Geographic Information Systems for ichnofabric analysis: modelling a modern lagoon (Grado, Italy) with the IchnoGIS method

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Introduction

The Grado-Marano lagoon is one of the major transitional systems of the Adriatic Sea, consisting of a barrier island system extended for over 30 km (Turri, 1999; Baucon, 2008a). Characterized by significant biodiversity and heterogeneous environments, this area provides optimal conditions to assess the ichnologic and sedimentary features of siliciclastic, marginal-marine settings.

The complex relationships that exist among ichnological, physical, and environmental proprieties require advanced, integrated analysis techniques to visualize spatial patterns and determine the factors controlling trace distribution. For these reasons, a new method for quantitative ichnosedimentological analysis (IchnoGIS) has been developed.

The goal of this work is to discuss a quantitative ichnological model of the external margin of the Grado lagoon and test the application of the IchnoGIS method for ichnofabric analysis.

Geographical and geological setting

The study area (Fig.1) is located on the external margin of the Grado basin, between Grado town and the locality Pineta. Tides, which are the main driving forces of the lagoon hydrodynamics, created a composite mosaic of marginal marine environments, among which vast siliciclastic intertidal flats. A very peculiar environment is represented by microbial-related settings: large sections of the tidal flat are colonized by microbial mats, which are presenting a diverse ichnofauna, preliminary described by Baucon (2008a) and discussed in this study.

Method and approach

Similarly to a geographic information system, the proposed approach integrates hardware, software, and data for capturing, managing, analyzing, and displaying geographically referenced ichnological data. For this reason, the method has been named 'IchnoGIS'. Its development derived from previous work on the application of GPS and GIS techniques to neoichnology (Baucon, 2008a, b). IchnoGIS is an orderly procedure consisting of 6 steps:

a. Survey design: The starting point is defining the objects of interest and the sampling size.

b. Sampling: If we want to know how traces are distributed in a particular habitat, it is usually impossible to count each and every one present. For this reason, the second step of IchnoGIS is based on quadrant sampling, a method widely used in the interpretation of large ecological data sets with environmental gradients (McIntyre & Eleftheriou, 2005). It consists of characterizing ichnological, sedimentological, environmental attributes (i.e. number of *Arenicolites*, grain size, salinity) contained in a square frame (in this study: 0.25 m^2; Fig.2).

c. Significance test: In the simplest case, the result of the sampling process is a spreadsheet including X Y coordinates, facies type and abundance of each structure (Fig. 3). For this reason, nearest neighbour analysis (Borradaile, 2003) is an efficient method to assess the sampling quality.

Figure 1. Study area. Modified from Baucon (2008a).

d. Descriptive statistics. One of the primary goals is to describe the influence of the sedimentological features on the numbers and types of traces. This aim can be achieved by cross-tabulating frequency counts of ichnotaxa respect to facies. Another possibility is to provide a measure of central tendency and/or distribution.

e. Ichnoassemblage analysis. Ichnoassemblages are verified by cross tabulating the abundance of a trace in relation to that of another trace.

