Spatial analysis of trace fossils for paleogeographic studies

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ABSTRACT

Understanding the spatial distribution of species is a fundamental issue in paleontology. Nevertheless, exhaustive quantitative descriptions of specimen distributions are rare. In this paper, a method is described for systematic acquiring and analyzing images of trace fossils of two species, *Gastrochaenolites lapidicus* and *Gastrochaenolites torpedo,* existing in Foz da Fonte (Sesimbra, Portugal) and investigate their spatial patterns. The procedures of field data acquisition and statistical analysis are described and the presented results are discussed. Emphasis is placed in close-range photogrammetry methods for data acquisition and spatial statistics for data analysis. Goals of the analysis are focused on the statistical description of the fossil species population, the investigation of some spatial relationship among groups of *G.lapidicus* of different dimensions, and finally the investigation of a preferential orientation of the *G.torpedo* population in order to draw paleogeographic/environmental conclusions. Feature extraction is done on the produced orthophotos of the site. The main results of this study revealed that both *G.lapidicus* and *G.torpedo* populations were significantly clustered during life. Furthermore, the preferential cluster location of different diameter classes of *G.lapidicus* on the surveyed block indicates the relative location and orientation of the paleoshore in this site 18 millions years ago.

1. INTRODUCTION

Carbonate hardgrounds are relatively common in the geological record from the Cambrian through the Pleistocene. They are associated with the end of a transgressive cycle, meaning a period during which the coastline moved landwards submerging new areas, before the development of a permanent sedimentary cover (e.g. Voigt 1959). These new submerged shallow bare areas form a distinct set of habitats for boring and encrusting organisms. Bioerosion means the process by which organisms sculpt or penetrate hard substrates (rock, carbonate skeletal material and wood) (Bromley 1970; 1994). The biogenic structures resulting from this process are known as trace fossils or ichnofossils.

From a strictly paleontological point of view, the identification and analysis of bioerosion structures produced by these organisms in hardgrounds is invaluable for the deduction of ecological parameters (Brett 1988) of each particular site to the time the organisms lived. Since bioeroded hardgrounds normally occur near the shoreline, some paleogeographic conclusions for the site can be drawn from the general “behaviour” of the trace fossil population. Gathering the clues for several contemporaneous sites in different geographic locations, palaeontologists interpret an approximate shoreline for the corresponding period in the time scale, which yields an important contribution to earth history.

Like most phenomena in the natural world, the distribution of trace fossils on a hardground is, in general, not homogeneous, exhibiting some kind of spatial pattern. Their distribution in space can provide clues to the geographic conditions existing at the time the borings were being produced.

The present work analyses the hardground of Foz da Fonte, representing a fundamental piece in several studies about the paleoenvironment in this particular region and being applicable to other regions with similar characteristics. It has the advantage over usually applied field counting methods of being supported by reliable, complete and systematic acquired geometric data and their processing by means of appropriated spatial analysis operators.

In this context, the aims of the study are:

- test the general applicability of the photogrammetric method to the palaeoichnological analysis of bioeroded surfaces;
- obtain a general statistical description of the two main bioerosion structures in the hardground (*Gastrochaenolites lapidicus* and *Gastrochaenolites torpedo*) produced by stone boring bivalves (endolithic);
- study the kind of spatial point pattern presented by these two ichnospecies;
- investigate the spatial relationship between large and small *G.lapidicus* specimens;
- investigate the orientation of the *G.torpedo* structures and try to relate it to the paleoenvironment, in particular to the paleoshore.

The project involves the following steps: photogrammetric survey of the whole object in order to obtain a complete coverage of the study region in a common reference system, photogrammetric processing of the images in order to obtain orthophotos, integration of orthophotos in a GIS environment for feature and geometric attributes extraction, and finally spatial analysis of the acquired data to determine some relevant statistical parameters for the study.

