Università degli Studi di Ferrara

DOTTORATO DI RICERCA IN
"SCIENZE DELLA TERRA"

CICLO XXIX

COORDINATORE Prof. Massimo COLTORTI

SEABED NATURE AND MORPHODYNAMICS: HIGH RESOLUTION INTEGRATED ACOUSTIC DATA ANALYSIS

Settore Scientifico Disciplinare GEO/04

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Anni 2013/2016

Summary

Scientific activity

- Fanelli, E., Delbono, I., Peirano, A., Ivaldi, R., Pratellesi, M., Niccolini, A., Dialti, L., Pellegrini, M., Cocito, S., Delfanti, R. 2014. Re-discovery of cold water corals in the Eastern Ligurian Sea (NW Mediterranean). *Deep-Sea Life*, 4, 16-17.
- Delbono, I., Ivaldi, R., Pratellesi, M., Fanelli, E., Peirano, A., Cocito, S., Dialti, L., Delfanti, R. 2014. Seafloor morphology: nature of the seabed and the cold water corals of the Levante Canyon (eastern Ligurian Sea, NW Mediterranean). Geophysical Research Abstracts, 16, EGU2014-14732.
- Pratellesi, M., Ivaldi, R., Delbono, I. 2014. Dual use Hydrographic Surveys for Seabed Nature and Morphological Research. Integrated Mapping of Seabed Features. Hydro International 18 (7), 26-29.
- Ivaldi R., Pratellesi M., (2015). Geoacustics in a Canyon System, IUGG - 26th General Assembly of the International Union of Geodesy and Geophysics.
- Pratellesi, M., Ivaldi, R., Ciavola, P., Sinapi, L., 2016. Last century seabed morphodynamics of the Magra River estuary (Western Mediterranean Sea). Geophysical Research Abstracts, 18, EGU2016-17357-2, 2016
- Pratellesi, M., 2016. Natura del fondale marino e morfodinamica di aree costiere e profonde: analisi integrate di dati batimetrici ad alta risoluzione, Rendiconti online della Società Geologica Italiana – Primo convegno "La geologia marina in Italia" - Roma, 18-19 febbraio 2016.
- Lamberti L.O., Guideri M., Ivaldi R., Pratellesi M., 2016. La geologia marina in Italia" - Roma, 18-19 febbraio 2016 su "Dati idrografici e la mappatura dei fondali marini, Rendiconti online della Società Geologica Italiana – Primo convegno "La geologia marina in Italia" - Roma, 18-19 febbraio 2016.
- Armanino E., Demarte M., Ivaldi R., Pratellesi M., 2016. Smart city del passato: Villa dei Pisoni (Parco sommerso di Baia, Golfo di Pozzuoli. Presentazione orale al Convegnio Nazionale Associazione Cartografica Italiana (AIC) – abstract – atti del convegno, S. Benedetto del Tronto, 11-13 maggio 2016.

- Fanelli, M., Delbono, I., Ivaldi, R., Pratellesi, M., Cocito, S., Peirano, A. (In press). Cold-water coral Madrepora oculata in the eastern Ligurian Sea (NW Mediterranean): historical and recent findings. 2017. In press in Aquatic conservation, DOI 10.1002/aqc.2751
- Pratellesi, M., Ivaldi, R., Ciavola, P.. Morphological changes over a 135-year period of a small Mediterranean estuary: The Magra River. To be submitted as regular manuscript in Marine Geology

Abstract

The multibeam echo sounder system can not only obtain high-precision seabed bathymetry data, but also high-resolution seabed backscatter strength data. A number of studies have applied acoustic remote sensing method to classify seabed sediment type with multibeam backscatter strength data (unsupervised), and to obtain a rapid, areal and therefore better classification results than the traditional sediment sampling method (supervised).
Through data integration and the use of seabed-mapping technologies it is possible to obtain a high-resolution (HR) study of seabed morphology and nature, discriminating specific targets, benthic features and habitats at different spatial scales in various water depth and bottom types (morphology and materials) such the deep coral banks in the Levante Canyon (Ligurian Sea), the volcanic complex of Panarea (Eolian Islands, Tyrrhenian Sea) case studies or highlighting the environmental dynamics trough time and space using hydrographic monitoring like the evolution of the Magra River and its adjacent Ligurian coast. This specific goal was achieved processing the historical data series stored in the archive of the Italian Hydrographic Institute and more recent surveys. Data are completely comparable because they follow the same hydrographic standards during time. In fact, the data available were collected in the last 135 years with different equipment (from lead line to acoustic multibeam system), scale and processing. The method used for this hydrographic research is based upon data integration and multiple focusing approaches to identify areas to be investigated with different resolution systems in order to perform data exploitation and multiple usages of available resources.

Riassunto

Gli ecoscandagli *multibeam* non sono solo in grado di acquisire dati batimetrici ad alta precisione ma anche di registrare l'intensità del *backscatter* del fondale ad alta risoluzione. Molti studi sono stati effettuati sul "remote sensing" acustico con lo scopo di classificare il fondale tramite il dato di *basckscatter* (approccio *unsupervised*) ed ottenere una rapida, aerea e possibilmente migliore classificazione rispetto il tradizionale campionamento diretto (approccio *supervised*).

Tramite l'integrazione di dati e l'impiego di tecnologie che consentono il *seabed mapping* è possibile ottenere uno studio ad alta risoluzione della morfologia del fondale, discriminando *feature* di fondo e habitat a differenti scale spaziali, a varie profondità e con differenti tipologie di fondale (morfologia e materiali) come i banchi di corallo profondi nel Canyon di Levante (Mar Ligure), il complesso vulcanico di Panarea (Isole Eolie, Mar Tirreno) o evidenziare le dinamiche ambientali nel tempo e nello spazio tramite il monitoraggio idrografico dell'evoluzione del fiume Magra e della costa adiacente. Questo specifico obiettivo è stato raggiunto grazie all'analisi delle serie storiche di dati dell'Istituto Idrografico della Marina e rilievi più recenti resi comparabili poiché conformi al medesimo standard idrografico. Infatti i dati analizzati sono stati raccolti negli ultimi 135 anni con differenti strumenti (dal filo a piombo al *multibeam*), scale e elaborazione.

Il metodo impiegato per questa ricerca idrografica è basato sulla integrazione di dati ed un approccio iterativo a diverse scale al fine di individuare le aree da investigare ulteriormente con sistemi a differente risoluzione e massimizzare così l'impiego delle risorse e dei dati a disposizione.

Introduction

Acoustic backscatter responses analysis allows morphological and sedimentary seafloor characterisation. Integrating acoustic backscatter data acquired thorough multibeam echosounders with seabed nature and water column information it is possible to describe seabed morphodynamics, with particular reference to the water-sediment interface.

The main aim of my work was developing a high resolution bathymetric data analysis method to be applied to characterize seafloor features at different temporal and spacial scales. The method has been tested in three scenarios with different characteristics and leading to different applications domains:

- Deep water, canyon with high biological interest;
- Medium water, volcanic area with high hydrothermal activity;
- Shallow water, historical evolution of a river mouth characterized by stable climatology, high human impact and peculiar geological factors.

Maps revealing the geophysical characteristics of the seabed represent an essential tool for the effective management of the marine environment, because they allow the wide-scale geology and present-day (Holocene) sedimentary processes to be determined and understood. A multiple scale methodology approach has to be chosen in accordance with instruments and software available. High resolution (HR) (S-44, 2008; C-13, 2012) bathymetric data are fundamental to a seabed map of the area with high detail of the seafloor morphologies. At a meter scale (medium scale), acoustic backscatter analysis permits to accurately describe deep seabed features and their geomorphic variability in relation with seabed nature. HR maps permit the identification of sites of interest for substrate geometries and specific features discovery and analysis. These peculiar morphologies can be deeply investigated at a larger scale (sub-meter) also with different type of instruments (e.g. Side Scan Sonar). Finally, the integration between all data available, morpho-bathymetric analysis and acoustic characterization of the sub bottom allow large scale area detection to be calibrated by ground – truthing.

The same approach was applied to a bathymetrical and sedimentological historical series of data (135-yrs) in order to estimate the morphological and volumetric changes of the delta system at the mouth of a small Mediterranean estuary. The data series were collected during several hydro-oceanographic surveys carried out from 1882 to 2014, processed following the hydrographic international standards and stored in the Italian Navy Hydrographic Institute database. In particular, bathymetric data characterized by the same standard and accuracy were collected using different devices such as sounding lines, single-beam and multi-beam acoustic systems. This research compares Digital Terrain Models (DTMs), derived from highly accurate bathymetric data and covering different time scales (secular, half-century and decade) in order to assess and quantify the seabed morphodynamics in relation with the river sedimentary budget. The methodology and data exploitation consist mainly in the production of DTMs to study the elevation change, two-dimensional and three dimensional maps, cross-sections of the seabed, difference surfaces and computation of net volumes as well as an historical sedimentological map.

The results of the analysis highlight changes in the geometry of the river mouth, of the coastal profile and bottom features primarily due to variations of the sedimentary budget and secondarily to wave dynamics. This behaviour is characterized by evident river mouth and coastal retreat, beach erosion and sediment bars decay and net accretion under periods of high river sediment discharge and elongate bar formation during relatively fair conditions. In the last century the main change is constituted by the disappearance of the typical constructive seabed delta morphology and the transformation into the present small estuary, with microtidal condition.

This work is structured in six chapters reflecting the temporal development of the study:

- Chapter 1: Acoustic seabed mapping using backscattered signal;
- Chapter 2: Hydrographic data seabed mapping;
- Chapter 3: Integrated mapping of deep water seabed features;
- Chapter 4: Acoustic seabed analysis of a hydrothermal area;
- Chapter 5: Geomorphological changes over a 135-years period of a small Mediterranean estuary: the Magra River,
- Chapter 6: Final considerations.

1. Acoustic backscatter

1.1. Acoustic seafloor Mapping Technology

While the earliest use of sonar in the sea was for simple echo-ranging, the need to locate and image objects on the seafloor led, mostly in the post-WWII era, to the development of side-scan sonar imagery systems. Improvements in transducer materials and array design offered the ability to transmit a narrow (in the along-track direction), fan-shaped pulse across a relatively wide (dependent on frequency) swath of sea floor. Constrained in early days to analog electronics and paper recorders, early side-scan sonar systems produced a simple amplitude-modulated image of the strength of the acoustic return as a function of travel time across the insonified swath of seafloor, transformed into a geometrical “sonar image” by assuming a flat seafloor. These early records were uncalibrated, though typically compensated for geometric spreading losses. While often difficult to interpret in terms of the nature of the seafloor, the geometry of the side-scan when deployed near the bottom cast shadows that proved extremely useful in the identification of small (e.g. mines) or large (e.g. wrecks) objects and other natural or manmade structures that stood out of the surrounding seafloor. This concept of a “shadowgraph” was used very effectively for many years to identify objects in mine-hunting sonars (Fish and Carr, 2001) and the use of shadows for the identification of natural and man-made targets in side-scan sonar records has continued the present days.

The high-frequencies (200 kHz to 1.4 MHz) used to achieve the resolution necessary for small object detection, limited the range of coverage available to these sonar systems and thus when there was a need to search for objects in the deep sea (e.g. the U.S. nuclear submarine *Thresher* in 1963 or the hydrogen bomb lost off Spain in 1966), deeply towed side-scan sonars were developed (Spiess, 1980; Tyce, 1986). Lower frequency (12 kHz or less) towed side-scan sonars were also developed providing broad, but low-resolution coverage for regional deep-sea geological studies and allowing the identification and mapping of large-scale (e.g. ridge crests, seamounts, fracture zones, channels) geologic structures and processes (Rusby and

Somers, 1977; Kasalos and Chayes, 1983).

With advances in transducer design, digital electronics, signal processing capabilities, navigation, and graphic display devices, the resolution and particularly the dynamic range available to sonar and processing software manufacturers greatly improved. These improvements led to higher resolution displays and the ability to more appropriately compensate the backscatter imagery produced by side-scan sonar for geometric distortions as well as the production of sonar mosaics – composite georeferenced images of the backscatter, typically normalized to a single angle (e.g. 45°). The resulting acoustic images began to offer a more realistic and more consistent picture of the seafloor leading to a rapid expansion of the applications of backscatter imagery for many geologic, engineering and environmental studies where information about the nature of the seafloor was required. The relationship between backscatter and seafloor type derived from these systems often depended on many "ground-truth" samples and years of user experience relating the returns from a particular system to the ground-truth samples. At best these studies were qualitative as the backscatter returned from these systems was uncalibrated with respect to output or received levels (either relatively or absolutely) and assumed a flat seafloor (thus not compensating for the angular dependence of backscatter). Despite these limitations, many valuable conclusions could still be drawn from major changes in average backscatter levels and the ability to manually separate regions of differing image texture. Focusing on a textural analysis of the returned backscatter image, more quantitative image-processing techniques began to be applied to the returned acoustic images segmenting the acoustic returns based on inter-pixel statistics and relating these segments to areas of differing geologic character or process.

Concomitant with the improvements described above there were several significant technological advances that have dramatically changed the nature of seafloor mapping. The use of multiple rows of side-scan sonar transducers and interferometric or phase-measuring processing allowed bathymetry to be measured along with backscatter and thus obviated the need to assume a flat seafloor when interpreting seafloor backscatter. Even more importantly, multibeam echosounders (MBES) became generally available. Multibeam echosounders transmit with the same geometry as a side-scan sonar but received the seafloor backscatter return on a series of narrow (in the across-track direction) formed beams and thus allows the determination of both depth across the swath (at the resolution of the receive beam spacing) and the recording of the backscatter time series at known angles across the swath (again at the resolution of the receive beam spacing).

With the introduction of multibeam sonar and the ability to measure backscatter as a function of true angle of insonification across the seafloor came a new recognition of the potential to use backscatter measurements as a means to remotely characterize the properties of the seafloor. An improved theoretical understanding of the interaction of sound with the seafloor (well summarized in Jackson and Richardson, 2007) indicated the angular dependence of backscatter as a key parameter in identifying seafloor type and opened the door to more quantitative analyses of multibeam sonar backscatter (e.g., Hughes Clarke et al., 1997; Fonseca and Mayer, 2007; Lurton et al., 2008). Further improvements in the capabilities of the sonars including improved motion compensation, greater spatial and angular resolution and most importantly, increased bandwidth have now set the stage for truly addressing the potential of quantitative analysis of backscatter for seafloor characterization and its broad range of military, geologic, engineering and environmental applications. The stage is set, but the production is not complete until we have fully resolved the challenge of robust seafloor characterization. To achieve this, we must do all we can to ensure that we fully understand the nature of the data produced by our sensing systems and how these data have been modified through the acquisition and processing streams. It is this over-arching concern – the desire to better understand and quantify the characteristics (e.g., frequency, source levels, beam angles and patterns, response to gain changes, etc.) of the backscatter data collected bringing us even closer to our ultimate goal of robust and quantitative remote seafloor characterization (Lurton and Lamarque, 2015).

