Quantitative Estimation of Bioturbation Based on Digital Image Analysis

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Abstract

Quantitative determination of modification of primary sediment features, by the activity of organisms (i.e., bioturbation) is essential in geosciences. Some methods proposed since the 60's are mainly based on visual or subjective determinations. The first semiquantitative evaluations of the bioturbation index, ichnofabric index, or the amount of bioturbation were attempted, in the best cases using a series of flashcards designed in different situations. Recently, more effective methods involve the use of analytical and computational methods such as X-rays, magnetic resonance imaging or computed tomography; these methods are complex and often expensive. This paper presents a compilation of different methods, using Adobe® Photoshop® software CS6, for digital estimation that are a part of the IDIAP (Ichnological Digital Analysis Images Package), which is inexpensive alternative to recently proposed methods, easy to use, and especially recommended for core samples. The different methods —"Similar Pixel Selection Method (SPSM)", "Magic Wand Method (MWM)" and the "Color Range Selection Method (CRSM)"— entail advantages and disadvantages depending on the sediment (e.g., composition, color, texture, porosity, etc.) and ichnological features (size of traces, infilling material, burrow wall, etc.). The IDIAP provides an estimation of the amount of trace fossils produced by a particular ichnotaxon, by a whole ichnocoenosis or even for a complete ichnofabric. We recommend the application of the complete IDIAP to a given case study, followed by selection of the most appropriate method. The IDIAP was applied to core material recovered from the IODP Expedition 339, enabling us, for the first time, to arrive at a quantitative estimation of the discrete trace fossil assemblage in core samples.

Keywords: Bioturbation, digital images, quantitative methods, marine core deposits, Integrated Ocean Drilling Program, Expedition 339, Site U1385

1. Introduction

The beginning of the twenty-first century has witnessed a rapid growth in ichnological research, which has become relevant in a wide range of fields, e.g, palaeobiology, palaeoecology, biostratigraphy, sedimentology, and most recently reservoir characterization, involving biologists, palaeontologists and sedimentologists.

In some of these disciplines, the quantitative determination of a modification of primary sedimentary features by bioturbation can prove fundamental. Such is the case of reservoir and aquifer characterization, and the impact of trace fossils and their associated ichnofabrics on fluid-flow properties, including sediment permeability and porosity (Cunningham et al., 2013; Gingras et al., 2013).

The intensity of bioturbation is characterized by the use of semi-quantitative index schemes (i.e., Marenco and Bottjer, 2011; Ekdale et al., 2012; Knaust, 2012), the most common ones being the "Bioturbation Index" (BI) (Reineck, 1963) and "Ichnofabric Indices" (ii) (Droser and Bottjer, 1986). The "Bioturbation index" of Reineck (1963), later revised by Taylor and Goldring (1993), was initially applied to box cores and has a scale from Bioturbation Index = 0 (no bioturbation) to 6 (completely bioturbated). In turn, the "ichnofabric indices" of Droser and Bottjer (1986), widely used in ichnological research, range from ichnofabric index = 1 (no bioturbation) to ichnofabric index = 6 (sediment nearly or totally homogenized), and rely on the use of flash cards for an easy visual assessment of the intensity of bioturbation. A modification of the ichnofabric indices, the "Bedding Plane Horizontal Index" (BPHI), was proposed by Miller and Smail (1997) for the degree of bioturbation on originally horizontal planes. All three methods are easy to apply and inexpensive, however, they are mainly based on visual observation, using grades or scores that represent different ranges of percentage, thus bearing the possibility of a subjective inaccuracy for estimation of bioturbation intensity.

