and this results in lower porosity than the host rock. However, heavy minerals, mainly glauconite, are located in the rim, showing higher porosity. Our results support the view that ichnological analyses are essential to determine reservoir quality in bioturbated reservoirs, evidencing that other ichnological properties in addition to those traditionally considered must be evaluated.

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MERCURY INTRUSION POROSIMETRY TO EVALUATE THE INCIDENCE OF BIOTURBATION ON POROSITY OF CONTOURITES

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ABSTRACT

The effect of bioturbation on rocks' flow-media properties (e.g., porosity and permeability) and its impact on reservoir quality has been previously documented. However, the occurrence of ichnological features and their impact on rock properties in contourite deposits, a facies of economic interest, is poorly known. The study evaluates the effects of bioturbation on different types of contourite facies, particularly dominantly calcareous contourites and sandy clastic contourites, using mercury intrusion porosimetry. Porosity (total, intraparticle and interparticle) is characterized in selected samples, comparing the host rock with the infills of the trace fossils; *Macaronichnus*, *Parahaentzschelinia* and *Scolicia* from El Adergha and Kirmta sections in Morocco, and *Chondrites*, *Planolites* and *Thalassinoides* from Petra Tou Romiou, Agios Konstantinos, and Kalavassos outcrops in Cyprus. The obtained data reveal variance between porosities according to different types of contourite facies and trace fossils. Total porosity shows similar values for the host sediment in clastic and calcarenitic contourites, but interparticle porosity is nearly absent in calcarenitic contourites, where intraparticle porosity is almost exclusive. This is owing to the abundance of foraminifera chambers that increase intraparticle primary porosity. Regarding the ichnotaxa, higher total porosity values were obtained from the infilling material of *Parahaentzschelinia*, *Scolicia* and *Macaronichnus*, which could be related with the redistribution of grains by trace makers during feeding activity. Considering the impact of bioturbation on reservoir quality, there are significant differences between clastic and calcareous contourites. In the clastic contourites, bioturbation increases in the total porosity, particularly interparticle porosity, suggesting a positive impact for the reservoir properties of the studied units. However, in calcarenitic and muddy chalk contouritic facies, bioturbation has a minor effect on porosity and no predictable influence on the flow-media characteristics.

PART VI

NEXT STEP: COUPLIG PRESENT AND PAST

“The present is the key to the past”

— Charles Lyell (1797-1875)

Chapter 10

FAUNAL ASSEMBLAGE CHANGES, BIOTURBATION AND BENTHIC STORMS AT AN ABYSSAL STATION IN THE NORTHEASTERN PACIFIC

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Faunal assemblage changes, bioturbation and benthic storms at an abyssal station in the northeastern Pacific

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ABSTRACT

This study investigates the evolution of deep-sea lebensspuren assemblages before, during, and after five high-energy episodes over a storm-events period lasting 25 days. Bioturbational changes were characterized through brief benthic storm events in the northeastern Pacific at the abyssal time-series site Station M (4000 m depth). Quantification of seafloor coverage was processed to evaluate variations on the substratum type. A total of 15 lebensspuren morphotypes were identified. Most traces could be associated with feeding faecal casts, crawling tracks, dwellings and resting structures. Lebensspuren assemblages were similar before and after the storm-events period; full assemblage was re-established in one week. This high energy period was associated with an impoverishment of lebensspuren abundance and assemblage diversity. Only elpidiid holothurian feeding faecal casts recorded a notable increase in abundance during this period of high energy. In addition, this energetic stage involved the appearance of exhumed surface patches. Holothurian feeding activity appeared to have been primarily influenced by the local-scale erosion and re-suspension of unconsolidated surface sediment, which led to the reorganization of organic matter resources. We propose the mobility of elpidiid holothurians allowed them to gain a competitive advantage in obtaining these new resources. This research presents a novel relationship between lebensspuren, faunal activity, and bottom currents that broadens our understanding of benthic community responses to deep-sea bottom currents. Finally, we discuss these results as they pertain to the fossil record to assess how bioturbational structure development could be controlled by substratum type, organic matter availability and duration of energetic episodes.

Keywords: Bioturbation, Benthic ecology, Deep-sea, Benthic storm, Holothurian, Lebensspuren

10.1. Introduction

10.1.1. Bioturbation, lebensspuren, and trace fossils

Bioturbation is the biological reworking of sediments, which alters chemical profiles and modifies physical properties such as grain size, porosity, and permeability among others (Bromley, 1996; Meysman et al., 2006; Seilacher, 2007; Buatois and Mangano, 2011). Throughout the Earth's history, bioturbation in deep-sea environments has been an important mechanism by which sedimentological, ecological, and chemical features were modified, creating significant heterogeneities on the seafloor (Gage and Tyler, 1991; Uchman and Wetzel, 2011). By contrast, the fauna responsible for bioturbation are constrained by limiting factors, such as temperature, salinity, oxygen, substrate consistence, current energy, and organic matter availability (Ekdale et al., 1984; Gage and Tyler, 1991; Bromley, 1996; Buatois and Mangano, 2011). Bioturbation reflects the behaviour of these animals as they respond to physical changes in their deep-sea environments.

The activity of benthic organisms can be imprinted on and within the sediment, forming biogenic traces called lebensspuren (German: meaning ‘life traces’) (Ewing and Davis, 1967). These modern traces (lebensspuren), left behind by epibenthic and endobenthic organisms, are the portrayal of behaviours such as feeding, resting, crawling and dwelling, among others. They represent crucial processes in the lives of present and past benthic fauna (Seilacher, 1967; Gage and Tyler, 1991; Bromley, 1996; Buatois and Mangano, 2011). Although under different and varied physical processes lebensspuren may be destroyed (i.e., Smith et al., 2005), certain environmental conditions can favour the preservation of these biogenic structures into the geological record as trace fossils (Gage and Tyler, 1991; Seilacher, 2007; Uchman, 2007).

The identification of the organisms responsible for distinct lebensspuren is not always easy (Ewing and Davis, 1967; Vardaro et al., 2009; Bell et al., 2013). This is especially true for crawling lebensspuren that have similar features, but are produced by both holothurians and echinoids (Dundas and Przeslawski, 2009). A similar challenge exists for smooth faecal casts which can be produced by different species of holothurians. Previous studies have shown that distribution, diversity and abundance of preserved modern lebensspuren will depend on surface productivity, organic-matter flux, and oxygenation (e.g., Wheatcroft et al., 1989; Anderson et al., 2011; Przeslawski et al., 2012; Bell et al., 2013; Durden et al., 2019). Moreover, Bell et al. (2013) indicated that an organism's feeding mode plays a pivotal role in controlling lebensspuren abundance, and may be related to habitat heterogeneity and food-searching behaviour (Anderson et al., 2011). Despite the prevalence of bioturbation and the important role that it plays in deep-sea environments, detailed lebensspuren studies are very scarce, and the role of bioturbation may be underestimated. Few studies cover deep-sea lebensspuren assemblages in detail (e.g., Ekdale and Berger, 1978; Kitchell et al., 1978; Young et al., 1985; Turnewitsch et al., 2000; Wetzel, 2008; Przeslawski et al., 2012; Bell et al., 2013). To date, most of the studies were developed to catalogue or compare lebensspuren assemblages with ecological features in different locations, without considering their temporal variation in detail.

The study of trace fossils, paleo-ichnology, offers invaluable insights into trace maker behaviour in response to the environment, thereby preserving key information about paleoenvironmental conditions (Bromley, 1996; Buatois and Mangano, 2011; Knaust and Bromley, 2012). Many trace fossils as well as their associated behaviours remain unchanged throughout the geological record until present day (see *Paleodyction* in Durden et al., 2017 for a controversial biogenic structure). Nevertheless, ichnotaxonomical nomenclature and ichnotaxobases are not usually applied to modern lebensspuren, as it is difficult to compare and relate trace fossils with their recent analogues (Bertling et al., 2006; Seilacher, 2007; Przeslawski et al., 2012).

10.1.2. Benthic storms

Physical disturbances on the seafloor play a critical role in structuring marine ecosystems, and constraining spatial patterns of biodiversity (Sousa, 2001; Harris, 2014). From slope to abyssal depths, benthic storms are one of the processes that may produce these disturbances in the benthic habitat (Harris, 2014). Benthic storms can be defined as episodic periods of vigorous deep-sea currents and significant benthic nepheloid layer development (Gardner et al., 2017). They can cause both press and pulse disturbance; press disturbances act over a timespan that is intolerable to benthos and pulse disturbances exceed a threshold above which benthos are unable to remain attached to the seabed or are buried under rapidly deposited sediment (Harris, 2014). Benthic storms usually last from 2 to 22 days and have a return frequency of 8–10 storms per year where near-bottom currents attain speeds of up to 70 cm/s (Richardson et al., 1981; Hollister and Nowell, 1991; Hollister, 1993; Aller, 1997; Cronin et al., 2013; Harris, 2014; Gardner et al., 2017). Also, at abyssal depths beneath the Circumpolar Current in the Drake Passage, bottom currents of more than 0.7 m/s were sustained for up to 70 days (Chereskin et al., 2009). However, contrary to what happens with seasonal variations in the downward flux of organic detritus from surface waters (Lampitt, 1985), it is hard to find evidence for seasonality of particulate-matter concentration in nepheloid layers (Gardner et al., 2018a, b; Thran et al., 2018).

Since benthic storms were first described at the High Energy Benthic Boundary Layer Experiment (HEBBLE) area on the Nova Scotian continental rise, they have been observed along other continental margins (e.g., Gardner and Sullivan, 1981; Hollister and McCave, 1984; Weatherley and Kelley, 1985; Hollister and Nowell, 1991; Richardson et al., 1993). Nevertheless, benthic storms are not exclusive to continental margins, and analogous high-energy episodes have been described in abyssal areas (e.g., Woodgate and Fahrbach, 1999; Guidi-Guilvard, 2002 among others). These examples suggest benthic storms could occur in some parts of most oceans. Together with other relatively short-lived bottom-current events, benthic storms are an important trigger mechanism by which the majority of deep-sea sediment is reworked throughout the year (Harris, 2014; Thran et al., 2018).

The origin and correlation of benthic storms with upper-ocean dynamics have been intensively discussed since the origin of the term (see Gardner et al., 2018a). Recent studies conducted in the western North Atlantic margin corroborated the idea that bottom-boundary currents are too weak to generate and maintain episodically intense nepheloid layers, which require benthic storm events for development (Gardner et al., 2017). A global comparison of benthic nepheloid layers has shown that benthic storms are intensified below areas of high surface-eddy kinetic energy, suggesting a strong link with upper-ocean dynamics (Gardner et al., 2018a, b). The geographic emplacement of energetic nepheloid layers seems to coincide with areas of high energy dissipation in the bottom-boundary layer (Gardner et al., 2018a, b). Although the role of eddies has been strongly implicated for nepheloid layer formation, and it has been demonstrated that benthic storms are common in some deep-sea environments, studies addressing the impact of those energetic episodes on benthic fauna are still scarce (e.g., Thistle et al., 1991; Aller, 1997; Baldwin and McCave, 1999).

