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High-resolution image treatment in ichnological core analysis: Initial steps, advances and prospects

Javier Dorador*, Francisco J. Rodríguez-Tovar

Department of Stratigraphy and Paleontology, University of Granada, Av. Fuente Nueva s/n, CP 18071 Granada, Spain

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ABSTRACT

Ichnological studies have become popular during the last decades, particularly those associated with the development of two major concepts —the ichnofacies model and ichnofabric approach. They have driven ichnology into diverse fields of Earth Sciences, including paleoecology, sedimentology, paleoceanography and basin analysis, as well as applied fields for the oil and gas industry and aquifer characterization. Whereas early ichnological analyses focused on outcrops, later the number of ichnological studies on well cores increased noticeably. Still, ichnological research on cores is hampered by certain limitations (i.e., mainly narrow exposed surface), and the characterization of ichnological properties is complicated when cores are involved. To facilitate ichnological analysis in cores from modern deposits, several techniques (among them, X-rays, magnetic resonance and computed tomography) have been used. With the development of computer software, a new high resolution image treatment has emerged as a powerful tool in different branches of ichnological studies, especially for cores from modern marine deposits. Because applications are numerous and perhaps not familiar to all the scientific community, this paper provides an overview of the usefulness of image treatment in ichnological analysis, its first steps and subsequent development, the novel techniques most recently used in the study of cores from modern marine deposits, and some challenges for future research.

1. Introduction

Ichnology, the study of traces produced by organisms on or within a substrate (e.g., Bromley, 1990), has undergone an immense growth over the past few decades. Two main paradigms in ichnological analysis have been developed, the ichnofacies model and the ichnofabric approach.

The ichnofacies model was introduced by Seilacher in the 1950s and 1960s (e.g., Seilacher, 1964, 1967), though the ichnofacies concept has since been revised. According to Buatois and Mángano (2011) "*Seilacherian or archetypal ichnofacies are based on the identification of key features shared by different ichnocoenosis of a wide range of ages formed under a similar set of environmental parameters*". In recent reviews, "*the ichnofacies paradigm stands as a multidimensional framework that is underpinned by recurring, facies-controlled (i.e., environmentally related) groupings of biogenic structures that reflect animal responses (ethology) to paleoenvironmental conditions*" (MacEachern et al., 2012 and references therein).

The ichnofabric approach as proposed by Ekdale and Bromley (1983) has likewise evolved and became profusely applied, and at present it embraces any textural or structural aspect resulting from bioturbation and bioerosion at any scale. It considers trace fossils assemblage and other ichnological features as cross-cutting, tiering, or degree of bioturbation (see reviews in Buatois and Mángano, 2011; Ekdale et al., 2012; Knaust, 2017).

Ichnofabric concept is mainly the analysis of different bioturbation stages while ichnofacies concept is focused on the recognition of recurrent ichnocoenosis (Knaust, 2017). Both the ichnofacies model and the ichnofabric approach have made ichnology highly relevant in very different fields, including paleoecology, sedimentology, evolutionary paleoecology, paleoceanography and paleoclimatology (Mángano and Buatois, 2012). Their usefulness has extended to applied fields, for instance in the geological interpretation of subsurface data by the oil and gas industry (Knaust, 2017 and references therein) and in aquifer characterization (e.g., Cunningham et al., 2012). All these advances have led to the publication of numerous monographs dedicated to ichnology applied to different disciplines (e.g., Pemberton et al., 2001; Hasiotis, 2002; McIlroy, 2004; Bromley et al., 2007; MacEachern et al., 2007; Miller, 2007; Seilacher, 2007; Gerard and Bromley, 2008; Wisshak and Tapanilla, 2008; Buatois and Mángano, 2011; Knaust and Bromley, 2012; Mángano and Buatois, 2016a, 2016b; Genise, 2017; Knaust, 2017 for some examples from this millennium) and it is

* Corresponding author.
E-mail addresses: javidr@ugr.es (J. Dorador), fjrtovar@ugr.es (F.J. Rodríguez-Tovar).

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becoming more widely recognized by the scientific community.

In the beginning, most ichnological analyses involved outcrops, but since then ichnological studies on cores have increased noticeably. Scientific oceanic expeditions began drilling an abundance of cores in the second half of the twentieth century, providing an extensive dataset of subsurface sediments where bioturbation is commonly present and can be studied (e.g., Pemberton, 1992; McIlroy, 2004; Gerard and Bromley, 2008; Knaust, 2017). However, ichnological research in cores entails particular limitations due to features such as the narrow exposed surface, two-dimensional core slabs, or the usual absence of complete structures, complicating the characterization of trace fossils and ichnofabrics (e.g., Knaust, 2012; Dorador et al., 2014a). The ichnotaxonomical classification of bioturbational structures may be further impeded by scarce information on diagnostic criteria or ichnotaxobases (Bromley, 1990, 1996; Bertling et al., 2006; Knaust, 2012, 2017), so that a precise ichnotaxonomical classification at the ichnospecies level is often impossible (usually conducted at the ichnogenus level; Bromley, 1990, 1996). Ichnological research in cores from modern marine deposits is particularly difficult when the material is unconsolidated, and the differences between biogenic structures and host sediment is weak (Dorador and Rodríguez-Tovar, 2015).

In order to improve ichnological analysis on cores, researchers have turned to several techniques allowing a better visualization, and then characterization and differentiation, of trace fossils: X-ray (e.g., Löwemark and Werner, 2001; Löwemark, 2003; Gingras et al., 2014); magnetic resonance (Gingras et al., 2002a, 2002b); computed tomography (e.g., Joschko et al., 1991; Delefosse et al., 2015; Seike and Goto, 2017) or microtomography (Baniak et al., 2014). Software development has been conducted by Baucon and Felletti (2013) to apply geostatistical analysis to ichnology in recent deposits to determine the spatial distribution and pattern recognition; and by Timmer et al. (2016) to collect ichnological parameters as trace fossil size from logging research. Despite the utility of these techniques to improve trace fossil visualization and the analysis of ichnological attributes, they are not quite effective in the study of cores from modern marine deposits, owing to the usually unconsolidated or poorly consolidated material and the weak density contrast between trace fossil filling material and the surrounding host sediment. To overcome these limitations, and in conjunction with software development, a new high resolution image treatment has emerged in the framework of ichnological studies of cores from modern marine deposits. This novel method has proven to be a powerful tool for the ichnofacies model (Dorador and Rodríguez-Tovar, 2015) and ichnofabric approach (e.g., Rodríguez-Tovar and Dorador, 2015), and its usefulness has been demonstrated in numerous studies involving paleoenvionmental reconstructions, ocean-atmosphere dynamics and sedimentary basin analysis (e.g., Rodríguez-Tovar et al., 2015a, 2015b; Dorador and Rodríguez-Tovar, 2016b; Hodell et al., 2017; Zeeden et al., 2015, 2017). Because of its recent and rapid development in different areas, we think that it would be very useful to review the progress of high resolution image treatment, and foresee future advances.

This review paper looks at the usefulness of the image treatment in ichnological analysis, showing several specific examples conducted on cores from IODP Expedition 339. The main body of the paper focuses on the novel high-resolution imagery recently used in the study of cores from modern marine deposits, from its first steps to its development and applications. Finally, some challenges for future research will be discussed. As our "natural laboratory", most of cases are focused on marine Quaternary sediment cores from the Gulf of Cadiz, but it can be extended to any geological period and area as the presented techniques are not affected by age or environment, being mainly controlled by stratigraphic (e.g., lithology, grain size, etc.), or ichnological (e.g., type of trace, size, shape, etc.) properties.

