GEOLOGICAL/GEOPHYSICAL STUDY OF SHALLOW-WATER AREAS: AN INTEGRATED APPROACH

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INTRODUCTION

Due to their natural and economic importance, shallow-water environments, such as submerged beaches, coastal lagoons and, in general "wetlands", require periodical monitoring because they are prone to ecological crises often related to anthropogenic impact. The study of these ecosystems involves a combination of investigative approaches, such as biology, physical and chemical oceanography, and geology. Geophysical imaging of the sediment-water interface and of the shallow subsurface is important for a number of applications, such as costal erosion, submarine earthquake geology, marine geology and archeology.

We present here some case studies where high-resolution geophysical techniques have been successfully employed in shallow-water areas, and indicate some possible perspectives.

MORPHOBATHYMETRY AND REFLECTIVITY MAPS

The starting point for studies of shallow-water environments is the knowledge, at different levels of accuracy, of the morphology of the sediment-water interface, i.e., the bathymetry, which is also important for describing the status of the system and monitoring its changes in time caused by sedimentary processes.

Compilation of bathymetric map in extremely shallow-water environments present peculiar problems, mainly for 3 reasons 1) the average depth is often below the limit of conventional echosounders; 2) if these areas are in connection with the sea, tidal excursions might be of the same magnitude of the bathymetric range, and this results in potentially large errors; 3) the “soft” nature of the bottom favours penetration of acoustic signal, giving rise to errors in depth estimate.

Although water-depth mapping in coastal areas can be achieved using satellite remote sensing techniques, conventional sonic/ultrasonic soundings are still more accurate, because satellite data are restricted to shallow, clear water areas with small changes in bottom types and free from atmospheric contamination. While typical multi-beam system are not effective in shallow-waters, since their swath width is extremely limited, interferometric multi-beam echosounders partially overcome these problems, covering relatively large sectors of the seafloor (30-40 m). However, single-beam echosounders allow a more effective quality control on soundings, and enable reflectivity estimates of the sediment-water interface which can be used to infer sediment distribution patterns. The study of Valle Fattibello, Comacchio (Gasperini, 2005) has shown the potential of this type of studies.

Valle Fattibello is part of the Valli di Comacchio, a shallow, brackish water, coastal lagoon system, that extends south of the Po river between Comacchio and the Reno River. These lagoons (valli) formed around the tenth Century as a consequence of subsidence and were originally fresh water basins supplied by river floods. Valle Fattibello is located at the northern edge of the lagoon system, near the town of Comacchio.

A vertical incidence echosounder, the PSA900 manufactured by Datasonics, was used during the survey. This echosounder is particularly suitable for shallow-water environments because is characterized by a high operating frequency (200 kHz), a narrow (8°, conical) beam width, a short pulse length (350 μsec), and a minimum depth range of 0.75 m. However, due to the characteristic of the study area, we were forced to modify the echosounder to cover the shallower sectors of the lagoon; the pulse length was shortened to 200 μsec and the bottom-detection/depth-estimate section was disabled, obtaining, *de facto*, a 200 kHz externally triggered ultrasonic pinger. In this way, the shallow-depth limit was reduced to ~0.2 m. The echosounder and the GPS antenna were mounted on a small catamaran towed from a flat-keel boat, equipped with the instruments used during the survey. The towing cable was deployed by a mobile arm that was used to separate the track of the catamaran relative to that of the boat. The tidal excursion was measured during the survey using a tide-recording station consisting of a mareograph, a data-logger, and a GPS receiver, which provided an accurate time-base.

Bottom sediments were sampled at 47 stations using a box-corer. Samples were collected to a maximum subbottom depth of 17 cm and subsequently sub-sampled at 1–2 cm intervals (Frascari et. al, 2002). Grain-size analysis involved an initial wet sieving of sediment samples to separate the finest (< 63 μm) from the coarser fractions. The finer fractions were analyzed by a X-ray sedigraph.