2. OBJECT DESCRIPTION

The hardground surface is located on the Atlantic coast of Portugal, 30 km southwest of Lisbon (Fig. 1) at about 10 m height. It was produced over Lower Cretaceous limestones during a transgressive trend (inland progression of the coastline) occurred in this region during the Lower Miocene, around 18 million years ago. It is extensively bored, showing numerous ichnofossils. The most prominent trace fossil found is the bivalve boring *Gastrochaenolites* preserved as concave epireliefs on the hardground surface (Fig.2). Some borings are oriented perpendicular to the bedding plane (*Gastrochaenolites lapidicus*), while others, with larger dimensions, are sub-parallel to it (*Gastrochaenolites torpedo*). The trace fossil assemblage present on the Foz da Fonte corresponds to a very shallow marine rocky substrate environment with a negligible sedimentation rate.

The surface to survey consists of four distinct blocks in SW-NE orientation (Fig. 1). The first three blocks are nearly horizontal and the fourth block has a slope of 13º.

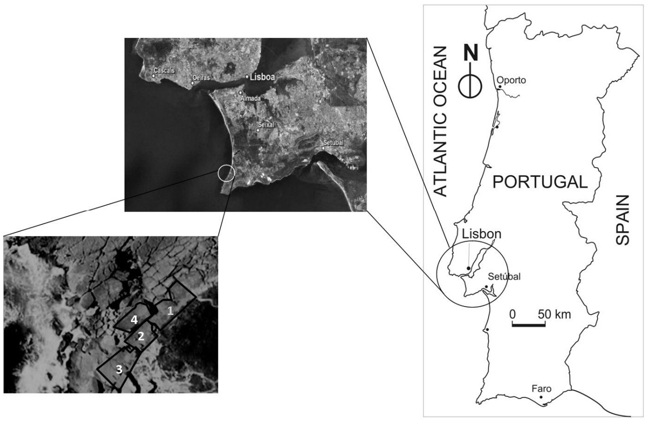

Figure 1: Study area and disposition of the blocks (bottom left)

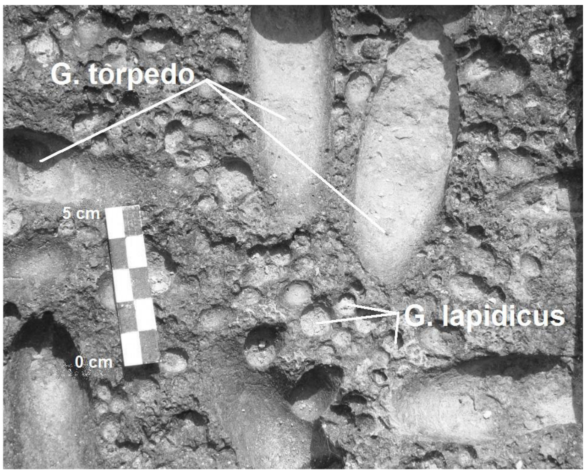

Figure 2: Ichnofossils as they show in the field

3. IMAGE ACQUISITION

Due to the rectangular configuration and dimension of the surface to survey, approximately 36 m length and 7 m width, and due to the disseminated distribution of the fossils all over the surface it was decided to make a systematic photogrammetric coverage on each block by rows of vertical stereoscopic pairs. A common spatial reference for the blocks was materialized on the surface by signalized ground control points (GCP).

In order to obtain vertical photos, with an appropriate scale to survey the trace fossils, an aluminum structure with two perpendicular segments as shown in figure 3 was built. The camera was fixed at the end of the horizontal rod by means of an adaptor in order to maintain the camera axis in a near vertical position. With this portable structure, the camera objective was about 1.85 m over the ground in operational conditions.

