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ICHNOFABRIC CHARACTERIZATION IN CORES: A METHOD OF DIGITAL IMAGE TREATMENT

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Abstract: Ichnofabric analysis, as a relatively young ichnological approach, has witnessed rapid growth, showing its usefulness in basin analysis, with special attention to palaeoenvironmental interpretations. The ichnofabric approach has evolved from the description of trace composition and the intensity of bioturbation to integrate detailed information on numerous ichnofabric features, such as primary sedimentary structures, ichnological diversity, ichnological features, cross-cutting relationships or tiering structures. This development has been associated with its application to the study of deep-sea sediments, especially in research on cores, which is not easy, owing to the particular features of cores. Here a method for improving ichnofabric characterization in modern marine cores is presented, on the basis of digital high-resolution image treatment, with special emphasis on the quantification of ichnofabric attributes. The proposed methodology is based on the modification of three image adjustments (*image adjustment*), the estimation of the percentage of the area occupied by bioturbation (*digital estimation*), the lateral and vertical quantification and comparison of pixel values for the infill of the trace fossils and the host sediment (*pixel counting*), and the integration of the information obtained in the visual representations of ichnofabrics (the *ichnofabric representation*). The sequential application of these proposed steps allow, 1) better identification of trace fossils, together with cross-cutting relationships and the characterization of trace-fossil assemblages, 2) estimation of the percentage of bioturbation associated to each ichnotaxon, the whole ichnocoenosis, or a complete ichnofabric, 3) differentiation between biodeformational structures and trace fossils, discrimination between ichnotaxa, distinction between passively and actively infilled structures, and 4) evaluation of the depth of penetration by particular tracemakers.

Key words: trace fossils, image treatment, ichnofabric approach, ichnofabric attributes and representations.

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INTRODUCTION

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

Ichnofabric analysis don't consist in the enumeration of an amount of trace fossils, but in the integration of a variable information, involving the original sedimentary fabric together with the bioturbation and bioerosion fabrics, and finally the taphonomic filter (Taylor *et al.*, 2003; Buatois and Mángano, 2011; Ekdale *et al.*, 2012). Ichnofabric characterization has evolved from the description of the trace composition and intensity of bioturbation to include detai- led information on major ichnofabric attributes, including primary sedimentary structures, ichnological diversity, ich- nological features (i.e., dimensions of ichnotaxa), cross-cutting relationships and tiering structure (i.e., Taylor *et al.*, 2003; McIlroy, 2004, 2007, 2008). All these features reveal a number of ecological and depositional controlling parameters and determine the usefulness of the ichnofabric approach in palaeoenvironmental interpretations and in basin analysis.

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

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

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

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

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

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

METHODS

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

Step 1 – image adjustments

The first step (*image adjustments*) consists of the modification of three image adjustments (*levels*, *brightness* and *vibrance*) using Adobe Photoshop CS6 software (http://help.adobe.com/archive/en/photoshop/cs6/photoshop_reference.pdf) (Fig. 1; Dorador *et al.*, 2014a). *Levels* adjustment stretches the histogram of pixel values, increasing the distance between values. *Brightness* modifies the reflected light and controls the contrast by the modification of two parameters (contrast and brightness). *Vibrance* adjustment turns the image to less artificial tones resulting from the application of previous adjustments. The three adjustments are applied sequentially: firstly *levels* were applied to an image to stretch the histogram and improve the contrast, secondly the *brightness* increases the contrast and controls the brightness, and finally the *vibrance* allows slight modifications.

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

Step 2 – digital estimation

The second step (*digital estimation*) of the proposed method is applied to the previously treated image, allowing a quantitative evaluation of bioturbation. It consists in the execution of three methods, the similar pixel selection method (SPSM); the magic wand method (MWM), and the colour range selection method (CRSM). These methods are