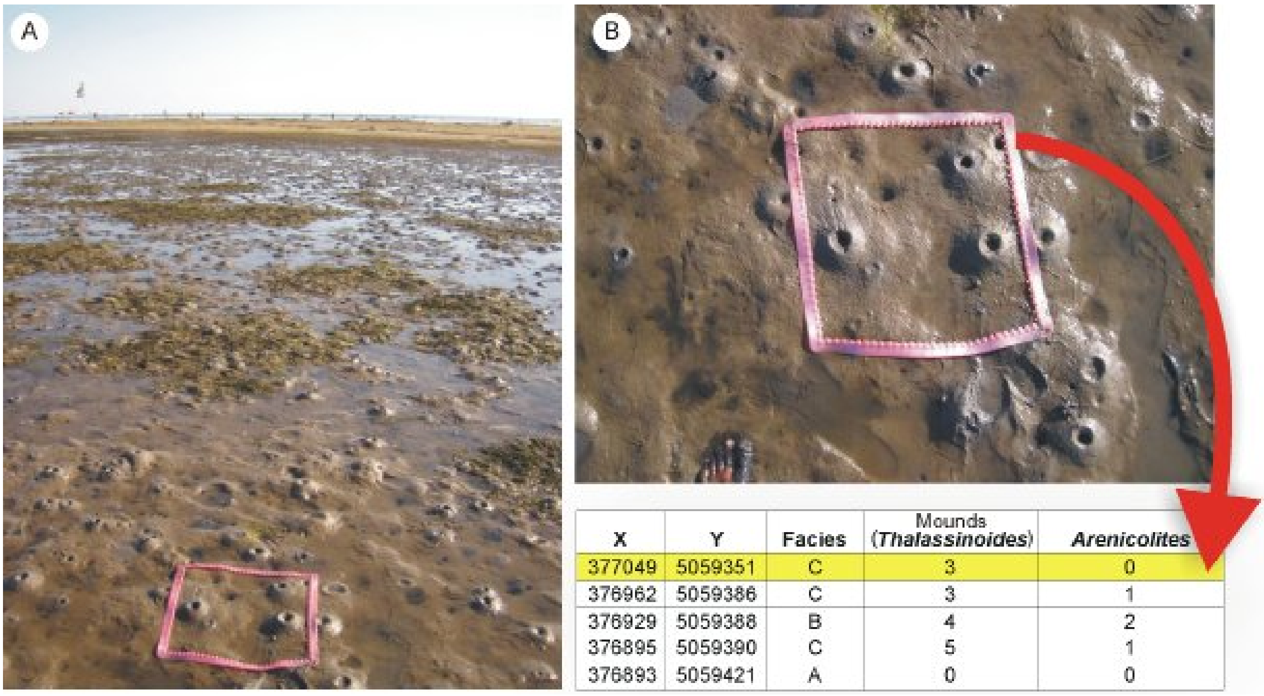
f. Spatial analysis. Spatial analysis is performed through (a) classed post maps, and (b) geostatistical interpolation techniques (i.e. Figs.4B,5B). Classed post maps are simpler to implement, but interpolation can estimate the value of a variable (facies type, number of traces) in unsampled positions, delivering accurate ichnosedimentary maps.

It appears manifest that IchnoGIS emphasizes the recognizement of distinct structures on the sediment surface. This is apparently in contrast with the ichnofabric approach, whose application is usually related to vertical rock slabs/core samples. However, the approach of this study aims to integrate these philosophies by complementing ichnofabric analysis with the quantitative study of discrete ichnofabric-forming ichnotaxa.

Ichnofabrics

The studied area comprises six ichnofabrics, which are named for their most representative ichnotaxa. Some structures presents doubtful affinities with existing ichnogenera, therefore the corresponding ichnofabrics are named for their producer.

- ***Arenicolites*** **(large type) ichnofabric:** This ichnofabric mainly occurs within medium- to fine-grained sands with abundant ripple marks (facies B in Figs.4,5). The ichnofabric is characterized by large U-shaped burrows (*Arenicolites*) penetrating for 20-40 cm into the substrate. *Thalassinoides* and *Siphonichnus* can be present, although in rare clusters. Intensity of bioturbation is variable, usually low (BI 1-2).



X	Y	Facies	Mounds (*Thalassinoides*)	*Arenicolites*
377049	5059351	C	3	0
376962	5059386	C	3	1
376929	5059388	B	4	2
376895	5059390	C	5	1
376893	5059421	A	0	0

Figure 2. Quadrat sampling in IchnoGIS. Frame area: 0.25m^2. **(A)** Overview of the tidal flat with the sampling frame (quadrat). **(B)** Spatial, sedimentological and ichnological attributes are collected for each sampling site and stored in a spreadsheet.