This study aims to describe for the first time the development of lebensspuren assemblages (abundance, distribution and diversity) before, during and after benthic storm events at Station M, northeastern Pacific (Fig. 10.1). We evaluate and elucidate how sporadic high-energy events affect benthic fauna and their associated behaviour. Moreover, the study covers a particular abyssal area of special interest which hypothetically should have less energetic capacity for benthic storm development (see Fig. 6 in Gardner et al., 2018b). What implications can this geographic location have for lebensspuren assemblages? The results of this study contribute to increasing knowledge of modern deep-sea lebensspuren, and improve understanding of sporadic stressful events' (i.e., benthic storms) impact on deep-sea benthos, both aspects being relevant to the interpretation of fossil lebensspuren.

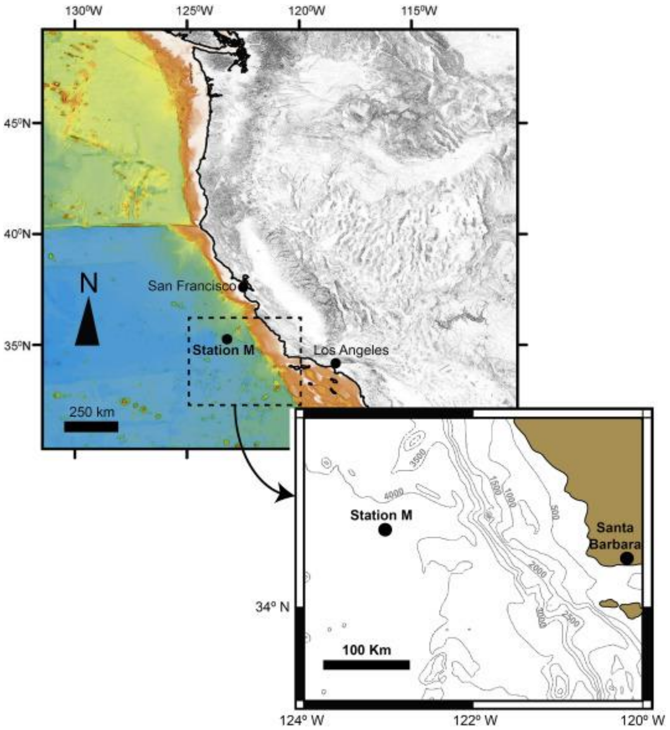

Fig. 10.1. General location of Station M in the northeastern Pacific (modified from Smith et al., 2016). Zoom-view map shows detailed location of Station M (4000 m) with 500 m contours (slightly modified from Lampadariou et al., 2019).

10.2. Methodology

10.2.1. Study site and instrumentation

Data were collected from the abyssal time-series site Station M in the northeastern Pacific (34°50 N, 123°06 W, 4000 m water depth; Smith and Druffel, 1998) (Fig. 10.1). The seabed is mainly composed of soft silty clay sediment (Kaufmann and Smith, 1997). Food falls are particulate organic carbon and detrital aggregates comprised primarily of phytodetritus but sometimes also gelatinous zooplankton (e.g., Smith et al., 2014). Moreover, a strong relationship has been noted between surface-water productivity and lagged megafaunal responses on the abyssal seafloor (Ruhl and Smith, 2004). The distribution of food is not always homogeneous, and patches of organic matter are common (Lauerman et al., 1996). Near-bottom current measurements have shown variations in flow velocity, but during the 2 1/4-yr time series (1993–1996), Station M did not experience any single benthic storm event (see Beaulieu and Baldwin, 1998). Near-bottom average flow speed at 2.5 m above bottom never exceeded 5 cm/s for periods greater than 2 d (Beaulieu and Baldwin, 1998). Evidence of local resuspension of recently deposited detritus was observed in time-lapse photographs, but near-bottom flow was not strong enough to originate the resuspension of sediments (Beaulieu and Baldwin, 1998). Nevertheless, Beaulieu and Baldwin (1998) indicated that benthic storm events might be expected at Station M. These results are consistent with more recent near-bottom current measurements that were collected from October 2014 to October 2018 (Connolly et al., 2020). Although flow velocity varied significantly at different time scales (i.e., tidal, monthly, seasonal, annual), current speeds necessary to qualify as benthic storm energetic conditions have not been documented (Connolly et al., 2020).

A time-lapse camera recorded the presence and activity of the benthic community over a seafloor area of 39.8 m2 (Sherman and Smith, 2009). The camera system was comprised of a Canon EOS 5D digital camera and 50 mm lens, along with a custom interval timer, inside a titanium housing with a flat-plate viewport. Two custom 250 J zenon strobes lights provided illumination. The system was powered by a 4.8 kWh lithium-primary battery in its own housing, capable of operating the camera for up to a year. All components were mounted to a titanium tripod frame, which held the camera and strobes 2.6 m above the seafloor. The camera system captured images at 1 h intervals for 189 d (4529 images). The study interval comprises the time interval from 07/04/2014 at 13:00 until 13/10/2014 at 05:02 local time.

10.2.2. Lebensspuren identification and quantification

Lebensspuren morphotypes were named to match as best as possible with existing names given to similar morphotypes in other locations (e.g., Ewing and Davis, 1967; Young et al., 1985; Bett et al., 1995; Dundas and Przeslawski, 2009; Przeslawski et al., 2012; Bell et al., 2013). Lebensspuren were classified based on the original groups proposed by Seilacher (1953): i. Resting lebensspuren; ii. Crawling lebensspuren; iii. Feeding structures (faecal casts and pellets); iv. Grazing lebensspuren; and v. Dwelling lebensspuren (mounds and burrows). Lebensspuren with unclear origin and bioturbation-like structures were artificially grouped into ‘Indeterminate origin traces’ (Hughes and Gage, 2004).

Morphological image measurements of the different lebensspuren were processed in order to characterize and describe the lebensspuren assemblage. Physical dimensions were obtained using a trigonometric perspective correction (Wakefield and Genin, 1987) in the open-source software “Video Annotation and Reference System” (Schlining and Stout, 2006). Using this technique, given the height, down-tilt angle and field-of-view of the camera, the distance between any two points lying in the plane of the seafloor can be determined. Abundance counting varied according to the type of lebensspuren: resting lebensspuren were counted only the first time that they appeared in the record; crawling lebensspuren were counted when the entire track was produced; feeding and dwelling lebensspuren were counted and plotted representing the abundance variation (except for enteropneust faecal casts which were quantified in the same way as crawling lebensspuren). Moreover, lebensspuren were semi-quantitatively ranked according to the following categories: abundant, common, frequent, occasional and rare (see Box 12.2 in Morris and Therivel, 2001).

According to the obtained results (see below), a constant area (3.3 m2, same as for the exhumed surface quantification) was selected to study in detail the percent coverage of holothurian faecal casts. For this purpose, we also used the Fiji image processing package (Schindelin et al., 2012). First, image visibility was increased with the automatic Contrast Limited Adaptive Histogram Equalization tool (CLAHE) in order to enhance contrast of the bioturbational structures (Miguez-Salas et al., 2019a). Individual holothurian faecal cast lebensspuren areas were then calculated by drawing around each trace with the free-hand tool. Only full faecal cast structures were considered; no disarticulate faecal casts were considered for area measurements. Then, the summed area measurements of holothurian feeding lebensspuren were reported as a percentage.

10.2.3. Benthic storm characterization

Benthic storm events at Station M were identified through a backscatter analysis of the time-lapse images (Fig. 10.2). The mean gray value of the top one-sixth of each image was measured and used as a proxy for the quantity of particulate matter in the water. These values were then passed through a three-point median filter to remove the effects of transient events not related to detrital activity (e.g., fishes that pass in front of the camera). This method provides a relative turbidity index during a single time-lapse camera deployment, even if exact measures are not possible. Particulate organic carbon flux data were not available for this period due to a sediment trap clog.

In parallel, a constant sea floor area (3.3 m^2) with optimum lighting of each frame was analysed with special attention to the substratum type (Fig. 10.2A; yellow rectangle). High-energy bottom currents usually erode the soft, unconsolidated surface substratum and expose buried, consolidated surfaces (Wetzel et al., 2008) (Fig. 10.2E). Exhumed surface percent exposure was measured semi-automatically, quantified using Fiji drawing and binary tools (Schindelin et al., 2012). First images were converted to an 8-bit grayscale image. Then, the threshold was defined to establish a differentiation range for black and white pixels (black pixels were assigned to exhumed surface). Manual corrections were conducted using eraser or painting tools in most of the frames. Finally, the black and white binary image was used to quantify the amount of exhumed surface (see Miguez-Salas et al., 2019a).

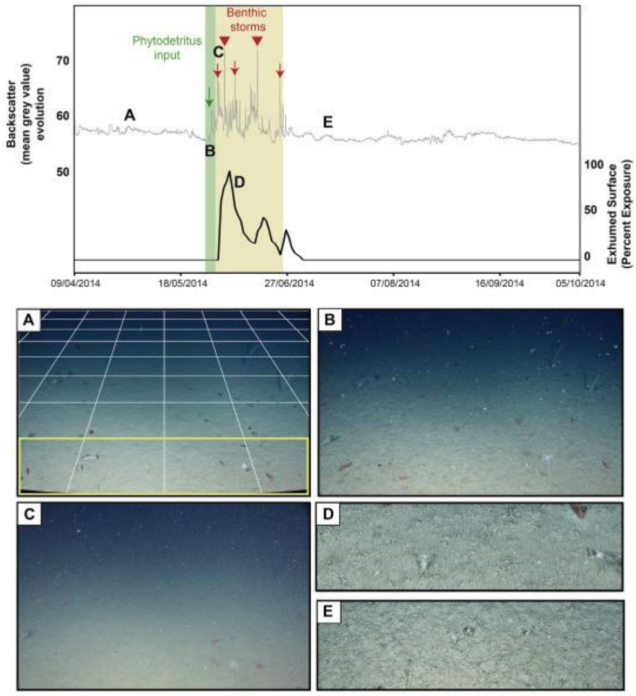

Fig. 10.2. Exhumed surface exposure and benthic storm evolution at station M. Seafloor images during different conditions: A) Stable and steady deep-sea environment with a superimposed 1×1 m grid (yellow rectangle indicate the area selected for the study of the exhumed surface and percent coverage of holothurian faecal casts); B) Phytodetritus input (base of the panel is ~4 m width); C) Benthic storm event (base of the panel is ~4 m width); D) Exhumed surface after benthic storm event (base of the panel is ~1 m width); and E) Detailed view of soft substratum coverage (base of the panel is ~1 m width). Notes: Green arrow (phytodetritus input); red arrow (smaller benthic storms) and red triangle (main benthic storms). Letters on time series plots point to the timing of each sea floor image panel. The scale varies in oblique views as you can appreciate in the grid. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

10.3. Results

10.3.1. Lebensspuren classification

We identified 15 lebensspuren morphotypes and indeterminate origin traces in 4529 images (Fig. 10.3, Fig. 10.4). Morphotypes were grouped by their primary behavioural origin: resting (2 morphotypes), crawling tracks (3 morphotypes), dwelling (4 morphotypes), and feeding casts (6 morphotypes).