1.1.1. Acoustic Basic principles

Acoustics may be defined as the generation, transmission and reception of energy in the form of vibrational waves in matter. The displacement of the atoms or molecules of a fluid or solid from their normal configuration causes an internal elastic restoring force, e.g., springs or fluid compression. The most common acoustic phenomenon is the sound wave which is a longitudinal wave. As sound waves travel through a medium, the particles of the medium vibrate to produce density and pressure changes along the path of motion of the wave. Underlying the propagation of sound is a number of basic equations of physics (Urick, 1983). The sonar parameters represent the diverse effects in underwater sound propagation and can be divided as follows (Lurton, 2010):

- Parameters determined by the equipment
  - Projector source Level SL
  - Self-Noise Level NL
  - Directivity Index DI
  - Detection Threshold DT
- Parameters determined by the medium
  - Transmission Loss TL
  - Reverberation Level RL
  - Ambient Noise Level NL
- Parameters determined by the target
  - Target Strength TS
  - Target Source Level SL

The relationship between sonar parameters, the relationship between effects of medium, equipment and target, are described by the sonar equations. The functions of the sonar equations are:

- Prediction of performance of sonar equipment.
- Sonar equipment design.

A transducer echo-ranges the target, and it produces a source level that reaches the target and returns to the transducer after being reflected (echoed). If SL is produced by the transducer source level at unit distance on its axis, then $SL\text{-}TL$ will be the source level once it reaches the target, i.e., the source level reduced by the transmission loss $SL\text{-}TL+TS$ will be the source level after reflection from the target, the source level reduced by the transmission loss TL and reflected by the target.

$SL - TL + TS - TL$ will be the echo level which returns to the transducer, the source level reduced by the transmission loss TL, reflected by the target and reduced again by the transmission loss TL. Thus the echo level at the transducer is $SL - 2TL + TS$.

The echo level will be further affected by the background effect. It can be considered as noise or reverberation. In the case of noise:

NL is isotropic noise.

NL – DI is isotropic noise reduced by the directivity index (directivity gain) *DI* of the transducer acting as the receiver. In the case of reverberation, *NL* - *DI* will be replaced by an equivalent plane-wave reverberation level *RL*. At the transducer terminals, the echo-to-noise ratio is thus *(SL* - 2*TL + TS)* - *(NL* - *DI).* The detection threshold *DT* equals the signal-to-noise ratio when the target is just being detected,

$$\text{i.e.,} \quad (SL - 2TL + TS) - (NL - DI) = DT \quad [1]$$

The above equation is called the active-sonar equation [1]. Another form of the active-sonar equation with a more convenient arrangement is:

$$SL - 2TL + TS = NL - DI + DT \quad [2]$$

After interacting with the seafloor, a portion of the scattered wave propagates back toward the target (backscatter), experiencing the same type of spreading and absorption losses as on the way to the target. The received intensity can be described as an echo from the target, which in decibel notation is referred to as the echo level, EL (Ulrick, 1983; Lurton, 2010)

1.1.2. Echo from a target

As anticipated, the Echo Level quantifies the sound wave that we are typically interested in measuring; however, the target echo is not the only sound wave to be received. When we measure the echo level, we are often confounded by unwanted acoustic waves, that we refer to globally as noise: either ambient noise (e.g., ship traffic, bursting bubbles under breaking waves, marine animals), self-noise (generated by the sonar itself or by its platform) or reverberation (e.g., the sound wave we projected that scatters from objects we are not interested in). It is assumed here that the echo level is sufficiently high so that noise level is negligible; useful discussions of noise in this context can be found, however, in Urick 1983 (Lurton and Lamarque, 2015).

While it is useful to think of the sonar equation in terms of the echo level observed at the receiver, the quantity relevant to acoustic backscatter from the seafloor is the

Target Strength (*TS*) which includes a combination of effects related to the sonar and to the target. The nature of this combination is dependent on the morphological characteristics of the target (size, shape, material) and characteristics of the sonar (frequency, angular orientation).

The simplest *TS* scenario is that of a discrete target (i.e., small compared with the sonar beam and pulse length). It is often the case that the targets extend throughout a volume defined by the sonar beam and pulse length. For example, if the echo was returned from a large aggregation of fish or gas bubbles in the water origin from an hydrothermal activity (see Chapter 3) then *TS* could be considered as the the incoherent sum of the individual echoes from the fish present inside an instantaneously “active” volume (Lurton and Lamarque, 2015).

The target acts as a secondary source retransmitting the acoustic wave. The TS is the ratio between the intensity sent by the target back to towards the transmitter and the incident intensity. It is therefore the relative amount of energy sent back by the target towards the sonar. It depends on the physical nature of the target, its external (and possibly internal structure), and the characteristics of the incident signal (angle and frequency). The intensity EL (echo level) of the echo received by the sonar system after backscattering is:

$$EL = SL - 2TL + TS \quad [3]$$

where SL is the level transmitted by the source, TL is the transmission loss (counted twice, once in the way in, once on the way back).

Two types of targets can be envisaged. First there are target with dimensions small enough to be completely insonified by the sonar beam and signal. They behave as “points”: theirs strength is an intrinsic strength, independent of the distance to the sonar or its characteristics. On the contrary, other targets may be too large to be insonified completely at once by the same beam (e.g. seabed surface large fish schools, etc…). The strengths of these large targets depend on their geometric intersection with the sound beam. The TS is no longer a point value but uses the insonified space (surface or volume), associated with a surface or volume backscatter coefficient (Lurton, 2010).

1.2. Basic principles of backscattering

The remote observation of the inner oceans relies widely on the use of underwater acoustics; in particular seafloor mapping implies the generalized design and operation of specialized sonar systems (Lurton, 2010). Along the years, as anticipated in the first paragraph, the available technology has evolved (Figure 1) from single-beam echosounders (measuring one sounding point vertically under a ship or an underwater vehicle) to sidescan sonars (towed at a low altitude above the seafloor and recording "acoustic images" of the interface details at shallow grazing angles) and to multibeam echosounders (scanning the seafloor interface though a high number of narrow beams covering a wide swath across the ship's route) which are prevalent today in mapping operations (Lurton and Lamarque, 2015).

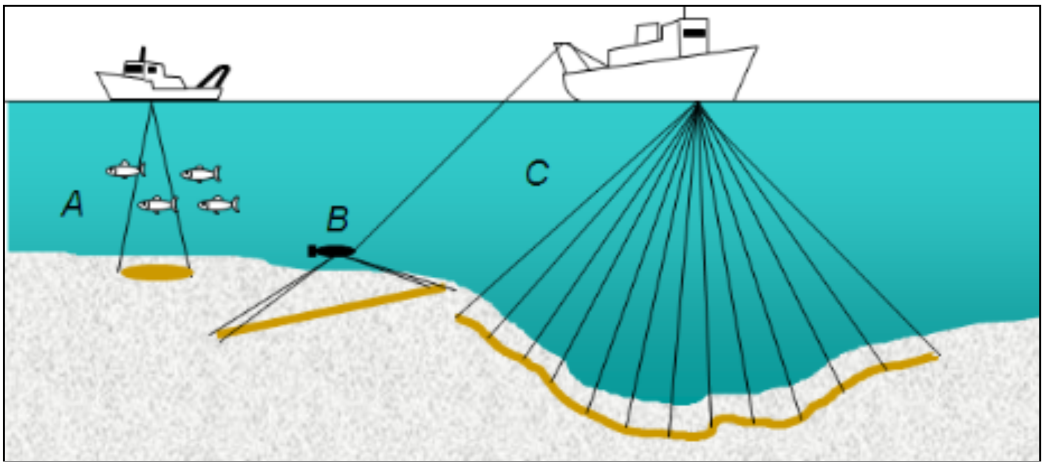

Figure 1 - Schematic representation of the three main types of seafloor-mapping sonars (A: singlebeam echosounder; B: sidescan sonar; C: multibeam echosounder) (Lurton and Lamarque, 2015).

The working principles for echosounders are similar to those for all active sonar systems (Urick, 1983; Jackson and Richardson, 2007; Lurton, 2010, Lurton and Lamarche, 2015). These various seafloor-mapping sonars rely on one same physical phenomenon: backscatter of the sound wave by the seafloor interface; or in other words, the generation, by the target-seafloor, of a return wave as an echo to the incident signal sent by the sonar. Different types of echoes can also be generated by local obstacles present in the water column. Because of their shape these irregularities scatter acoustic energy in all directions, and are therefore more likely to

affect the signals received in any configuration. The scattering of acoustic energy back towards the sonar is called backscattering. This backscatter strength, which is associated to the type of seafloor, has been used implicitly for years in the design and operation of sonars: highly reflective seafloors have been known as detectable from further by a sonar, while being also prone to generate more parasitic echoes than softer sediments. Progressively the idea emerged that reflectivity could provide information pertinent to the nature and the structure of the target. The latter are highly varied in nature and in structure: seabed insonified at normal or oblique angles of incidence, single fish, submarines, objects laid on the bottom, buried objects (natural sedimentary layers or artificial objects like pipelines), etc… (Lurton, 2010).
The incident acoustic wave will be scattered by the target in all directions of space, and a portion will be scattered back towards the transmitter. The target acts as a secondary source retransmitting the acoustic wave (Lurton, 2010) (Figure 2).
A strong point of seafloor-mapping sonars is that they are intrinsically able to record the two types of information (target geometry and reflectivity) altogether in an ideally compatible way, since one same echo signal can be used for both purposes. However, it took years for the two functionalities to be usable at the same level of quality – and it is still an ongoing progress. Nevertheless, and without being over-optimistic, there is a widely accepted agreement today that sonar systems used for seafloor mapping (which also is potentially true for any type of active sonar system) can usefully provide two levels of information from the same recorded signals (Figure 2):

- water-depth or bathymetry, i.e. a geometrical information from measured echo times and angles;
- seafloor acoustic reflectivity, i.e. a measure of energy obtained from the echo intensity, which relates directly to the nature of the seafloor.

Conceptually, bathymetry is relatively straightforward information to derive from the record of time delays of echoes: it is all a matter of time measurements and geometry (at least in theory; accurate measurements actually require sophisticated technologies and demanding procedures). The processing is far less obvious when the aim is to obtain information on the nature of the seafloor from echo intensities. Indeed, the backscatter phenomenon (and hence its measurement) is a peculiar concept: it is both intuitive (a sound that is sent back towards its source, more or less intense according to the target and its range) while still very complex structurally – the received echo is a combination of acoustic and geophysical processes, accounting for both transmitting and recording electronics of the sonar and intricate physical phenomena happening both in the water and at the interface.

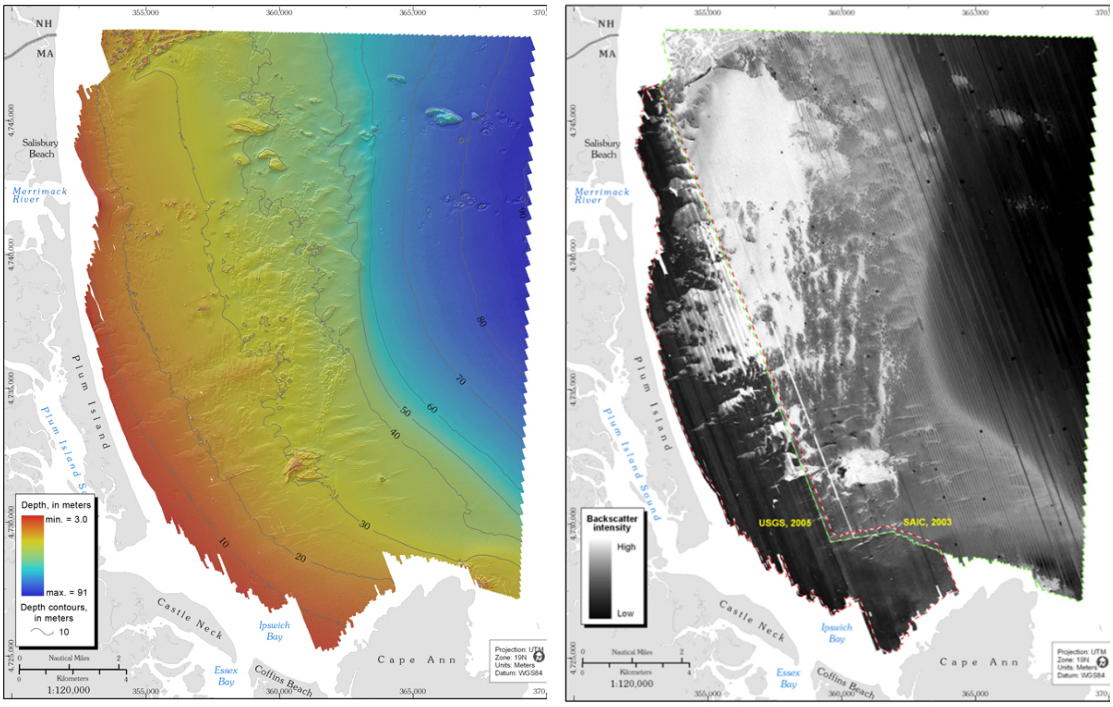

Figure 2 – a) Map showing shaded-relief topography of seafloor offshore of north-eastern Massachusetts between Cape Ann and Salisbury Beach. Coloring and bathymetric contours represent depths in meters, relative to the local mean lower low water (MLLW) datum; b) Map showing acoustic-backscatter intensity offshore of north-eastern Massachusetts between Cape Ann and Salisbury Beach. Higher values (light tones) represent rock, boulders, cobbles, gravel, and coarse sand. Lower values (dark tones) generally represent fine sand and muddy sediment (Barnhardt et al., 2009).

Hence, in order to access the backscatter information intrinsic to the seafloor, the recorded echo first needs to be cleaned of that part of the signal that is not directly related to the target itself. This means first that the characteristics of the sonar sensor per se (obviously the transmission level and the reception sensitivity, but also the beam aperture and the signal duration) should not affect the estimation of the target reflectivity, while they certainly impact on the received echo observable intensity. It is also intuitive that the measured echo level depends on the range between the sonar and the target – a distant target obviously raises a fainter echo than a close one; hence the propagation loss inside the water column needs to be corrected, according to the local environmental conditions and to the particular acquisition geometry. After these appropriate compensations have been applied, the measured echo intensity can be reasonably considered as representing the seafloor effect alone, and can be translated into the backscatter strength of the target, which is its inherent capability for sending back acoustic energy to the sonar system. This "reflectivity" characteristic is linked fundamentally to the target's material mechanical characteristics (a "hard" material sends back higher echoes than a "soft" one) and its fine-scale geometry (a "rough" interface scatters more acoustical energy than a "smooth" one) (Figure 3). Hence measured backscatter can, up to some point, be considered as a first-order indicator or proxy for the seafloor interface nature, composition and small-scale structure, and hence provide a direct link with geology, biology and ecology – which is indeed the goal to keep in mind. The angular dependence of the backscatter response is a paramount feature, implying both constraints in the data processing and in the potentialities of their interpretation (Hughes Clarke et al., 1997; Le Chenadec et al., 2007). A rough and hard seafloor interface (coarse material or rocks) tends to scatter the sound waves homogeneously in all directions, and the echo level depends little on incidence angle; the intensity recorded over the swath width is then rather stable whatever the angle (Figure 1-4). On the other hand, a soft and flat fluid-like sediment has a mirror-like response, sending back a maximum of intensity at the vertical and very little at oblique angles; the sonar image shows then a strong maximum in its center, and a fast decrease on the sides. All intermediate cases are indeed possible, depending on the interface roughness and the presence of scatterers either lying on the interface or buried in the surficial layers.