- ***Thalassinoides-Arenicolites* (small type) ichnofabric:** This ichnofabric is commonly associated to sandy muds (facies C in Figs.4,5). The predominant component of this ichnofabric is *Thalassinoides*, at times associated to small *Arenicolites* (penetration depth: 5-8 cm; Fig.3A). The degree of bioturbation is moderate to high (BI 3-6).
- ***Thalassinoides* ichnofabric:** This ichnofabric consists of monotypic *Thalassinoides*-dominated firmgrounds (facies F, Figs.4,5). The degree of bioturbation is low to moderate (BI 1-3).
- **'Insect burrows' ichnofabric:** This ichnofabric is present within microbial-bound deposits, consisting of laminated sands with an upper, organic-rich layer and a lower mineral-rich one (facies E, Figs.4,5). The ichnoassemblage is dominated by vertical clavate burrows (Fig.3B) and horizontal unbranched burrows, respectively produced by coleopterans and larvae of Diptera. Small *Arenicolites* can be present. Intensity of bioturbation is generally low (BI 1-2).
- ***Macanopsis-Arenicolites* (small type) ichnofabric:** This ichnofabric occurs in sandy muds colonized by filamentous algal turf (facies D). The ichnoassemblage is dominated by crab traces, consisting of gently bending unbranched burrows with a circular-to-oval cross (*Macanopsis*). Crab burrows are often accompanied by small *Arenicolites.* Intensity of bioturbation is generally high (BI 3-6).
- **Unbioturbated deposits:** Sands with indisturbed lamination are common in the study area (i.e. facies A, Figs.4,5). Intensity of bioturbation is low (BI 0).

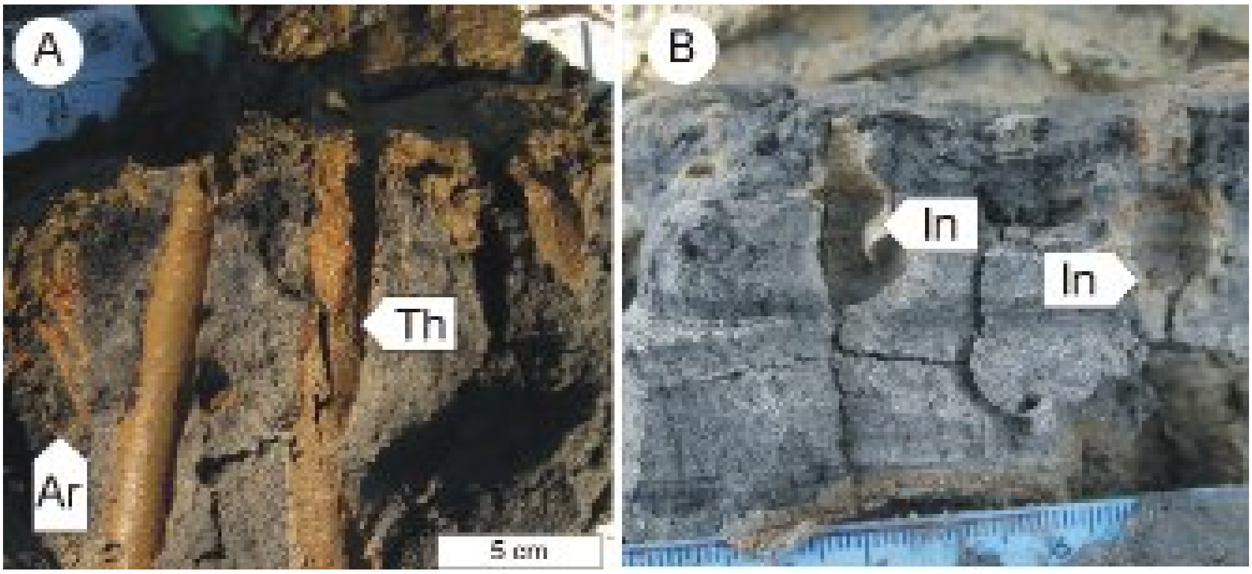


Figure 3. Ichnofabrics from the Grado lagoon. **(A)** *Thalassinoides* (Th)-*Arenicolites* (Ar) ichnofabric. **(B)** 'Insect burrows' (In) ichnofabric.

