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Automated detection of sedimentary features using wavelet analysis and neural networks on single beam echosounder data: A case study from the Venice Lagoon, Italy

Fantina Madricardo [a,*], Jarosław Tęgowski [b], Sandra Donnici [a]

[a] Istituto di Scienze Marine, Consiglio Nazionale delle Ricerche, Arsenale – Tesa 104, Castello 2737/F, 30122 Venezia, Italy
[b] Institute of Oceanography, University of Gdansk, al. Marszalka Pilsudskiego 46, 81-378 Gdynia, Poland

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ABSTRACT

Acoustic methods are well established and widely used for the exploration of the seafloor and the sub-bottom sediments. However, the mapping and reconstruction of the sedimentary features revealed by acoustics can require a very long time because often large acoustic datasets need to be described and interpreted. To reduce the time of the geophysical visual interpretation, we implemented a new procedure for facies classification based on wavelet analysis and neural networks applied to the acoustic profiles. The optimized algorithm applied to a data set of the very shallow Lagoon of Venice classifies automatically the echo shape parameters to identify and map the main lagoon sedimentary features, such as palaeochannels and palaeosurfaces. The classification algorithm contains a set of wavelet transformation parameters as inputs to a neural network analysis based on the self-organizing map (SOM). The analysis was applied on 580 km of acoustic profiles acquired in a very shallow (less than 1 m) and turbid area of the lagoon with a sub-bottom penetration of about 6–7 m under the bottom. Without any special pre-requirement on the data, the algorithm was successfully tested against the results of the visual interpretation and allowed an automated and more efficient full 2D mapping of the sedimentary features of the area. We could distinguish and map different types of palaeochannels, buried creeks, palaeosurfaces as well as areas characterized by homogeneous mudflat facies. The results were validated by comparison with 5 cores sampled in the survey area corresponding with the main sedimentary features revealed by the acoustics.

1. Introduction

For many decades different acoustic methods have been used worldwide for seafloor mapping and for sedimentary features reconstruction (e.g., Mitchum et al., 1977; Mitchum and Vail, 1977; Veeken, 2007; Lurton, 2010). In general, acoustic methods either utilize the envelopes of relatively high frequency (from kHz to MHz) echo signals, or they are based on the processing of full low frequency (from of Hz to kHz) signals and commonly known as seismic methods. Thus, the differences in acoustic/seismic signal characteristics require different processing procedures. With the help of the acoustic/seismic sections, the local sediment properties defined through core sampling can be extended allowing a 2D and in some cases a 3D reconstruction of the sub-bottom content. Only recently have acoustic and seismic methods been applied to very shallow environments such as lagoons, (pro)deltas and estuaries (e.g., Missiaen et al., 2005; Caiti et al., 2006; Foote, 2008). These very shallow water environments are among the most dynamic coastal zones and they represent a stratigraphic archive of short-term environmental changes and human activity. These environments are still largely under-exploited because their exploration often represents a serious technological challenge for both navigation and instrumental issues. Moreover, the very shallow water, the presence of biogenic gas in the soft sediments and of algae on the bottom can often cause strong multiple effects.

In general, the sedimentary record of very shallow water environments is the complex result of flood deposits, channel migrations and local erosion/sedimentation processes and it requires detailed imaging and sediment characterization. Therefore, for very high resolution sub-bottom reconstructions, there is a need of a dense grid of acoustic/seismic survey lines. As a consequence, the surveys often give rise to very large datasets that need to be interpreted and described. This process of interpretation and the collection of the information in a Geographic Information System (GIS) is generally very labor intensive

* Corresponding author. Tel.: +39 041 2407986; fax: +39 041 2407940.
E-mail address: fantina.madricardo@ismar.cnr.it (F. Madricardo).

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and time consuming. It is often difficult to have a clear map of the sedimentary features on the same days as the survey, and the data elaboration is mostly postponed until a post-processing after the end of the survey. To overcome these problems there is a need of automated procedures to reduce the processing time of seismic/acoustic data.

During the last thirty years, different automated classification systems have been developed to study bottom surface sediments or to characterize hydrocarbon reservoirs. These systems are based on the analysis of single beam, multi beam echosounder or sidescan sonar data (e.g., Anderson et al., 2007), of 3D seismic data (e.g., Coléou et al., 2003), of chirp or 3D chirp sub-bottom profiler (e.g., Plets et al., 2007, 2008). However, despite the rapid progress in underwater-measurement technology, single beam echosounders (SBES) are easy and relatively cheap to implement in extremely shallow water (less than 1 m) environments. In particular, a high frequency (30 kHz) SBES with a relatively short pulse and low energy was suitable for acoustically soft, e.g., muddy sediments of the lagoon of Venice while it does not penetrate hard, sandy sediments. In our case, it allowed the exploration of the first few meters of the subbottom that contain the information about the lagoon evolution. The use of other systems with lower frequency like a chirp sub-bottom profiler or a boomer would ensure a better penetration. Long and high energy signals, though, in such a shallow environment would produce multiple reflections of the bottom with a consequent loss of information from the first meters of sediment. Moreover, the classification systems based on the analysis of SBES data are still the most accurate and extensively developed. Among the numerous approaches to signal processing for sediment classification, the most widely adopted are the following two. The first approach extracts the different bottom properties, mainly the backscatter strength of the first and second echo returns (e.g., Orłowski, 1984; Chivers et al., 1990). This method is commercially developed in a few classification systems such as *RoxAnn* (Greenstreet et al., 1996) or the Biosonics Visual Bottom Typing-VBT (Stepnowski et al., 1996). The second approach identifies the characteristic features of the first echo envelope as an indicator of the bottom type (e.g., Pace and Ceen, 1982; Preston et al., 2000; Tęgowski and Łubniewski, 2000; Tęgowski, 2005; van Walree et al., 2005). The latter approach was developed in many sediment classification systems as, for example, the widely diffused QTC-VIEW (QTC, 2004), which utilizes up to 166 parameters of the first echo envelope for bottom sediment classification (Hamilton et al., 1999).