The intensity modulations caused by the angle dependence in the seafloor image require specific compensations in order to make the graphical display easily interpretable. Dedicated processing operations are hence devoted to flattening the angle response so that a geologically-homogeneous flat seafloor appears at a constant level on the processed image, whatever is the original angle dependence.

On the other hand, the angular dependence, if correctly preserved, is a very powerful tool for a classification operation. These contradictory objectives imply in both cases to master accurately the angle characteristics of the observed scenes, implying a correct estimation of the local bathymetry. This justifies the interest found in the backscatter measurement by multibeam echosounders (MBES): these sensors are the first ones able to provide angular reflectivity concurrently with a bathymetry obtained at a comparable resolution, making it possible to fulfil both expectations.

The spatial resolution (a.k.a. footprint extent) of a swath seafloor-mapping sonar is given basically by the extent of the beam section intersecting the seafloor interface; hence it is obviously a function of both the range to the seafloor (increasing at oblique angles, for a given water depth) and the beam aperture (typically 1° hence about 2% of range). Hence the resolution of ship-borne MBES is indeed very fine, let alone that of remotely-operated or deep-towed vehicles working close to the seafloor. It is debatable in any case, as to whether habitat mapping applications need such a high resolution capability for reflectivity data. (Lurton, 2010; Lurton and Lamarque, 2015)

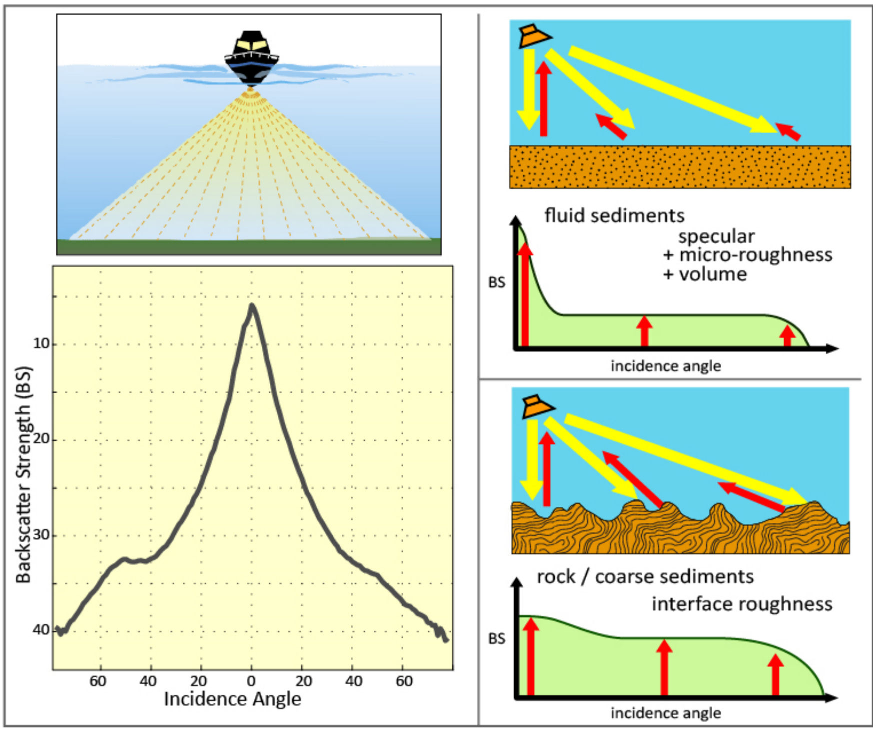

Figure 3 - The angular dependence of Backscatter Strength (BS). The rapid decrease in the BS intensity with incidence angles shows well in the BS angular profile (bottom left): high BS values at the nadir (0° incidence) decrease rapidly with gazing angle. The shape of the angular profile is directly influenced by the interface roughness (right); it is not necessarily symmetrical in practice (example shown here), depending on local features (Lurton and Lamarque, 2015).

After interacting with the seafloor, a portion of the scattered wave propagates back toward the target (backscatter), experiencing the same type of spreading and absorption losses as on the way to the target. The received intensity can be described as an echo from the target, which in decibel notation is referred to as the echo level, EL (Ulrick, 1983; Lurton, 2010)

The echo level quantifies the sound wave that we are typically interested in measuring; however, the target echo is not the only sound wave to be received. When we measure the echo level, we are often confounded by unwanted acoustic waves, that we refer to globally as noise. It is assumed here that the echo level is sufficiently high so that noise level is negligible; useful discussions of noise in this context can be found in Urick 1983 (Lurton and Lamarque, 2015).

While it is useful to think of the sonar equation in terms of the echo level observed at the receiver, the quantity relevant to acoustic backscatter from the seafloor is the Target Strength (*TS*) which includes a combination of effects related to the sonar and to the target. The nature of this combination is dependent on the morphological characteristics of the target (size, shape, material) and characteristics of the sonar (frequency, angular orientation).

The simplest *TS* scenario is that of a discrete target (i.e., small compared with the sonar beam and pulse length). It is often the case that the targets extend throughout a volume defined by the sonar beam and pulse length. For example, if the echo was returned from a large aggregation of fish or gas bubbles in the water originating from an hydrothermal activity (see Chapter 3) then *TS* could be considered as the the incoherent sum of the individual echoes from the fish present inside an instantaneously "active" volume (Lurton and Lamarque, 2015).

1.2.1. Backscattered signal from a smooth seafloor

In a first step, we consider a sonar-generated sound wave impinging on a seafloor that would be flat and horizontal on average, but with a rough surface at a small scale. This simplified description neglects both seafloor topography, inner structure of sediments, and presence of heterogeneities (biological, mineral, gas, etc.). It is, however, sufficient for the comprehension of a number of fundamental notions and phenomena.

If the interface is sufficiently smooth, the incident acoustic wave is reflected along an angle symmetrical to the incidence angle and away from the direction of the arriving signal: this is the specular reflection. The intensity of this reflected signal is then only controlled by the "hardness" of the seafloor and the direction of arrival. Hardness is defined here as the contrast between the characteristic impedance of the water and the seafloor: for a given medium, the acoustical impedance is the product of density and sound speed. For a perfectly smooth interface, the reflected signal is an exact copy of the incident one except for the loss of intensity related to the wave that is transmitted into the seabed, and the interface acts as a mirror.

Obviously the projector and receiver must be physically separated in order to record this specular echo. This is the "bistatic" configuration used by low-frequency seismic reflections: thanks to the offsets of the receivers along the receiving streamers, the layered seabed can then be investigated according to a wide range of incidence angles (Lurton, 2010). The only exception to this requirement for physical separation is when the beam direction is perpendicular to the seafloor (i.e., at normal incidence), which is the working principle of the classic single beam echosounder. This normal-incidence echo also contributes to the signals recorded by multibeam echosounders, which project and receive sound over a wide range of angles; of a different nature from the oblique backscattered echoes, it raises a number of specific issues (both for bathymetry and reflectivity), especially penalizing in low frequency.

It is possible to determine how much of the incident acoustic wave is reflected or transmitted by equating boundary conditions at the seafloor (e.g., at the boundary, the sum of the pressures associated with incident and reflected waves must equal the pressure of the transmitted waves - see Kinsler et al. (1999) for details). At normal incidence, the reflection coefficient (ratio of reflected to incident pressure) is governed by the contrast between the characteristic impedances Z c of the seawater and the seafloor

Table 1 presents typical values of acoustical quantities (density, sound speed, absorption factor) corresponding to a variety of sediment types.

	Clay	V. Fine Silt	Fine Silt	Medium Silt	Coarse Silt	V. Fine Sand	Fine Sand	Medium Sand	Coarse Sand
Grain Size Mz(ϕ)	> 8	7-8	6-7	5-6	4-5	3-4	2-3	1-2	0-1
Density (kg/m^3)	1145	1147	1148	1149	1195	1268	1451	1845	2231
Velocity (m/s)	1470	1476	1479	1482	1523	1585	1661	1767	1875
Absorption (dB/λ)	0.08	0.11	0.17	0.37	1.18	1.02	0.87	0.89	0.89
V (0°) (dB)	0.058 (-24.8)	0.060 (-24.4)	0.062 (-24.2)	0.063 (-24.0)	0.096 (-20.3)	0.145 (-16.8)	0.233 (-12.7)	0.370 (-8.6)	0.472 (-6.52)
Critical angle (°) *(intromission angle)*	*(68.6°)*	*(71.2°)*	*(72.5°)*	*(74.0°)*	80.0°	71.2°	64.6°	58.1°	53.1°

Table 1 - Geoacoustical characteristics of typical sediments. Adapted from APL 1994, using the classical Wentworth scale for sediment nomenclature (Lurton and Lamarque, 2015).

The higher the impedance contrast, the larger the reflected echo from the seafloor. The reflection coefficient can be either positive or negative, varying between +1 in the case of a perfectly rigid boundary and -1 in the case of a pressure release boundary (approximating the water-air interface). In the case of a soft, slow sediment like clay (much of the acoustic pulse is transmitted into the sediment and the reflection coefficient is weak (*V=0.255*). For denser, coarser sediments like coarse sand the reflection coefficient is more than two times higher.

At oblique incidence, application of boundary conditions (expressed for the normal components of the sound field) shows that the reflected wave is directed along the specular direction and the reflection coefficient (V) is angle-dependent

The oblique-incidence reflection coefficient is again dependent on the impedance contrast between the seawater and substrate, but is now dependent on both the incident and transmitted wave angles. Figure 3 shows examples of the reflection coefficient for both clay, coarse silt, fine sand, and coarse sand. In the case of the coarse silt and the sands, the reflection coefficient grows with increasing incidence angle until it reaches a critical angle, at which point all of the transmitted wave is reflected and only an evanescent wave (exponentially decaying) is transmitted into the seafloor. This condition is commonly met since most often the seabed has a sound speed faster than seawater (Table 1). For clay, slightly slower than seawater, for a particular high-incidence angle no sound intensity is reflected.

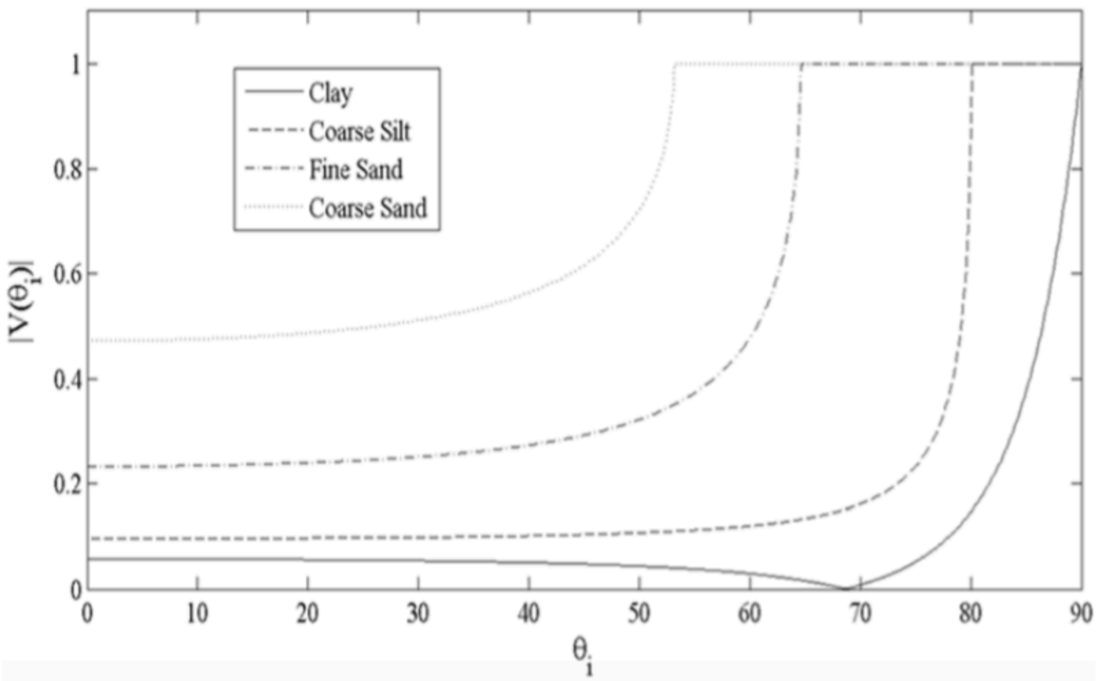

Figure 4 - Angle-dependent smooth-surface reflection coefficient for clay, coarse silt, fine sand, and coarse sand using the properties from Table 2

1.2.2. Impact of seafloor roughness

In reality the seafloor is never perfectly smooth and the ideal specular reflection does not actually occur. Instead, the acoustic wave arriving at the seafloor is scattered around the specular reflection direction by the roughness features, which can heuristically be considered as small (compared to the signal wavelength) targets. The angular spread of this scattered wave depends on the details of the roughness. For low-moderate roughness, most of the scattered wave is still concentrated around the specular direction and a lesser part occurs in the direction that is back toward the projector. Conversely, for high roughness, the incident wave intensity is significantly scattered in all directions, and the specular component vanishes. This backscatter gives rise to the acoustic echo and its presence, even at grazing angles, is the fundamental working principle for all swath-sounding systems (multibeam echosounders and side-scan sonars), which have a co-located projector and receiver. Although backscatter is often very low compared to the incident intensity, this returned echo proves to be still detectable and measureable.

Seen by a sonar system, the interface roughness has to be considered in relation to the acoustic wavelength. For multibeam echosounders, wavelengths range from 12 cm (12-kHz deep-water systems) to 0.5 cm (450 kHz used for applications in coastal waters). Acoustic backscatter may be interpreted in terms of the "acoustic roughness", which is defined as the ratio of the geometrical roughness to the acoustic wavelength. If the geometric roughness is expressed as the standard deviation h of the seabed interface elevation, then:

- A **smooth interface** corresponds to h: the interface irregularities are much smaller than the wavelength and only slightly perturb the behavior of a perfectly smooth interface. This condition suggests that the specular reflection should be very high, and the scattered field very low.
- A **rough interface** corresponds to h: the interface irregularities are much greater than the wavelength and scatter a significant proportion of the incident power. For this condition, the "plane and smooth" character of the seabed interface disappears, the ideal specular reflection is greatly diminished, and more acoustic energy is scattered to all directions.

According to this definition of acoustic roughness, no seafloor is intrinsically rough or smooth – it all depends on the acoustic frequency considered. For seismic investigation using wavelengths ranging from 1 to 100 m, the seafloor (especially layered sediments) is very seldom "rough" compared to a wavelength, and considering mainly the coherent specular reflection from the seabed interface(s) is a valid approach for interpretation. On the other hand, for very high-frequency sonars, roughness is significant at the millimeter-scale of sand grains. Here, the specular echo is likely diminished, most of the acoustic field is scattered over a wide range of angles, and interpretation of the echo from the seafloor involves consideration of the roughness（Lurton and Lamarque, 2015）.

At the frequencies used by seafloor mapping sonars the backscattering from the seabed can generally be separated into two contributions (Lurton, 2010):

- Energy scattered by the interface (specular backscattering).
- Energy penetrating the sediments and reflected back by volume heterogeneities (volume backscattering). This process can become predominant at oblique incidents.