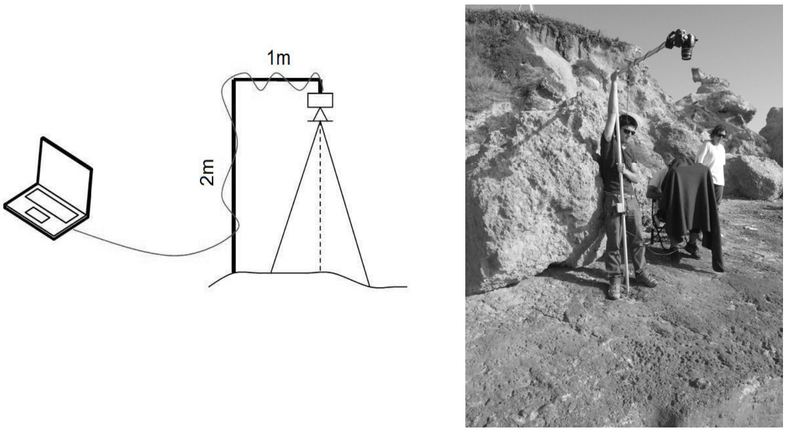

Figure 3: Camera holding structure with connection to laptop and field darkroom

The camera used was a digital Canon EOS 450D with 12 megapixel of resolution with an 18 – 55 mm objective. The focal distance was fixed in a position without zoom, marked by an index on the objective ring, corresponding to ~18 mm. Auto-focus was disabled and the camera was set under remote control through an USB connection with a laptop using the EOS Utility software. The use of a dark blanket over the laptop to create a pseudo darkroom avoided the operator to be disturbed by sun light while analyzing the image quality (Fig. 3).

A set of 31 artificial marks has been distributed over the four blocks in order to serve as GCPs. A local North oriented reference system was established and materialized through two main stations. All the marks were coordinated by a radial traverse using a total station Leica TC4700.

The camera has been calibrated using the LICAL routine (MapTEC, 2007) of the LISA® software for the focal length set in the field survey. For orthophoto generation a set of resolution reduced images has been used with a pixel dimension of 15µm (~ 1.5mm at the object), still smaller than the smallest fossil to be evaluated, resulting in an acceptable compromise between resolution and software capacity.

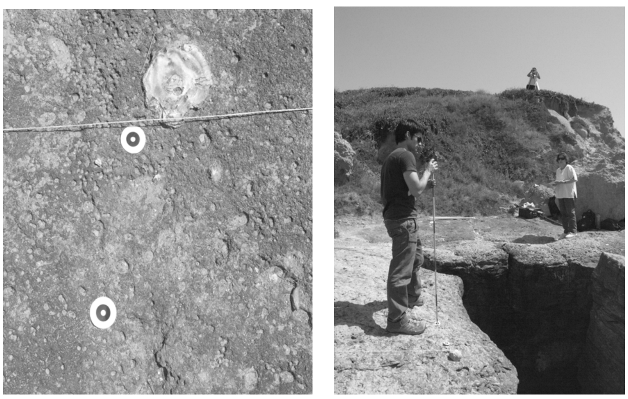

Figure 4: GCP marks (left) and measuring (right)

The 4 blocks were covered independently with sets of parallel strips of vertical photos with 60% overlap and 20% side lap in a similar design of a photogrammetric flight plan. A 90 cm long base has been kept along the strips. The longer side of the photos was parallel to the strip axis. Eighty-eight photos in eight parallel strips covered Blocks 1, 2 and 4. Block 3 is to be surveyed after the submission of the present paper.

4. PHOTOGRAMMETRIC PROCESSING

The photogrammetric processing of each block is being done independently although a final spatial analysis will consider all the blocks as a unit (a hardground unit). The whole process was performed using the LISA software (Linder 2003). In the following, the results for Block 2 will be presented as an example of what can be achieved for the other blocks in the same way.

The triangulation of Block 2 for the determination of the exterior orientation of the photos succeeded with a σ_0 of 17 µm, approximately the pixel dimension. The resulting Root Mean Square Error values on the control points were about 1 cm in X ,Y and 5 cm in height. These results are acceptable for the kind of analysis to pursue, where the priority lies in the relative rather than in the absolute position of the trace fossils and the height component is not relevant.

A digital surface model (DSM) was produced for each stereo model independently by means of image correlation and spatial intersection. The mosaic of all DSMs (Fig. 5 left) shows a height amplitude of about 60 cm, the block surface is generally smooth and has a quite homogeneous slope perpendicular to its longer axis.