The first step of the data processing was the estimate of water-depths from the raw echograms. The presence of soft sediments and the consequent penetration of the ultrasonic signal below the “soupy”, highly hydrated water/sediment interface, affect the accuracy of the bottom detection. In fact, during the acquisition of some test profiles, carried out using a conventional echosounder, we noted discrepancies of several tens of cm in the water-depth estimate of adjacent pings. If errors of this magnitude could be neglected in deeper areas, they are important in such an extremely shallow environment. In order to avoid this effect, taking advantage of the dense spacing of the data along each profile (1 ping / 0.1 m, average), a trace mixing algorithm, that increased the lateral coherence of the bottom reflector, was applied to the data and a robus procedure to track the sea bottom was followed (Gasperini 2004); finally, we applied the tide-effect corrections using the tide-excursions time series After data correction, over 20,000 valid depth measures were used to compile a morphobathymetric map of Valle Fattibello (Figure 1). Several unexpected features are visible in this map, such as: a channel intersected by several small mounds; a sedimentary fan, in the NW sector, probably related to the loss of competence of the current at the lagoon entrance; a dredge cut affecting the fan; and other features not obviously related to sedimentary processes, such as small mounds and ridges flanked by sub-circular depressions. This unexpectedly uneven morphology might be related to human activity in Valle Fattibello, that underwent continuous modifications since its early formation, such as channel creation and maintenance. During most of these works, the material dredged from the bottom has been dumped partly outside and partly within the lagoon itself; currents, particularly in the SE sector, were not strong enough to rework these deposits.

The acquisition of the entire echosounder sweep at each sounding point, rather than the simple depth estimate, gave us the opportunity to calculate the bottom reflectivity, and infer the distribution of sediments in the lagoon after "ground-truthing" the reflectivity measures with mean grain size estimates (Gasperini, 2005). We note that a simple working hypothesis of linear correlation between relative occurrence of coarse-grained sediments and normalized reflectivity accounts for most of the overall variability in the lagoon bottom sediments (Figure 1).

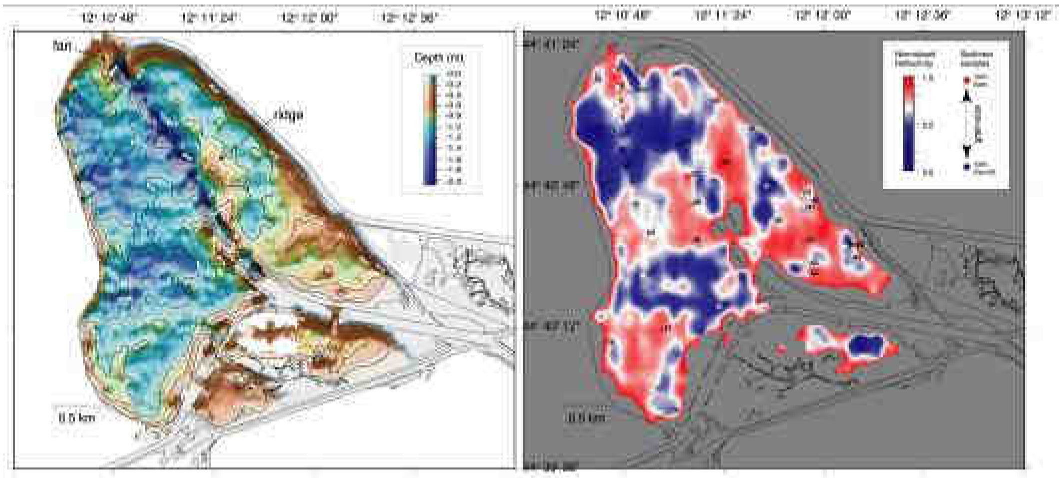

Figure 1. *Left*: morphobathymetric map of Valle Fattibello coastal-lagoon. *Right*: reflectivity-strength map of lagoon-bottom. Reflectivity is normalized using the maximum (71.46%) and minimum (0.85%) occurrence of sand in the samples, and is displayed using a color palette ranging from red (high values) to blue (low values). The relative occurrence of sand vs. silt+clay is coded at each sampling station (circles) using the same red-to-blue color scale.

Relating morphobathymetry and reflectivity gives us an overall picture of the depositional setting in Valle Fattibello. Our approach of referring the reflectivity data to local variability of the sediments limits generalizations, but greatly simplifies the interpretation of the results. In fact, the analysis of bottom types based on linear variations from two end-members, allows us to immediately translate our reflectivity images to geological features. This can be particularly useful in those environments where "low-energy" and "high-energy" processes co-exist, or are superimposed. Valle Fattibello is presently a mud-dominated, low-energy environment. However, reflectivity and the physical properties of the sediment show the presence of arcuate, sand-rich features, not in equilibrium with the present-day sedimentary regime. An interpretation of this pattern is that the high-reflectivity sand-rich bands might constitute the substratum over which the lagoon system has been formed, in agreement with regional-scale geological reconstruction of the Po delta area during the Holocene.