In the wake of the early semi-quantitative approaches of Reineck (1963), Droser and Bottjer (1986) and Taylor and Goldring (1993), more objective methods appeared that involved either grid-based techniques, computer-aided image analysis or advanced image technology (Marenco and Bottjer, 2011). Grid-based methods, which can be used with different scales of grids, are particularly useful for estimating the quantity of bioturbation on bedding planes or on vertical cross-sections (Heard and Pickering, 2008; Marenco and Bottjer, 2010). They are inexpensive and simple to perform, requiring little specialized equipment, but they are time-consuming and accuracy depends on grid and trace sizes. Computer-aided image analysis has been used to improve the visibility of complex ichnofabrics in photographs (Magwood and Ekdale, 1994; Dorador et al., 2013), and to estimate the amount of bioturbation (Francus, 2001; Löwemark, 2003). Computer-aided image analysis is appropriate for specialized applications, such as thin-sections or x-radiographs, and sometimes calls for the use of Scanning Electron Microscopy; a further limitation is the reduced field of view. Image techniques, such as x-radiography (e.g., Löwermark, 2003; Marenco and Bottjer, 2008), computed tomography (e.g., Fu et al., 1994; Dufour et al., 2005), and magnetic resonance imaging (e.g., Gingras et al., 2002), have been recently applied to acquire information on trace fossils and ichnofabrics, but scarcely applied for estimation of the amount of bioturbation (e.g., Dufour et al., 2005). Except for x-radiographs, imaging techniques as computed tomography and magnetic resonance imaging are complex and very expensive.

This paper presents a novel, easy to use, and inexpensive package (IDIAP; Ichnological Digital Analysis Images Package) of different methods for digital estimation of discrete trace fossil assemblage in digital images using Adobe® Photoshop® software CS6. The method can be applied on images of samples acquired from outcrops and cores, but is especially appropriate for the latter due to the specific features of cores (i.e., limited size, restricted surface, among others) make ichnological research difficult. The package consists of three different methods enabling its application in a great variety of material having different sediment and ichnological features. We demonstrate the usefulness of the IDIAP by applying it to core material from the IODP Expedition 339 (Fig. 1).

2. The Ichnological Digital Analysis Image Package (IDIAP)

The Ichnological Digital Analysis Images Package (IDIAP) integrates three methodologies of digital image analyses: the "Similar Pixel Selection Method (SPSM)", the "Magic Wand Method (MWM)" and the "Color Range Selection Method (CRSM)" (Fig. 2). IDIAP provides a quantitative assessment of the percentage of area occupied by discrete trace fossils in core material. Depending on the particular sediment and its ichnological features, any one of the three methods may be considered more appropriate, or an integrative approach using all of them may be best.

2.1. Similar Pixel Selection Method (SPSM)

This method allows finding pixels on the full image with values in the range of those pixels registered in a previously selected particular area, which correspond to the studied trace fossil. It is useful when objects need to be selected with a variable range of colors because an area with a certain number of pixels is chosen. In cases where objects cannot be defined by only one pixel color, this method has a major advantage. A representative area within the desired object is selected using any Photoshop selection tool. After that, click 'Select' in the menu bar and choose 'Similar'. The method's great disadvantage, however, is that the selection sensitivity cannot be modified; it is not useful if the difference between pixels is low. Further, it can only be executed once; if there are different objects of different colors, they cannot all be selected. The SPSM may be considered as a more complete and easier method than the one presented by Honeycutt and Plotnick (2008). The method used by Honeycutt and Plotnick (2008) is an automatic quantitative method to determine the Bioturbation Index using the complex software Matlab 7.1 ® from digital images, based on gray-level matrices (one value per pixel) while the SPSM uses an easier software based on digital color images (three values per pixel).

2.2. Magic Wand Method (MWM)

This method alludes to the 'Magic Wand tool' used by Coimbra and Olóriz (2012) for the manual selection of objects, this tool selects pixel nearby (by default) having similar variations of color of the previously selected pixel. The maximum percentage difference between the reference pixel and the selected pixels is defined by a parameter called 'Tolerance'. This method has been used to derive percentage estimations of bioclasts and other applications, but not to ichnological data, based on pixel counting using Adobe® Photoshop® software CS2 (e.g. Perring et al., 2004; Johansson et al., 2008). It can be time-consuming, especially if there are small objects in the image, calling for clicks on each object to be selected. However, it affords the great advantage of multiple executions. To proceed, the 'Magic Wand Tool' is selected and one representative pixel within each object is chosen. The sensitivity is controlled by 'Tolerance' that can be modified in the menu bar until obtaining the desired selection. To add more than one object, simply click on the 'Add to selection' option in the menu bar and click on a new object. Especially, when objects are large and possess more than one color this method is useful. Additionally, the method can be modified to be applied to the complete given image. It even works with smaller objects when these clearly differ from the background.