Data analysis

This section presents the results of the IchnoGIS method.

- **Callianassid mounds and openings.** Callianassid shrimps are responsible for producing *Thalassinoides* burrow systems, whose surface expression is represented by sediment mounds and characteristic funnel-like openings. When abundant, they are responsible for the *Thalassinoides–Arenicolites* and *Thalassinoides* ichnofabrics. IchnoGIS revealed two peculiar trends in their distribution:
- **Distance from the coastline.** These structures are absent in the upper (landward) foreshore. This phenomenon is probably linked to prolonged subaerial exposure during low tide, which is a stressful condition for the *Thalassinoides* producers (Fig.4B).
- **Facies-dependent distribution.** Such structures are restricted in sedimentological range, being more abundant in protected conditions with disposability of organic material. However, they can be also associated to firmgrounds (Fig.5A).
- **Large *Arenicolites*.** High numbers of *Arenicolites* are mainly related to sandy sediments (Fig.5B) with moderate to low exposure times. Such conditions correspond to the *Arenicolites* ichnofabric.
- ***Macanopsis*.** From the ichnologic characterization of sedimentary facies (Fig.5A), it emerges a clear facies-related distribution of crab traces (*Macanopsis*). Crab burrows are present specifically within the algal turf zone.

Discussion and conclusions

Ichnofabric analysis, integrated with the IchnoGIS approach, revealed four main environmental controls: exposure time, hydrodynamism, sediment binding (algal or microbial) and firmness. Environmental significance of each ichnofabric is shown in Fig.6. It should be noted that the application of quadrant sampling alone would not cover all the ichnofabric-forming ichnogenera (i.e. insect traces). Hence the necessity of complementing the quadrant sampling approach with observations of vertical sections or, more accurately, with quantitative measurements in section. One possible technique could be quantifying burrow type and abundance within sections of a given area. As Gingras *et al.* (2011) argued, the models we have for animal-sediment relations are largely based on neoichnological studies of the 1950s, 1960s and 1970s. For higher-resolution models, new studies on modern environments are required. The IchnoGIS method could contribute to solve these issues by producing realistic models of trace distribution in modern environments that are immediately comparable with examples from the fossil record.