HIGH RESOLUTION IMAGES OF THE SUBBOTTOM

Shallow-water lagoons and hinterland waters are often characterized by fine-grained sediments and extremely “soft” sediment-water interfaces. This occurrence enhances the quality of high-resolution seismic reflection profiles, which can be virtually multiple-free, since seismic energy is not trapped between water-air/water-sediment interfaces. On the other side, is not uncommon that fine grained sediments of shallow-water environments are rich in organic matter and thus saturated by biogenic gas. High-resolution seismic refection data suffer the diffuse presence of gas in the sediments, because it prevents signal penetration in the subsurface.

Acoustic images of the subsurface can be obtained in submerged areas with a variety of systems. One of the most widely used is the Chirp-sonar, a wideband frequency-modulated seismic reflection system able to collect acoustic images with vertical resolution approaching 1 cm for bandwidths exceeding 20 kHz. This high-resolution provides detail about the sediment structure near the sediment-water interface and eventually allows to detect buried objects. The chirp sonar system transmits FM acoustic pulses to attain high pulse energy; consequently, the imagery has a high signal to ambient noise ratio. The images are normally scattering limited; that is, the subsurface depth of usable imagery is limited by acoustic noise scattered from inhomogeneities within the sediment structure. The chirp sonar has become the industry standard for generating high resolution images of the uppermost 10 to 100 meters of sediments in the seabed. In Figure 2, an example of Chirp sonar profile from a shallow (< 2 m) area is presented. We note that penetration of the signal reaches the ~40 meters; the high vertical resolution allows to analyse internal geometries of sesimostratigraphic units, diagnostic of tectonic and depositional processes.

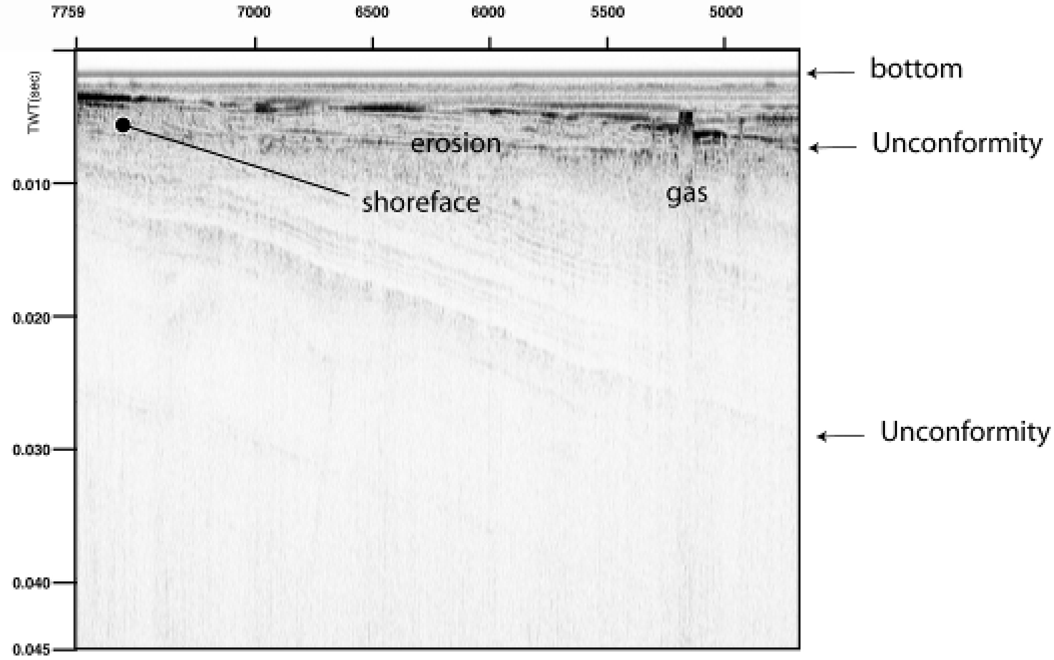

Figure 2. Example of high-resolution seismic reflection profile collected from a shallow (<4m) lake. We note reflectors dipping towards the right side of the section as a consequence of tectonic tilting, as well as buried shoreface deposits marking a past episode of water level low-stand.