In this study, we extend the experience acquired for the bottom classification to the sub-bottom, focusing our analysis on the detection of the buried sedimentary features.

Our aim is to rapidly distinguish and map areas where different types of sediments can be found in the lagoon subsoil. The planar reconstruction of the sedimentary features integrated with geological information is not only important to assess the anthropogenic impact on the environment in the past, but it also provides important information required by coastal management in new engineering interventions.

Therefore, we developed an algorithm for the automated classification of the echo shape parameters based on wavelet analysis and neural networks (Tęgowski, 2005; van Walree et al., 2005; Ostrovsky and Tęgowski, 2010). The wavelet transformation coefficients are very sensitive to changes in the shape of echo signals. In contrast to other methods, like for example the one described by Plets et al. (2008) which uses amplitude maps of chirp data to detect buried reflectors, our approach does not require a homogeneous data set in terms of power radiated and gain. The algorithm automatically extracts the information on the sub-bottom content from acoustic datasets.

As a case study, we focused on a complicated environment such as the Lagoon of Venice (Fig. 1a), which is a unique result of natural evolution and more than two thousands years of anthropogenic action. The general complexity and the high horizontal variability of the sedimentary architecture in lagoon environments is very difficult to image on the basis of few seismic/acoustic profiles. Therefore, we decided to carry out a very high spatial resolution survey (Madricardo et al., 2007). A pseudo-3D network of more than 920 acoustic survey lines for a total of about 580 km were collected along parallel lines with 2–3 m spacing (Fig. 1b). This very high spatial resolution was necessary to obtain a detailed 2D reconstruction map of the main sedimentary features, including ancient salt marshes, buried creek and palaeochannel patterns within the lagoon sediments.

The paper is organized as follows: first, we describe the acoustic dataset and the classification algorithm; secondly, we associate the results of the classification algorithm to the stratigraphic and palaeoenvironmental information obtained from the acoustic profiles and the cores extracted in the survey area; finally, we compare the results of the automatic procedure with the visual geophysical interpretation of the acoustic dataset underlying the advantages of the automatic procedure.

2. Regional settings

2.1. The present-day Venice Lagoon

In its modern configuration, the Lagoon of Venice is the largest lagoon in Italy, with a total surface of 550 km^2 (Fig. 1a). The lagoon has three inlets (Lido, Malamocco and Chioggia) and includes a complex system of intertidal marshes, intertidal mudflats, submerged mudflats, artificial and natural channels, and creeks. In recent times, also artificial salt marshes (like the ones depicted in Fig. 1b and c) were built within a land reclamation program. Altogether these elements reflect a microtidal regime with a mean tidal range of 0.40 m and about 0.80 m during neap and spring tides.

2.2. The origin of the Venice Lagoon

After the Last Glacial Maximum (LGM), ca. 20 kyrs before present (BP), the northern epicontinental Adriatic shelf was a low-gradient alluvial plain, characterized by an extensive network of fluvial channels. With the onset of the post-LGM sea-level rise, the area became progressively flooded by marine waters accompanied by the formation and drowning of barrier-lagoon systems in progressively more landward positions (Trincardi et al., 1994, 1996; Correggiari et al., 1996; Storms et al., 2008). In this framework, the Lagoon of Venice, at the northern end of the Adriatic Sea, began to form about 6000 yrs BP (Gatto and Carbognin, 1981). Since then, a sediment succession of lagoon environments with various morphologies and hydrological regimes overprinted the oldest marine deposits (Canali et al., 2007; Tosi et al., 2009; Zecchin et al., 2008, 2009). Over the centuries, natural causes and anthropogenic activities changed radically the path of channels the form and extension of salt marshes, the freshwater inflow from the mainland and marine water input. The position of ancient coastlines was reconstructed and the presence of large emerged areas during the Roman age was found (Alberotanza et al., 1977; Serandrei-Barbero et al., 1997, Tosi et al., 2009). Starting from the 15th century, major rivers (e.g., the rivers Bacchiglione, Brenta, Piave and Sile) were diverted and extensive engineering works were carried out over the following centuries up to the present day (including dredging of navigation channels, digging of new canals and modifications on the inlets) (Carbognin, 1992). Overall, these changes have had and are still having a dramatic impact on the lagoon hydrodynamics and sediment budget (Molinaroli et al., 2009; Sarretta et al., 2010; Ghezzo et al., 2010).