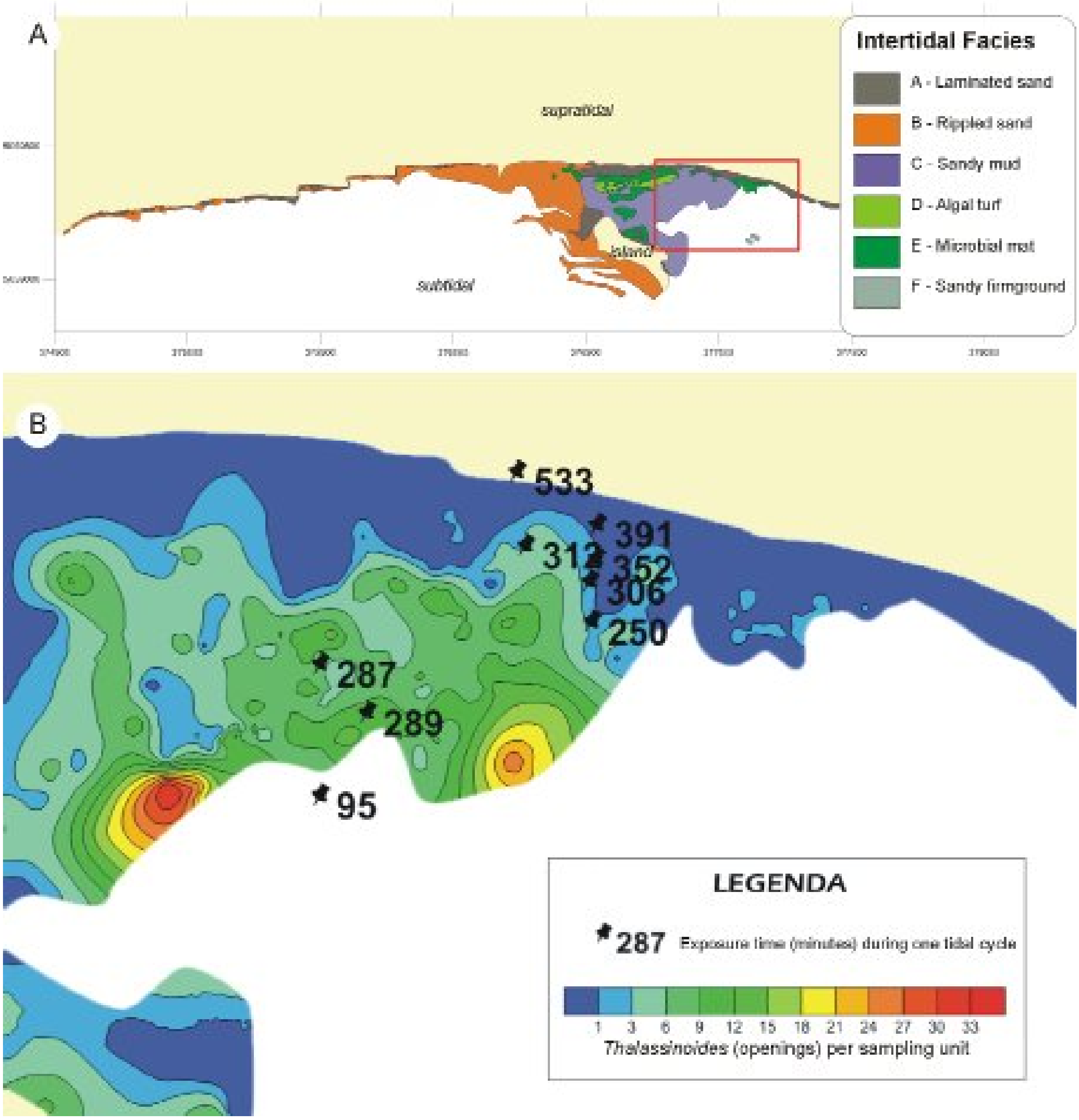


Figure 4. Spatial analysis. **(A)** Facies map, derived from the information gathered during quadrant sampling. Coordinates in metres (Datum: WGS84). **(B)** Exposure time controls the abundance of *Thalassinoides.* Area corresponds to the rectangle in A.