1.2.3. Combined model of the seafloor

As described above, the acoustic effects of the seafloor are driven by many different processes and their relative importance depends on the signal frequency (Lurton, 2010):

- The seafloor basically acts as a rough interface scattering the incident sound wave. The backscattered signal is the one used by seafloor mapping sonars.
- A noticeable part of the incident energy may penetrate the seabed because of the small impedance contrast between water and sediment. Even if absorption inside sediments is much higher than in water, low acoustic frequencies can propagate with reasonable levels.
- Processes similar to those in water propagation may occur inside the sediment.
- Various scattereres lie at the interface or are buried inside the sediment (shells, living organisms, minerals, etc...). They may generate additional scattering.

The various ideas above regarding reflection and scattering from the seafloor are incorporated into models that describe the seafloor backscatter strength at all angles (Lurton and Lamarque, 2015). Moreover, the physical processes, their interpretation and modelling differ greatly with frequency considered.

One of the important predictions of these models, which is borne out in experiment, as anticipated, is the strong angle-dependence of the seafloor backscatter. Close to vertical, the specular reflection phenomenon takes over, and this is the direction of the most intense echo level from the seafloor (Figure 5). Seafloors composed of grain-size sediments (e.g., silt and clay) tend to have low roughness, and in these cases the influence of the specular reflection decreases very quickly with increasing incidence angle. The smoother the interface, the more pronounced the specular regime is (i.e., highest level relative to oblique incidence angles, and the narrowest angular sector for the specular region). At oblique incidence angles, the scattering effect dominates because few, if any, facets of the seafloor point back towards the echosounder.

At oblique incidence angles, the angular dependence is generally small. The backscatter level is primarily controlled by the interface hardness (impedance contrast) and roughness; for soft sediments, this is the angle range where volume backscatter is at its highest. This "plateau" regime presents many advantages for seafloor-type mapping, thanks to its stability and to the good separation that is observable between various seabed types.

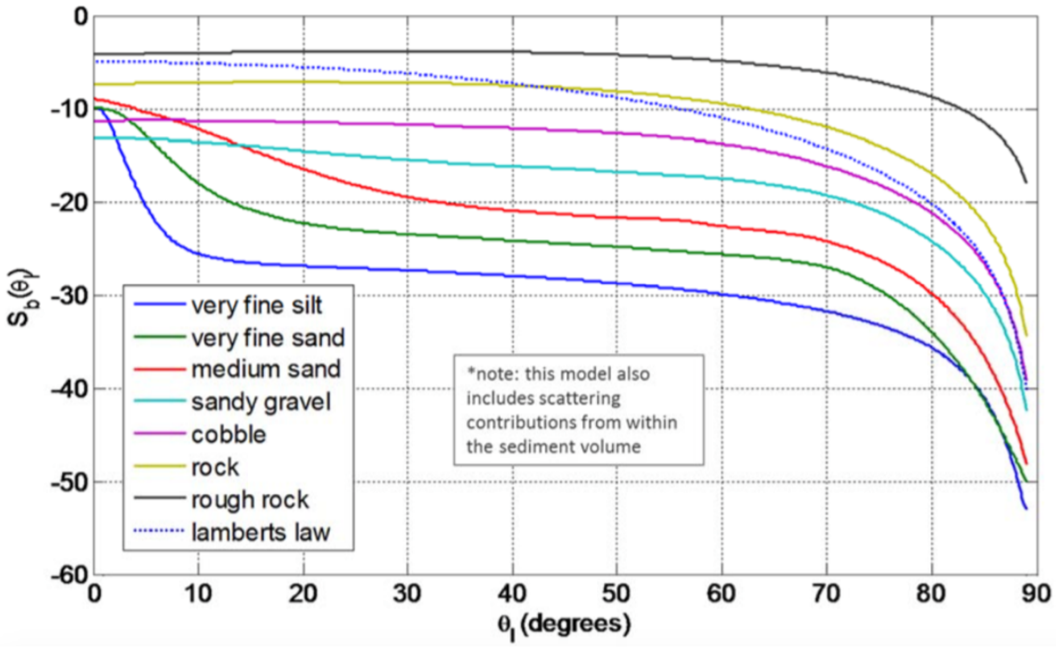

Figure 5 - Example of angle-dependent backscatter for different substrate types at 100 kHz, based on model results using the APL-UW High-frequency Ocean Environmental Acoustic Models Handbook, APL-UW TR9407 (1994) (Lurton and Lamarque, 2015).

At very low grazing angles, the backscatter response of the seafloor collapses as (1) the seafloor intercepts little (per unit area) of the acoustic power available to it; (2) the roughness response decreases; and (3) shadowing effects appear, decreasing the effective backscatter cross section.

The most favourable angle sector for BS measurement appears to be the "plateau" regime. This explains why backscatter mosaics often "normalize" angle-dependent backscatter to a reference value taken within this range of angles: the idea is to replace the slow angle variation of the plateau regime by no variation at all, after an appropriate compensation – and to affect one value measured at a reference angle (40° or 45°). As a result, a geologically homogeneous area will appear with a constant BS (on average) – the way it should have been recorded if the whole swath width would have been insonified at a constant angle.

The predictions shown in Figure 5 assume a frequency of 100 kHz. It has already been suggested that a smooth surface at low frequencies may look rough at high frequencies. This frequency- dependent behaviour is also predictable by models, as shown for a medium-sand seafloor in Figure 6. The same surface that looks smooth at 30 kHz, with a high specular reflection and a low oblique incidence scattering (dominated, in this case, by volume scattering), provides a much more uniform (with angle) backscattering strength at 400 kHz where the wavelength is an order of magnitude shorter. Over this decrease of frequency, Figure 6 suggests that the seabed response should change by as much as 7 dB at oblique incidence, and by nearly 14 dB at normal incidence. These ranges are rough guidelines: the exact frequency dependence should depend on characteristics of the roughness spectrum.

Taken together, the predictions shown in Figure 5 and Figure 6 suggest some caution must be taken when interpreting seafloor backscatter measurements collected with MBES. Current MBES collect data over a wide range of incidence angles (0°-65° or more) and have the ability to change frequency by an octave or more. These changes in incidence angle and geometry are likely to manifest themselves as changes in seafloor backscattering strength that if left non-accounted for could provide for significant errors in interpretation.

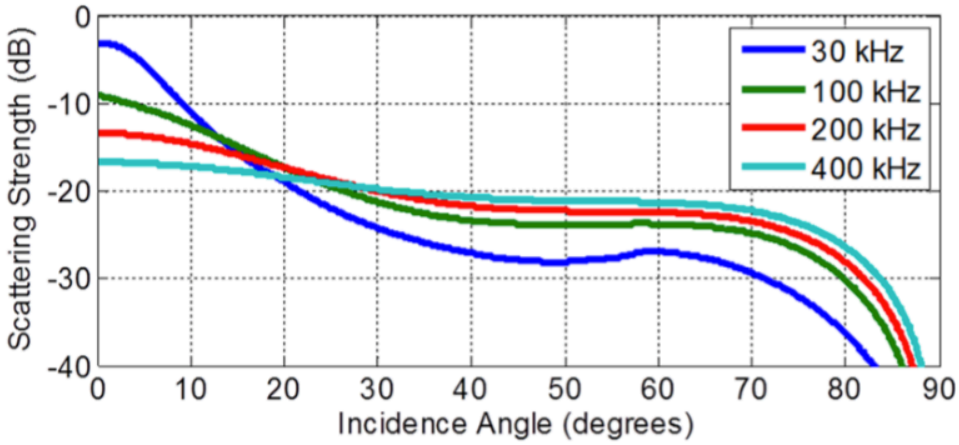

Figure 6 - Example of angle-dependent backscatter for medium sand at different frequencies, based on model results using the APL-UW High-frequency Ocean Environmental Acoustic Models Handbook, APL-UW TR9407 (1994) (Lurton and Lamarque, 2015).

1.3. Use of backscatter for seafloor mapping

Sediment mapping is important for understanding the physical processes, the impact of human activity, and the conditions for marine life on the seabed (Eidem and Landmark, 2013). Acoustic seabed classification (ASC) is a technology for mapping surficial seabed properties and sediment distribution with echo sounders (Anderson et al., 2008). The idea is that a change in sediment composition often implies a change in acoustic properties. This results in a systematic difference in the recorded echoes, provided the data have been corrected for extraneous influences, such as variable water depth or instrument settings.

Information about seabed composition is useful in a range of problems, including sonar performance prediction, benthic habitat mapping and marine resource management (Brown and Blondel, 2009; Ellingsen et al., 2002; Freitas et al., 2003; Haris et al., 2012), environmental monitoring (Medialdea et al., 2008; Wienberg and Bartholomä, 2005), and geotechnical engineering (Bartholomä, 2006). A scientific understanding of the physical processes that form the seabed is also a goal in itself, and new acoustic techniques for seabed mapping are instrumental to achieve this (Eidem and Landmark, 2013).

The prime and arguably the most objective information derived from MBES acoustic data, after water depth, is the acoustic facies, the spatial organization of seafloor patches with common acoustic responses and the measurable characteristics of this response. Maps of acoustic facies – most often simply represented by the post-processed backscatter data – are the initial material available to scientists to interpret habitat from remotely-sensed data. Although ultimately the classification of the acoustic facies in sediment classes is arguably the best approach to derive seafloor nature and obtain habitat maps, The acoustical facies correspond correctly to the habitat typology only on a relative scale, and some ambiguities remains as acoustic reflectivity may be not a fine enough indicator of habitat nature subtleties (Lurton and Lamarque, 2015).

Seafloor backscatter measurement has long been considered as a by-product of multibeam bathymetry and, at best, as a qualitative high-level indicator of the possible nature of the seafloor. Because backscatter data directly relates to sediment grain-size (Figure 3) and seafloor roughness, it has the ability to provide qualitative and quantitative information on the composition, i.e. the nature, of the substrate (e.g. Jackson and Briggs, 1992; Hughes Clarke et al., 1996). Furthermore, because the seafloor is the physical support of the benthic habitat, backscatter data has the added advantage to indirectly provide information related to fauna, flora and biodiversity at large (e.g. Cochrane and Lafferty, 2002; Anderson et al., 2008; Brown and Blondel, 2009; Brown et al., 2011). However, regional-scale quantitative applications of backscatter data for habitat mapping are recent and technically challenging (Brown and Blondel, 2009; Lamarche et al., 2011; Lucieer and Lamarche, 2011), but clearly, one of the key potential of backscatter data lays in its ability to represent a proxy for substrates and benthic habitat (see Chapter 3). This potential, in parallel with the need for objective and quantitative information on the seafloor from remote-sensed data, has resulted in a line of research that has developed acquisition, processing and interpretation of the backscatter signal as quantitative tools for geological and environmental purposes.

Seafloor studies have used backscatter data in different and complementary ways. Processing procedures can be broadly divided into signal processing and image processing methods. Signal processing focuses on data represented in angular or time space where the raw amplitude of returned signals is preserved. With image processing methods the backscatter signals are modified (flattened) to produce smooth looking image mosaics.

Due to seabed physical properties influence upon dispersion and attenuation of acoustic signal, many seabed classifications exist. The most common one refer to a textural analysis (Hughes Clarke et al., 1997; Collier, Brown, 2005).

Acoustic seabed classification (ASC) is a technology for mapping surficial seabed properties and sediment distribution with echo sounders (Anderson et al., 2008). The idea is that a change in sediment composition often implies change in acoustic properties (Eidem and Landmark, 2013). Seabed classification can be done visually, mechanically, and acoustically. All visual methods (divers, video, photography) and mechanical methods (divers, grab samples, cores, probes) are slow and manually intensive, thus expensive and not suited to extensive survey work. Acoustic methods, however, can cover large areas quickly as there is no need to stop the survey vessel.

However, sediment classification using acoustics alone is possible only in specific and unusual situations. The power of acoustic seabed classification is the ability to apply visual or mechanical classifications over much larger areas than point data alone would allow; that is, the sediment properties obtained from the point samples can be applied with confidence over entire regions that have been mapped acoustically.

Non-acoustic data, from direct sampling or observation, is usually used to relate the acoustic classes to the physical properties of the marine sediments.

Preston (2009) gives a statistical approach based on image amplitudes and texture that leads to automated segmentation of multibeam images. Seabed type (physical parameters) and acoustic system effects are compensated with a statistical approach comparing images and bathymetric data. By compiling tables of amplitude against range and grazing angle, systematic changes in amplitude with these two variables can be removed consistently. Classification, based on a large number of features, is done in image space to avoid artefacts common in mosaics. Unsupervised segmentation requires clustering, in which records are divided into their natural classes (Preston, 2009).

2. Hydrographic data Seabed Mapping

2.1. Generalities of hydrographic data Seabed Mapping

Hydrography is that branch of physical oceanography dealing with the measurement and definition of the configuration of the bottoms and adjacent land areas of oceans, lakes, rivers, harbours, and other water forms on Earth. Hydrographic surveying in the strict sense is defined merely as the surveying of a water area; however, in modern usage it may include a wide variety of other objectives such as measurements of tides, currents, gravity, Earth magnetism, and determinations of the physical and chemical properties of water.

The principal objective of most hydro-graphic surveys being conducted is to obtain basic data for the compilation of nautical charts with emphasis on the features that may affect safe navigation. Other objectives include acquiring the information necessary for related marine navigational products and for coastal zone management, engineering, and science.

The set of minimum criteria that must be met to achieve a recognised level of accuracy, or 'Order' of survey, is set out in Special Publication No. 44 *Standards for Hydrographic Surveys* (S-44), produced by the IHO, and now in its fifth edition (2008). Accuracies attained for all hydrographic shall equal or exceed S-44 specifications that form the basis from which IHO member states can produce their own national standards, and are intended to ensure a consistent quality of hydrographic information contained on internationally recognised nautical charts.

Typically, Special Order, or Order 1, applies to surveys of ports and harbours. The IHO Manual of Hydrography (C-13, 2012) provides more specific details of the application of surveying methodology.

Due to accurate standards and codified procedures hydrographic can be used for high resolution analysis of scientific values. Moreover, different data type or source integration naturally guarantee precise assessments about the area being investigated.

As discussed in chapter 1, multibeam echosounders con register many different type of data allowing high resolution seafloor morphology definition and acoustic backscatter (BS) intensity record. Acoustic BS, associated with in site calibration, allows seabed nature assessment, defining its physiographical, sedimentological and benthonic characters. Data integration leads a thematic cartography (thematic layers) throughout study marine environment with special reference to those areas with specific interest: biological (see chapter 3), volcanic risk and hydrothermal activity (see chapter 3), high antrophic impact (see chapter 5), etc.

Specific software allows, for example, morphological analysis of a bathymetric dataset, seabed classification and volumetric computations. One of the difficulties for establishing standardizations for operating with multibeam backscatter data is the reference to a wide variety of discipline backgrounds of the user community where the acoustic technical knowledge required for backscatter interpretation varies greatly. Not only is a product of user training but also user experience with MBES backscatter.

Seabed mapping requires:

- Specific data quality or data quality knowledge
- Availability of different type of dataset to be integrated
- Possibly dataset at special and temporal scales.

Backscatter data further supports the view of currently active canyon axes and heads, shelf areas around them and gullied canyon walls in terms of erosion and coarse sediment accumulation, as the high backscatter pattern found at these locations is indicative of hard, locally steep bottoms resulting from either rocky outcrops or sandy–silty deposits.