Resting morphotypes were formed as impressions in the sediment due to the organism ceasing movement for a considerable period of time. They were preserved as concave epireliefs at the sea floor (Fig. 10.3).

Depressions were large, round, concave craters with no obvious related tracks or associated dwelling structures. Depressions were rare, and their diameters ranged from 50 to 250 mm (Fig. 10.3E, black arrow). They sometimes appeared as a collapsed mound, and might have multiple origins, with cnidarians being the common trace makers (*Liponema brevicornis*).

Star impressions refer to star-shaped depressions (Fig. 10.3G). The epirelief was smooth and preserved in the soft sediment. The maximum length of the impressions was 200 mm. The dimensions of the impression were proportional to the asteroid size and sometimes a wide trail leading to it was observed (Fig. 10.3G). Star impressions were occasional. They were produced by asteroids.

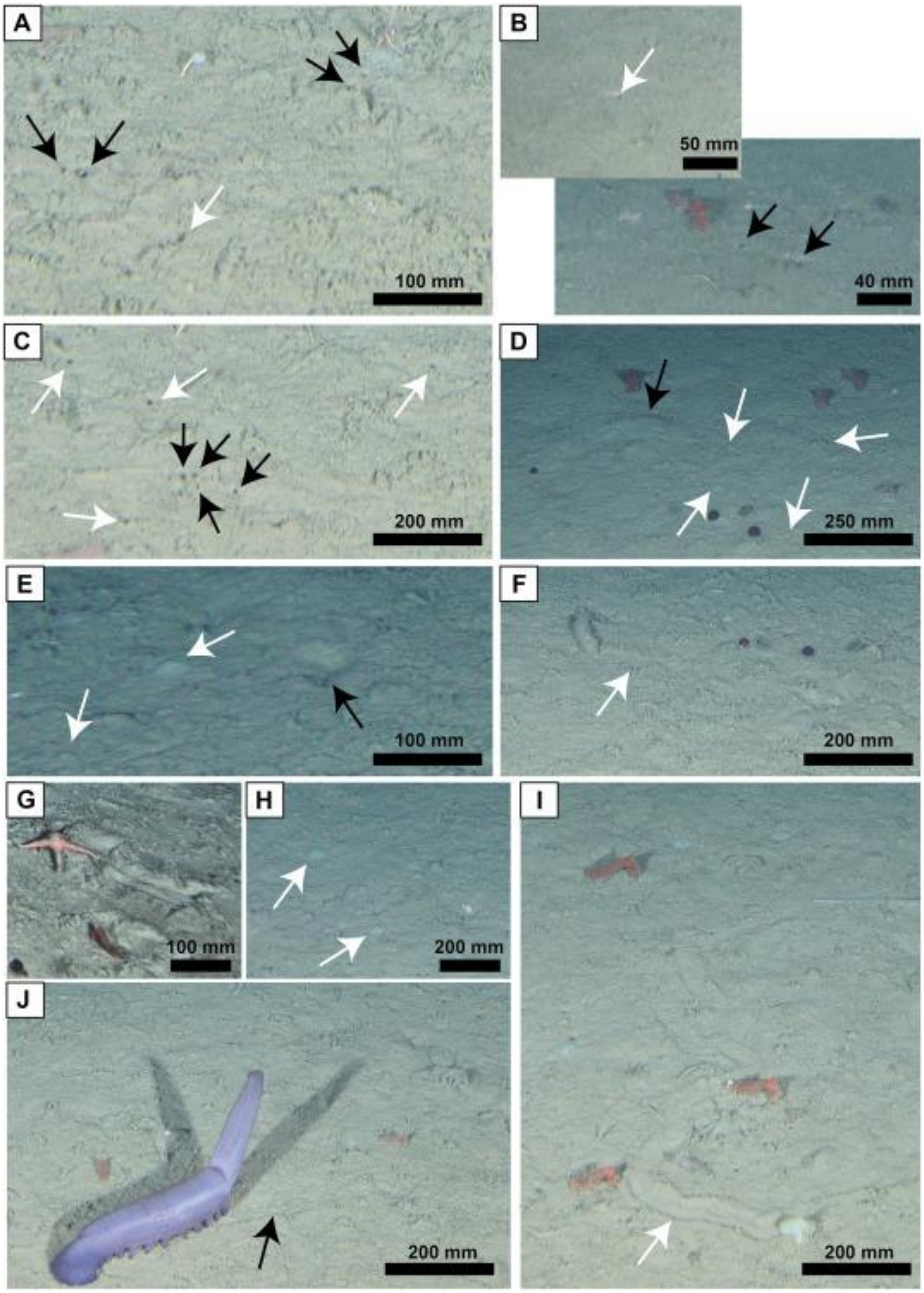

Fig. 10.3. Lebensspuren morphotypes observed and quantified at Station M. A) Single (white arrow) and paired burrows (black arrows); B) Single (white arrow) and paired burrows (black arrows) in exhumed surfaces; C) Single (white arrows) and cluster burrows (black arrows); D) Dwelling mounds (white arrows) and mounded track (black arrow); E) Dwelling mounds (white arrows) and depression (black arrow); F) Thick shallow trail by *Pseudostichopus mollis*; G) Two star-shaped impressions and associated thick trail left by an asteroid; H) Dwelling mounds with entry holes at the apex; I) Thick deep trail by *Echinocrepis rostrata*; and J) Thick shallow trail by *Psychropotes* sp. Note: Scale bars correspond to the dimensions of the image where they are located, because the scale varies in oblique views (see grid in Fig. 10.2A).

Crawling morphotypes consisted of thin, thick, and mounded trails (Fig. 10.3, Fig. 10.4). They were formed as the organism moved across the seafloor (on or within the substrate). The trails varied in size, shape and thickness. Length of the track was usually limited by the time-lapse coverage. The appearance of thin and thick trails was not restricted to the surface substrate. However, the displacement of organisms along an exhumed surface left shallow trails with poor durability (less than 2 h).

Thin trails were smooth, concave epirelief trails of varying length and less than 20 mm thick. Trails might form linear, meandering or completely random paths (Fig. 10.4D). Thin trails made by polychaete worms (Opheliidae) involved straight paths and linear patterns, more so than trails produced by holothurians. Thin trails were common and widespread, and had multiple origins. Their trace makers were holothurians (*Abyssocucumis abyssorum*) (Fig. 10.4D) and presumably worms.

Thick trails were smooth, concave epirelief trails of varying length and depth, up to 150 mm thick. These trails formed linear, meandering, or completely random paths. Thick traces generated by the echinoids penetrated deeper into the sediment than those left by the holothurians, which formed shallower depressions. Thus, the durability of the former was greater. Thick trails were common. Their trace makers were echinoids (*Cystocrepis setigera* and *Echinocrepis rostrata*) (Fig. 10.3I), holothurians (*Pseudostichopus mollis*, *Paelopatides confundens* and *Psychropotes* sp.) (Fig. 10.3F, J) and sporadically asteroids (Fig. 10.3G).

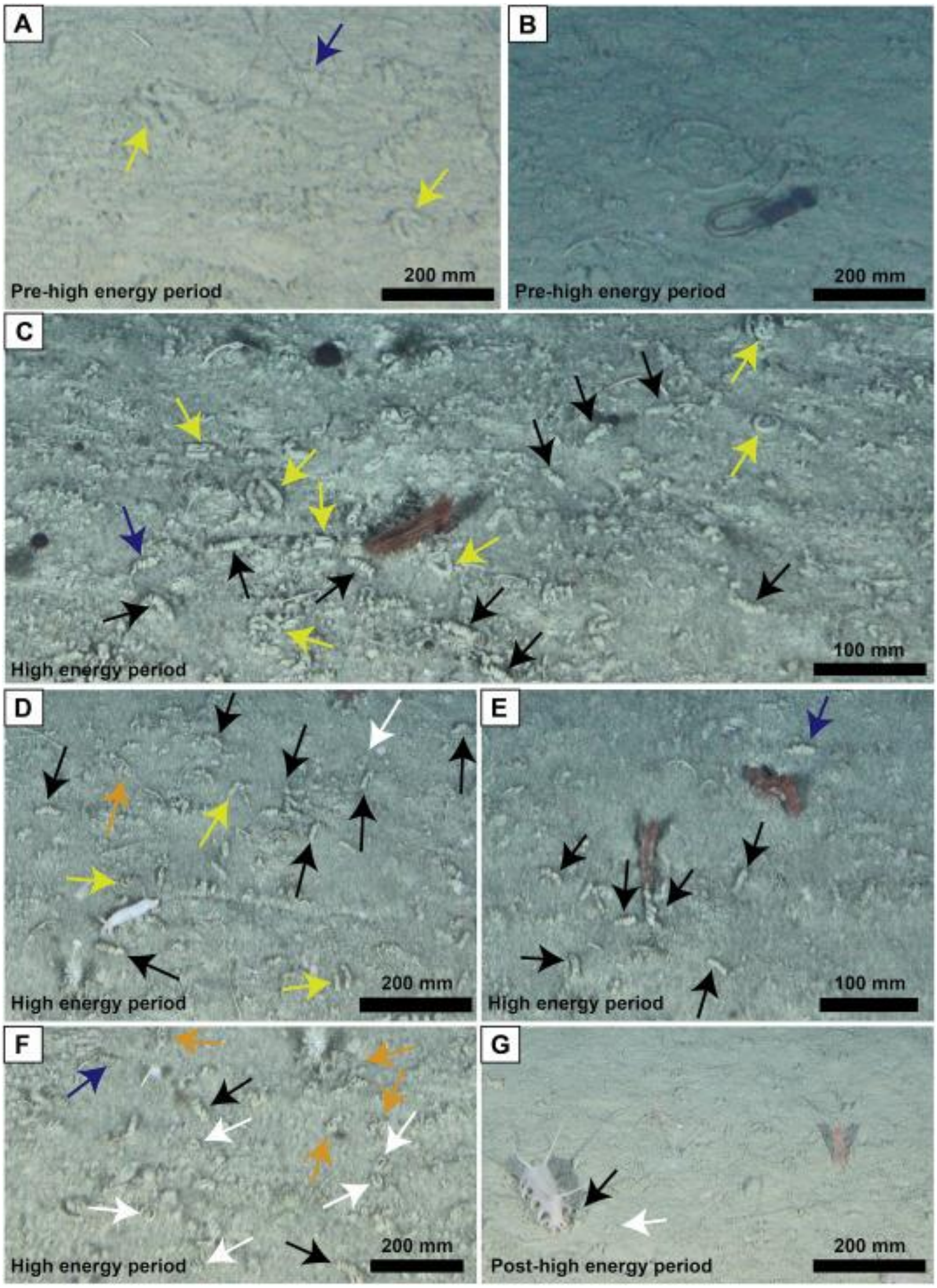

Fig. 10.4 Feeding lebensspuren morphotypes (faecal casts) observed and quantified at Station M. A) Pre-high energy period assemblage; B) Pre-high energy period enteropneust faecal cast; C) High energy period lebensspuren assemblage; D) High energy period lebensspuren assemblage with *Abyssocucumis abyssorum* making an ephemeral thin trail; E) *Peniagone* spp. Producing knotted faecal casts; F) High energy period lebensspuren assemblage with numerous rounded faecal casts; and G) Post-high energy period assemblage. Note: black arrows (knotted faecal casts), yellow arrows (smooth faecal casts), orange arrows (wavy faecal casts), blue arrows (coiled faecal casts) and white arrows (round faecal casts). Note: Scale bars correspond to the dimensions of the image where they are located, because the scale varies in oblique views (see grid in Fig. 10.2A). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.