The pixels selected can be manually modified with different tools if there is any object whose selection is not possible with one of these automatic methods.

2.3. Color Range Selection Method (CRSM)

This method is based on the localization of pixels in the whole image that are similar to only one manually selected. It shares a great advantage with the SPSM: the selection extends over the full image, but in the case of the CRSM only one representative pixel can be selected, while in the SPSM all pixels registered in the selected particular area are considered by the method. The method allows choosing a selection or a desired pixel range with the modification of a parameter called 'Fuzziness'. This method is the quickest and most useful when there are a lot of small objects of the same or similar color. In order to execute it choose 'Select' from the menu bar and click on 'Color range…', and a window opens. You may define the reference color to extend the selection, but the best and easiest way to select similar objects is to choose 'Sampled Colors'. Under this option, the cursor is a sampled color, and you have to click on a representative pixel of the object color. Then, a selection takes place, and it can be viewed in a little window so that the fuzziness parameter can be modified until all objects are selected, and then you click on 'OK'. This method only can be executed once.

3. Results From The Expedition 339 Core Material

The IDIAP was applied to IODP Expedition 339 cores (Expedition 339, 2013; Hernández-Molina et al., 2013). Some intervals with trace fossils were selected from the core material of site 1385 (southwestern Iberian margin; 37°34.285’N, 10°7.562’W; Hodell et al., 2013). The sediments recovered in the core are dominated by Pleistocene hemipelagic mud- and claystones. No primary sedimentary structures were observed. The discrete trace fossil assemblages include *Zoophycos*, *Chondrites* and *Planolites* as the dominant ichnotaxa (Expedition 339, 2013). The section of this site is typical of a hemipelagic continental margin succession under normal marine conditions (Expedition 339, 2013; Hernández-Molina et al., 2013; Hodell et al., 2013). The principal colors of lithologies range from gray to greenish gray, impeding trace fossil distinction and identification at first glance by digital images. To facilitate the recognition of distinct trace fossils, selected images were slightly treated beforehand to identify and select the trace fossils as follows: Each image was modified, using Photoshop, by increasing its contrast up to ‘100’ to improve quality. After application of the IDIAP, selection of discrete trace fossils must be checked visually and in some cases slightly modified by hand. This modification is done because sometimes there are selected pixels that are unrelated to trace fossils but they are interpreted as traces by the software. Modification was done using ‘Elliptical or Rectangular Marquee Tools’, which make it possible to add an area (‘Add to selection’) or diminish an area (‘Extract to selection’). These modifications were also used when cross-cutting relationships existed (Figs 4, 5; examples B and C), to distinguish in the estimation between those areas occupied by the first generation of traces and that by the second generation.

After selection, every ichnotaxon was painted with different colors applying the “Paint Bucket Tool” to emphasize the selection and facilitate the percentage estimation. The number of selected pixels is shown in the ‘Histogram’ window; pixel selection value (P_s) should be compared with the number of pixels in the total area of the image (P_I) and converted in percentage. (Note: the histogram does not show cached data). The whole procedure was executed more than one time in the same picture and the variation in the area occupied by traces was lower than 5%. This procedure has been summarized in a flow-chart (Fig. 2). To test the IDIAP, three examples were selected, representing different cases of abundance, diversity and complexity of discrete trace-fossil assemblages:

Our first example A (Fig. 3), located in 1385E-13H-6A, 38-42 cm, shows scarce *Thalassinoides*-like and *Phycosiphon*, without cross-cutting relationships. The three methods were applied with different results. Owing to the lack of contrast between traces and sediment, the SPSM gave wrong selections and therefore did not only select pixels belonging to the trace fossils but also of the surrounding sediment. The CRSM on the other hand, selected not all pixels belonging to the *Thalassinoides*-like pixels. The best CRSM result was obtained with a fuzziness value of 11. Visually, the MWM was superior although every trace had to be clicked on. The best tolerance values used were 3-5, due to slight differences between *Phycosiphon* and the surrounding pixels. Thus, the best estimation overall was obtained using MWM: the bioturbated percentage value corresponding to trace fossils was roughly 5% (4.3% *Thalassinoides*-like, 0.8% *Phycosiphon*).