Submerged sites knowledge requires high resolution bathymetric survey that allow features recognition and, moreover, information about sediments physical properties. As discussed in chapter 1, seabed classification can be obtained visually, mechanically and acoustically, or, better, mixing the three techniques.

Visual methods (divers, video, photo) and mechanical (divers, grab samplers, coring), as punctual, are less rapid and manually challenging, wasteful and not ideal for a large survey.

Acoustic methods (singlebeam, multibeam, side scan sonar) allow faster survey coverage without stopping the ship. Seabed classification that uses only acoustic data, without ground truth, is possible only in specific situations thanks to acoustic backscatter signal analysis.

2.2. Hydrographic standards IHO S-44

The document provides minimum standards to be achieved for different types of hydrographic surveys. It is updated from time to time to reflect new survey techniques and practices. The first edition came out in 1968 and was entitled “Accuracy Standards for Hydrographic Surveys”.

Depth accuracy[1] is understood to be the accuracy of the reduced depths. In determining the depth accuracy, the sources of individual errors need to be quantified (e.g. errors in the positioning system, errors in the various sensors, errors in the geometry of the vessel, errors caused by tidal- and draft corrections, etc...). All error sources shall be combined to obtain a Total Propagated Uncertainty[2] (TPU). TPU results from the combination of all contributing errors, which include among other things:

1. measurement system and sound speed error;
2. tidal measurement and modelling errors;
3. data processing errors.

A statistical method for determining depth accuracy by combining all known errors shall be adopted and checked.

In fact, the TPU, determined statistically at the 95% confidence level[3], is the value used to describe the depth accuracy achieved. The TPU shall be recorded together

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[1] *The extent to which a measured value agrees with the true value.*

[2] *The interval (about a given value) that will contain the true value of the mea- surement at a specific confidence level (S-44, 2008). Uncertainty is based on either limitations of the measuring instruments or from statistical fluctuations in the quantity being measured (S-44, 2008).*

[3] T*he probability that the true value of a measurement will lie within the specified uncertainty from the measured value. ...the 95% confidence level for 1D quanti- ties (e.g. depth) is defined as 1.96 x standard deviation and the 95% confidence level for 2D quantities (e.g. position) is defined as 2.45 x standard deviation (S-44, 2008)*

with the sounding value. It is composed of a horizontal component (THU = Total Horizontal Uncertainty) and a vertical component TVU (Total Vertical Uncertainty). The maximum allowable vertical uncertainty for reduced depths as set out in Table 2 specifies the uncertainties to be achieved to meet each order of survey. Uncertainty related to the 95% confidence level refers to the estimation of error from the combined contribution of random errors and residuals from the correction of systematic errors. The capability of the survey system should be demonstrated by the TVU calculation.

	ORDER	Exclusive	Special	1a	1b	2	3 (Imprecise)
	Examples of Typical Areas	Shallow water in Harbours, berthing areas, and associated critical channels with minimum under-keel clearances or engineering surveys	Harbours, berthing areas, and associated critical channels with minimum under-keel clearances	Areas shallower than 100 metres where under-keel clearance is less critical but *features* of concern to surface shipping may exist.	Areas shallower than 100 metres where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area.	Areas generally deeper than 100 metres where a general description of the sea floor is considered adequate.	All areas where the accuracies do not meet the requirements of the previous orders
H	**Horizontal Accuracy (95% Confidence Level)**	1m	2m	5m + 5% of depth	5m + 5% of depth	20m + 10% of depth	> 20m + 10% of depth
V	**Depth Accuracy for Reduced Depths (95% Confidence Level)** (1)	*a* = 0.15m *b* = 0.0075	*a* = 0.25m *b* = 0.0075	*a* = 0.5m *b* = 0.013	*a* = 0.5m *b* = 0.013	*a* = 1.0m *b* = 0.023	Same as order 2
D	**System Detection Capability**	Features > 0.5m cubed	Features > 1m cubed	Features > 2m cubed in depths up to 40 m; 10% of depth beyond 40m (3)	N/A	N/A	N/A

C	**Type of coverage (M270)**	
	1. complete coverage	(multibeam, multi-transducer, acoustically swept);
	2. systematic survey	(single-beam echo sounder lines run parallel at pre-planned line spacing, LiDAR);
	3. sparse coverage	(lead-line surveys, reconnaissance, track soundings, spot soundings);
	4. unsurveyed	

Table 2 - Standards for Hydrographic Surveys (S-44, 2008)

Recognising that there are both depth independent and depth dependent errors that affect the uncertainty of the depths, the formula below is to be used to compute, at the 95% confidence level, the maximum allowable TVU. The parameters “a” and “b” for each order, as given in Table 2, together with the depth “d” have to be introduced into the formula in order to calculate the maximum allowable TVU for a specific depth:

$$[a^2+(b*d)^2]^{1/2}$$

where:

a represents that portion of the *uncertainty* that does not vary with depth (i.e. the sum of all constant errors in metres);

b is a coefficient that represents that portion of the uncertainty that varies with depth;

b*d represents that portion of the *uncertainty* that varies with depth.

2.3. Survey equipment procedures

The hydrographic surveyor contributes to the measurement of factors such as tidal height, accuracy of declared depth, and the required frequency of hydrographic surveys in accordance with the standardised survey procedures (C-13, 2012). The surveyor may also contribute expertise necessary for the measurement of a vessel's squat and roll, pitch and heave movement. Various methodologies exist for the collection, processing and presentation of hydrographic survey information. Whilst the presentation of such information is largely determined by the needs of the end user, the fundamentals of hydrographic data collection remain the same (e.g. the accurate measurement of water depth (Z) below a stated datum, and the position of this measured depth (X,Y)). Additionally, the hydrographic surveyor would be concerned with determining bottom type and as well the positioning of "intertidal" and shoreline features above a stated datum.

The widely accepted method for obtaining depth data has been with a singlebeam echo sounder (SBES), with position provided by electronic ranging equipment. Positioning has been made easier with the advent of the Global Positioning System (GPS), particularly in differential (DGPS) and real time kinematic (RTK) modes (see 2.3.1). The introduction of the multibeam echo sounder (MBES) has provided the ability to ensonify and measure much greater areas of seafoor to a higher level of detail, but it also requires greater knowledge to effectively use this technology.

Different methods for sounding are required when using either SBES or MBES. In general, the traditional methods, which involve soundings taken along parallel lines, at set distances apart according to the desired scale of the survey chart, apply to SBES, but are not necessarily appropriate for MBES operations. Significant differences of methodology for MBES operations include the orientation of the

survey lines in relation to depth contours, and the varying of line spacing dependent on the least depth of water, which determines the effective swath width.
Regardless of the type of equipment used, the running of additional lines (check or cross-lines) for the sole purpose of validating water level or tidal reductions is considered essential.
It is important that the limitations of the survey equipment used are fully considered during sounding operations. In particular, the performance of motion sensor equipment should be carefully monitored, and survey operations suspended when it is apparent that the equipment is not coping with existing sea conditions. This is particularly important in MBES operations where error tolerances are much smaller.
In the following paragraph the main equipment used for an Hydrographic survey is presented.

2.3.1. Positioning survey equipment

Differential GPS is widely used to fix vessel position during hydrographic surveys. The source of the differential corrections should be proven by comparison with a known survey control point, particularly if a local base station is established. GPS receivers should be configured to output positions in the desired datum (normally WGS84) with associated quality tags. The quality of the position should be monitored during sounding operations through examination of the GPS parameters in use (number of tracked satellites, dilution of precision (HDOP and PDOP), etc), and real-time comparison with a second positioning system is recommended. Post-processed differential is an alternative to RTK in instances where a high accuracy positioning solution is required. Users can navigate with a Satellite Based Augmentation Service (SBAS) such as WAAS while logging raw GPS aboard, and simultaneously at a reference (control) station ashore.
Real time kinematic GPS offers increased precision of the horizontal position, provided that the footprint of the echo sounder in use is of a comparable dimension. Users of the sounding data need to be aware that the horizontal accuracy quoted for an RTK GPS survey (or any other positioning system) may be affected by the beam width of the echo sounder. If the beam width is large, an increase in depth will increase the footprint on the seabed and degrade the actual positioning of the

soundings. This is, potentially, more of a problem with SBES as MBES beam width is usually much smaller. Additionally, the accuracy of position of the soundings will be improved with the use of motion sensor equipment.

2.3.2. Motion sensor equipment

The accelerometer is the standard type of motion sensor equipment, and different units range in their complexity, and in the precision they are capable of achieving. The correct installation and definition within the vessel reference frame is vital, and consideration should be given to obtaining assistance from the manufacturer if the user is unfamiliar with the equipment.

Kinematic GPS is becoming increasingly popular as an alternative method of correcting vessel motion, either in conjunction with, or in lieu of, accelerometer-based motion sensors. While providing a low cost alternative for measuring roll, pitch and heading, the update rate of the GPS (typically 10Hz) limits its ability to serve as an accurate heave measurement sensor. Thus, users of both types of motion sensors should take all practical steps to check their correct operation, preferably by some means of ground-truthing (e.g. quantifying the motion error residual in data collected over a known at seabed).

2.3.3. Tidal records

Sea level (tide) measurements of height and time are required to reduce collected soundings to Chart Datum, and they are subsequently used (as a continuous record over long periods) to determine tidal reference levels (e.g. MHWS[4]). Tidal observations are normally obtained via automatic recording gauges, which are permanently installed in many ports.

Other methods used to obtain tidal information include: manual tide pole (or staff) readings, referenced to a recognised datum (normally Chart Datum); and RTK GPS with centimetric precision in the vertical (Z) dimension. This latter method provides

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[4] *The mean high water springs (MHWS) is the highest level that spring tides reach on the average over a period of time (often 19 years). The height of mean high water springs is the average throughout the year (when the average maximum declination of the moon is 23.5°) of two successive high waters during those periods of 24 hours when the range of the tide is at its greatest*

a total height measurement, including tide height, but the geoidal separation must be accurately known, and the base station-rover range limitations clearly understood.

If Kinematic GPS is used in this manner, it is considered good practice to regularly correlate the results against tidal observations obtained by traditional (e.g. tide gauge) methods. Regardless of the type and method used, the equipment must be capable of measuring the tide to the required accuracy. If the method of tidal reduction requires interpolation between individual observations, the interval between observations must be such as to provide an adequate representation of the tide curve.

If automatic tide gauges are used, these must be regularly calibrated against a sta gauge to ensure their accuracy. The accuracy of the tide readings used to reduce soundings impacts directly on the overall accuracy of the survey.

In addition to the use of tide readings to reduce sounding data, a continuous record of tidal data (at least one lunar cycle of measurement) is important for the maintenance of accurate predictions for the port. It is recommended that an unbroken record of tidal readings is maintained and archived (accompanied by relevant calibration records) for this purpose.

It is good practice to confirm automatic gauge readings with the level of the tide observed on a co-located tide pole or tape, referenced to Chart Datum, at least weekly, if not daily, during survey operations.

These comparisons provide a valuable record of the gauge performance and should be retained (e.g. in the equipment data-pack). Where a permanently recording automatic tide gauge is installed, a full calibration of this system should be conducted at least annually, or when necessary after maintenance etc. This procedure involves manual observation of the pole readings over a full tidal cycle (preferably 25 hours although 12.5 hours may be sufficient) in order to correlate gauge readings with the theoretically 'correct' pole readings.

Regardless of the type of automatic gauge equipment being used to observe tidal data, confirmation of the tide pole zero against the Standard Port Reference Benchmark should be carried out by levelling at least annually, or whenever the pole is moved. Results should be fully documented, and retained with the tidal archive and/or equipment data-pack. Likewise, the benchmarks that reference the vertical datum should be checked regularly for movement by a closed levelling loop.

2.3.4. Survey vessel equipment offsets

The position of the various sensors on the survey vessel should be carefully measured in relation to a common reference point, and correctly applied within the survey acquisition or post processing software. This information must be included in the survey documentation. Furthermore, it should be noted that not all equipment and software engineers adhere to the same conventions when applying the axes and arithmetic signs used to describe a vessel's [Cartesian] reference coordinate system (Figure 7).

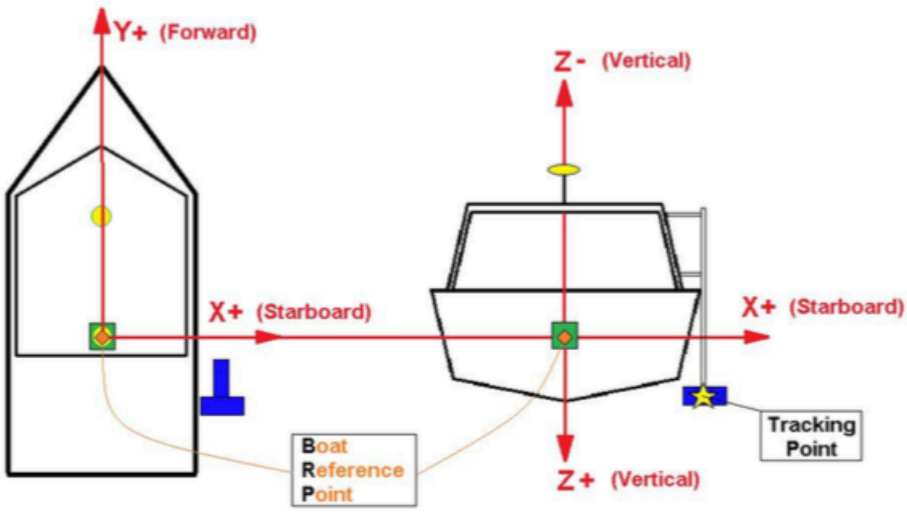

Figure 7 – Example of convention for Offset Measurements. Minor inaccuracies in the offset measurements can have significant effects on your Patch Test and any subsequent survey data that you collect.

2.3.5. Equipment calibration (patch test)

Preparation for the survey involves the planning of hydrographic observations and ancillary activity necessary to support the collection of data, the most important of which is calibration of the surveying equipment also called patch test. Equipment calibrations need to be conducted at regular intervals and documented in order to support the quality estimate given to the final survey dataset.

A patch test is a combination of hydrographic survey data collection procedures and the subsequent statistical analysis that is performed on this collected data to determine angular misalignments and timing differences in the multibeam system hardware (Figure 8).

The Pitch test determines the offset or angular misalignment between the fore/aft orientation of the multibeam sonar head with respect to the motion reference unit (MRU) or inertial motion unit (IMU). The Roll test determines the offset or angular misalignment between the port/starboard orientation of the multibeam sonar head with respect to the motion reference unit (MRU) or inertial motion unit (IMU). The Yaw Test determines the offset or angular misalignment between the orientation of the multibeam sonar head with respect to the heading sensor.