Mounded trails were smooth, convex trails of varying length, up to 100 mm thick (Fig. 10.3D; black arrow). These trails could form linear or slightly meandering paths. They had multiple origins but were probably formed by subsurface deposit feeding echinoderms, holothurians, gastropods or scaphopods (Gage and Tyler, 1991; Dundas and Przeslawski, 2009). Mounded trails were rare.

Dwelling morphotypes were formed by burrowing organisms that lived within the deep-sea sediment (Fig. 10.3). They were the most abundant morphotypes in the pre- and post-high energy period lebensspuren assemblages. Most dwelling structures were single or paired burrows.

Mounds were large, smooth-sided cone structures. The cone apex had a burrow entry hole that was sometimes difficult to distinguish (Fig. 10.3D, E and H; white arrows). The diameter of the mounds ranged between 50 to 200 mm. Occasionally, the mounds involved disturbed pelletoidal sediment surrounding the base. These structures might have been produced by amphipod crustaceans (Gage and Tyler, 1991). Mounds were common.

Cluster burrows were complex burrow structures usually comprising a randomly spaced burrow hole system (Fig. 10.3C; black arrows). The spacing between burrows was between 20 and 100 mm. We typically saw one larger burrow surrounded by several smaller peripheral burrows. The diameter of the burrows ranged from 5 to 15 mm. Sometimes the burrow system exhibited a rectilinear pattern, recording aligned holes. These structures might have been produced by infaunal worms. Cluster burrows were rare.

Single burrows were smooth entry holes within the sediment surface (Fig. 10.3A and C; white arrows). The diameters were varied, as large as 20 mm, but usually between 5 to 15 mm. Single burrows were abundant and could appear on the exhumed surface (Fig. 10.3B; white arrow), remaining open for 2 to 4 h. Single burrows likely had multiple origins, including crustaceans or polychaete worms among others (see Gage and Tyler, 1991; Przeslawski et al., 2012).

Paired burrows refer to two small entry holes very closely spaced (Fig. 10.3A; black arrows). Paired burrows appeared randomly along the seafloor. The hole spacing was less than 30 mm, and diameters varied from 5 to 15 mm. Paired burrows were very common and also appeared on the exhumed surface (Fig. 10.3B; black arrows), remaining open for 2 to 4 h. Their trace makers were possibly crustaceans, worms or buried bivalve siphons, based on Gage and Tyler (1991).

Feeding cast morphotypes were formed as the organism excreted sediment particles from which organic material was likely consumed (Fig. 10.4). The casts varied in size, shape, thickness and length. Five feeding cast morphotypes belonged to holothurian trace makers and one to acorn worms. As with enteropneust lebensspuren (Smith et al., 2005), the holothurian lebensspuren disintegrated and degraded very quickly, which made it difficult to classify them into different morphotype groups. Shape and size were altered in less than four days. Small morphological features, such as loops or ring shapes, were obliterated after two days.

Coiled faecal casts were tightly coiled faecal trails with a characteristic loop at the end (Fig. 10.4A, E and F; blue arrows). We observed straight cylindrical casts of coils with cylinder lengths up to 100 mm. The loop dimensions ranged from 10 to 20 mm, sometimes detached from the main coil, which made them difficult to differentiate from knotted faecal casts. Coiled faecal casts were rare. Their trace makers were *Peniagone* spp., and occasionally *Paelopatides confundens* and *Psychropotes*.

Wavy faecal casts were thin, straight or meandering faecal remains, variable in length and often in fragmented form (Fig. 10.4D and F; orange arrows). The length reached a maximum of 250 mm, with a diameter less than 50 mm. Wavy faecal casts sometimes incorporated coiled faecal casts. Wavy faecal casts were frequent. While they were associated with holothurian feeding activity, their trace makers are unknown.

Round faecal casts were represented by short spirals of thick faecal matter (Fig. 10.4F and G; white arrows). The cast diameter was between 25 and 50 mm, with smooth walls. Round faecal casts were common and widespread. Their trace maker was *Scotoplanes globosa*.

Knotted faecal casts were elongated cylindrical casts of tightly grouped rings without a loop at the end (Fig. 10.4; black arrows). They were either straight or had a slight curvature. The length was between 30 and 120 mm and the diameter could be up to 30 mm. Knotted faecal casts were abundant and widespread. Their trace makers were *Peniagone* spp.

Smooth faecal casts were smooth, cylindrical casts of variable thickness and length (Fig. 10.4; yellow arrows). They exhibited straighter patterns and usually larger dimensions (both thickness and length) than round faecal casts. Their diameter was between 30 and 50 mm, and their length was up to 100 mm. Smooth faecal casts were common, and had multiple holothurian origins. Their trace makers were *Scotoplanes globosa* and occasionally *Abyssocucumis abyssorum* and *Pseudostichopus mollis*.

Enteropneust faecal casts exhibited a distinctive spiral shape (Fig. 10.4B). The spiral tracks followed both clockwise and anti-clockwise paths. The width of the faecal cast that created the spiral was between 15 and 25 mm. The total diameter of the spiral morphotype ranged from 200 to 500 mm. They were frequent, and were associated with their acorn worm trace maker, *Tergivelum baldwinae* (Enteropneusta).

Indeterminate origin traces represented the highest proportion of the lebensspuren assemblage. This group comprised bioturbation structures that cannot be clearly associated with a trace maker. Examples included undifferentiated crawling tracks, feeding faecal casts which were small or did not record any distinctive morphological feature, pellets, depressions related with burrow system collapse, and undifferentiated mounds, among others.

10.3.2. High-energy episodes and seafloor coverage

Energetic conditions varied during the 189-d interval studied here (Fig. 10.2), indicated by variable turbidity and levels of exhumed substrate. Low-energy stable conditions were dominant. High-energy episodes were documented during a 25-d period from 31/05/2014 11:00 until 24/06/2014 20:00 local time (Fig. 10.2). We call this the “high-energy period”. Inside this period two main benthic storms events stand out, the first one on 03/06/2014 and the second one 15/06/2014 (red triangles in Fig. 10.2). Besides those two strong events, three weaker events occurred on 31/05/2014, 06/06/2014 and 23/06/2014 (red arrows in Fig. 10.2).

For most of the interval, the sea floor was completely covered by silty clay sediments. Appearance of an exhumed surface coincides with the first energetic episode (31/05/2014 11:00). Then, average area coverage by exhumed surface (Fig. 10.2) experienced a progressive increase until 04/06/2014, reaching a maximum value of 88%. This peak occurred one day following one of the main energetic events (03/06/2014). Later, two exhumed surface growth stages were recorded again after the storm events of 15/06/2014 and 23/06/2014. These two peaks reached exposure values below 50%, which were considerably smaller than the first event (88%). A single phytodetritus input event was documented, starting on 25/05/2014 and lasting until the first storm event (green arrow in Fig. 10.2).

10.3.3. Lebensspuren development

Lebensspuren assemblages, as the whole of observed lebensspuren (Fig. 10.5), and especially holothurian faecal casts (Fig. 10.6), showed different development before, during and after the high-energy period. Similar lebensspuren assemblages were observed before and after benthic storm events with indeterminate origin traces covering the largest area (Fig. 10.5). Nevertheless, time recovery for some morphotypes was different and changes could be observed.

The pre-storm lebensspuren assemblage was composed of 15 morphotypes (Fig. 10.5). The most abundant lebensspuren during this period were dwelling morphotypes. Feeding morphotypes (faecal casts) were also common. Crawling tracks were frequent and resting traces were rare. The morphotypes responsible for major area coverage prior to the high-energy period were mounded dwelling structures, thick crawling tracks and enteropneust faecal casts. Phytodetritus input prior to benthic storms was followed by an increase in holothurian feeding faecal casts from 0.4% to 0.9% (Fig. 10.6).

The lebensspuren assemblage varied during the high-energy period with benthic storms. First, storm events produced an immediate impoverishment in dwelling-mounded morphotypes, and later in crawling and resting lebensspuren (Fig. 10.5). These changes were not related to the disappearance of the trace maker. Echinoids (*Cystocrepis setigera* and *Echinocrepis rostrata*) and holothurians (*Abyssocucumis abyssorum*, *Pseudostichopus mollis*, *Peniagone* spp. and *Scotoplanes globosa* among others) were still observed at the seafloor. However, enteropneusts (*Tergivelum baldwinae*) were not noticed. Holothurian feeding faecal cast coverage increased rapidly to reach local peak values of 2.5% (07/06/2014), and become the dominant lebensspuren (Fig. 10.6). Feeding morphotypes during the high-energy period comprised abundant knotted, common smooth and frequent round faecal casts (mainly elpidiid holothurian trace makers). Also, some isolated single or paired dwelling burrows appeared in the exhumed surface, remaining open for a couple of hours after storm events. The displacement of crawling trace makers produced shallow depression tracks with similar preservation. The last stages of the high-energy period were associated with the highest values (3.5%) of holothurian feeding faecal cast coverage (Fig. 10.6). Also, the decrease in values below 50% of exhumed surface exposure allowed the appearance of star impressions located in patches of the seafloor with softer sediment. Discontinuous crawling lebensspuren related to echinoderm or holothurian activity were again documented.