2. A new high-resolution imaging in ichnological analysis of core material – a new methodology

2.1. First steps

Many meters of modern marine cores have been drilled by oceanic expeditions during the last decades, providing a very interesting and considerable record of sediments, especially of those ones deposited in the last million years (Knaust and Bromley, 2012; Knaust, 2017). These materials are studied by well-regarded scientists specialized in various disciplines (e.g., micropaleontology, sedimentology, geochemistry, geophysics or paleomagnetism). However, ichnologists rarely participate as active members of the scientific teams and the information from bioturbation provided in the core description is not a detailed ichnological report, despite the fact that many of these cores are intensely bioturbated. This scarcity of dedicated studies is most likely due to the complexity of trace fossil characterization of modern marine cores. The challenge was to create a new method for the identification of ichnological features that could be widely used by the scientific community, not only by specialists, with four major strengths: non-invasive (not damaging the studied core), of a broad spectrum (applicable to any core, regardless of particular features or lithology), easy to use (even for non-specialists) and inexpensive. High resolution image treatment was selected as a suitable solution, as this kind of imagery is obtained on board in every expedition, and the proposed technique can be applied upon digital images using inexpensive image software (Adobe Photoshop CS6) with which most researchers are familiar.

The proposed methodology entailed three sequential steps: a) firstly, modification of those image adjustments which provide the best trace fossils visualization to support the ichnotaxonomical approach of cores from modern marine sediments (Dorador et al., 2014a; b) afterwards, new advances were made working with the quantification and treatment of pixel values, to determine ichnological features such as the degree of bioturbation, or penetration depth, among others (Dorador and Rodríguez-Tovar, 2014; Dorador et al., 2014b); and c) finally, all the obtained ichnological information was summarized by implementing graphs traditionally used in the ichnofabric characterization (Rodríguez-Tovar and Dorador, 2015) (Fig. 1).

2.1.1. Ichnotaxonomical approach: Differentiation between biodeformational structures and trace fossils

The first contribution of the developed method was to support: a) the identification of bioturbational sedimentary structures within core material, b) the differentiation among bioturbational sedimentary structures, distinguishing between biodeformational structures or bioturbated texture (having undifferentiated outlines and the absence of a definitive geometry, a mottled background) and trace fossils (having differentiated outlines and characteristic shape) (Uchman and Wetzel, 2011; Wetzel and Uchman, 2012), and c) the ichnotaxonomical classification of the discrete trace fossils. A technique based on image adjustment modifications was developed to enhance ichnoassemblage visualization and characterization (Dorador et al., 2014a). A great variety of adjustments —brightness, levels, curves, exposure, vibrance, hue/saturation, color balance, etc.— were checked using Adobe Photoshop CS6, and the variable incidence of some image features was controlled to confirm their effect on trace fossil visualization. Finally, a sequence composed of three adjustment modifications (levels, brightness and vibrance) was proposed as the optimal means of enhancing the visibility of biogenic structures (Dorador et al., 2014a).

This procedure was applied to cores from hemipelagic deposits drilled during IODP Expedition 339, allowing us to discern bioturbational sedimentary structures (biodeformational structures vs. discrete trace fossils) and enrich ichnotaxonomical classification by observing particular ichnotaxa which would not be discernible by the naked eye and conventional trace-fossil analysis. As seen in Fig. 2, showing three intervals from hemipelagic cores drilled at site U1385, in the original

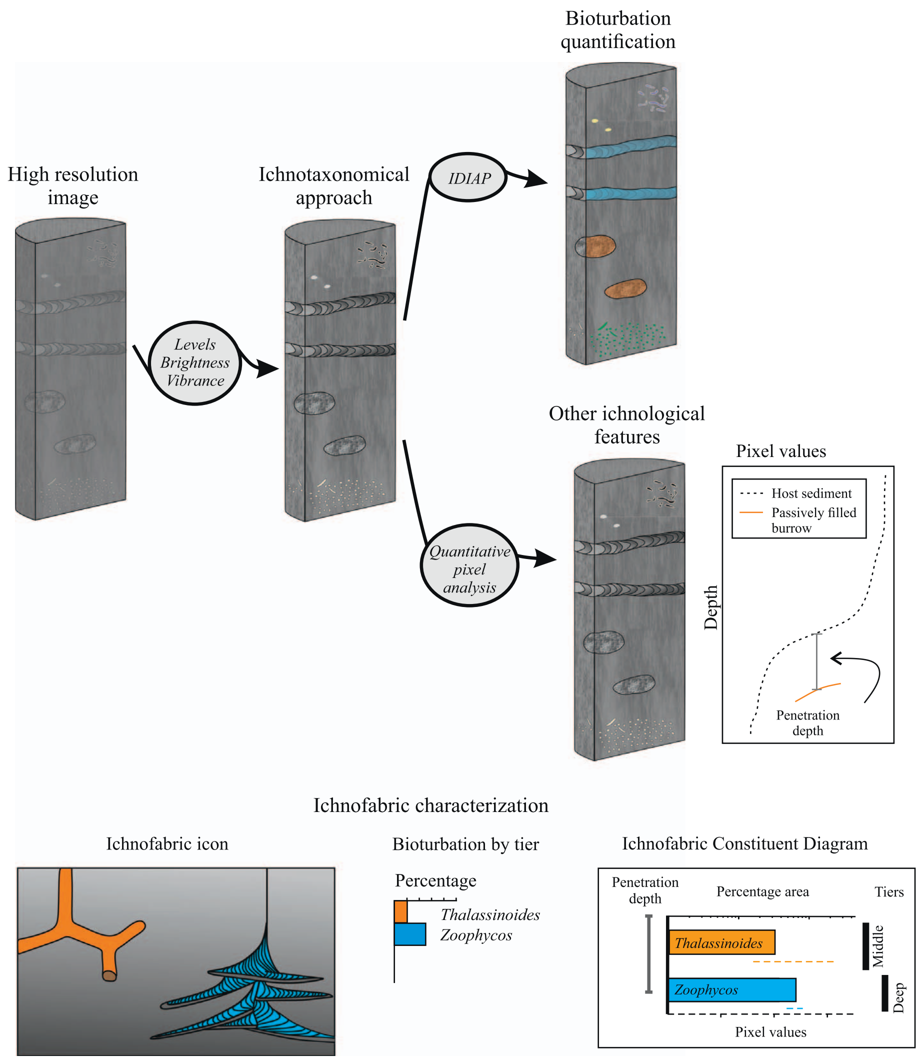

Fig. 1. Schematic diagram of the developed high resolution image treatment.

core sections ichnotaxa cannot be characterized; but modification of the three adjustments (levels, brightness and vibrance) allows for a better visualization of *Planolites* (*Pl*), *Thalassinoides* (*Th*), *Thalassinoides*-like (*Th*-l) and light/dark *Zoophycos* (*Zo*).

2.1.2. Bioturbation quantification

The quantification of bioturbation is a main point in any ichnological analysis, traditionally given through the use of indices. The most popular ones are the bioturbation index (BI) (Reineck, 1963, 1967; Taylor and Goldring, 1993) and the ichnofabric indices (ii) (Droser and Bottjer, 1986, 1989), both mainly based on the percentage of bioturbated surface. The scheme proposed by Reineck (1963, 1967) differentiates seven grades of bioturbation (from 0 to 6), from 0 (0%; no bioturbation), to 3 (31–60%; moderate bioturbation), and finally 6 (100%; complete bioturbation). Later, Taylor and Goldring (1993) revitalized this scheme defining bioturbation indexes based on the categories established by Reineck yet favoring a descriptive approach instead of a semiquantitative one (see Buatois and Mángano, 2011 for a review). Droser and Bottjer (1986, 1989) present a semi-quantitative approach based on the comparison with a series of flash cards on which five ichnofabric indexes are illustrated, from ii 1 (0%) to 5 (60–100%), while ii 6 would designate complete burrow homogenization (see comparison in Knaust, 2012). Both classifications use categories with disproportionate weights. Then, an additional procedure has been alternatively proposed, but rarely used, based on a linear increase using categories with equal size (detailed explanation in Knaust, 2012, 2017).