Although the height amplitude along the block is not insignificant, the height distribution of the objects is irrelevant for this study. Therefore, it was decided to produce an orthophoto of the whole block for a later monoscopic feature extraction instead of a stereoscopic one. The previously produced DSM was used in the generation of the orthophoto (Fig. 5 right). This presents a pixel dimension on the ground of 1.5 mm and an estimated planimetric accuracy of ± 1 cm.

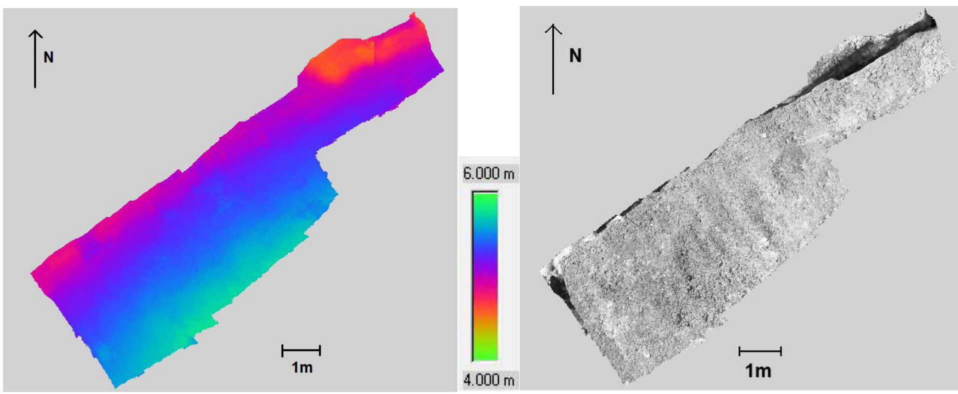

Figure 5: DSM (left) and orthophoto (right) of Block 2. (Height color scale refers to local reference)

5. FEATURE EXTRACTION

In order to perform a systematic extraction of the most significant trace fossils existing on the block surface, together with their main geometric characteristics, the orthophoto was imported into a GIS. For the extraction operation the block was divided in regular tiles and every visible and identifiable fossil of the two types was interactively acquired (Fig.6). Attributes recorded for each type of trace fossils are shown in Table 1. The class *G.lapidicus* counted a total of 3208 elements while 603 elements of the class *G.torpedo* were extracted. Figure 7 shows the complete sets of extracted features.

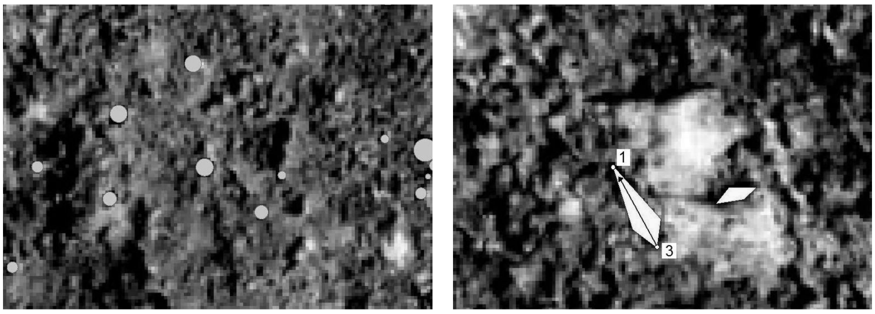

Figure 6: Examples of extracted features : *Gastrochaenolites lapidicus* (left) and *G.torpedo* (right). Arrow indicates mouth direction.

Table 1: Attributes to extract

Object	Centroid X,Y	Diameter	Max. length	Max. width	Orientation
G.lapidicus	X	X			
G.torpedo	X		X	X	X