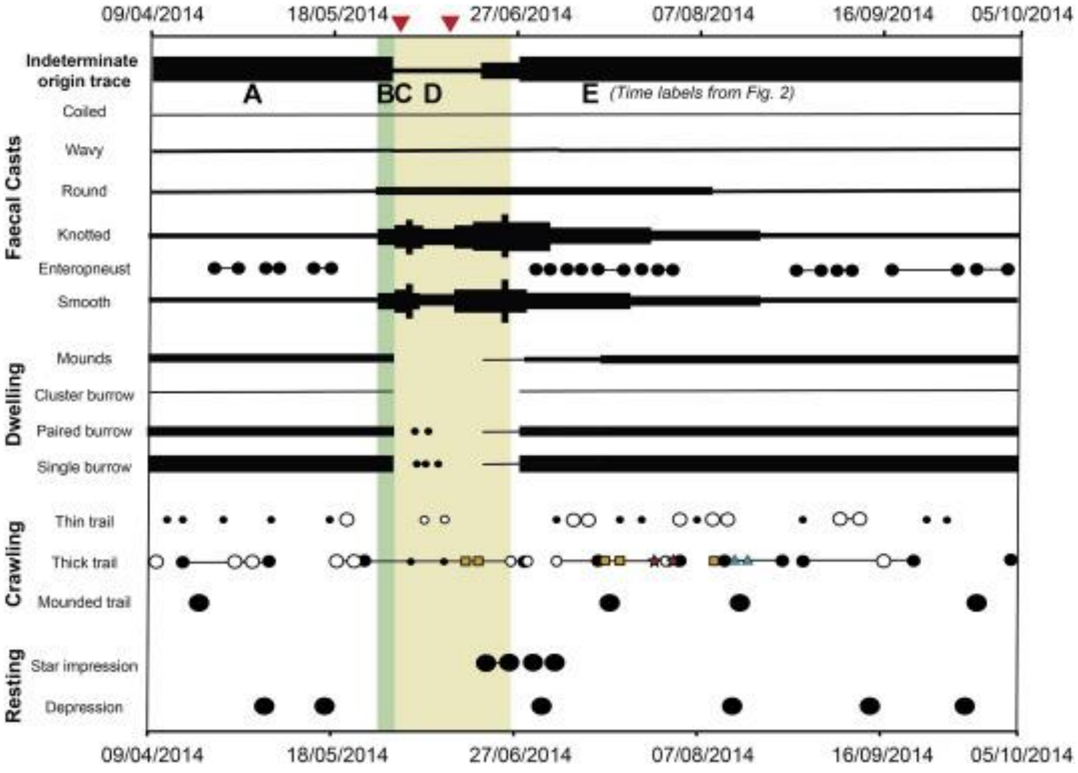

Fig. 10.5. Lebensspuren morphotype abundance from 09/04/2014 until 05/10/2014. Thickness of the bars represents relative abundance. Dots represent appearance, dot diameters indicate durability, and line

between dots indicates continuous appearance. Red triangles are main benthic storms. Color corresponds to trace maker (thin trails: black dots--presumed to have been created by worms, white --*Abyssocucumis abyssorum* traces; thick trails: white dots--*Cystocrepis setigera*, black dots--*Echinocrepis rostrata*, blue triangles--*Paelopatides confundens*, orange squares--*Pseudostichopus mollis*, red stars--*Psychropotes* sp.). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The post-storm lebensspuren assemblage was similar to the pre-storm assemblage (Fig. 10.5). Coverage of holothurian feeding casts decreased progressively, reaching pre-storm values (0.4%) three months after the first storm and eight weeks after the final storm (Fig. 10.6). Mounded dwelling structures were the last to reappear, one week after the final storm. Crawling lebensspuren were slightly more abundant in the post-storm lebensspuren assemblage than in the pre-storm lebensspuren assemblage.

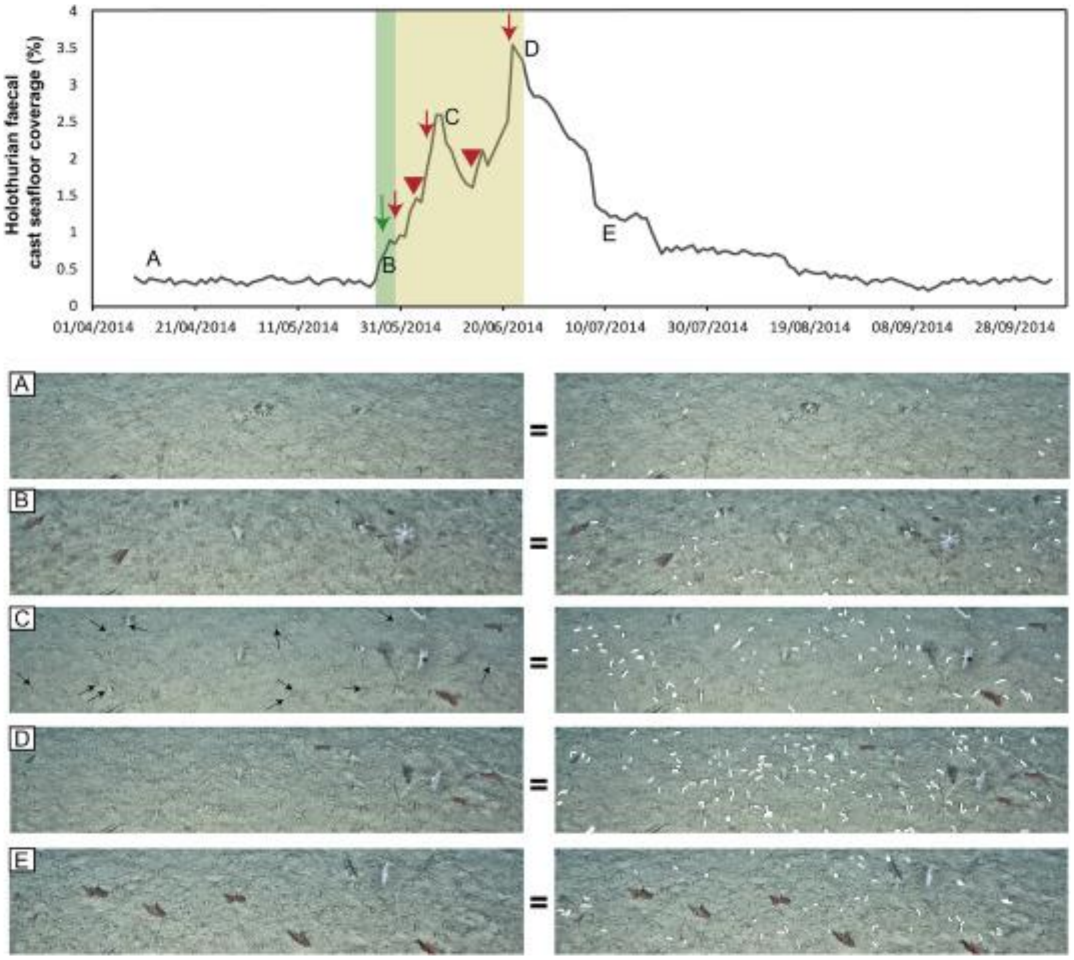

Fig. 10.6. Holothurian feeding-faecal-cast abundance from 07/04/2014 until 13/10/2014, with faecal casts coloured white in right-side panels. A) Stable and steady deep-sea environment; B) Phytodetritus input; C) After the first main storm (black arrows indicate redeposited organic matter); D) After the second main storm; and E) During the readjustment phase. All panel bases are ~4 m width. Note: green arrow (phytodetritus input); red arrow (benthic storms) and red triangle (main benthic storms) in the time series plot (Fig. 10.2). Letters on the time series plot point to the timing of each sea floor image panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

10.4. Discussion

10.4.1. Holothurians and benthic storms

Holothurians are one of the main bioturbators and consumers of organic carbon at abyssal depths (Ginger et al., 2001). Holothurians transit the seafloor foraging for food resources while they perform their deposit-feeding activities (Bett et al., 2001). Selective deposit-feeding strategies exhibited by holothurians have been previously proposed in relation to particle size as well as to the quality of food input; they consume preferably freshly settled phytodetritus when available (e.g., Billett, 1991; Roberts et al., 2000; Ginger et al., 2001). These parameters have been suggested to control the composition of the holothurian community along deep-sea environments (Wigham et al., 2003). Studies at Station M have also proved that quantity/quality of detrital aggregates altered tracking rates and that food inputs controlled density, immigration patterns and body size (Smith et al., 1994; Huffard et al., 2016).

Organic matter commonly exhibits a vertical stratification within abyssal sediments (Santos et al., 1994), with holothurian deposit feeders employing different strategies to access each particular sediment horizon (Roberts et al., 2000). These strategies can be subdivided into surface (epibenthic) deposit feeders, subsurface (infaunal) deposit feeders, and funnel feeders, which construct funnel-shaped depressions in soft sediments that act as sediment traps where organic material is collected or slumps in (Jumars, 1993; Roberts et al., 2000). However, hypothetically, if an erosive event (i.e., benthic storm) takes place, the holothurian species associated with subsurface or funnel feeding strategies will no longer be capable of exploiting those sediment horizons. The erosion, resuspension, and resettling of surface/subsurface sediments will reorganize sediment depth horizons and organic matter resources. Taking into account the different density between inorganic material and organic matter compounds (McCave, 2008), a selective sinking in the lower water column will occur, leaving the organic matter at the uppermost sediment and surface levels. Thus, as pointed by Aller (1989) during transitional periods (when bottom current velocity decrease), there will be a vertical and horizontal influx of organic material. Progressive deposition and relocation of organic matter will take place (Fig. 10.6C), and any surface vs. subsurface succession of deposit-feeding activity will be reset.

In this study a notable increase in holothurian surface-feeding faecal casts was recorded one to two days following the benthic storm events. Knotted faecal casts (*Peniagone* spp.) were the dominant forms, followed by smooth faecal casts (*Scotoplanes globosa*). Preceding studies have shown that those holothurian species which are more efficiently able to detect and utilize newly relocated detritus coverage are expected to gain a competitive advantage over those that are confined to slower locomotion or other physiological limitations (Wigham et al., 2003; Neto et al., 2006; Huffard et al., 2016). This fact has been especially corroborated for elpidiid holothurians (e.g., *Peniagone* spp., and *Scotoplanes globosa* among others), which have a high mobility range allowing them to exploit new food resources (Amaro et al., 2015; Huffard et al., 2016). Present results seem to indicate that these mobility skills may have allowed a rapid increase in elpidiid holothurians feeding activity after benthic storm events.

The data obtained at Station M suggest two types of behaviours for elpidiid holothurians: i) a selective feeding strategy when fresh phytodetritus, non resuspended, organic matter input occurs; and ii) a non-selective surface feeding strategy when food is relocated due to erosion, resuspension and resettling. It should be noted that when fresh surface-derived organic matter input occurred, the coverage of faecal casts doubled. By contrast, after sediment that was resuspended during benthic storms resettled, the coverage of holothurian faecal casts increased nearly another four-fold (Fig. 10.6). The rapid decreases in holothurian faecal cast abundance after maximum peaks corroborate previous discoveries which revealed that a high density of holothurians can quickly deplete organic material in abyssal surface sediments (Bett et al., 2001; Ginger et al., 2001).