In either scheme, the amount of bioturbation is gauged by the naked-eye, meaning the assigned percentage is at least partly subjectively determined. However, working with image treatment and pixel analysis, the percentage of bioturbated surface is objectively quantified and thus the grade of bioturbation assigned is more reliable. That is, the number of pixels pertaining to a given trace fossil can be determined and compared with the host sediment, a great aid in calculating the percentage of surface that is bioturbated. The percentage of bioturbated surface corresponding to each ichnotaxon, to the whole ichnocoenosis, or to the complete ichnofabric can therefore be estimated.

Working on this main objective, Dorador et al. (2014b) developed a package to characterize the percentage of bioturbated surface in a semi-automatic way (Fig. 3). Three pixel selection methods (similar pixel, magic wand and color range) were compared using imaging software on previously treated images. It was concluded that each selection tool is useful, depending on the particular core features. In intervals where the trace fossils are small, abundant and clearly differentiated, the similar pixel and color range methods prove more efficient; in cases dominated by large trace fossils, the best option is the Magic Wand method (Dorador et al., 2014b).

Five intervals where bioturbation was quantified using this method have been selected to illustrate different ichnofabric indices in Fig. 3. They are briefly described from top to bottom (from ii: 1 to 5).

The first case (ii: 1) has no bioturbation (0% of bioturbated surface). In the second one, discrete *Thalassinoides* are identified, representing

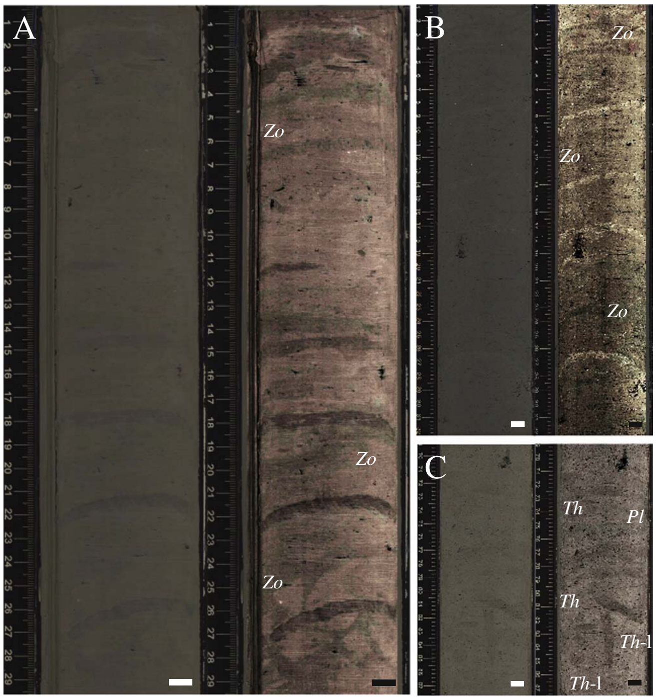

Fig. 2. Original and obtained images after adjustment modifications from different core intervals from IODP Expedition 339 Site U1385 (specifically: A, U1385A-6H-4; B, U1385B-8H-4; C, U1385A-5H-5). *Pl*, *Planolites*, *Th*, *Thalassinoides*, *Th*-l, *Thalassinoides*-like, *Zo*, *Zoophycos*. Scale bars 1 cm.

the 6.8% of bioturbated surface (ii: 2), while the third one shows 17.6% of the surface bioturbated by *Chondrites* and *Thalassinoides* (ii: 3). The fourth example shows a multi-tiering association represented by *Chondrites*, *Thalassinoides* and *Zoophycos* that bioturbate the 43.9% of the surface (ii: 4); and finally, the fifth case illustrates an interval where more than 60% (ii: 5) is bioturbated by some discrete trace fossils (possible *Planolites*, *Zoophycos* and *Thalassinoides*).

2.1.3. Other ichnological features

Other relevant aspects such as tiering (i.e., vertical partitioning of a community; Bromley, 1996) and penetration depth can be approached using image treatment. Its application allows one to recognize overlapping situations, of special interest under the ichnofabric approach (see below). These cross-cutting relationships between trace fossils, difficult to see without any image treatment, can be related to different tier levels or the colonization of more than one depth level (more details in Section 2.3). Such data is important for inferences of the complexity of a community or the stability of paleoenvironmental conditions, for instance.

Moreover, Dorador and Rodríguez-Tovar (2014) characterized and compared the pixel values of infilling material of trace fossils and of host sediment to assess the horizon of colonization and, therefore, the vertical penetration of burrows, particularly the passively filled ones (that is, filled by material that enters the burrow gravitationally). An example of hemipelagic deposits from the Gulf of Cadiz is illustrated in Fig. 4. Characterization of host sediment pixel values and infilling material of *Thalassinoides* allows one to estimate a penetration depth around 7–8 cm (Fig. 4). This data cannot be commonly evaluated, yet in paleoecological research it is key to interpret paleoenvironmental conditions at the time of bioturbation by a tracemaker, aside from the present location of a burrow within the sediment. Moreover, taking into account the incidence of bioturbation in the vertical (downward and upward) redistribution of biotic and abiotic components in sediment (e.g., vertical displacement of microfossils in Rodríguez-Tovar et al., 2010; Kędzierski et al., 2011; Alegret et al., 2015), the evaluation of penetration depth helps avoid paleoenvironmental or biostratigraphic misinterpretations.

2.2. Development: application to ichnofabric approach and ichnofacies model

All the described advances allow for the characterization of the bioturbation degree and provide information about tiering, overlapping situations and other features considered in the ichnofabric approach. Especially during the last decade, this ichnological concept has grown to become a very useful tool in paleoenvironmental reconstruction