The example B figured in Fig. 4, located in 1385A-5H-5, approximately 126-132 cm, shows two phases of colonization with a more abundant first generation of traces with *Thalassinoides*-like, *Thalassinoides* and *Planolites*, crosscut by a less abundant second generation of *Chondrites*. SPSM and CRSM results were very similar.

The first gave 56% area of trace fossils, and CRSM, which was applied with a fuzziness value of 20, gave 49%. On the other hand, the result from the MWM was 37% area of trace fossils with applied tolerance values of 5-10. Yet for this example, full image methods prove more successful visually because there were many small traces that were difficult to identify and using MWM would be very time-consuming. The percentage of area corresponding to trace fossils was around 52%, according to SPSM and CRSM values; from these 52%, 47.3% were produced by the first generation of traces (23% *Thalassinoides*-like, 22% *Thalassinoides* and 2.3% *Planolites*) and 5.3% by the second generation (*Chondrites*).

From Hole 1385E, Core 13H-4A, 117-125 cm approximately, example C (Fig. 5) shows two phases of colonization with a comparatively less abundant first generation with *Planolites* and *Thalasinoides*, crosscut by a more abundant second generation of *Zoophycos*. We used the “Magic Wand Method” with a tolerance value of “3”. When SPSM was used, most of *Zoophycos*- and *Planolites*-pixels were selected but pixels corresponding to diffuse *Thalassinoides* were not. Several non-trace pixels were selected, so the 19% value obtained is not reflecting the true grade of bioturbation corresponding to trace fossils. CRSM, with a fuzziness value of 92, selected the most trace pixels (except some *Thalassinoides* pixels) but also selected a lot of non-trace pixels, thus giving around 51% area of trace fossils which is much, higher than the real value. The best results were achieved with the MWM, because *Thalassinoides* could be selected using the ‘Magic Wand Tool’ with a tolerance value of 3 and non-trace pixels were not selected. The real percentage of area corresponding to trace fossils, then, was about 17%, as estimated by the MWM: 3% for the first generation of traces (2.7% *Thalassinoides*, and 0.6% *Planolites*) and 14% for the second one (*Zoophycos*).

4. Discussion And Conclusions

The IDIAP represents a novel, easy to use, and inexpensive package of digital imaging methodologies for quantitative estimation of the percentage of discrete trace fossils in core material. The IDIAP allows for quantitative estimation of area occupied by particular ichnotaxa, the whole ichnocoenosis, and even a complete ichnofabric. Each one of the three methods —"Similar Pixel Selection Method (SPSM)", "Magic Wand Method (MWM)" and the "Color Range Selection Method (CRSM)"— shows advantages and disadvantages depending on the sedimentological and ichnological features of the core material, as demonstrated by the analyses conducted on cores from the IODP Expedition 339.

The SPSM was most successful in example B (Fig. 4), where numerous small traces are clearly differentiated from the host material. In cases involving poorly differentiated traces with respect to the host material (e.g., A; Fig. 3), this method proves inconsistent and should not be applied, as it selected a full image. However, this method is the quickest because it is not necessary to define parameters. Hence it is especially appropriate for situations of abundant small discrete traces possessing large differences in pixel color in comparison to the surrounding sediment, making it possible to choose the vast majority of traces at the same time. It would not be the method of choice in situations with minor differences between pixels, because its 'sensitivity' cannot be modified and it would select too many pixels. Furthermore, this method does not allow for adding another selection. For the cores from site 1385 of the IODP Expedition 339, consisting of hemipelagic sediments with scarce differences in pixels between the trace infilling and the surrounding material, this method is inappropriate; In such cases the MWM and the CRSM should be used, because these methods allow the necessary modifications of the sensitivity.