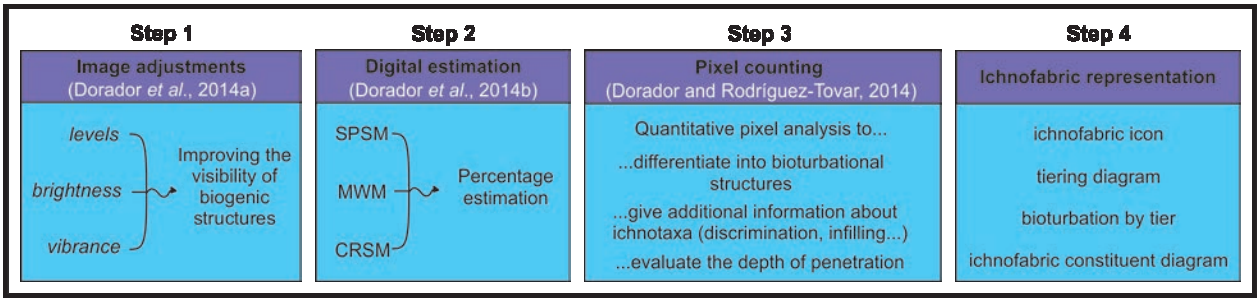

Fig. 1. Schematic diagram of the proposed method. SPSM (similar pixel selection method); MWM (magic wand method); and CRSM (colour range selection method).

grouped in the "ichnological digital analysis images package" or IDIAP (Dorador *et al.*, 2014b).

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

Step 3 – pixel counting

The third step (*pixel counting*) is based on the lateral and vertical quantification and comparison of pixel values for the infilling trace fossils and for the host sediment (Dorador *et al.*, 2014c). Each pixel is characterized by three values corresponding to the red, green and blue channels, which are counted using Photoshop CS6 and then plotted with Matlab R2010. In general, fifty measured pixel values are considered the minimum amount to represent an ichnotaxon. The analysis of vertical variation requires a particular treatment with vertical subdivisions into 1 cm-thick parts. Quantitative pixel analysis allows the improvement of ichnofabric characterization, confirming some of the features approached during step 1 (*image adjustments*), and giving additional information through differentiation between biodeformational structures and trace fossils, discrimination of ichnotaxa, distinction between passively and actively infilled structures, and evaluation of the depth of penetration of particular tracemakers.

Step 4 – ichnofabric representation

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

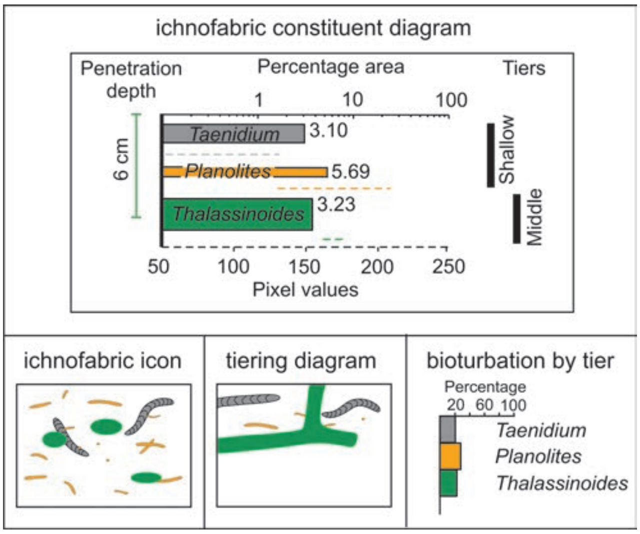

Fig. 2. Ichnofabric diagrams of a theoretical interval, described in this study.

CASE STUDY

To evaluate the usefulness of the method presented, it has been applied to Pleistocene-Holocene marine cores of hemipelagic sediments, obtained in the Gulf of Cádiz during IODP Expedition 339. Two intervals from the core material of site 1385 (southwestern Iberian margin; 37°34.285 N, 10°7.562 W; Hodell *et al.*, 2013) were studied: A (U1385E-5H-4-A_104–111 cm), and B (U1385D-8H-4-A_74–85 cm). The materials studied had been deposited in a hemipelagic setting, characterized by a low sedimentation rate and comparatively good environmental conditions for a macrobenthic community. Tracemaker activity is important. Biodeformational structures had produced a mottled background and pri-