Finally, it is important to highlight the enigmatic affinity between holothurian movement patterns and the direction of bottom currents. In the present study, a unidirectional migration along the bottom-current flow seems to take place before and after the high-energy period, especially in *Peniagone* spp. However, when a benthic storm occurred, a seemingly random movement pattern was observed. By contrast, a more random movement pattern was observed for *Scotoplanes globosa* during all conditions. This evidence is not unexpected; previous studies noticed that *Peniagone japonica*, along with several other holothurians, swam downstream on the continental slope of Japan (Ohta, 1983). However, studies in the San Diego Trough showed that *Scotoplanes globosa*, which can “walk” over the sediment using leg-like lateral podia, are able to go upstream against weak bottom currents (Barham et al., 1967). The data observed at Station M suggest that surface-deposit-feeding holothurians changed their prevailing movement pattern when food resources became high enough after a benthic storm event. Hansen (1975) advanced that the distribution of some bathyal and a few abyssal holothurian species is closely linked to ocean currents, which transport them either as adults or during their juvenile phase. Nevertheless, a more detailed analysis in the future is necessary for further consideration.

10.4.2. Benthic storms and lebensspuren

To our knowledge, the relationship between lebensspuren and benthic storms has not been documented previously. The deep-sea is a food-limited environment in which the abundance and density of the benthic community is broadly controlled by organic matter inputs reaching the seafloor (Gooday and Turley, 1990). Therefore, organic matter distribution will control feeding strategies and changes in benthic diversity that force benthic fauna to forage in order to encounter sufficient resources (Jumars and

Wheatcroft, 1989). Bottom current interactions with seafloor topography are important mechanisms controlling organic matter cover of the sea floor (see Morris et al., 2016). Thus, bottom current processes and associated intensities would control the amount of organic matter that is re-suspended, deposited, or directly provided by the hemipelagic rain and the thickness of the nepheloid layer (McCave, 2008; Gardner et al., 2017, 2018a).

Previous studies have shown that interaction between energetic bottom currents and the deep-sea benthos is ambiguous, and effects can be either positive or negative (Levin et al., 2001). Generally, moderate currents can enhance the food supply, increasing the abundance and diversity of benthic fauna (Thistle et al., 1985; Aller, 1989). On the other hand, strong currents may depress diversity directly by eroding surficial sediments and carrying away the organisms living in them (Aller, 1997). Nevertheless, a high-energy regime is not continuous, creating breaks for opportunistic recolonization (Thistle et al., 1991; Lambshead et al., 2001).

Within the time frame of the present study, benthic storms were the dominant effect structuring benthic faunal behaviours and lebensspuren diversity. Lebensspuren assemblages before and after benthic storm events were similar. Storm events induced a decrease in lebensspuren diversity and abundance during the high-energy period, while some holothurian faecal morphotypes became more abundant. This change in lebensspuren assemblage was not associated with the disappearance of the trace maker community living on the seafloor, but with the erosion of the sedimentary cover. The removal of the unconsolidated sediment (soupy-, soft-substratum) prevented the generation of crawling, dwelling and resting lebensspuren by the fauna. Pre-storm lebensspuren assemblage could not be re-established until an undetermined minimum thickness of sediment was deposited after the event. The full lebensspuren assemblage was re-established in 1 week at Station M.

Similar trends were observed at the HEBBLE site in the northwest Atlantic where benthic storms smoothed the seafloor, with some tracks and burrows being obliterated. However, three weeks later, after a quiet period with weaker currents and less suspended material, tracks and burrows had returned to their pre-storm state (Gross et al., 1988). Therefore, in this case, restoration time at Station M was shorter than at the HEBBLE site. Moreover, Aller (1997) considered that recovery time following disturbance events is relatively short for meiofaunal and macrofaunal abundances at the HEBBLE site. Those rapid recovery times at the HEBBLE site could be interpreted as indicating that the habitat was not truly disturbed in the sense of disturbance-clearing processes (Harris, 2014). Following the discussion proposed by Harris (2014), benthic storms occur too frequently for benthic fauna to establish a disturbance at the HEBBLE site according to "intermediate disturbance hypothesis" (Connell, 1978; Huston, 1979). Considering the Station M and HEBBLE results, two main questions can be addressed: What intensity and duration must be attained by a benthic storm before it causes a clearing disturbance? How do frequent versus sporadic storms determine disturbance regimes?

Compared to the HEBBLE site, Station M is located in a different geographical context in terms of kinetic energy; high bottom-current velocities, and benthic storm development are not as intense or frequent as in other oceanic margins (Gardner et al., 2018a, b). Therefore, hypothetically, benthic storms should be considered as pulse-type disturbance events in the northeastern Pacific. The current study showed that those energetic events were not sufficient to carry away the megafauna living on the seafloor. Thus, apparently benthic storms at Station M cannot be considered clearing disturbance processes either. This result is not totally unexpected, as Harris (2014) postulated “while benthic storms are potential agents for meiofauna disturbance regimes, unless we can identify areas where their return frequency is measured in years or decades, they are not likely to be agents for megafauna disturbance regimes.”

If we address the results from a bioturbational point of view, the implications are totally different. Benthic storms generated a quick impoverishment of lebensspuren assemblage diversity (Fig. 10.5). Thus, benthic storms caused an abrupt clearance disturbance by exceeding a threshold (reducing soupy/soft sediment thickness below a required minimum) above which the benthos were unable to bioturbate, and requiring them to modify their associated behaviours. Therefore, we suggest that benthic storms should be considered as pulse-clearing-disturbance regimes (according to Harris, 2014) in studies of lebensspuren diversity at Station M. Furthermore, Station M benthic storm events can be tentatively classified as selective-pulse-disturbance regimes because not all lebensspuren morphotypes were affected in the same way. Future studies should try to investigate how lebensspuren assemblages evolve when benthic storms act as press type disturbance (see Harris, 2014).

10.4.3. Benthic storms through the lens of ichnology and further considerations

Trace fossils, lebensspuren preserved in the geological record, are impressions of activity produced by organisms on or within the substrate (Seilacher, 2007). Relationships between trace fossils and strong bottom-current episodes cause distinct responses (Wetzel et al., 2008; Rodríguez-Tovar and Hernández-Molina, 2018; Miguez-Salas et al., 2019b). On smaller time scales, ichnological features of precise ichnotaxa, or the appearance of particular firmground and hardground-ichnofauna (i.e., *Glossifungites* and *Trypanites* ichnofacies), can indicate variations in sedimentation rates, erosion and changes in substrate consistency related to bottom-current dynamics (Wetzel et al., 2008; Rodríguez-Tovar et al., 2019). Therefore, deep-sea erosion associated with vigorous bottom currents will lead commonly to discontinuous surfaces marked by a stiff-to hardground-ichnofauna (Wetzel et al., 2008). Nevertheless, establishing a time scale in the stratigraphic record for those energetic events, as well as for the faunal recovery, is usually complicated, remaining unknown in most cases. Considering the aforementioned, one question arises: Why did the modern counterpart of these firm/hardground ichnofauna not appear on the freshly exhumed surfaces after benthic storm events at Station M?

Wetzel et al. (2008) emphasized that “When bottom currents prevent deposition for a considerable time span, and/or erode sediments, submarine hiatuses develop, represented by semi-consolidated firm- or hardgrounds or stable cohesive partially dewatered muddy substrates”. Thus, timespan between energetic episodes along with duration of the same, seem to be controlling factors in the establishment of extensive changes in the bioturbational community. At Station M after benthic storm events, punctual-dwelling, single-burrow lebensspuren appeared on the exhumed surface, but they were not dominant, and they disappeared after a couple of hours. Therefore, the occurrence of an exhumed surface may not have been exposed long enough to be colonized by specialized fauna. The timespan of pulse disturbance events seems to be a limiting factor that would make it difficult to establish analogies with the ancient record. The fossiliferous potential of faecal-cast lebensspuren, which undergo a significant change after benthic storms at Station M, is considerably lower than other crawling, dwelling or resting structures (i.e., Smith et al., 2005). Thus, a minimum time of exhumed surface exposure would be necessary for the appearance of dwelling lebensspuren that can be observed in the fossil record.

Inter-annual variation in abyssal bottom-current (i.e., contour current) speed and/or direction have been considered as possible press-type disturbance (Harris, 2014). Recent studies have corroborated that eddy kinetic energy is also the major driver for these bottom-current fluctuations (Thran et al., 2018). Thus, areas that have affinities with eddy disturbance should be interpreted in terms of a bottom current's susceptibility to experiencing periodic, high-speed current events (Thran et al., 2018). From an ecological perspective, several studies have shown that small changes in ocean circulation could potentially have a significant ecological impact on abyssal fauna (Thistle, 1981, 2003). Therefore, changes in deep-sea bottom currents could lead to the appearance of cleared patches of habitat, inducing colonization by a different benthic community (Harris, 2014). This press-type disturbance seems to be more conducive to the establishment of a shift that could be registered in the geological record. Accordingly, ichnological changes in relation to bottom-current dynamics may consider press-type disturbances as the most plausible analogues instead of pulse-type disturbance (i.e., benthic storms). Nevertheless, sedimentological criteria (i.e., sedimentary structures) should remain as the pivotal point for initial ichnological considerations.

Finally, this study reveals some remarkable insights for future ichnological and palaeoenvironmental reconstructions. As mentioned before, benthic storms eroded and resuspended the unconsolidated, soupy/soft sediment, removing bioturbation and leading to the appearance of exhumed surfaces. Although pre-storm benthic fauna was not removed from the seafloor, dwelling, crawling or resting lebensspuren structures did not appear again until a minimum depth of sediment was redeposited. From an ichnological perspective, the absence of certain trace fossils in the deep-sea due to a stressing event, even at small scale, is commonly associated with the disappearance of the fauna which generate these traces (Uchman and Wetzel, 2011). The results obtained in this study prove that the absence of the traces/lebensspuren is not always linked to the disappearance of the fauna. Factors such as sediment disposition, duration, or intensity of energetic events will control not only the distribution and appearance of the traces/lebensspuren but also the removal or maintenance of the benthic community. Future ichnological studies should consider other options, such as the ones exposed in the present case, when absence of traces are recorded, especially at small scales (sequence facies level).