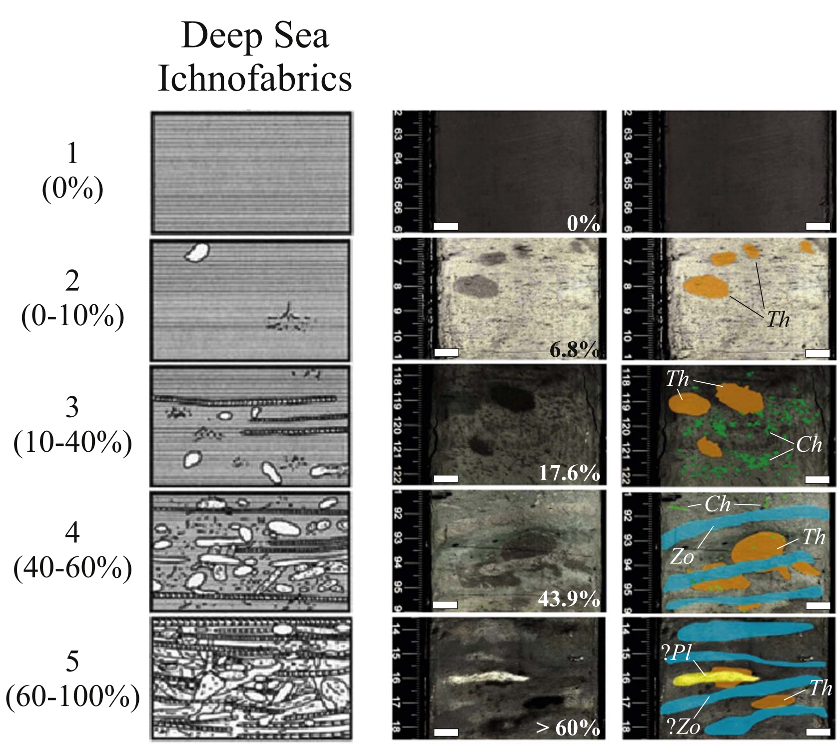

Fig. 3. Intervals from hemipelagic cores corresponding to different ichnofabric indices from top (ii: 0) to bottom (ii: 5). From left to right, visual chart (from McIlroy, 2004), treated image and quantified image representing every ichnotaxa with a different color. *Ch*, *Chondrites*; *Pl*, *Planolites*; *Th*, *Thalassinoides*; *Zo*, *Zoophycos*. Scale bars 1 cm. Intervals were taken: ii:1, from U1385E_17H_6A (113–118 cm); ii: 2, from U1385E_17H_6A (6–11 cm); ii: 3, U1385E_13H_2A (117.5–122.5 cm); ii:4, U1385E_13H_1A (91–96 cm); ii:5, U1385E_12H_5A (13.5–18.5 cm).

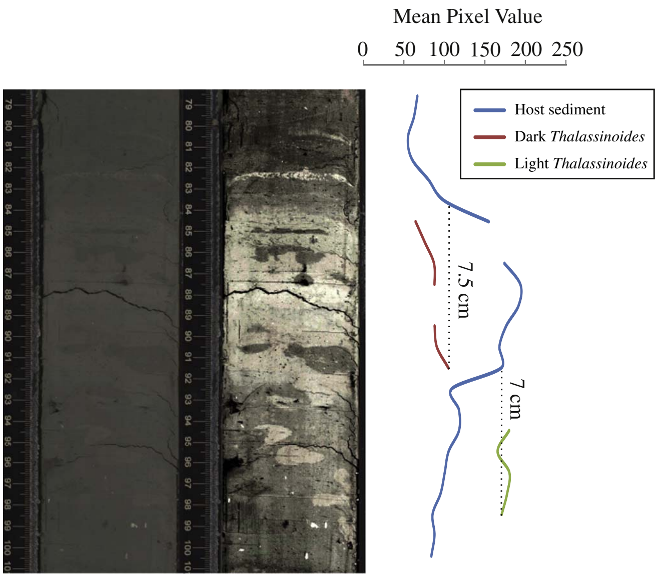

Fig. 4. Penetration depth of dark (red) and light (green) *Thalassinoides* in the U1385E-17H-3-A core. To the left, original and treated images. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

studies, both in outcrop and core analyses (e.g., Buatois and Mángano, 2011; Knaust and Bromley, 2012; Savrda, 2016). Moreover, ichnofabric studies have been applied to analyze the effects of bioturbation on sediment porosity and permeability, in the context of reservoir or aquifer characterization (Cunningham et al., 2012). This progress is partly the consequence of a sound characterization of composite ichnofabrics (Ekdale and Bromley, 1983; Bromley and Ekdale, 1986) reflecting: a) the progressive upward migration of a single, tiered benthic community, during continuous sediment accretion, self-generated by a particular assemblage of tracemakers and recently referred to as autocomposite ichnofabrics (Savrda, 2016), or b) the successive occupation of a sediment by multiple communities of organisms in response to autogenic or allogenic changes in environmental conditions within a depositional system, comprising two or more different ichnocoenosis and being referred to as heterocomposite ichnofabrics (Savrda, 2016). In either case, recognition of the sequential overprinting of trace fossils is essential for a correct ichnofabric approach, and here again the proposed high resolution image treatment reveals its usefulness.

Specifically, the cited treatment has been tested in a study of modern marine cores from the IODP Expedition 339 (e.g., Rodriguez-Tovar and Dorador, 2014; Rodríguez-Tovar and Dorador, 2015). One clear example is the ichnological study of hemipelagic records from site U1385, where it enabled us to identify nine ichnotaxa, differentiating seven ichnofabrics whose analysis pointed to generalized good environmental conditions for macrobenthic tracemakers in terms of oxygen and nutrients (Rodriguez-Tovar and Dorador, 2014).

Advances in image treatment have likewise proven very useful in ichnofacies analysis, a branch of research developed by Seilacher (1964, 1967), based on the identification of features shared by ichnotaxa over a long time period, whose presence could be associated with particular environmental conditions (see detailed review in Buatois and Mángano, 2011). Originally six ichnofacies were described, but this concept has evolved substantially, and nowadays 15 ichnofacies are differentiated based on invertebrate trace fossils. High resolution image treatment was fundamental in the ichnofacies analysis of hemipelagic sediments from site U1385, and hence in the sedimentary basin analysis. Its indications support the generalized characterization of the *Zoophycos* ichnofacies, though they suggest there are three different expressions of this ichnofacies, based on the presence of some ichnotaxa commonly associated with the *Cruziana* or the *Nereites* ichnofacies that allow the interpretation of subtle changes in paleoenvironmental conditions (Dorador and Rodríguez-Tovar, 2015).

2.3. Consolidation: utility in paleoenvironmental research and sedimentary basin analysis

The young methodology described here has nonetheless met widespread acceptance (see a mention in the recent book on trace fossils in well cores; Knaust, 2017) in the realm of the Earth Sciences (paleoenvironmental reconstructions, ocean/atmosphere dynamics or basin sedimentary analysis).

High resolution digital image treatment conducted at the "Shackleton Site" (IODP Expedition 339, Site U1385) served to characterize the macrobenthic tracemaker community developed during the Pleistocene at the Iberian margin (Rodriguez-Tovar and Dorador, 2014), as pointed out above. A multi-tiered assemblage was interpreted: biodeformational structures revealed colonization of uppermost tiers, above or just below the seafloor, with *Planolites*, *Palaeophycus* and even *Taenidium* as upper tier traces, *Thalassinoides*-like/*Thalassinoides* occupied a middle tier, and *Zoophycos* and *Chondrites* were found to be deep tier forms associated with the final phases of colonization. In Fig. 5, two examples of overlapping situations can be viewed. The first case (Fig. 5A) shows interaction between two generations of *Thalassinoides*, and the second (Fig. 5B) shows a *Zoophycos* (belonging to a deep tier) overlapping a *Thalassinoides* section (from a middle tier assemblage). Paleoenvironmental conditions were envisaged as presenting a major incidence of pore-water oxygen conditions and organic matter availability.

In turn, paleoclimatic and ocean-atmosphere dynamic changes determining variations in deep-sea paleoenvironmental conditions were addressed through an integration of ichnological information, obtained after applying the described methodology, along with foraminifera data. Terminations 1, 2 and 4 were analyzed, to interpret long-term variations at the glacial/interglacial scale as well as short-term millennial-scale climatic events (Rodríguez-Tovar et al., 2015a). Marine Isotope Stages (MIS) 12 and 11 were also studied, revealing that the

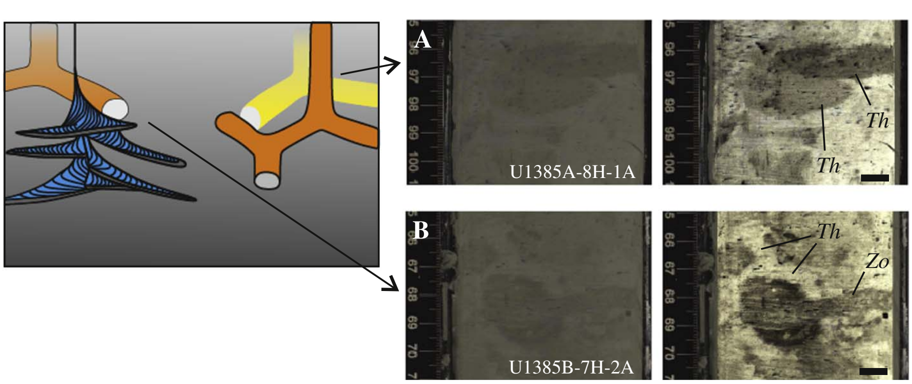

Fig. 5. Multi-tiered community diagram representing overlapping between two generations of *Thalassinoides* (A) and *Zoophycos* (B). *Th*, *Thalassinoides*; *Zo*, *Zoophycos*. Scale bars 1 cm.