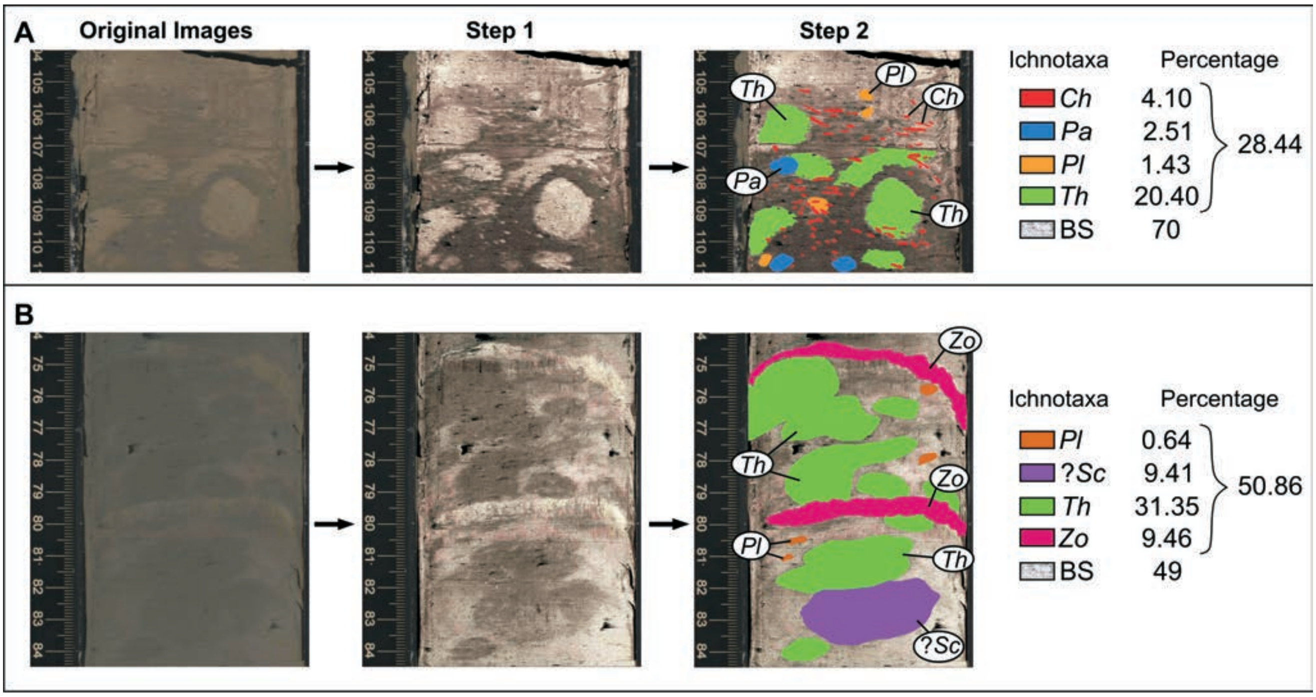

Fig. 3. Application of the method to two examples in an IODP core. Original images, results after first and second steps and percentage represented by each ichnotaxa are shown from left to right. *Ch* – *Chondrites*, *Pa* – *Palaeophycus*, *Pl* – *Planolites*, ?*Sc* – ?*Scolicia*, *Th* – *Thalassinoides*, *Zo* – *Zoophycos*, BS – biodeformational structures.

mary sedimentary structures were not observed. However, the bioturbation index values used in this study consider only discrete trace fossils against the mottled background.

The methodology was applied following the sequential steps 1 to 3, resulting in the images illustrated in Fig. 3, and the information obtained (Figs 4, 5) was presented following some of the most usual ichnofabric illustrations, those proposed by Taylor and Goldring (1993) and Bromley (1996).

Example A

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

Integration of the information obtained to the visual ichnofabric representations (Taylor and Goldring, 1993; Bromley, 1996) allows clear representation of the ichnofossil assemblage, including the relative percentage of ichnotaxa, as well as the illustration of cross-cutting relationships (Figs 4A, 5A). A multi-tiered trace-fossil community is differentiated. The first, shallowest tier is represented by the mottled background and associated biodeformational structures, produced by organisms in the mixed layer. The shallow tier (1.4%) is formed by *Planolites*, produced by vagile deposit feeders. The middle tier (22.9%) is characterized by *Thalassinoides* and *Palaeophycus*, produced by semi-vagile and vagile deposit feeders. In the lower part, a deep tier (4.1%) is represented by *Chondrites*, reflecting permanent structures of possible chemosymbiotic organisms. The ichnofabric constituent diagram of Taylor and Goldring (1993) contains the estimated depth of penetration of *Thalassinoides*, belonging to the middle tier (around 4.5 cm of penetration depth), together with data on pixel values. The biodeformational structures are characterized by pixel values lower than 110 and discrete trace fossils from 98 to 203 and therefore usually they are lighter than the mottled background (Fig. 5A). Especially interesting is the short range of pixels for *Thalassinoides*, which could be useful for rejecting a doubtful *Thalassinoides* assignment, if values of the trace are not in this range.