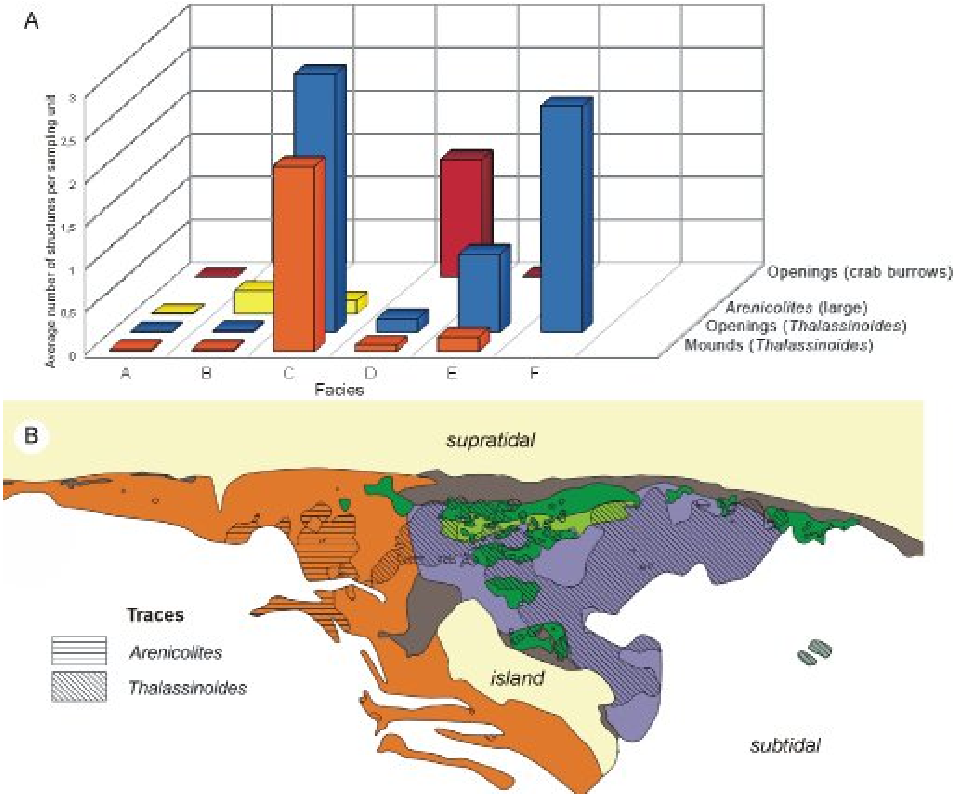


Figure 5. Traces and facies. **(A)** Ichnologic characterization of sedimentary facies. Facies codes refer to Fig.4. **(B)** Interpolated distribution of *Arenicolites* (large) and *Thalassinoides* (openings) stacked on facies map. The dashed areas correspond to *Arenicolites*≥1 per sampling unit; the same is valid for *Thalassinoides.*

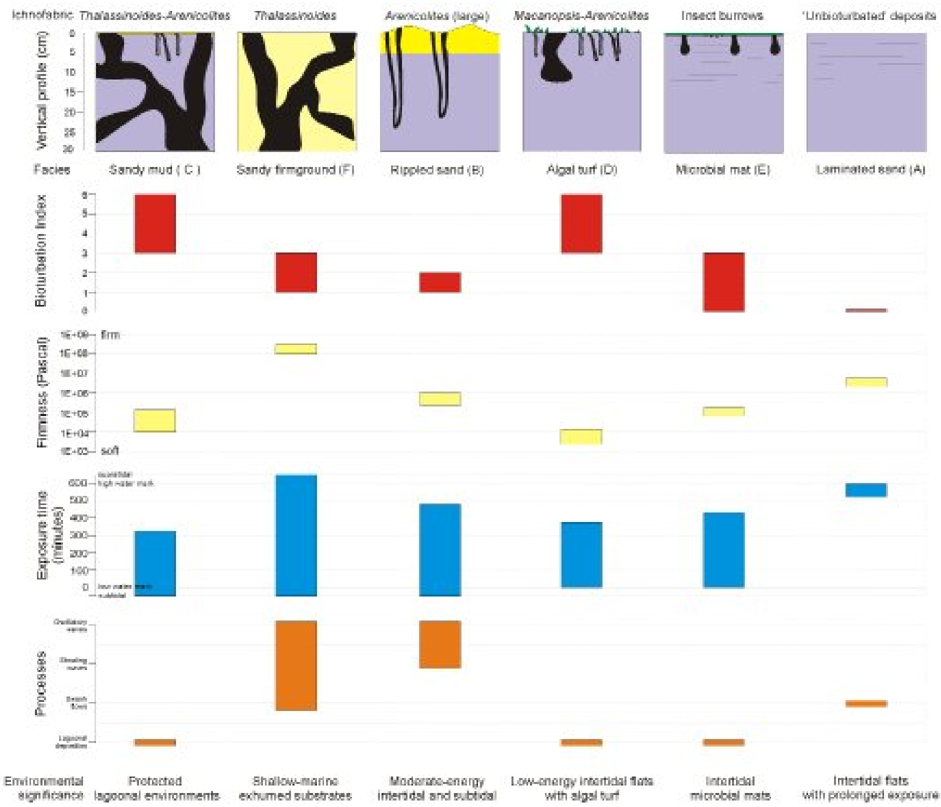


Figure 6. Environmental significance of the studied ichnofabrics. Firmness measured with the modified Brinnell test (Gingras & Pemberton, 2000); main processes derived from field observations and examination of the main geomorphic features (island, shoreline) in Fig.4A.

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