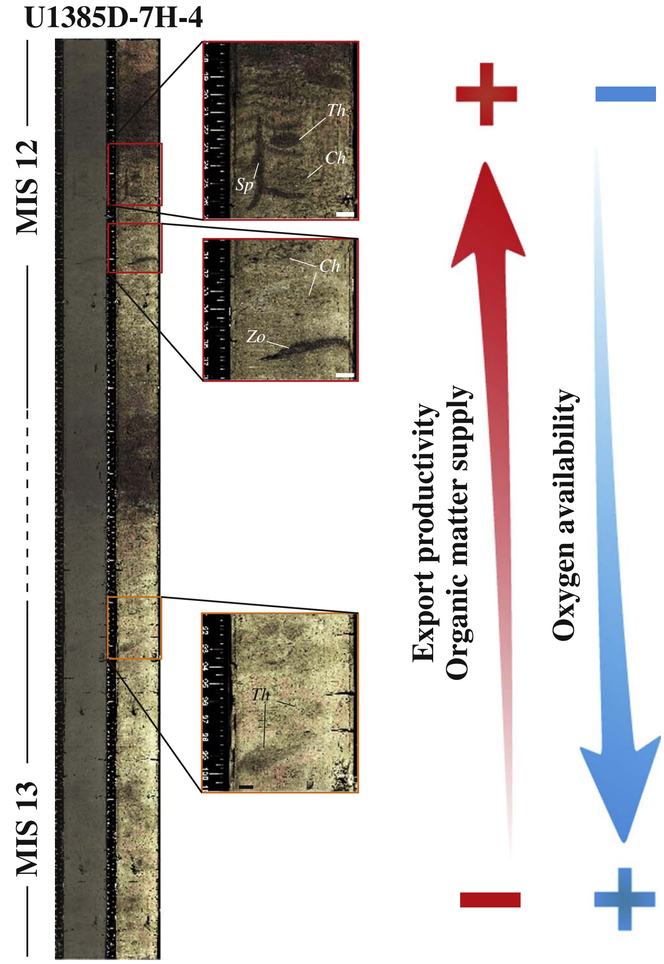

Fig. 6. Core corresponding to transition between MIS 13 and MIS 12, where differences in ichnological content, productivity and oxygenation can be observed. *Ch*, *Chondrites*; *Sp*, *Spirophyton*; *Th*, *Thalassinoides*; *Zo*, *Zoophycos*. Core length 150 cm. Scale bars 1 cm.

evolution of the macrobenthic tracemaker community during MIS 13 and 11 responded to major changes in bottom water ventilation, probably linked to variations in deep water (North Atlantic) thermohaline circulation (Rodríguez-Tovar et al., 2015b). Concretely, the last stages of MIS 13 were characterized by low productivity values, light-color sediments and a dominance of *Planolites* and *Thalassinoides* (Fig. 6), pointing to high oxygenation levels and a relatively low organic carbon flux to the bottom (Rodríguez-Tovar et al., 2015b). This situation was modified in MIS 12, projecting a rapid increase in organic matter and a decrease in available oxygen, thereby favoring the record of *Chondrites*, *Spirophyton* or *Zoophycos* (Fig. 6).

In this context of application, paleoenvironmental interpretations linked to paleoceanography and climatic changes, image treatment was focused on the particularly informative ichnotaxa of *Zoophycos* (Dorador et al., 2016). Changes in the observed occurrences of *Zoophycos* in deep-sea sediments were interpreted as indicating the seasonality of organic matter deposition and primary productivity, and of sedimentation rates, during glacial-interglacial variations (Dorador et al., 2016).

Applying the new digital image treatment methodology to the ichnofabric approach, including bioturbation index, was intended to control stratigraphic variations in the type of differentiated ichnofabrics of Site U1385, IODP Expedition 339 (Dorador and Rodríguez-Tovar, 2016a) and enhance paleoenvironmental interpretations. Short-term fluctuations were correlated to millennial-scale climatic perturbations, and the long-term cyclic pattern to orbital climate variability, entailing a notable change in the climate system (Dorador and Rodríguez-Tovar, 2016a).

Finally, high resolution image treatment can by no means be restricted to ichnological analysis, as it provides abundant sedimentological information. During the last decades, digital image processing has been used to get different features from sediment cores in paleoenvironmental studies (Francus, 2004). For example, Nederbragt et al. (2006) determined color sediment from images and link the observed variations with Total Organic Carbon content; Zeeden et al. (2015) analyzed cyclostratigraphy using the sediment color extracted from images; or Wilkens et al. (2017) who developed a software to get depth and age data from cores based on digital images and comparing with global records. Pixel quantification for color evaluation on some cores from IODP Expedition 339 shed new light on stratigraphic properties (Dorador and Rodríguez-Tovar, 2016b). This color approach provided a more precise characterization than the one obtained on-board using the Munsell Color chart for core description. Accordingly, color differentiation was related with the percentage of sand, a stratigraphic feature used to define deep-sea deposits as turbidites or contourites (e.g., Stow, 1979; Voelker et al., 2006). Darker sediments were linked with coarser ones, having a high presence of sands (Dorador and Rodríguez-Tovar, 2016b). The color approach moreover allows for a precise characterization of color from the host sediment, distinguishing the infilling material of trace fossils, unlike the usual methods applied. Any color modification induced by trace fossils is considered, so that the sediment analysis in cores of bioturbated modern marine deposits is improved and misinterpretations are avoided. Then, bioturbation should be characterized in those studies based on the analysis of sedimentological features obtained from imaging (e.g., Nederbragt et al., 2006; Zeeden et al., 2015; Wilkens et al., 2017) to avoid any modification induced by trace fossils.

3. New advances: Application on penetrative methods images and lithified cores

Having demonstrated the usefulness of the proposed high resolution imagery for ichnological analysis of cores of modern marine deposits, further advances can be obtained by treating other types of images, or working with lithified (consolidated) cores, with specific modifications of the procedure. Depending on the case at hand, particular image adjustments such as brightness and vibrance may be beneficial.

3.1. Penetrative methods (X-ray and CT images)

Although high resolution images of cores are commonly obtained in drilling expeditions, occasionally images from penetrative methods such as radiographs or CT-images are also gotten. They provide data about biogenic structures that cannot be observed on the exposed surface, if there is a contrast in density, constituting additional information; high resolution image treatment can heighten the power of these observational resources. There are many examples of X-ray application as the case of Löwemark and Werner (2001) that used X-ray images to study *Zoophycos* in detail and control age errors induced by this structure; or Gingras et al. (2014) to analyses the iron distribution in bioturbated deposits. Thus, the use of radiographs has been revealed as a very useful technique to get information about internal structures of sediment cores (Knaust, 2012). At present, high resolution image treatment is applied on radiographs from highly bioturbated Arctic cores to reconstruct paleoclimate and paleoenvironmental conditions (Chao and Löwemark, 2017; Fig. 7). Trace fossil visibility is clear in the original X-ray image, but the application of image treatment facilitates ichnofabric analysis, allowing for the determination of bioturbation percentage per ichnotaxa. In the illustrated example (Fig. 7C), the background is completely bioturbated and any primary sedimentary structure can be observed. Over this mottling, discrete *Planolites* (0.8%), *Thalassinoides* (5.6%) and *Zoophycos* (10.3%) can be identified, representing 16.7% of the surface corresponding to a bioturbation index (BI) of 2, considering just discrete trace fossils.