10.5. Conclusions

The lebensspuren evolution observed at Station M during benthic storm events revealed a selective influence on benthic fauna behaviour. Benthic storms induced an impoverishment in both diversity and abundance of lebensspuren assemblages. Only elpidiid holothurian feeding faecal casts showed a notable increase in abundance during the high energy interval. Local-scale erosion and resuspension of unconsolidated seafloor sediments led to the reorganization of organic matter resources. The mobility of elpidiid holothurians allowed them to increase their feeding activity (i.e., knotted and smooth faecal casts) and rapidly consume these new food resources. The appearance of exhumed surfaces after benthic storm events is not related to the colonization by hard-substrate benthic fauna; however, it would control the appearance of distinct lebensspuren morphotypes even if the previous benthic fauna are not removed. The intensity, frequency, and duration of energetic episodes seem to be controlling factors in establishing changes in the benthic community. These three parameters should be considered as primary features for future ichnological and palaeoenvironmental reconstructions, with press disturbances more likely to be imprinted in the geological record.

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PART VII

CONCLUSIONS

Chapter 11

CONCLUSIONS

CONCLUSIONES

11.1. Conclusions

The main objective of the present PhD Thesis was to conduct a detailed ichnological analysis of ancient contourite succesions (Late Miocene channelized clastic contourite deposits at Morocco and Eocene-Miocene calcareous contourite drift deposits at Cyprus) with the motivation to demonstrate the relevant role of ichnology in the palaeoenvironmental and reservoir characterization of this facies. A precise study of ichnological features, including ichnofacies analysis and ichnofabric approach, was developed, providing palaeoenvironmental insights, involving palaeoecological and sedimentological changes, and on ocean dynamics at different scales. The obtained results have been published as research papers, some of them included as chapters in this volume or as supplementary material, showing the usefulness of ichnology as a proxy to study ancient contourite succesions. Considering all the advances achieved in the framework of the PhD, the main conclusions are:

In Cyprus carbonate drifts, the ichnofacies replacement from the *Zoophycos* ichnofacies to the distal-archetypal-proximal *Cruziana* ichnofacies is observed. Channelized clastic contourite deposits at Morocco are characterized by the proximal expression of the *Cruziana* ichnofacies. Instead, turbidite deposits are typified by the *Ophiomorpha rudis* ichnosubfacies from the *Nereites* ichnofacies.

Contourite deposits are not exclusively related to a single ichnofacies. However, variability in ichnofacies attributes could help in the differentiation between type of contourites and respect to other deep-sea sediments as turbidites or hemipelagites / pelagites.

Trace fossil assemblages and differentiated ichnofacies are controlled by complex interactions between variable environmental factors with **bottom current hydrodynamics and sea level variability playing a major role.** These interactions determine changes in sedimentation rate and food availability. Highly energetic conditions typical of shallower settings are present in deeper-water environments, contributing to ichnodiversity impoverishment into ichnofacies.

Major controlling depositional and ecological factors during contourite deposition affecting macrobenthic environment are hydrodynamic energy and food availability. Other paleoenvironmental conditions as oxygenation, substrate consistence or temperature have a secondary role.

Ichnofabric analysis reveals differences between and intra pelagites/hemipelagites, turbidites and contourites. Calciturbidite intervals show ichnofabrics consisting of post-depositional U-shaped traces (i.e., *Arenicolites*) and vertical borings typical of consolidated substrates. Instead, sandy contourite deposits are dominated by ichnofabrics with horizontal deposit-feeder trace fossils (*Planolites* and *Thalassinoides*). The record of ichnofabrics with deformed trace fossils (i.e., *Planolites*) in the interbeds of sandy contourites or in the transition between the facies reveals variations in sedimentation within the bi-gradational contourite succession. Autocomposite ichnofabrics, associated to a well-developed and diverse trace maker community characterize pelagic/hemipelagic, chalky, sediments.

Ichnofabric analysis allowed the characterization of complex interactions between settling of pelagic and hemipelagic particles in the water column, sediment gravity flows, and bottom-currents.

Integration of new applied methodologies (X-ray microtomography, mercury intrusion porosimetry or blue epoxy resin) reveals that the role of bioturbation in modification of petrophysical features of the studied contourites and its impact on reservoir quality is variable. In the clastic contourites, bioturbation can increase or decrease the total porosity and its distribution; being the trace maker´s behavior a key factor. The results of ***Macaronichnus*** **trace fossil analysis are impressive and have shown a clear zonation in the burrow porosity** (lowest porosity in the tube core and higher values associated with the surrounded rim). This finding suggest a positive impact of *Macaronichnus* for the reservoir properties. On the other hand, in calcarenitic and muddy chalk contouritic facies, bioturbation has a minor effect on porosity and no predictable influence on the flow-media characteristics.

Ichnological analyses are essential to determine reservoir quality, evidencing that other ichnological properties in addition to those traditionally considered must be evaluated.

The comparison with actual macrobenthic communities proves that **the absence of the traces/lebensspuren is not always linked to the disappearance of the organisms.** Factors such as sediment disposition, duration, or intensity of energetic events will control not only the distribution and appearance of the traces/lebensspuren but also the removal or maintenance of the benthic community.

Consequently, the results obtained in this PhD demonstrate the usefulness of ichnological studies for contourite characterization and differentiation respect to associated deep-sea facies. The information provided by the ichnological approach offers a new perspective for palaeoenvironmental interpretations and presents a very interesting tool in reservoir exploration. Also, worth noting that comparison with actual benthic ecology research can help to understand how deep-sea bioturbators are affected by bottom current events.

11.2. Conclusiones

El objetivo principal de la presente Tesis doctoral fue realizar un análisis icnológico detallado de afloramientos contorníticos (canales contorníticos clásticos del Mioceno tardío en Marruecos y depósitos contorníticos calcáreos del Eoceno-Mioceno en Chipre) con la motivación de demostrar el papel relevante de la icnología en la caracterización paleoambiental y económica de estas facies. Para ello, se desarrolló un estudio icnológico detallado, incluyendo los análisis de icnofacies e icnofábricas, que proporcionó nuevos conocimientos paleoambientales; los cuales implican cambios paleoecológicos, sedimentológicos, y en la dinámica del océano a diferentes escalas. Los resultados obtenidos han sido publicados como trabajos de investigación, algunos de ellos incluidos como capítulos en este volumen o como material complementario, mostrando la utilidad de la icnología como indicador para el estudio de sucesiones contorníticas. Considerando todos los avances logrados en la presente Tesis, las principales conclusiones son:

En las contornitas calcareas de Chipre, se observa el reemplazo de las icnofacies de *Zoophycos* por las icnofacies distal-arquetípica-proximal de *Cruziana*. Los depósitos de contornitas clásticas en Marruecos se caracterizan por la expresión proximal de las icnofacies de *Cruziana*. En cambio, los depósitos de turbiditas están tipificados por las icnosubfacies de *Ophiomorpha rudis* de las icnofacies de *Nereites*.

Los depósitos contorníticos no están relacionados exclusivamente con una sola icnofacies. Sin embargo, la variabilidad en los atributos de las mismas podría ayudar en la caracterización de los distintos tipos de contornitas y diferenciarlas con respecto a otros sedimentos de aguas profundas como turbiditas o hemipelagitas / pelagitas.

Las asociaciones de trazas fósiles y las icnofacies diferenciadas se encuentran controladas por interacciones complejas entre distintos factores ambientales, variables como **el hidrodinámismo de las corrientes de fondo y los cambios en el nivel del mar**. Estas interacciones determinan variaciones en la velocidad de sedimentación y la disponibilidad de nutrientes. Por tanto, condiciones altamente energéticas típicas de medios someros están presentes en ambientes de aguas más profundas, lo que contribuye al empobrecimiento de la icnodiversidad en las icnofacies.

Los principales factores sedimentarios y ecológicos durante el depósito de contornitas, que afectan a la comunidad macrobentónica, son la energía hidrodinámica y la disponibilidad de nutrientes. Otros factores paleoambientales como la oxigenación, la consistencia del sustrato o la temperatura presentan un papel secundario.

El análisis de icnofabricas revela diferencias entre e intra pelagitas / hemipelagitas, turbiditas y contornitas. Los intervalos calciturbidíticos muestran icnofábricas que constan de trazas post-deposicionales con forma de U (*Arenicolites*) y perforaciones verticales típicas de sustratos consolidados. En cambio, los depósitos de contorno arenosos están dominados por icnofábricas con trazas fósiles horizontales producidas por organismos depósitivoros (*Planolites* y *Thalassinoides*). El registro de icnofábricas con trazas fósiles deformadas (*Planolites*) en las intercapas de contornitas arenosas o en la transición entre las facies revela variaciones en la sedimentación dentro de la secuencia contornítica bi-gradacional. Las icnofábricas autocompuestas, asociadas a una comunidad bien desarrollada y diversa, caracterizan a los sedimentos pelágicos / hemipelágicos calcáreos.

El análisis de icnofábricas ha permitido la caracterización de interacciones complejas entre el depósito de partículas pelágicas y hemipelágicas desde la columna de agua, los flujos gravitacionales y las corrientes de fondo.

La integración de nuevas metodologías (microtomografía de rayos X, porosimetría de inyección de mercurio o resina epoxi azul) revela que el papel de la bioturbación en la modificación de las características petrofísicas de las contornitas estudiadas, así como su impacto en la calidad del reservorio, es variable. En las contornitas clásticas, la bioturbación puede aumentar o disminuir la porosidad total y su distribución; siendo el comportamiento del organismo generador de la traza un factor clave. Los resultados del análisis de ***Macaronichnus* son sorprendentes y han mostrado una clara zonación en la porosidad dentro de la traza** (porosidad más baja en el núcleo del tubo y valores más altos asociados con la pared). Este hallazgo sugiere un impacto positivo de *Macaronichnus* en las propiedades del reservorio. Por otro lado, la bioturbación observada en las facies calcareníticas y de creta tiene un efecto menor sobre la porosidad y ninguna influencia predecible sobre las características de flujo en el reservorio.

Los análisis icnológicos son fundamentales para determinar la calidad del reservorio, evidenciando que se deben evaluar otras propiedades icnológicas además de las consideradas tradicionalmente.

La comparación con comunidades bentónicas actuales demuestra que **la ausencia de trazas / lebensspuren no siempre está ligada a la desaparición de los organismos generadores**. Factores como la disponibilidad de sedimento, la duración o la intensidad de los eventos energéticos, controlarán no solo la distribución y apariencia de las trazas / lebensspuren sino también la remoción o mantenimiento de la comunidad bentónica.

En consecuencia, los resultados obtenidos en esta Tesis demuestran la utilidad de los estudios icnológicos para la caracterización y diferenciación de contornitas con respecto a otras facies marino profundas. La información proporcionada por el análisis icnológico ofrece una nueva perspectiva para las interpretaciones paleoambientales y además constituye una herramienta primordial para la exploración de reservorios. Además, merece la pena remarcar que la comparación con investigaciónes actuales de ecología bentónica puede ayudar a comprender cómo los bioturbadores de zonas profundas se ven afectados por los eventos de corrientes de fondo.