The methodology applied improves the characterization of a trace-fossil assemblage, with especial attention to *Chondrites*, difficult to differentiate directly in cores images without any treatment, and reveals significant cross-cutting relationships, allowing the characterization of a well-developed deep tier. These improvements have significant palaeoecological consequences. Thus, the tiering structure interpreted could reveals gradual changes in the sediment; ichnological changes from shallow to deep tier could be a conse-

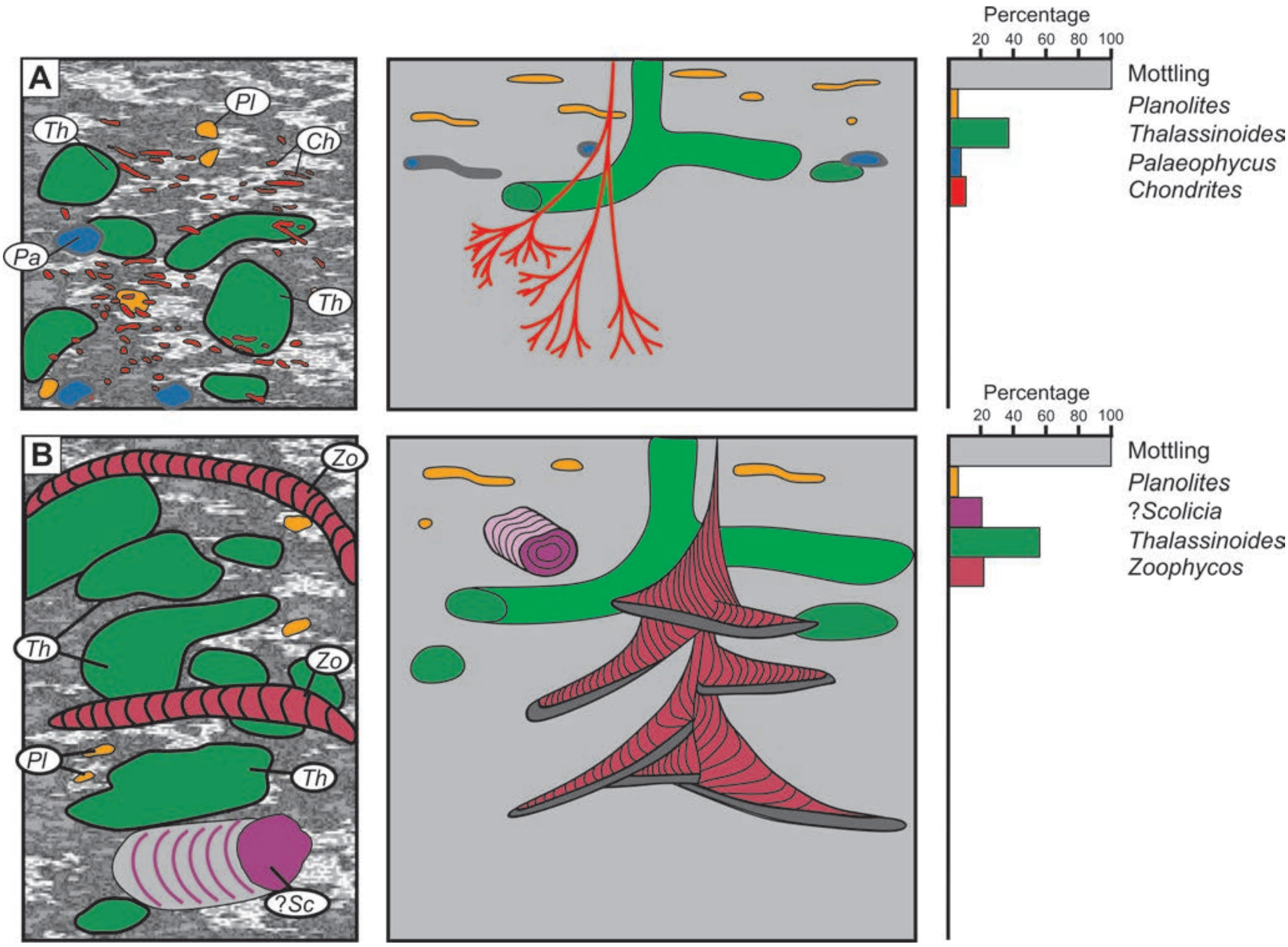

Fig. 4. Ichnofabric icon, tiering diagram and amount of bioturbation by tier of example A (above) and B (below). *Ch – Chondrites*, *Pa – Palaeophycus*, *Pl – Planolites*, *?Sc – ?Scolicia*, *Th – Thalassinoides*, *Zo – Zoophycos*