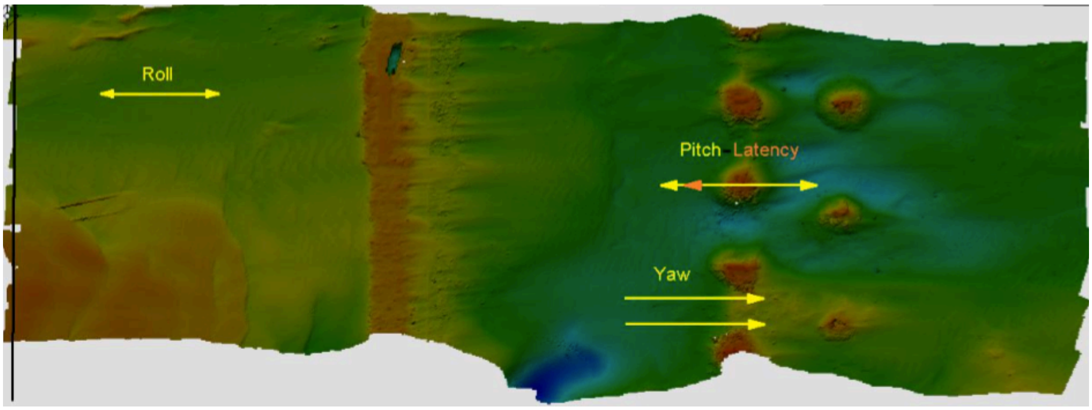

Figure 8 - Patch Test Areas

The Latency Test determines any time-synchronization differences between the time-tagging of the multibeam soundings with respect to the time-tagging of the position records. Take care that the time-tagging for the motion and heading data are also synchronized with the rest of the data collected.

2.3.6. Sound water profile measurement

A majority of bathymetric data are obtained using acoustic echo sounders where depths are derived from time measurements of an acoustic pulse traveling in a column of water. The velocity of the sound wave in the water column will vary depending on a series of factors, temperature and salinity being the major ones. The depths obtained must be corrected for this variation in sound speed throughout the sounding area in order to compute true depths. A Multibeam Echo Sounder (MBES) system must have a Sound Velocity Profile (SVP) applied while a Single Beam Echo Sounder (SBES) system or a Multi-transducer (MTES) system may have either a sound speed profile, a single sound speed, or a bar check correction table applied (C-13, 2012).

2.4. Data acquisition and processing

Data acquisition involves the proper collecting and recording of information. Care must be taken so that all written information (descriptions, sketches, calculations, etc.) be entirely understandable to anyone who may be required to process or verify any of the data successively.

One of the main requirements of data processing is to be able to ensure or qualify that you are in fact collecting what you say you are collecting and to verify that what is being acquired meets the standards specified for the survey. If a product is to be derived, data processing may be necessary to condition acquired data to meet the product specifications.

Ideally, all acquired data should be processed, coded and validated as the survey progresses. All data shall be processed according to the practices described in the regional Hydrographic Survey QMS procedures in use.

The processing of hydrographic survey data involves the removal of erroneous data, and through the selection of valid data, the preparation of a ‘cleaned’ data set for further processing, or for the generation of required products (e.g. sounding sheets) for subsequent analysis. It is also the stage where tidal data is normally applied, or where water level data collected and applied in real-time data acquisition (e.g. from RTK GPS) is validated. Typically, the practice of running survey check lines will serve to provide a comparison data set to validate the applied tide reductions, and detect as well, any changes in vessel draft or squat.

It is recommended that data is processed using a dedicated hydrographic processing package that preserves data integrity through audit functions, and is capable of shoal bias thinning. Modern packages offer almost complete flexibility and the potential to ‘manipulate’ or overly ‘smooth’ data – this practice is potentially misleading and should be avoided unless the magnitude of the change in the raw to the smoothed record is clearly stated.

Perhaps the most crucial aspect of data analysis is the assessment of the accuracy achieved. Soundings on a chart, sounding sheet, or other plots used as decision aids in navigation (including post dredge surveys), are meaningless without associated inforfomation on their quality.

The accuracy of soundings cannot simply be estimated without proper justi cation. In determining depth accuracy, all sources of individual errors need to be quantified and incorporated into a statistical model to derive the 'Total Propagated Uncertainty' (TPU).

2.5.Interpretation of geomorphology using bathymetry data

In the past, interpretation of undersea features would have been made from nautical charts or contour maps generated from bathymetric soundings. Now that full coverage data is more widely available, the most common method for visualization of bathymetric data is through the use of shaded relief Digital Terrain Models (DTM). These may be combined with color shaded maps representing depth to give an overall picture of the seabed terrain

Whilst color shaded relief is popular as an end product, many experts prefer to use simple grey-scale shaded relief for interpretation of features. Shading may be achieved through the application of a variety of algorithms implemented in desktop mapping software, which provide either a single, multiple or moveable light source (Figure 9).

The type of light source employed, and whether or not the bathymetry is vertically exaggerated is a matter of personal choice for the interpreter, will depend to a certain extent on the dataset being considered. Software offering a three dimensional view of the data, with the opportunity to 'fly' around the seabed is also employed by some scientists for interpretation of geomorphology. Traditionally geomorphology has been interpreted by geologists with regard for the processes affecting the geomorphic features created, and there is a whole scientific sub-discipline of geomorphology within the terrestrial realm. However, in the marine realm we have not yet seen any real specialism in this direction and marine scientists, whilst having a background in one of the traditional sciences, tend to be more multi-disciplinary. Since the advent of desktop GIS and related technologies, shaded relief maps can easily be viewed and, to a certain extent at least, interpreted/classified by scientists from all disciplines who are interested in benthic habitat.

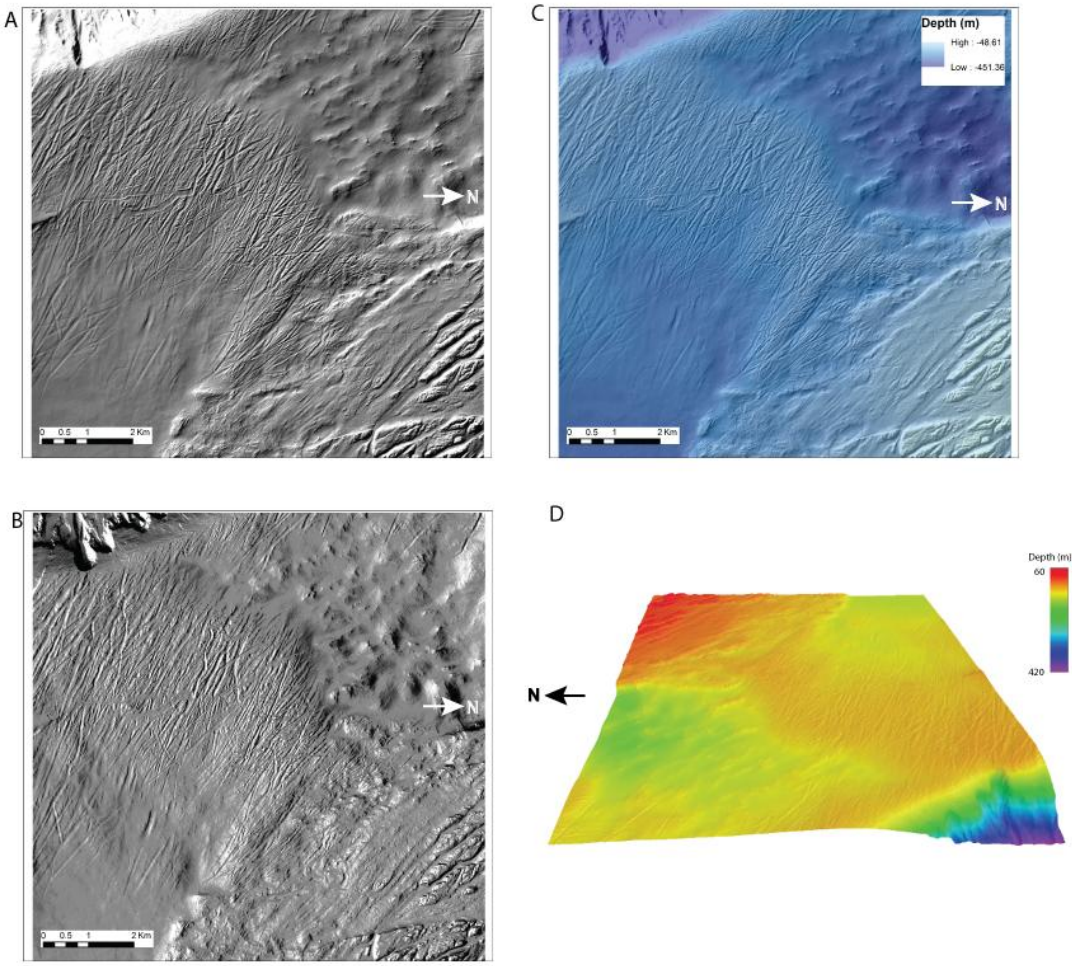

Figure 9 - Examples of 5 m resolution bathymetry as shaded relief (hillshade) (a) ArcGIS® grey-scale shaded relief with default parameters (single light source) (b) Jenness multi- directional grey-scale shaded relief (c) ArcGIS® colour-shaded relief (d) Fledermaus 3D colour shaded bathymetry – note orientation reversed to highlight bathymetric features. Figure M. Dolan. Data MAREANO - www.mareano.no.

Seeing such data can also help the biological community set a spatial context to their observations and has raised awareness among biologists and geologists alike that geomorphology is intrinsically linked to habitat (see Chapter 3). Interpretation of geomorphology by non-specialists, without full understanding of geological/geomorphic processes, however, can have its drawbacks. The overgeneralization of geomorphic features is one such potential risk; another is the misapplication of terminology.

2.5.1. Use of terrain variables derived from bathymetric data

There is a long term stream of literature related to terrain analysis of Digital Elevation Models (DEMs) in terrestrial applications, particularly in connection with soil science. Summaries focused on terrestrial terrain analysis and morphometric classification are available and all offer quite detailed insights into the computation methods involved and the key issues, including scale. Bathymetric data have more recently become widely available as raster data or digital terrain models (DTMs) which is equivalent to the terrestrial DEM. Bathymetric data, particularly full coverage multibeam data, offers tremendous potential for the generation of terrain variables that can be derived, and these data are now available at comparable resolutions to terrestrial DEMs, depending on the survey equipment used. Many desktop Geographic Information System (GIS) software packages offer tools to readily compute at least some quantitative terrain variables from bathymetry data (e.g. slope). These derived variables can be useful in describing, interpreting and classifying geomorphology in the marine environment, similar to practices for land data. They can also be of further use in geological interpretation and habitat mapping/modelling.

Calculation of terrain variables requires some method for mathematically representing the topographic surface and then using this to calculate the required terrain parameter. Surface representation is typically achieved by either using neighborhood analysis of raster pixels, or by fitting a polynomial expression to describe the surface, or digital terrain model.

Terrain variables con be divided into 4 main types describing different properties of the terrain: slope, orientation, curvature/relative position, terrain variability. Each of these terrain parameters was used in this work with different purposes: habitat mapping, seabed mapping, seabed morphology analysis.

2.6. Crowd source bathymetry

The hydrographic community is discussing right now about the use of crowded sourced bathymetric data to empower marine knowledge and give an answer to the constant need of data especially in those areas not frequently surveyed. It is clear that in order to ensure data usability it is necessary to define standards and best practices to be assimilated inside the methodological approach previously described. This is the main aim of the International Hydrographic Organization (IHO) Crowded Sourced Bathymetry Working Group[5] (CSBWG) .

Crowdsourced bathymetry (CSB) data may be collected by any type of vessel, using a variety of sonar systems and for myriad reasons. Enlisting the resources of recreational boaters, pilot boats, tug boats, cruise ships, as well as fully equipped research ships in the "opportunistic" mode, this acquisition of bathymetric data may potentially open data streams of current observations to navigators, cartographers, scientists, engineers, and coastal zone planners. In fact, technology has reached the point where any boater can buy an echo sounder kit, add a GPS system, record depth measurements, and make their own geospatial observations in a common reference frame. The strengths and benefits of CSB data are the temporal frequency in repetitive and constant observations in heavily trafficked areas, access to an unlimited workforce, availability of critical nautical data for the maritime community within a short timeframe, and engagement of the wider user community that will readily contribute to the mapping of our coastal zone.

For example, approximately 50% of the sounding data shown on US NOAA nautical charts is pre-1940, collected by antiquated lead-line soundings and wire drags. Even the 500,000 square nautical miles of the most navigationally significant Economic Exclusive Zone (EEZ) waters would require 167 years to survey. Crowdsourced data can significantly augment authoritative geo-databases and provide answers to critical mapping deficiencies. The challenge in the marine geospatial sector is to ensure the reliability of crowdsourced data by managing and structuring the process to ensure

[5] https://www.iho.int/srv1/index.php?option=com_content&view=article&id=635&Itemid=988&lang=en

that it can be confidently relied upon as useable and accurate.

However, navigation safety depends on data quality and accuracy. Hydrographic surveying is a rigorous, professional engineering discipline. There is general definite appeal to the concept of crowdsourced bathymetric data but the issues around using crowdsourced data are complex. Data quality, data processing and liability are at the top of this list. Looking into the future, it is necessary to take a measured approach to accepting third party data for use in nautical charting to help fill in the blanks.

Hydrographic Offices and Services charting products are compiled from high-quality, standards-compliant hydrographic survey data, since the chart will never be better than the data that went into it. A cadre of willing but untrained volunteers using uncalibrated equipment of differing quality, with unknown software and algorithms, under varying operating conditions and gathering incomplete supporting and metadata is not a substitute for controlled measurements.

Data processing is also an issue. Once collected, hydrographic survey data is processed using consistent and standard methods to arrive at a final answer and charted to help mariners to make sound navigation decisions. This is a labour-intensive process in which human judgment is intentionally applied. Experience has shown that feeding non-standard sources into this process explodes the labour required but accepting data into databases is costly and inefficient.

The aim to CSBWG is to provide guidance to empower a wide range of mariners to collect and contribute bathymetric data in a way standard enough to make the data as useful as possible to the broadest group of users. The important social engagement aspects of crowdsourcing such as gamification and recognition are also beyond the scope of the guidance document under preparation.

Although crowdsourced bathymetric data has the potential to improve global hydrographic charts by providing reconnaissance information for future systematic surveys and the identification of possible hazards to navigation, much of the data will not be suitable for direct incorporation into nautical charts. An analysis of data uncertainty will help users determine the feasibility of using the data for various applications.

Moreover, crowdsourced bathymetry can be used to assess chart accuracy. Crowdsourced reports serve an important role in focusing attention on trouble areas.

The data helps cartographers determine whether a charted area needs to be re-surveyed, or if they can make changes based on the information at hand. Even with very sparse data, cartographers can make improvements to nautical charts.