The MWM proves to be an interesting option that allows the selection of each distinct trace fossil by clicking on it. Of course when dealing with small and abundant discrete traces, such as *Chondrites* (example B; Fig. 4), this is cumbersome, however, it is useful when dealing with larger traces like *Thalassinoides* or *Thalassinoides*-like (examples A and C; Figs 3, 5). In case of only a few traces in a given picture, it is a quick method, requiring just one click per trace fossil. The great advantage is that the sensitivity can be modified through 'Tolerance'. This is a useful parameter in the analyzed cores, as differences between pixels are so low that the right selection has to be made by setting the tolerance value very low. The MWM gave the best results in situations with large to medium size trace fossils (more than 5mm) infilled by material similar in color to the host sediment.

The CRSM gave results similar to those obtained with the SPSM. It was most useful for our example B (Fig. 4) to control the sensitivity by using the fuzziness parameter. Given this advantage, we recommend the CRSM for situations where small traces are present whose fills have a sufficient color difference in comparison to the surrounding sediment.

A complete application of the IDIAP is advisable in any case study, each of the three methodologies having its pros and cons. For images with small discrete traces with similar colors, the SPSM and the CRSM would be best as the selection is easily extended to the full image and they are quicker than the MWM. The SPSM, as the quickest of the three methods, does not allow for modification of the sensitivity, so the color of the infilling material of the trace must be clearly distinguished from the background color. If this difference is not sufficient enough, or the traces have no representative color, the CRSM is the best option because more than one pixel can be selected and the sensitivity for the selection made can be controlled. In situations where there are scarce but large-scale traces, or traces with different colors, the MWM is recommended despite being more time-consuming, again depending on the differences in color between the infilling material and the host sediment.

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Figure Captions

Fig. 1. Geographical map showing the west Iberian Margin with location of site site U1385 from the IODP Expedition 339.

Fig. 2. Flow chart showing sequential of processes conforming IDIAP (Ichnological Digital Analysis Image Package) methodology applied to the Expedition 339 core material (see text for explanation). SPSM: Similar Pixel Selection Method, MWM: Magic Wand Method and CRSM: Color Range Selection Method.

Fig. 3. Example A, showing the scarce discrete trace fossils *Thalassinoides*-like (*Th*-l) and *Phycosiphon* (*Phy*), without cross-cutting relationships. From top to bottom; original image without any treatment, "Similar Pixel Selection Method (SPSM)", "Magic Wand Method (MWM)", "Color Range Selection Method (CRSM)", and image showing different colors for the differentiated ichnotaxa.

Fig. 4. Example B, showing two phases of colonization with a comparatively more abundant first generation of trace fossils composed by *Thalassinoides*-like (*Th*-l), *Thalassinoides* (*Th*) and *Planolites* (*Pl*) crosscut by a less abundant second generation consisting of *Chondrites* (*Ch*). Note: Legend as in Figure 3.

Fig. 5. Example C, showing two phases of colonization with a comparatively less abundant first generation of trace fossils composed by *Planolites* (*Pl*) and

Thalassinoides (*Th*), crosscut by a more abundant second generation consisting of *Zoophycos* (*Zo*). Note: Legend as in Figure 3.