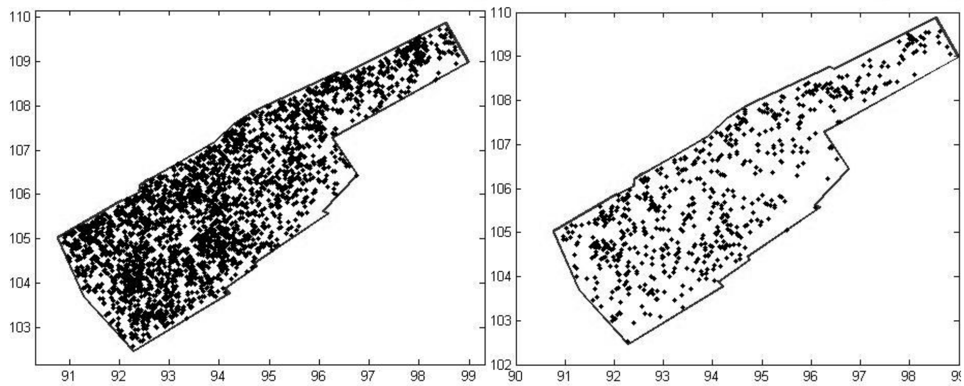

Figure 7: Maps of complete sets of extracted *G.lapidicus* (left) and *G.torpedo* (right) in Block 2. (Axes in meters)

6. SPATIAL ANALYSIS

The distribution of the trace fossils in Foz da Fonte can be seen as a spatial point pattern (Diggle 1983). To describe the spatial pattern of the fossil structures, the kernel density estimation was used. Other than the representation in figure 7, the obtained density maps (Fig. 8) clearly reveal several zones with a higher concentration of *G.lapidicus* or *G.torpedo*. This clustering tendency was confirmed through the nearest-neighbor method applied to both populations. A set of 9999 simulations was performed in order to test the observed average nearest-neighbor-distance against the CSR hypothesis (Cressie 1993) (Fig. 9). The small p-values indicated in Table 2 corroborate a clustering tendency of both populations.

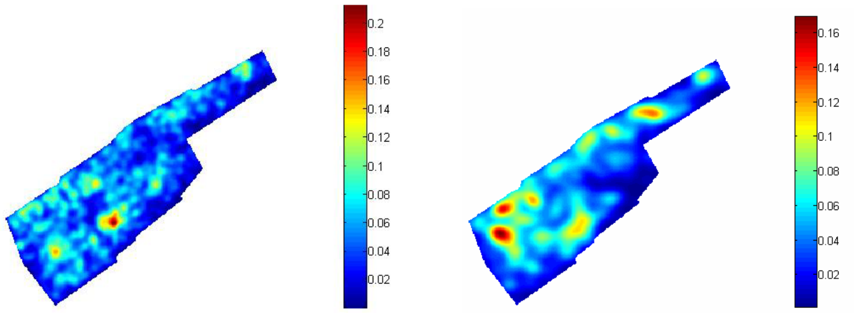

Figure 8: Kernel density estimation for *G.lapidicus* (left) and *G.torpedo* (right). Scale indicates number of specimens per square centimeter

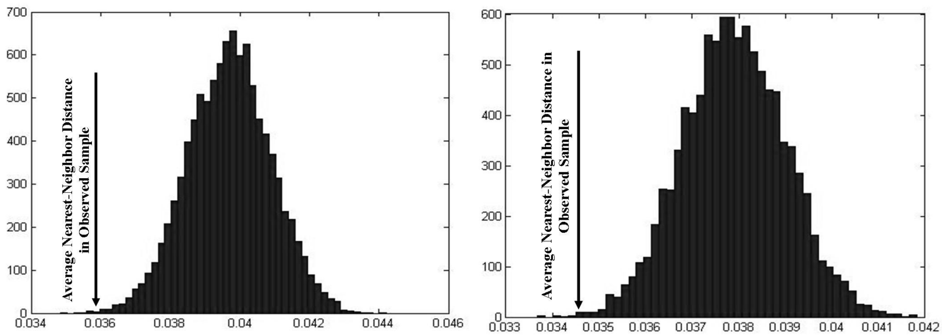

Figure 9: Histogram of the 9999 simulated average nearest-neighbor distances for *G.lapidus* (left), sample size 3208, and *G.torpedo* (right), sample size 603. The vertical bars indicate the number of simulated samples with the average nearest-neighbor distances (in meters) in the x-axis

Table 2: Statistics for the test of nearest-neighbor-distance (NND) against CSR

Population	Observed Average NND [cm]	Expected NND under CSR [cm]	p-value
G.lapidicus	3.57	3.97	0.0008
G.torpedo	3.45	3.79	0.0009

Since the diameter of the boring has a direct relation with the development stage of the living *G.lapidicus* bivalve, there was a paleontological interest to evaluate the spatial disposition of the larger and smaller specimens independently. Therefore, the *G.lapidicus* population was stratified in three classes of different diameter: < 7 mm, 7 - 10 mm, > 10 mm. All these classes show a tendency for clustering formation but at different locations in the surface (Fig. 10).