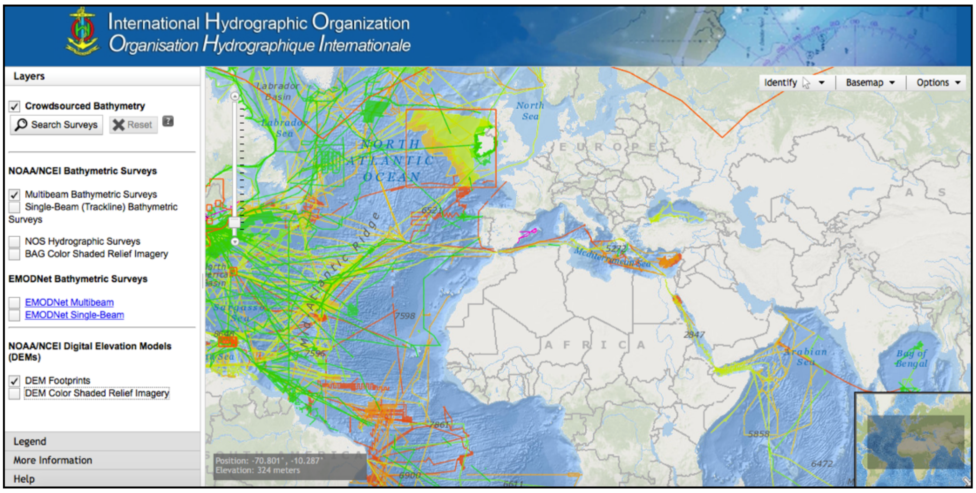

Figure 10 – Crowdedsourced bathymetry viewer (https://maps.ngdc.noaa.gov/viewers/csb/index.html)

Less than 5% of our oceans are mapped with in situ soundings, making it critical to preserve and share the data already collected and to identify and work together to fill high priority data gaps to support these important uses. The International Hydrographic Organization Data Centre for Digital Bathymetry (IHO DCDB), established in 1988 to steward worldwide bathymetric data on behalf of the IHO Member States, provides long term archive of and access to single and multibeam deep and shallow water ocean depths contributed by a range of mariners (Figure 10). IHO DCDB welcomes bathymetric data and metadata, accepts descriptions and spatial footprints of data that is already online and of data that are not publicly available to provide easy search and discovery. The United Kingdom Hydrographic Office (UKHO), other IHO Member States, and the IHB in cooperation with the Professional Yachting Association (PYA), have recently been engaged in various pilot CSB projects that have confirmed the feasibility of the CSB approach. There are also a number of commercial and volunteer based organisations using similar methodology (e.g., Olex mapping system, Sea ID, TeamSurv, ARGUS, etc…).

3. Integrated mapping of deep water seabed features

3.1. General settings of the survey

The Italian Navy, using hydrographic survey vessel and personnel from the “Istituto Idrografico della Marina” (IIM), in cooperation with ENEA Marine Environment Research Centre, surveyed the Levante Canyon system, located in the offshore area of “Cinque Terre”, eastern Ligurian Sea, NW Mediterranean (Pratellesi et al., 2014).
The purpose of the operation was on the one hand to collect the data necessary for the updating of nautical documentation and on the other hand to carry out scientific research on the seabed nature and specifically on deep coral banks. The current investigation was based on those historical records, and in this chapter the results of this morphological and biological studies are presented, focused between 525 and 575 m.
High-resolution (S-44, 2008; C-13, 2012) bathymetric data method analysis was applied in order to characterize seabed features supporting geomorphological and biological studies in this peculiar deep sea area. Both survey and processing phases were carried out taking into account precise standards (hydrographic), developing a multi-focus approach that allowed the discrimination of particular features in a deep water domain.
In the last 30 years, technological developments and stimulating discoveries have promoted deep-sea research, and new marine habitats and ecosystems have been described and investigated at an increased pace (Ramirez-Llodra et al., 2014). Among them, habitat-forming, deep-living cold-water corals (CWC) have been mapped in progressively more regions thanks to the improvement of remote sensing technologies for high-resolution bathymetry and ROVs and AUVs for direct exploration and experimentation (Huvenne et al., 2003, Wynn et al., 2014).
In particular, throughout data integration and the use of seabed-mapping technologies it was possible to obtain a high-resolution (HR) study of seabed morphology and nature, discriminating benthic features and habitats at different spatial scales. The

methods used for this hydrographic research are based upon data integration and multiple focusing approaches to identify areas to be investigated with different resolution systems in order to perform data exploitation and multiple usages of available resources.

This survey provides not only a detailed mapping of the variable morphology of the proximal area of the Levante Canyon, but it also investigates the seabed nature and biological communities within the canyon system for the assessment of a potential Site of Community Importance (SCI) under the European Commission Habitats Directive (92/43/EEC). In particular, Cold Water Corals (CWC) provide a complex structural marine habitat hosting high levels of biological diversity, which are in the reef habitat three times higher compared to the surrounding seabed. For this reason they fall within the habitats that deserve protection (EU-Habitat 1170 "Reefs").

Preliminary observations and data interpretations suggest that the Levante Canyon shows interesting geomorphologic underwater features. Further studies, already planned, will focus on ecological aspects, for a complete characterization of the habitat of CWC to suggest appropriate protection measures.

The results of this integrated survey and the dual use approach were presented at the European Geoscience Union (EGU) Meeting (Vienna, 27 April – 02 May) (Delbono et al., 2014).

3.2. Cold water corals in the Ligurian Sea

Cold Water Corals live over a wide range of latitudes from tropical to polar regions and from shallow waters to the deep sea (Roberts *et al*., 2003). Ecosystems formed around CWCs are generally found at depths from 40 m to 2000 m (Roberts *et al*., 2006; Cordes *et al*., 2016) in waters with temperatures between 4 and 13 °C (Freiwald, 2002), on different hard substrates including canyon walls, landslides and even the legs of oil rigs (Davies *et al*., 2007). These areas usually provide a complex structural habitat supporting a diverse associated fauna (Henry and Roberts, 2007), and so are recognized as biodiversity hotspots .

Although the inventory is continually growing, currently over 1300 species have been reported from CWC reefs (Myers and Hall-Spencer, 2004; Mortensen and

Fosså, 2006; Henry and Roberts, 2007; Guerra-García et al., 2008). In the Mediterranean, the CWC province of S. Maria di Leuca (Ionian Sea, Southern Mediterranean) is reported to host more than 250 species (D'Onghia *et al*., 2010; Mastrototaro *et al*., 2010).

Cold-water coral communities are frequently heavily impacted by fishing activities, mostly bottom trawling (e.g. Hall-Spencer *et al*., 2002, Roberts, 2002 and references cited therein), long-lining and gill-netting (Lumsden *et al*., 2007).

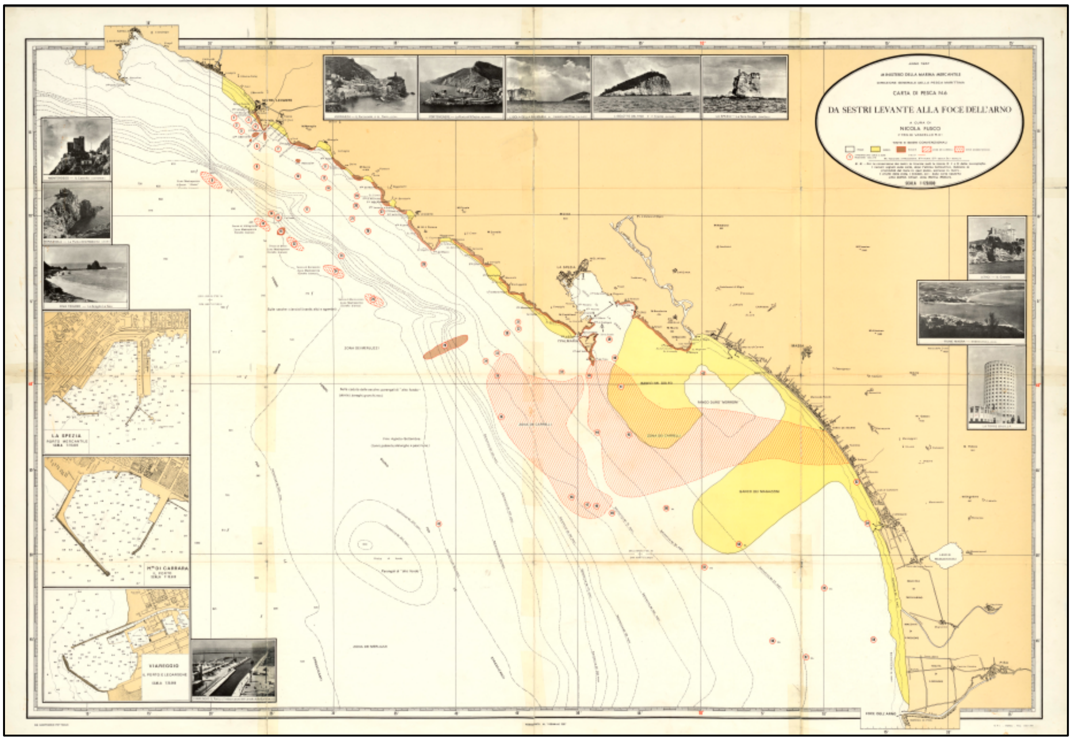

Figure 11 - Fishing map no. 6, Admiral Fusco (1967)

In the Ligurian Sea (NW Mediterranean), the first record of *Madrepora oculata* dates back to 1920, offshore from Punta Mesco. Later, an initial detailed report on CWC occurrence, specifically in the eastern sector (i.e. from Punta Mesco to Sestri Levante), was compiled by Rossi (1958) during the 'Calypso' cruise, carried out in 1957 (Blanc, 1959). The author referred to living colonies of *Madrepora oculata* from 200 to 500 m, in form of "*isolated areas, differing in their extension, recur frequently and approximately form a chain in the area examined*" with the deeper colonies (at 400-500 m) growing on a wide base of dead polyps covered by a brown oxide coating. Rossi also reported the occurrence at 600 to 700 m of dead colonies of *Lophelia pertusa* covered by a rich epifauna (different anthozoan species, including some rare records such as *Stenocyathus vermiformis*), together with live colonies of *M. oculata*.

Ten years later, in the 'Fishing map no. 6' (Figure 11), Admiral Fusco (1967) reported five 'madreporic' areas (accounting in total for *ca*. 900 ha) in the eastern Ligurian Sea, from Punta Mesco to Sestri Levante, from *ca*. 200 to 500 m depth, where trawl-fishermen occasionally collected branches of *Madrepora oculata*. Morri *et al*. (1986) reported the occurrence of CWC in the Tigullio Gulf (near Sestri Levante) and 15 years later Tunesi et al. (2001) confirmed the presence of coral, observing small colonies or sparse branches of *Madrepora oculata* between 210 and 561 m from the submersible 'Cyana'.

There are no data from the area suggesting the presence of CWC reefs below those depths (Fanelli *et al*., 2014). In the last five years, some local fishermen (trawl- and long-line fisheries) have reported the occurrence of coral branches in their nets. Additionally, older fishermen have testified to an intense and destructive trawl-fishery by a foreign fleet fishing in the area during the 1970s and 1980s using nets modified with rubber rollers similar to those used in the North-Atlantic (the so-called "rock hopper gear": Harrald and Davies, 2009).

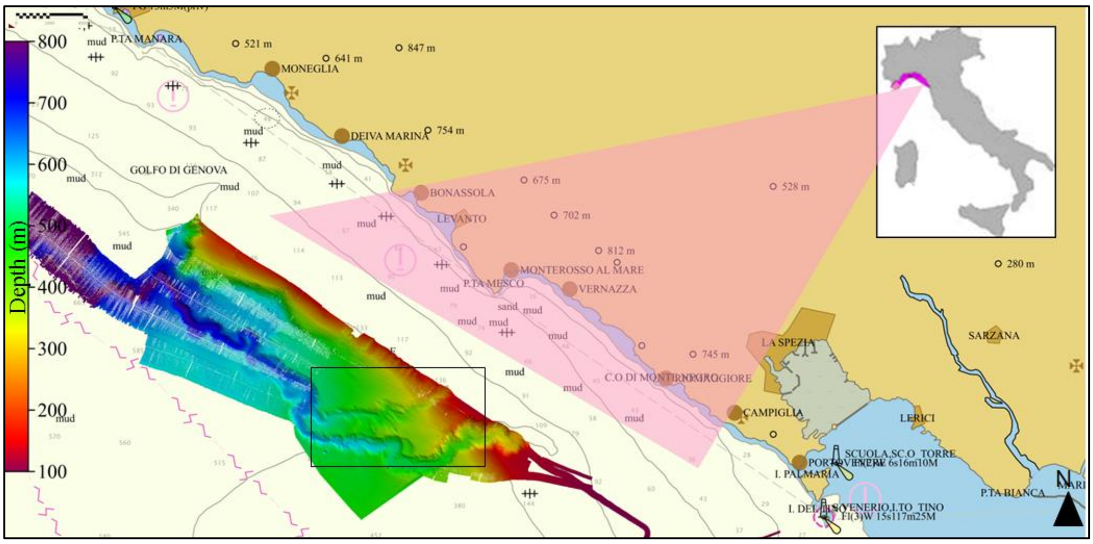

Figure 12 – Map of the research area showing MBES data. Investigated seafloor depth from 150 m to 800 m (red min/blue max). Black square indicate the section studied in detail (Pratellesi et al., 2014)

3.3. Matererials and methods

3.3.1. Study area

The Levante Canyon is the easternmost major indentation in the continental slope of the Ligurian Sea (NW Mediterranean); that slope drops away from a very narrow continental shelf with a maximum width of 2 km (Migeon *et al*., 2011). The Levante Canyon (Figure 12 and Figure 13) is the most prominent morphological feature of the Ligurian Apennine margin: a meandering submarine valley, incising the outer continental shelf approximately 6 km from offshore toward the village of Riomaggiore (between Punta Mesco and the city of La Spezia). Its direction is almost parallel to the continental shelf edge, extending west and finally merging with the Bisagno Canyon south of the city of Genoa (Figure 13).

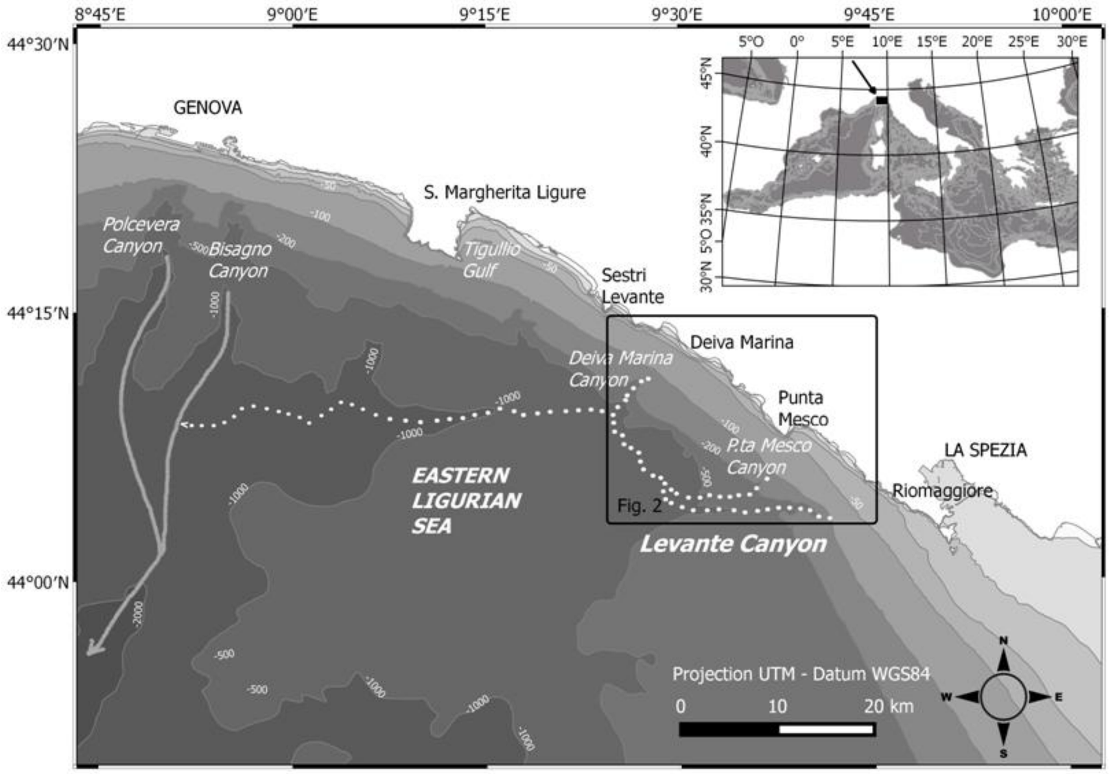

Figure 13 - Study area: the Levante Canyon in the Eastern Ligurian Sea and its tributary canyons (P.ta Mesco and Deiva Marina Canyons). The white dotted line indicate the approximate position of the canyon thalweg, finally merging the Bisagno Canyon offshore the city of Genoa.