Figure1
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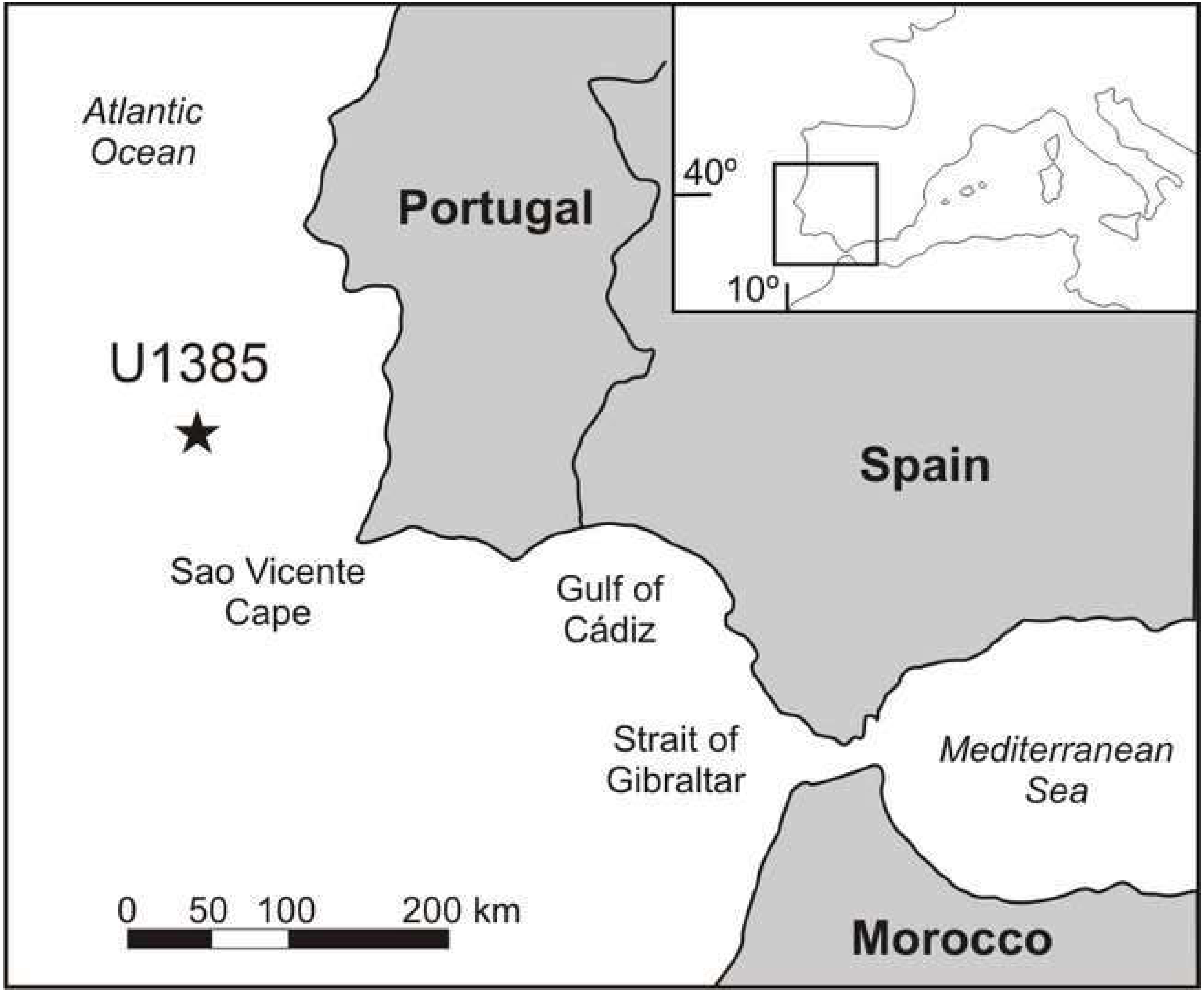