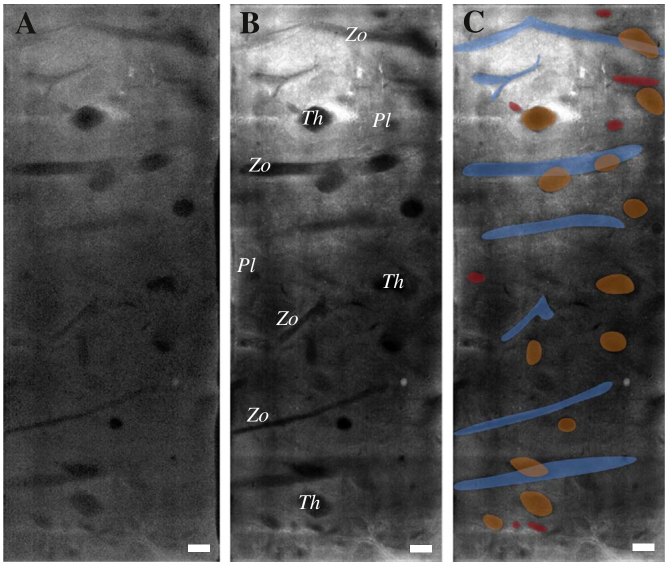

Fig. 7. Application of developed treatment over radiographs from cores drilled in Quaternary deposits from the Arctic Ocean. A, original X-ray image; B and C, treated images with trace fossil identification and quantification. *Pl*, *Planolites*; *Th*, *Thalassinoides*; *Zo*, *Zoophycos*. Scale bars 1 cm.

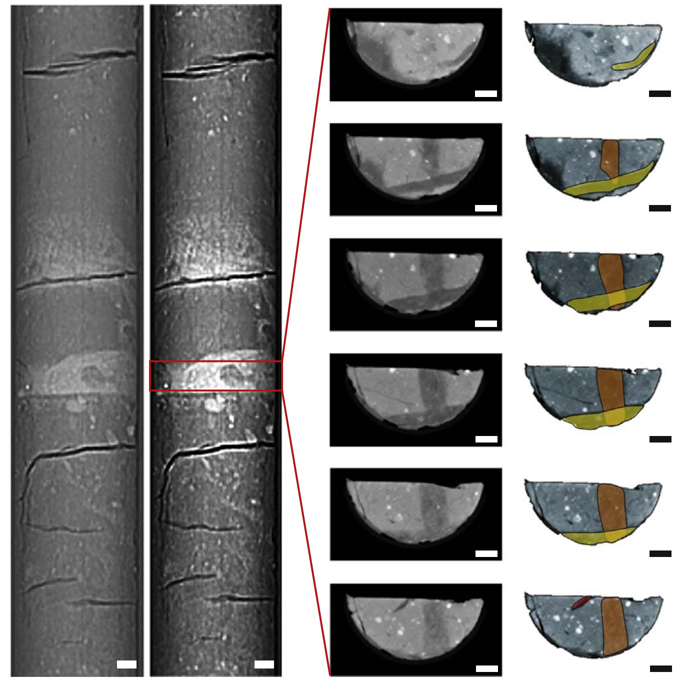

Fig. 8. Original and treated image from an interval of Site U1308 core (drilled in Hudson Strait), where Heinrich Stadial 1 can be detailed analyzed, and treated sections where overlapping situation can be clearly identified with the study of CT transversal sections. Scale bars 1 cm.

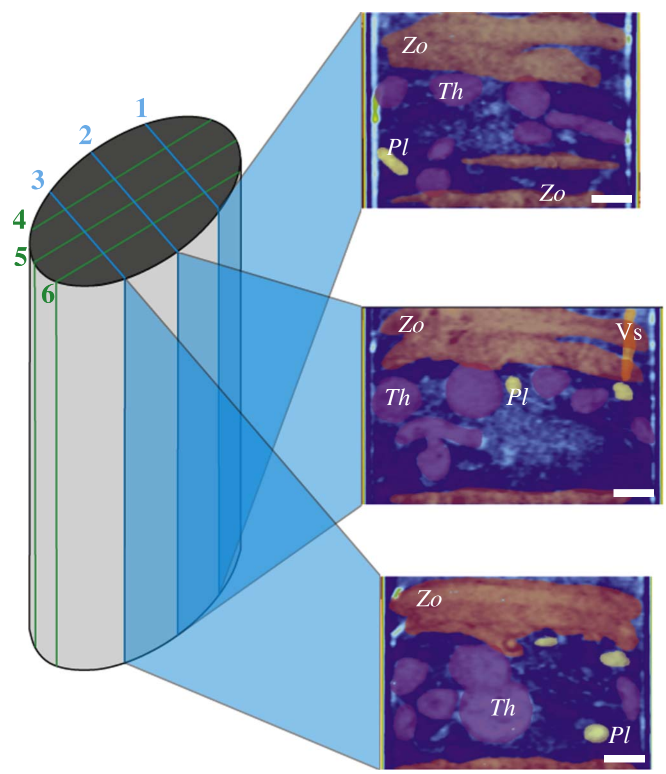

Fig. 9. Treated CT-images from the axial section and two parallel sections, from a SEL08–02 core recorded on the middle slope of the Galicia continental margin (NW Spain), showing differences in some ichnological features due to lateral variations. *Pl*, *Planolites*; *Th*, *Thalassinoides*; Vs, Vertical structures; *Zo*, *Zoophycos*. Scale bars 1 cm.

Other non-destructive techniques that have been commonly used are the Computed Tomography (CT) and the micro Computed Tomography (μ-CT). They allow obtaining different parallel sections which even enabling a 3D reconstruction after a complex software processing. These techniques have been used during the last decade in oil reservoirs and aquifer characterization (e.g., Cunningham et al., 2012), to study how bioirrigation is induced by benthic fauna (Delefosse et al., 2015) or to analyze the burrow system distribution (e.g., Hale et al., 2015). Over images generated using CT scanning, the high resolution digital image treatment is also being applied, with very significant results. Concretely, it is has been used in a study of CT transversal core sections probed from modern marine cores of North Atlantic sediments, providing for a detailed ichnological analysis in a core interval associated with Heinrich Event 1 (Hodell et al., 2017). It facilitates characterization of the trace fossil assemblage, bioturbation index and ichnological features (i.e., overlapping situations and penetration depth) throughout the studied interval (Fig. 8). The first application on Holes of Site U1308 revealed a disturbance of the Heinrich Layer 1 in Hole U1308B, and the complex anatomy of this layer in Hole U1308A (Hodell et al., 2017). A more detailed application reveals notable variations in the ichnological attributes related to changes in paleoenvironmental conditions associated with the double nature of Heinrich Event 1 (HE1.1 and HE1.2) and the intercalated Heinrich Stadial 1 (HS1) (Rodríguez-Tovar et al., 2017a).