quence of decreasing oxygen in pore waters and increasing substrate consistency deeper in the sediment (see a similar tiering structure in Rodríguez-Tovar and Uchman, 2004a, b),

Example B

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

As in the first example (A), the information obtained improved the visual ichnofabric representations (Figs 4B, 5B). In example B, the mottling produced by organisms that bioturbated the mixed layer corresponds to the shallowest tier. The shallow tier is poorly represented by scarce *Planolites* (0.6% of the observed bioturbated area). The middle tier is comparatively well-developed, representing ~41% of the bioturbated area, characterized by structures made by vagile and semi-vagile deposit feeders, consisting of *Thalassinoides* and ?*Scolicia*. The deepest tier also is well registered (9.5 %), showing the activity of *Zoophycos* tracemakers. As added in the Ichnofabric Constituent Diagram (Fig. 5B), *Thalassinoides* belonging to the middle tier coming from 4 to 8 cm above, according to the information provided by the quantitative pixel analysis. In this example, the pixel values corresponding to the biodeformational structures are commonly higher than those from the discrete trace fossils, as the mottled background is lighter than the traces, except *Zoophycos*, which is even lighter (Fig. 5B). In this *Thalassinoides* and *Zoophycos* ichnofabric, the narrow range of *Thalassinoides* pixels, is useful for recognition of this structure.

In this example B, the methodology applied has been demonstrated to be very useful for describing the tiering pattern, especially the well-developed middle tier. Differentiation between *Thalassinoides* and ?*Scolicia* has been possible, as well as the detailed characterization of *Thalassinoides*, including the horizon of bioturbation. Thus, good and

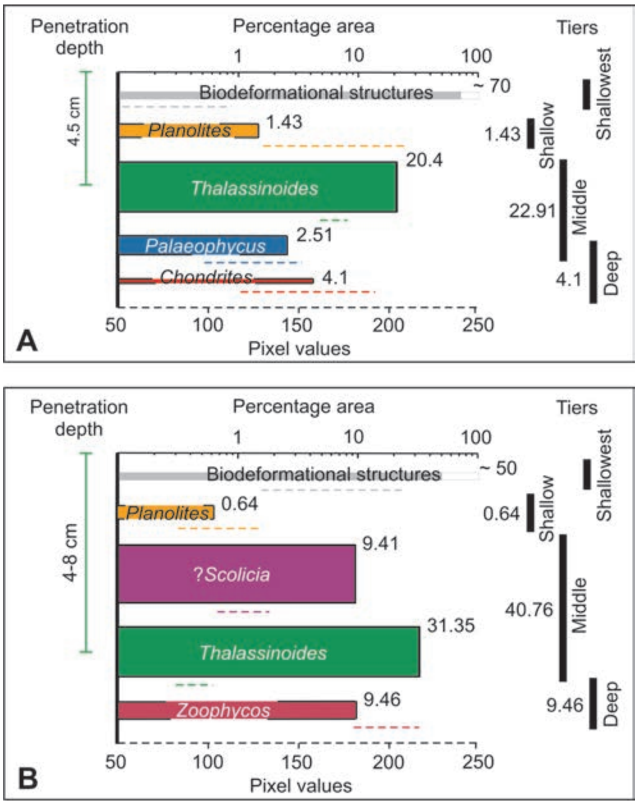

Fig. 5. Ichnofabric constituent diagram (ICD) of the ichno-fabrics, characterized in examples A and B. Percentage of surface (bar length), size (bar thickness) and tiering (order) of each ichnotaxon are represented in this diagram. The amount of bioturbation per tier (right), range of pixel values (broken lines) and penetration depth (left) are included in the original ICD in Figure 2.

probably prolonged palaeoenvironmental conditions deeper in the sediment, associated to the middle tier, can be envisaged, such as available benthic food and firmer substrates.

CONCLUSIONS

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

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

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