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

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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

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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