Recently, the treatment has been applied to successive longitudinal CT images pertaining to several sections of a single interval from gravity core FSG09-10 of the Galicia Interior Basin (NW Iberian Peninsula), again involving the Heinrich Event 1 (Rodríguez-Tovar et al., 2017b). A close comparison of perpendicular axial sections and other parallel ones just behind and in front makes it possible to more strictly characterize trace fossil assemblages and quantify degrees of bioturbation, revealing short-distance lateral variations in the ichnofabric attributes (Fig. 9). In the interval illustrated in Fig. 9, vertical structures (Vs) are observed in only one of the three sections, affecting ichnofabric characterization and its interpretation in terms of paleoenvironmental features. These lateral variations highlighted by the image treatment provide a more precise and objective characterization of ichnofabrics, hence a better interpretation of paleoenvironmental changes associated with the Heinrich Event 1.

3.2. Cores from consolidated/lithified deposits

The high-resolution image treatment method, designed for application to modern marine core research, later demonstrated its usefulness in

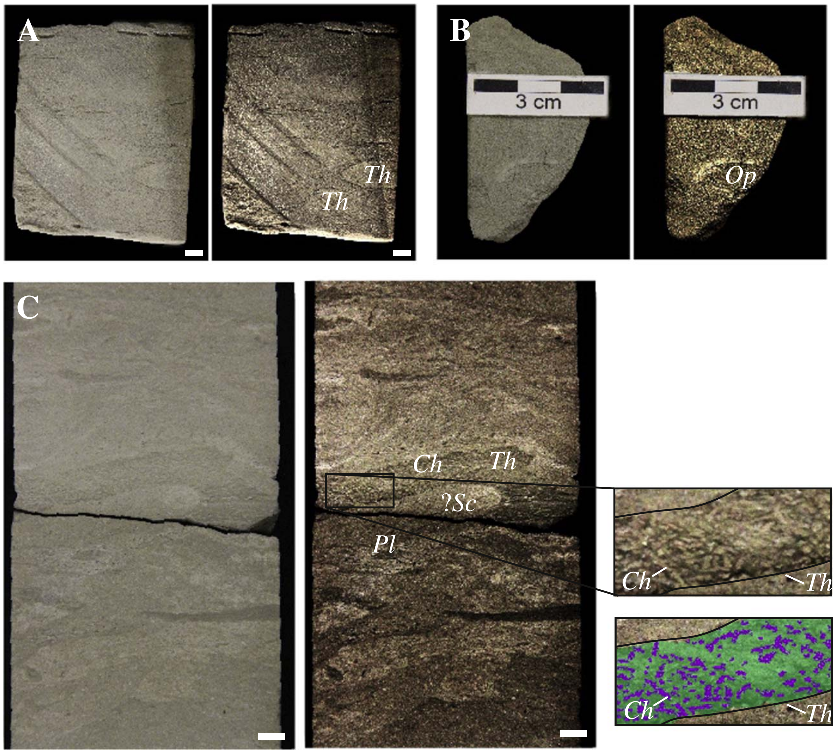

Fig. 10. Examples of original and treated images from lithified fossil cores (A, B, C) and close-up of a *Thalassinoides* section highly reworked by *Chondrites*. *Ch*, *Chondrties*; *Op*, *Ophiomorpha*; *Pl*, *Planolites*; ?*Sc*, ?*Scolicia*; *Th*, *Thalassinoides*. Scale bars 1 cm.

consolidated/lithified cores (Fig. 10). More specifically, high resolution image treatment was applied on cores from Miocene carbonate rocks from the southeastern Florida platform to aid in ichnofacies characterization, and indeed enriched the sequence stratigraphy proposal (Cunningham et al., 2016). Treatment supported the characterization of the *Glossifungites* and *Cruziana* ichnofacies, with a shift upward from a distal expression of the *Cruziana* ichnofacies to an archetypal *Cruziana* ichnofacies, as revealed by the record of ichnofabric attributes including the identification of *Thalassinoides* reworked by *Chondrites* (Fig. 10).

3.3. Outcrop research

The high-resolution image treatment is not restricted to cores, being useful in the ichnological analysis of fine grained rock samples (i.e., mudstones) where identification of trace fossils is not easy due to poor visibility. Usually, collected samples are cut in the laboratory, sectioned surfaces are polished, and the color contrast is enhanced by oil or water wetting to spot trace fossils (Bushinsky technique: Bushinsky, 1947; Bromley, 1981) then treated with a standard photo-image software (see recent applications in Rodríguez-Tovar and Uchman, 2008; Rodríguez-Tovar et al., 2010; Uchman et al., 2008, 2013a, 2013b; Rodríguez-Tovar et al., 2009a, 2009b, 2011, 2013, 2016; Monaco et al., 2012, 2015, 2016; Łaska et al., 2017; Stachacz et al., 2017). While this standard method has given some excellent results, the application of high resolution image treatment leads to improvements regarding certain ichnological attributes. As seen in Fig. 11, visualization of

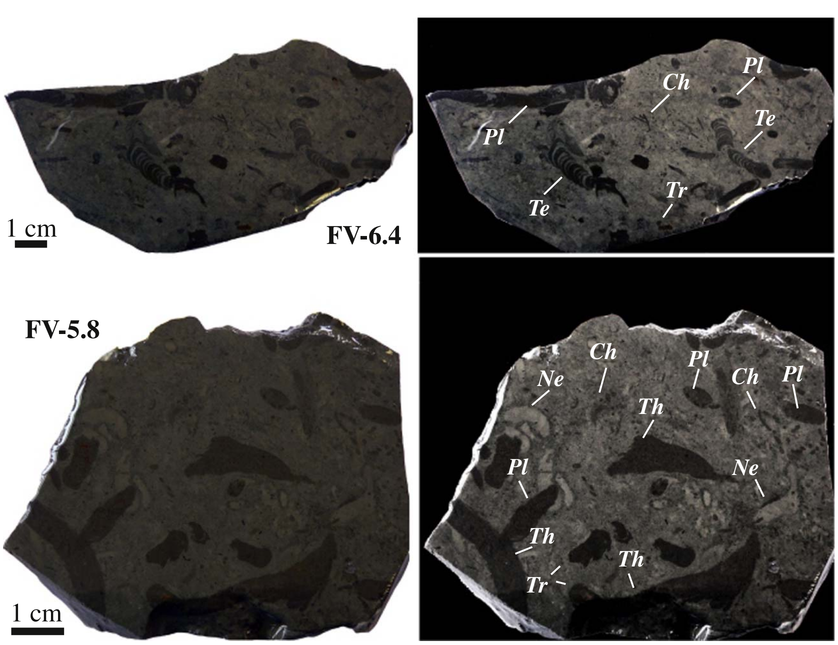

Fig. 11. Polished sections (left) and treated images (right) of rock samples from Lower Toarcian in Fuente de la Vidriera section (Betic Cordillera, Spain), related to the Toarcian Oceanic Anoxic Event, enhancing visibility of ichnological attributes. *Ch*, *Chondrites*; *Ne*, *Nereites*; *Pl*, *Planolites*; *Te*, *Teichichnus*; *Th*, *Thalassinoides*; *Tr*, *Trichichnus*.