3-D AND PSUEDO 3-D IMAGING

Although deep-towed high-resolution seismic reflection sources are widely diffused for surveys carried out in deep-water environments, shallow-waters allows to obtain high lateral resolution by using normally towed systems. This because shallow targets imply a narrow “Fresnel zone” and high horizontal resolution of seismic images; thus, it is possible to carry out close-spaced grids of profiles which can be used to obtain 3-D or pseudo 3-D images of the subsurface, which are useful to interpret geological features. A successful examples of these techniques is the attempt of imaging a surface buried below some tens of meters of mud deposited after the last sea-level rise in the Sea of Marmara. Figure 3 shows a comparison between the seafloor morphology collected using a multibeam echosounder and the gradient map of the base of the Holocene in a shallow shelf area of the Marmara Sea, across the North Anatolian Fault trace (Polonia et al., 2002). The subsurface pseudo 3-D imaging, obtained by semi-automatic picking of chirp-sonar images allows to measure the left-stepping strike-slip displacement of an abandoned river channel since 10,000 years before present, offering an accurate strain-rate estimate for this fault strand over geological time scales. These 3-D chirp-sonar techniques could be useful in a variety of fields, including archaeology, mining and environmental studies.

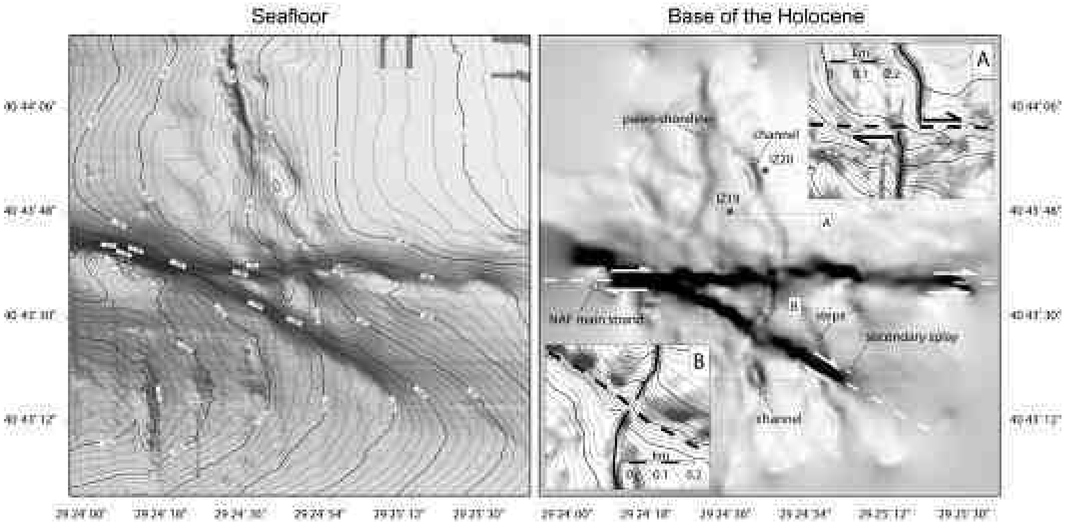

Figure 3. Left: shaded relief multibeam bathymetric map (contour each 1 m, illumination from NE). Right: gradient map of the base of the Holocene sediments obtained through a semiautomatic picking of CHIRP-subbottom profiles. It images sedimentary and tectonic features below the holocenic drape. (A) Laplacian (gray scale) and contour lines of the Holocene base topography in the area where the river channel intersects the main North Anatolian Fault (NAF). (B) Laplacian (gray scale) and contour lines of the Holocene base topography in the area where the river channel intersects a southern strand of the fault. The gradient map of the Holocene base topography shows a meandering river channel which is displaced along the NAF fault strands. We calculate an offset of ~80 and ~10 m in the main and secondary strand respectively (modified from Polonia et al., 2004).

CONCLUSION

High-resolution geophysical techniques in shallow-water environment are effective in solving geological problems through an integrated approach. All these techniques share the use of technological advanced instruments which can be deployed from small boats or ROV (Remote Operating Vehicles) / AUV (Autonomous Underwater Vehicles) systems to collect dense-spaced grids of profiles. Rapidity and low-cost will be important factors for feasibility of periodic surveys, that will be used to take a series of “snapshots” that will describe the changes of the sediment-water interface in time. This would allow the development of predictive geological models on sediment budgets of these complex environments characterized by multiple sediment sources sinks that are difficult to quantify.

REFERENCES

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