Figure2

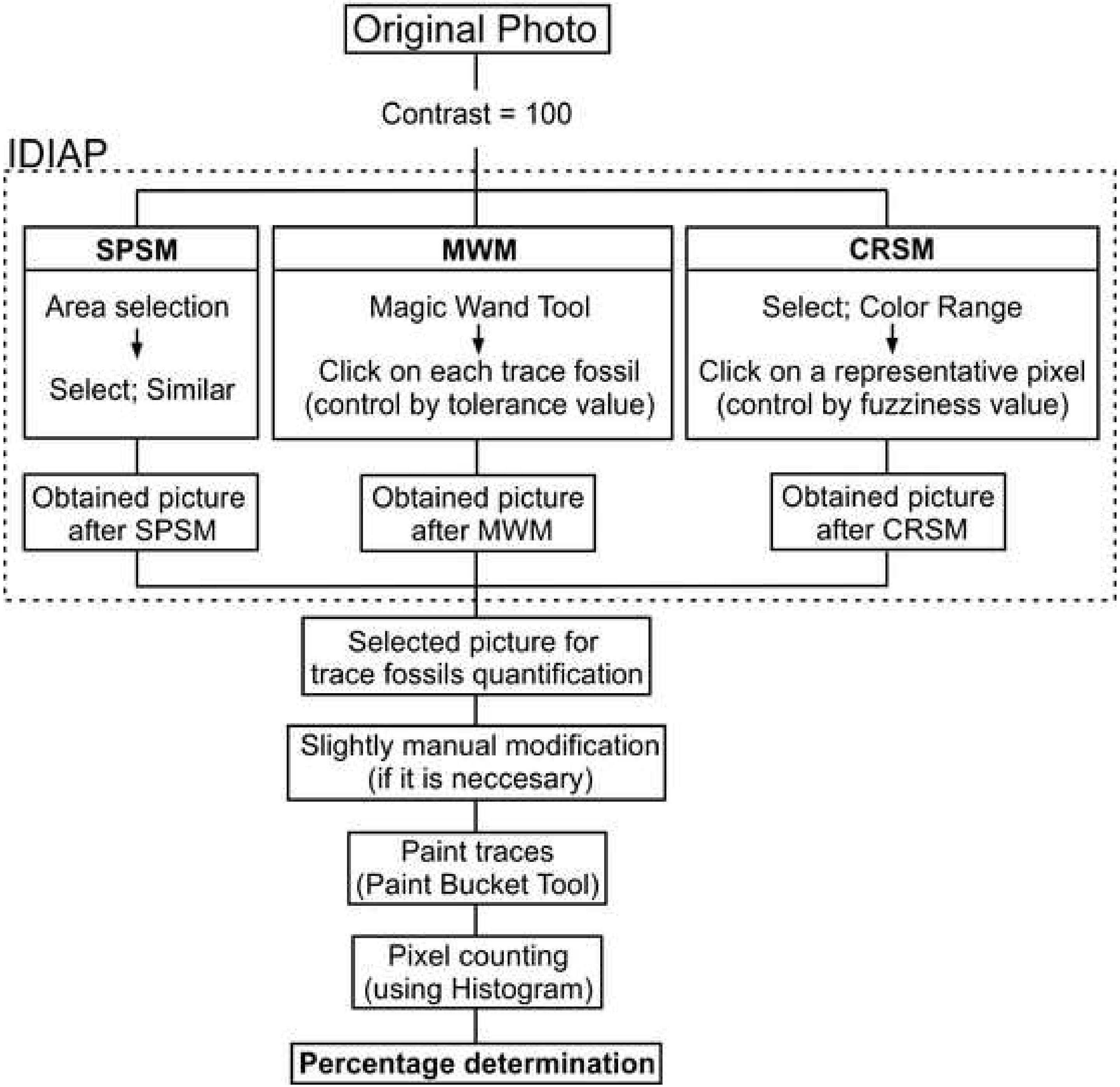
Original Photo
Contrast = 100
IDIAP
SPSM
Area selection
Select; Similar
MWM
Magic Wand Tool
Click on each trace fossil
(control by tolerance value)
CRSM
Select; Color Range
Click on a representative pixel
(control by fuzziness value)
Obtained picture after SPSM
Obtained picture after MWM
Obtained picture after CRSM
Selected picture for trace fossils quantification
Slightly manual modification (if it is neccesary)
Paint traces (Paint Bucket Tool)
Pixel counting (using Histogram)
Percentage determination