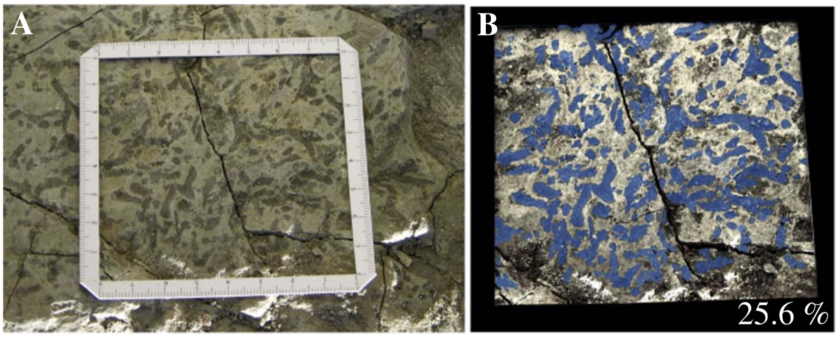

Fig. 12. Application of image treatment, focused on quantification of bioturbation, on a K/Pg boundary protected outcrop.

ichnotaxa and overlapping relationships were enhanced by treatment application. Identification of *Chondrites*, observation of relationships between *Nereites* and *Planolites*, or differentiation among several generations of *Thalassinoides*, are possible due to the treated images, yet they were not clearly recognized in the previous images.

When outcrop sampling is restricted, and it is difficult to obtain valuable material for ichnological analysis in laboratory (especially for attributes such as infilling material or cross-cutting relationships), traditional photography falls short. Application of high resolution digital image treatment is a highly valuable tool in the ichnological analysis of outcrop photographs (Fig. 12). Fig. 12 shows a picture taken from the Cretaceous/Paleogene boundary outcrop in Caravaca (Spain), where sampling is difficult. Image treatment allowed for the identification of some ichnotaxa, but it proved especially useful in quantifying bioturbation. In this example the outcrop was divided into squares, and pictures were treated later to derive the percentage of bioturbated surface (25.6% in the illustrated sample).

4. Future perspectives

Advances briefly described here underline the potential of the developed method in ichnological analysis of different core materials (soft and lithified cores), as well as several kinds of images (high resolution digital images, radiographs and CT-images). In our opinion, however, this is only the tip of the iceberg of this methodology, welcoming new research lines; for instance, two intrinsically diverse hot topics in the Earth Sciences, contourite research and the behavior of *Zoophycos* tracemakers. Moreover, potential methods should be tested as the terrestrial laser scanning data (TLS) which has been frequently used to analyze heterogeneities of sediment properties in outcrops (e.g., Franceschi et al., 2009, 2015; Zeeden et al., 2017), to link these variations to ichnological characterization.

4.1. Contourites and related sediments

Since the first papers on contourites from the mid ´60s, the study of these particular facies has shown significant progress. We have seen an increase in the number of studies on modern and fossil examples, the analysis of cores and outcrops, and an increasingly multidisciplinary approach. All of this, has favored debate —even heated debate— within the scientific community.

The study of contourite deposits is a hot topic among the Earth Sciences community, considered crucial for at least three fields: paleoclimatology and paleoceanography, slope-stability/geological hazard assessment, and hydrocarbon exploration. Notwithstanding, some relevant aspects of contourite research remain unresolved (Rebesco et al., 2014; Shanmugam, 2017 for recent reviews). One very relevant or promising feature is the bioturbation of contourite and associated deposits. Trace fossil analysis could contribute greatly to contourite characterization and differentiation with respect to associated facies (i.e., turbidites). Even though ichnological research of contourite sediments can be readily conducted in outcrops, the ichnological approach to cores would certainly prove useful in this area of study. In this context, some progress is underway executing ichnofabric analysis of contourite deposits and related sediments in cores thanks to the application of the proposed high resolution image treatment, shedding light on the involved phenomena and related paleoenvironmental conditions, e.g. hydrodynamic energy or rate of sedimentation (Alonso et al., 2016). As a future related topic, modifications of contourite properties such as porosity and permeability induced by bioturbation, of considerable relevance importance in reservoir characterization, can be also approached using the proposed methodology.

4.2. Improving ichnological features (Zoophycos + pellets)

In a very different branch of the Earth Sciences, high resolution digital image treatment can be a very useful tool to focus on some controversial paleontological topics regarding the paleobiology or behavior of past tracemakers. Such is the case of *Zoophycos*, one of the most important multi-level spreite structures in deep-sea sediments, probably the most controversial of all trace fossils (see Kotake, 2014; Löwemark, 2015; Zhang et al., 2015; Monaco et al., 2017, for recent reviews).

At the same time, no consensus exists regarding aspects of the *Zoophycos* structure such as the mode of construction or its ethological explanation. To try to solve these questions, numerous approaches have been proposed, including morphological studies, isotopic analysis, or radiocarbon dating, but interpretations remain inconclusive. One ichnological attribute of *Zoophycos* that might be used as a tool to approach these questions are the pellets within the infilling of *Zoophycos* structures.

However, pellets in *Zoophycos* cannot generally be observed; and when it is possible they are not clearly differentiated. Recent novel image treatment has allowed them to be characterized and quantified, as preliminarily reported in samples from Miocene outcrops from the Pacific Colombian (Celis et al., 2016). Promising developments such as this, together with the initial applications in specimens from modern marine cores, support previous interpretations and impressions. Fig. 13 presents a particular case of this approach, showing a characterization with quantification of *Zoophycos* pellets, where the spreiten structures and percentage of pellets in every spreiten can be evaluated.

5. Concluding remarks

Ichnology is being commonly used in different Earth Sciences disciplines (e.g., paleoecology, sedimentology, paleoceanography, basin analysis, reservoirs and aquifers characterization, among others), especially since the development of ichnofacies and ichnofabric concepts in the second half of the twentieth century. Very often, determination of some ichnological features and then trace fossils characterization, is not easy. In these cases, high-resolution image treatment has been widely applied and revealed as a very useful tool in both outcrop and, especially, core studies. During the last years, a new high-resolution image method has been developed and successfully applied in a

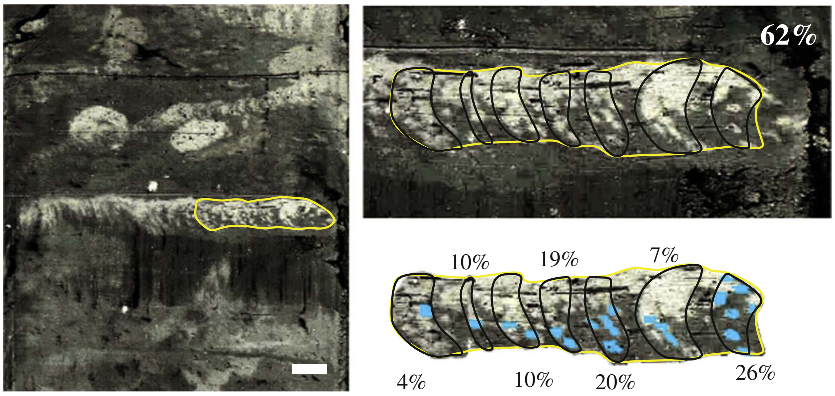

Fig. 13. Detailed characterization of *Zoophycos spreiten* and pellets in a specimen from U1385 IODP Site cores. Numbers represent percentages of the light lamellae of *spreiten* (image above) and pellets in each (image below). Scale bar 1 cm.

wide range of ichnological analysis, being especially helpful for studies of cores from modern marine deposits. Its application allows differentiating between biodeformational structures and discrete trace fossils, facilitating ichnotaxonomical classification, quantifying the amount of bioturbation and determining other ichnological features; supporting the ichnofacies and ichnofabric approaches. This methodology is being incorporated in Earth Sciences community by the use in paleoenvironmental studies and sedimentary basin analysis research mainly focused on ichnological analysis, but also integrating information from other disciplines. All these evidences, point this high-resolution image treatment as a very promising technique in further studies that nowadays are being developed. These new steps are demonstrating the wide range of use, including application on some other resources (e.g., radiographs, CT images) and materials (e.g. lithified cores). Due to its huge development, further applications will be tested a wide range of studies for support Earth Sciences research.

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