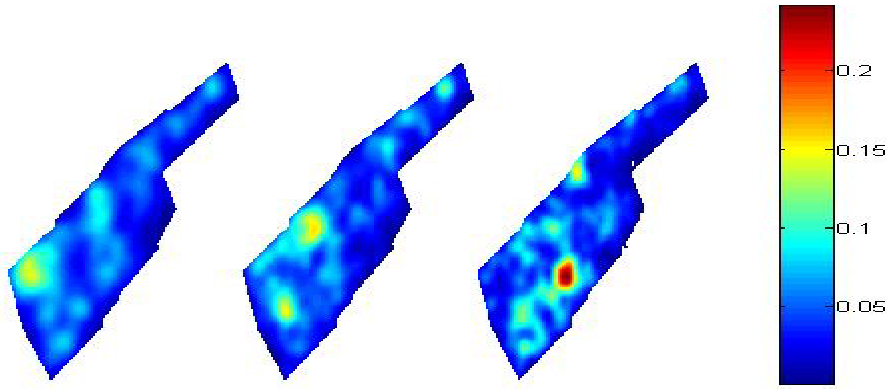

Figure 10: Intensity maps of *G.lapidicus* diameter classes. From left to right: large, regular and small specimens. Scale indicates number of specimens per square centimeter

The orientations of *G.torpedo* specimens' longest axis can be an important paleoenvironmental indicator. Therefore it was necessary to investigate whether the sample showed a preferential azimuth. Figure 12 shows a distribution of the sample azimuths classified over twenty classes. It is evident that the observed directions show a strong concentration between 0° and 36° and between 180° and 216°.

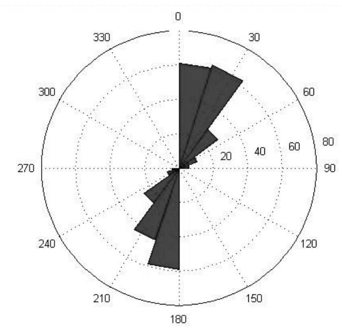

Figure 12: Rose diagram of the *G.torpedo* directions.

7. DISCUSSION AND CONCLUSIONS

Photogrammetric methods revealed to be strategic and quite useful for the study of rocky paleoshores with high density of bioerosion, allowing a complete coverage of the object and a systematic data acquisition of the bioeroded structures. However, dense occupation of the rock surface and low image contrast of some sectors made it difficult to automate every single step.

The main results of the undertaken spatial analysis showed a clear clustering tendency for both species. The same tendency appears as well in every *G.lapidicus* diameter class considered in this study. The rose diagram of all measured orientations shows two preferential azimuth sectors in opposite senses of a mean direction (~NNE-SSW).

Several preliminary paleogeographic considerations can be deduced from this spatial behavior:

- The clustered spatial distribution of the larger (older) and smaller (younger) individuals presumably indicates a preferential colonization by the larvae which may be related to small scale variations on current patterns, food availability and/or substrate hardness;
- Clusters of larger *G.lapidicus* tend to occur more or less aligned along the SW-NE direction as well as clusters of the smaller ones although in a nearly parallel alignment, reinforcing the assumption that this direction was the paleoshore orientation;
- The northwestward band of the rock surface is mostly occupied by clusters of older *G.lapidicus*. This pattern is compatible to successive colonization phases of the hardground following the Lower Miocene transgression (Santos et al. in press) responsible for the deposition of the marine sedimentary sequence that overlays this rock surface. The coastline progressed landwards (towards SE) locally increasing the water depth. This trend would have allowed colonization to progress towards SE to newly available submerged rock substrate.
- Being suspensivorous, the producers tend to orientate themselves according to the prevailing currents. This phenomenon has been described by Crame & Luther (1997) for the inoceramid bivalves from the Upper Cretaceous-Lower Tertiary in Antarctica. Here the bivalves aligned with their longer axis predominantly parallel to the prevailing water currents (positive rheotaxis).
  In shallow marine environments, however, *G.torpedo* is interpreted to have its longer axis normal to the wave direction, thus being favored by both high hydrodynamics and coastal drift currents but, at the same time, minimizing damage by thrown rolling pebbles. This would also justify the absence of a preference for one specific (unimodal) direction. Their bimodal trend would indicate no preference other than being perpendicular to the swell direction. Therefore, the results indicate that prevailing swell affecting the analyzed sector of the paleo-rocky shore would have a WNW-ESE direction (Fig. 13). From the present data it can be concluded that the Lower Miocene paleo-coastline had the same general orientation as the present day coastline of Setubal Peninsula at Foz da Fonte. However, the prevailing swell 18 million years ago had its direction rotated around 25º counterclockwise relative to present day conditions[1].

Future work concerning the spatial analysis will focus on the integration of data from contiguous blocks of the bioeroded surface and in the application of the lattice data models in order to incorporate correlation measurements and topological relations. Efforts are also being done towards automation especially on what concerns *G.torpedo* extraction through image processing and classification algorithms.

[1] See http://www.puertos.es/externo/clima/BD/PpalOleaje.html

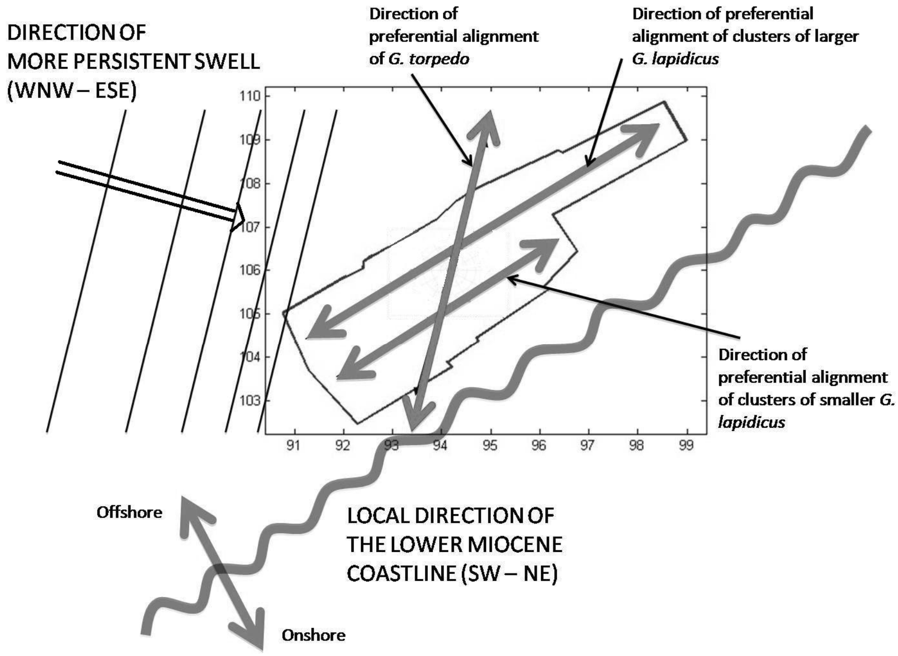

Figure 13: Paleogeographic conclusions of the study for Foz da Fonte site

ACKNOWLEDGEMENTS

A.Santos was supported by a Juan-de-la-Cierva contract (Ref:JCI-2008-2431). Junta-de-Andalucía (Spanish government) supported the Research Group RNM316. C.Freitas contributed to the discussion of results. M.Cachão's contribution was supported by the project FCT PTDC7MAR/102800/2008. FCUL technician Mr. Machado is also acknowledged for conceiving and producing the prototype for the digital camera field support.

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