Figure3

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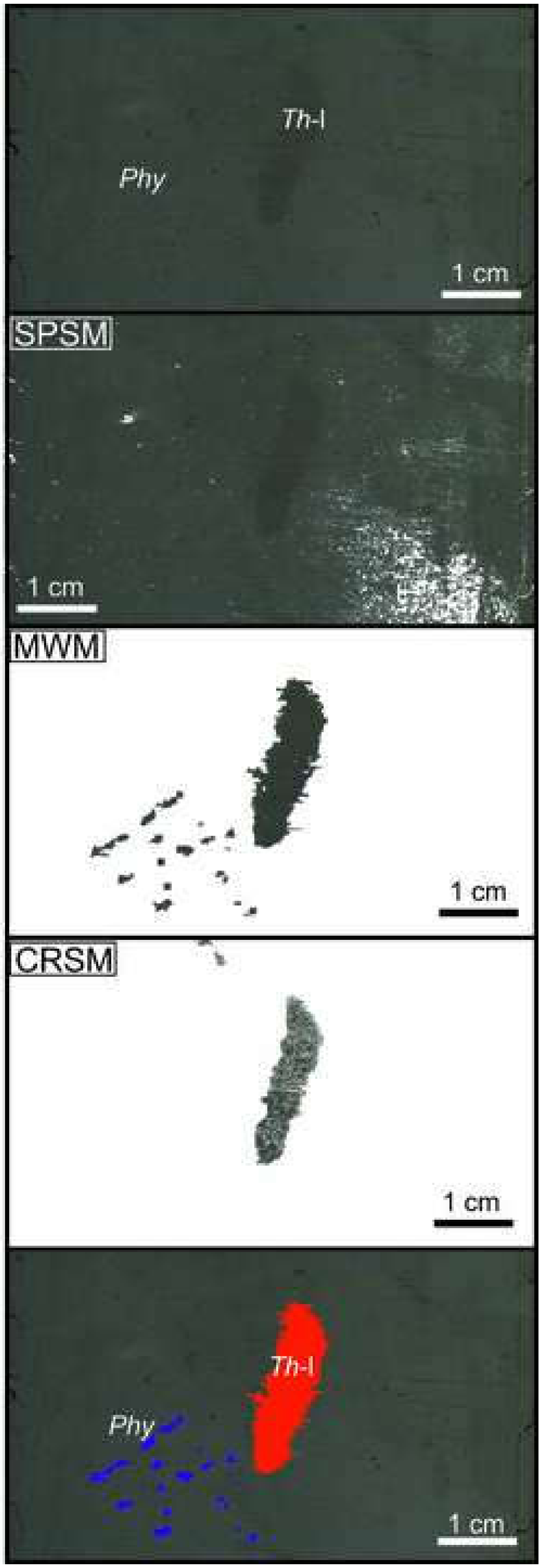

Figure4
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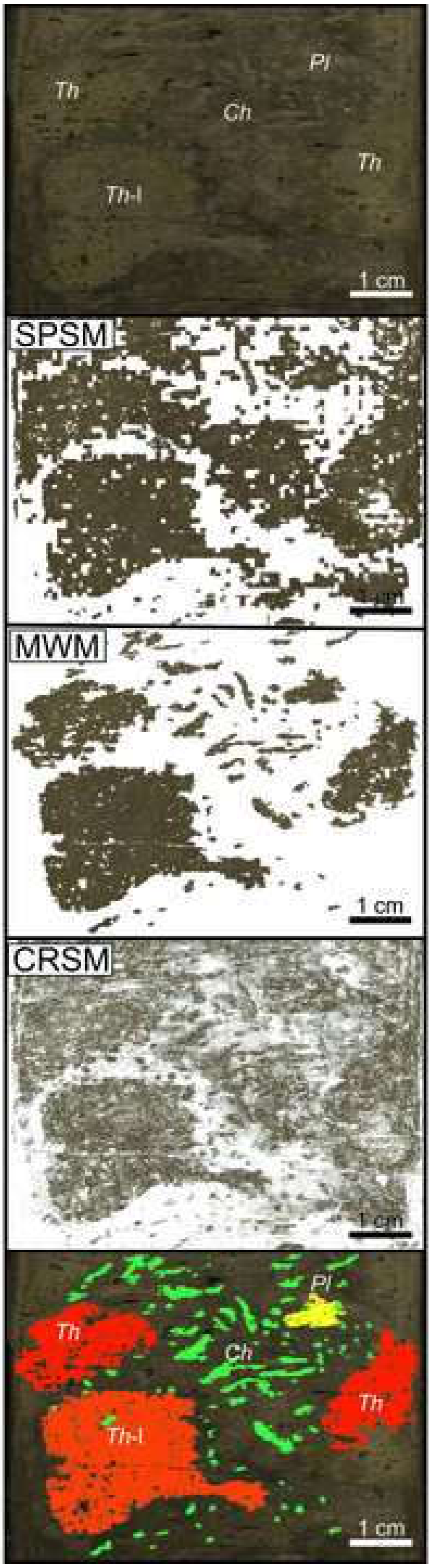

Figure5

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