11.3. Forthcoming research

The present PhD may be considered as a first step in the application of ichnological analysis in the study and interpretation of ancient contourite successions. According to the obtained results, some key points should be addressed in the future:

-Ichnological analysis of contourites at outcrop allows better differentiation of trace fossils respect to that usually obtained from core studies, improving characterization of trace fossil assemblages and then ichnofacies. Thus, to elucidate trace fossil diversity and ichnofacies assignation of contourite deposits more outcrop studies are required.

-Clastic and calcareous contourite deposits have demonstrated to present distinct ichnological features. Local and regional palaeoenvironmental conditions have been revealed as important factors controlling ichnological attributes. Thus, studies involving different types of contourites are mandatory to evaluate trace fossil information and the role of local/regional and global factors. Particularly, chemogenic contourites should be covered since they have never been studied from an ichnological perspective.

-The results obtained thus far from the relationship between ichnology and reservoir characterization are of great interest. On this topic, ichnology could provide useful information to determine reservoir quality in contouritic bioturbated reservoirs, especially on unconventional ones. The obtained results evidenced that other ichnological properties (i.e., burrow lining) in addition to those traditionally considered must be evaluated. In consequence, the detailed analysis of biogenic structures affecting petrophysical properties is fundamental for further reservoir characterization. In short, behavior of tracemaker, determining burrow features (i.e., passive vs. active infilling) should be considered.

-With respect to palaeoecological interpretations, the proven relationship between ichnological features, deep-sea ecology and benthic community changes would encourage advancing along this line of research. Thus, the study of actual biogenic structures could help to understand ichnological attributes and the characterization of short-range environmental changes, associated with ocean/atmosphere dynamics. Information from recent examples will improve paleoenvironmental studies. Highly detailed bioturbational analysis, and correlations with other ecological proxies (e.g., substrate consistency, organic matter fluxes, salinity, temperature) will offer a new perspective on how present and past can be correlated.

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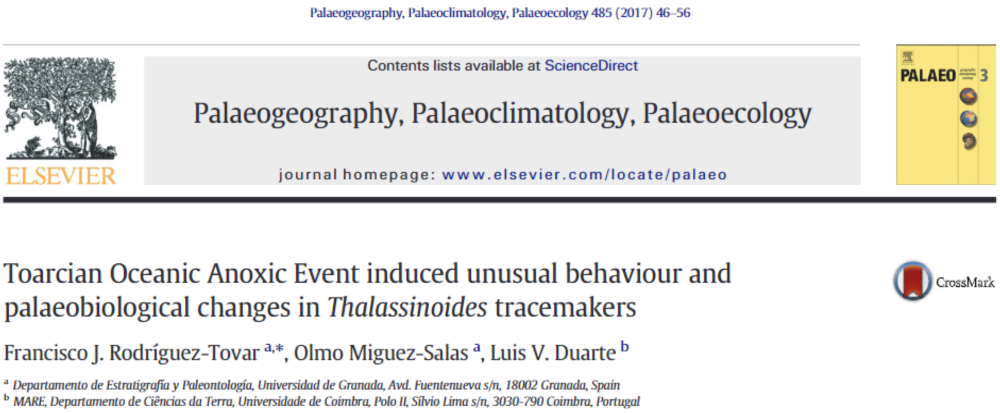
APPENDIX

Another topics addressed during the Thesis

THE TOARCIAN OCEANIC ANOXIC EVENT



Palaeogeography, Palaeoclimatology, Palaeoecology 485 (2017) 46–56

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Toarcian Oceanic Anoxic Event induced unusual behaviour and palaeobiological changes in *Thalassinoides* tracemakers

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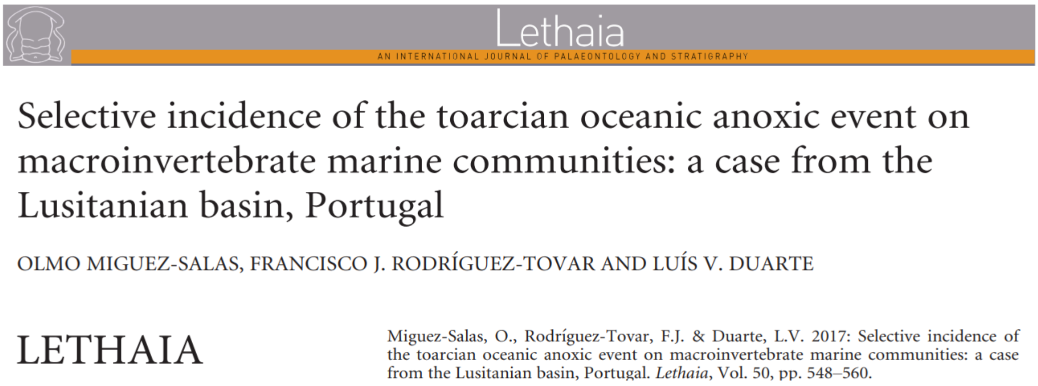


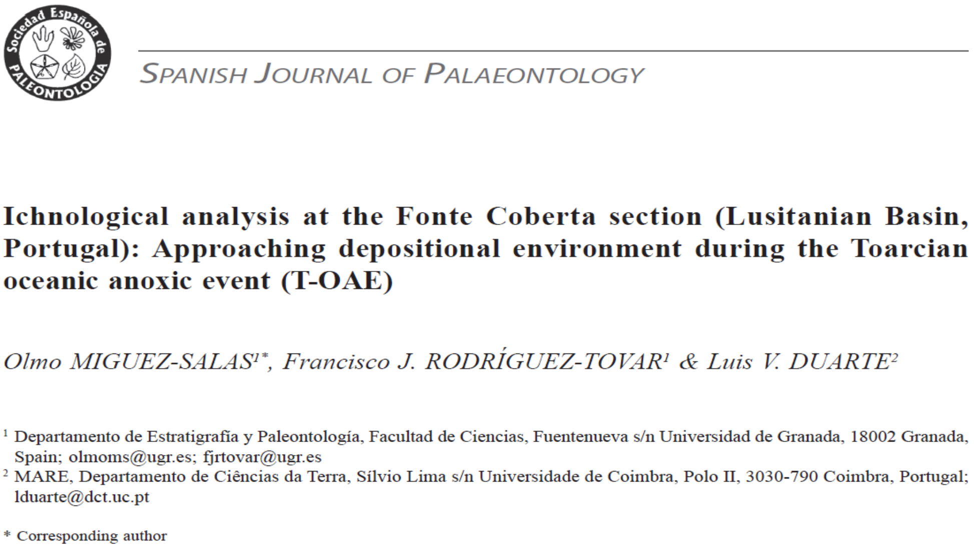
Lethaia
AN INTERNATIONAL JOURNAL OF PALAEONTOLOGY AND STRATIGRAPHY

Selective incidence of the toarcian oceanic anoxic event on macroinvertebrate marine communities: a case from the Lusitanian basin, Portugal

OLMO MIGUEZ-SALAS, FRANCISCO J. RODRÍGUEZ-TOVAR AND LUÍS V. DUARTE

LETHAIA

Miguez-Salas, O., Rodríguez-Tovar, F.J. & Duarte, L.V. 2017: Selective incidence of the toarcian oceanic anoxic event on macroinvertebrate marine communities: a case from the Lusitanian basin, Portugal. *Lethaia*, Vol. 50, pp. 548–560.



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SPANISH JOURNAL OF PALAEONTOLOGY

Ichnological analysis at the Fonte Coberta section (Lusitanian Basin, Portugal): Approaching depositional environment during the Toarcian oceanic anoxic event (T-OAE)

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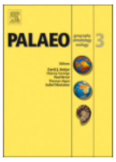

Opportunistic behaviour after the Toarcian Oceanic Anoxic Event: The trace fossil *Halimedides*

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ICHNOLOGICAL AND SEDIMENTOLOGICAL RECORDS OF PALEOENVIRONMENTAL CHANGES DURING THE MIOCENE IN TAIWAN

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The 20-million-year old lair of an ambush-predatory worm preserved in northeast Taiwan

Yu-Yen Pan[1,7], Masakazu Nara[2], Ludvig Löwemark[1]✉, Olmo Miguez-Salas[3],
Björn Gunnarson[4], Yoshiyuki Iizuka[5], Tzu-Tung Chen[6] & Shahin E. Dashtgard[7]

The feeding behavior of the giant ambush-predator "Bobbit worm" (*Eunice aphroditois*) is spectacular. They hide in their burrows until they explode upwards grabbing unsuspecting prey with a snap of their powerful jaws. The still living prey are then pulled into the sediment for consumption. Although predatory polychaetes have existed since the early Paleozoic, their bodies comprise mainly soft tissue, resulting in a very incomplete fossil record, and virtually nothing is known about their burrows and behavior beneath the seafloor. Here we use morphological, sedimentological, and geochemical data from Miocene strata in northeast Taiwan to erect a new ichnogenus, *Pennichnus*. This trace fossil consists of an up to 2 m long, 2–3 cm in diameter, L-shaped burrow with distinct feather-like structures around the upper shaft. A comparison of *Pennichnus* to biological analogs strongly suggests that this new ichnogenus is associated with ambush-predatory worms that lived about 20 million years ago.

ICHNOS
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Selective colonization after storm events in a delta environment: applied ichnology from the early Miocene of Taiwan

Olmo Miguez-Salas[a], Ludvig Löwemark[b], Yu-Yen Pan[b] and Francisco J. Rodríguez-Tovar[a]

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ABSTRACT
The sedimentological and palaeoecological interpretation of early Miocene age shallow marine deposits from one of the most emblematic geological areas of Taiwan – Yehliu peninsula – is not easy to approach in detail, and several contrasting proposals can be found in the literature. The present ichnological study helps to corroborate a delta environment as the most likely palaeoenvironmental setting, and to recognize the different sub-environments and hydrodynamic processes involved. The distal delta front displays the greatest trace fossil diversity, assigned to the *Cruziana* ichnofacies, including *Ophiomorpha*, *Phycosiphon*, *Planolites*, *Rosselia*, *Schaubcylindrichnus*, *Scolicia*, *Thalassinoides* and vertical equilibrium adjustment structures. The delta front records predominantly vertical traces attributable to the *Skolithos* ichnofacies. Amalgamated shell beds (most likely related to storm events) show concentrations of broken bivalve shells. After storm a selective colonization is interpreted, firstly by bioerosive tracemakers during times of decreasing sedimentation rate, followed by a dominance of trophic generalists such as those producing *Ophiomorpha* during post-storm sedimentation.

KEYWORDS
Ichnofacies; Miocene; mixed-influenced delta; storm; Taiwan

Ichnological analysis of ancient contourites: scientific and economic implications

Olmo Miguez Salas

PhD Thesis

Departamento de Estratigrafía y Paleontología

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2021

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