The morphology is due to both tectonic and erosive origin (Corradi *et al*., 1987):

Eastern Ligurian Sea continental margin is structurally controlled by actively disjunctive tectonics (Fanucci and Morelli, 2012), and the Levante Canyon does not show a clear connection with any sub-aerial valley or drainage system (Morelli, 2008). The active head of Levante Canyon cuts the outer continental shelf at around 100 m depth (Delbono, 2016), and the canyon is likely an efficient conduit, passing fine sediments, probably including significant amounts of terrestrial nutrients, from the continental shelf to considerable depths. The Canyon thalweg meanders, and its flanks are very steep (10°-25°) (Delbono et al., 2014, Pratellesi et al., 2014). Along the first 30 km downslope in the canyon, two tributary canyons converge into the main Levante Canyon: the Punta Mesco Canyon, joining around 5 km off Punta Mesco, and the Deiva Marina Canyon, which intersects on the outer continental shelf around 6 km off Deiva Marina.

The area is an important fishing ground for several trawlers that have their bases mainly in the harbours of Santa Margherita Ligure and La Spezia. Trawl fishing is practised between 50 and 700 m.

3.3.2. The survey

The Levante Canyon was investigated in autumn 2013 on board Italian Navy hydrographic ships through high resolution multibeam (MB), side scan sonar (SSS) and image data acquired by a Remotely Operating Vehicle (ROV) in order to study the seafloor features and ecological characters (Figure 14).

Bathymetric data were acquired using a multibeam system, SeaBeam Elac 1050 (with a nominal sonar frequency of 50 kHz, 126 beams and a swath equal to 100°), mapping the eastern part of the Levante Canyon between 150 and 800 m depth (Figure 14), covering a surface of around 170 km^2 using a 30% line overlap. Swath bathymetry data processing was carried out with the QPS QINSy, CARIS HIPS and SIPS software products; visualization of bathymetric data was obtained with the QGIS program, including contouring, bathymetric profiles and shaded-relief maps. GIS spatial analysis was also applied to the project data.

Additionally, a Side-Scan Sonar (SSS) survey was performed with a Klein 3000 (nominal frequency 100-450 kHz) on the easternmost CWC bed that, based on 'historical' findings (Fusco, 1967), is located in the upper part of the tributary Punta

Mesco canyon between 370 and 510 m (inset Figure 14), covering an area of 11 km^2. SSS data were processed with SonarPro software.

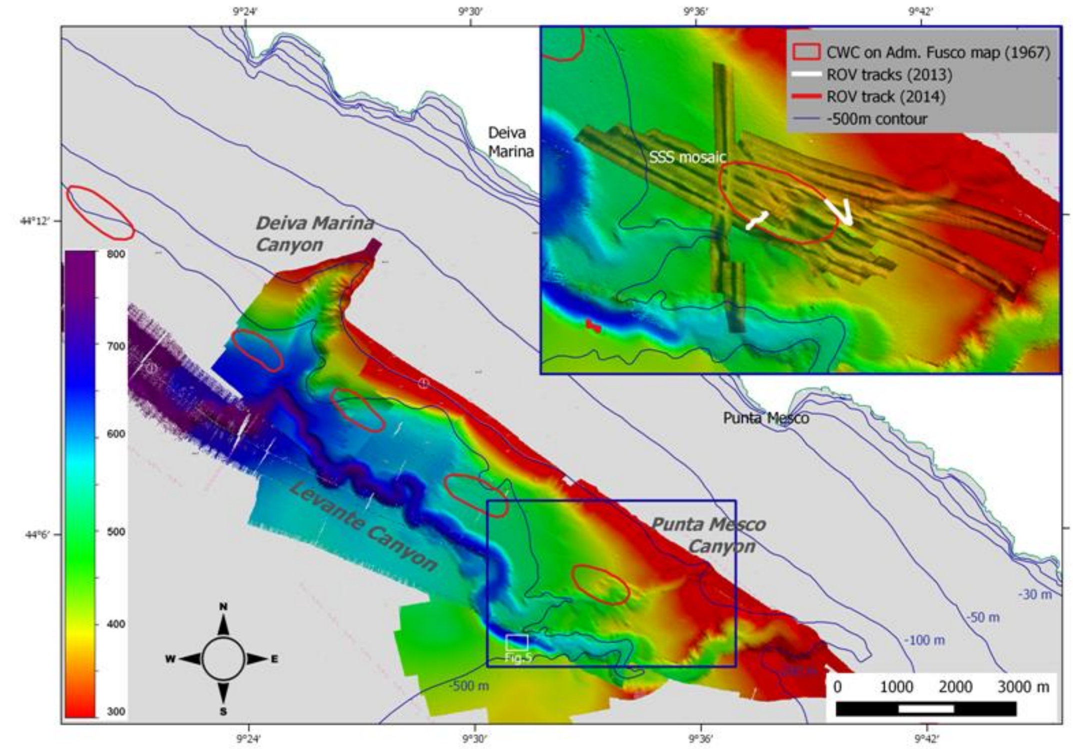

Figure 14 - Swath bathymetry of the Levante Canyon and location of five CWC historical areas indicated on 1967 Adm. Fusco map (red ellipses). Inset: Side Scan Sonar mosaic with indication of 2013 Pluto ROV tracks (white lines) and 2014 Pegaso ROV tracks (red line)

A further swath bathymetry mapping was conducted in May 2014 on board the Italian Navy Hydrographic Vessel 'Aretusa' with a hull mounted, multi-beam system, the Kongsberg Simrad EM-302 (30 kHz, swath 140°), with 50% line overlap, in order to map two areas of the Levante Canyon at higher resolution: an upper meandering part before it joins with the tributary Punta Mesco Canyon and Deiva Marina Canyon. Those had not been entirely mapped in the first multi-beam survey. Acoustic data were calibrated using sound velocity profiles from CTD data collected during the cruises and then processed and gridded with a cell size of 10 x 10 m.

Finally, two Remotely Operated Vehicle (ROV) missions were carried out, one in the upper part of the tributary Punta Mesco Canyon between 378 and 510 m and the other in a reach of the Levante Canyon between 510 and 580 m. In both surveys, ROV footage was taken at a constant distance (1-1.5 m) from the sea bottom Analysing videos from both ROVs, the presence/absence of thanatofacies (dead and/or partially buried corals) and living colonies were determined.

3.4. Data analysis and results

The integrated approach of multibeam (MB) and Side-Scan Sonar (SSS) allowed us to study the seafloor features of the Levante Canyon, which are characterised by a rough morphology of highs and depressions.
In fact, first data allow us to a seabed mapping of the study area with high detail of seafloor shapes, to be extended to other similar sectors of the canyon catchment area, constituted by a dendritic pattern of each individual gully network. The highest values of slope (17◦) can be found in the steep canyon heads and flanks. Slope values up to 10◦ can be seen depicting sea-bed mounds on the northernmost and central interfluve (Figure 15).
Through digital processing techniques, seabed morphology maps, based shaded-relief bathymetries, were obtained. Echo-strength data (reflectance) can be extracted and presented as seabed backscatter maps that display not only information on sediment types (Kenny, 2003), but also seabed morphodynamics and habitat (Kostylev, 2012).
MBES data show that the Levante Canyon is a peculiar meandering submarine valley, extending SE-NW (coast direction), strongly structurally controlled, characterized by a main valley with channels and drainage structures that determine moderate hydrodynamics. These geometries are typical of a valley with a complex origin, referring to different tectonics and hydrodynamics processes clearly shown by slope maps (Figure 15). In fact, from a combination of both shaded-relief bathymetries, slope analysis and backscatter maps, the seabed can be interpreted in terms of both relict and recent processes (erosive-depositional).

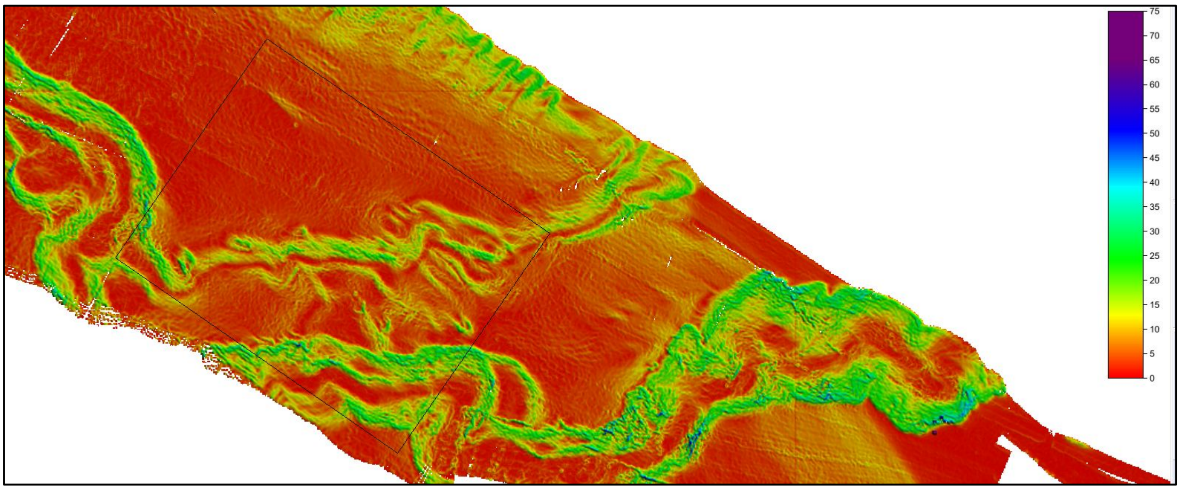

Figure 15 – Slope (%) map showing the particular meandering shape of the canyon system at different scales

Swath systems (such as SSS) are most likely to provide the best HR maps made out of pictures, particularly over wide areas, as the Levante Canyon. They provide information on sediment texture and bedform structure and allow for dynamic processes (e.g. sediment transport) to be deduced.

For broad-scale mapping of aggregate habitat (>1 km^2), SSS and MBES are considered to be the most cost-effective means of discriminating different sediment types and dynamic processes. For small-scale habitat classification (<1 km^2), high-resolution SSS, associated with ROV underwater cameras allow for the ground-truthing of the surveyed area.

It is clear that the different level of HR spatial analysis is just limited by the instruments and choice approach made during the advancement of the survey. However, the system selection will depend on survey objectives and scale of the area to be mapped. For baseline broad-scale mapping of the continental shelf, where geological features, such as sand valley, channels, gullies, mounds and reefs are of interest, the quantitative data offered by MBES in conjunction with object detection in the order of tens of meters (at 200 m depth) is often the preferred choice. However, for inshore areas and depths <50 m where identification of small (<10 m) habitat features may be required, a combination of MBES and SSS ensures that both quantitative bathymetric data (0,3 m - 1 m resolution) and qualitative, high-resolution habitat relief data (10 cm resolution) are obtained.

The MBES and SSS data highlighted the heterogeneous nature of the seafloor, characterised by stretches of homogeneous seabed with low acoustic backscatter intensity and also by intermittent high intensity signals (Figure 16). Moreover, they show higher acoustic backscatter in the deepest sections of the canyon than interfluve and the changes in the seabed nature over the mounds are highlighted as areas of variable intensity (Figure 16).

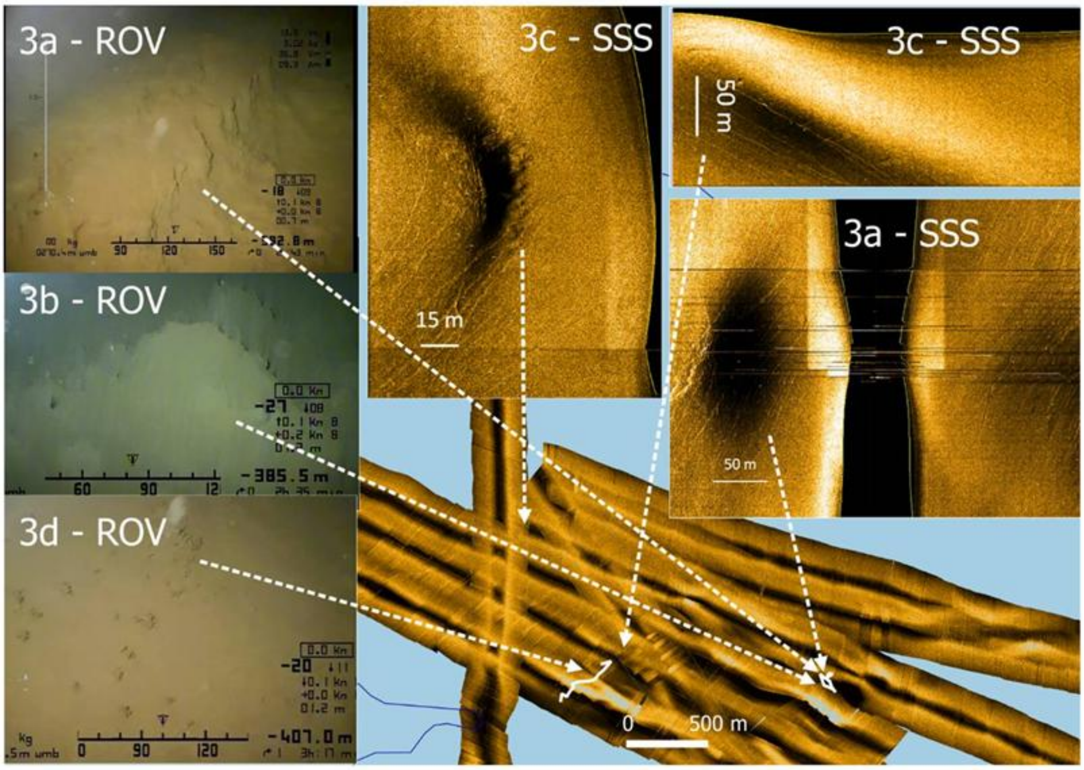

Figure 16 - SSS mosaic and SSS evidences of trawling signs and relevant morphologies observed by ROV: (3a) evidence of structural relief with a tabular shape or relict reef structure at 382 m depth shown both by SSS and ROV surveys; (3b) small bedform morphologies evidenced by ROV like sharp "ridges" around 0.5 – 1 m height above the seabed, likely indicating buried bio-constructions at 380 – 400 m depth covered by very fine sediment draping; (3c) signs of intensive trawling fishing evidenced in SSS sonograms; (3d) small coral formations around 10 cm height. White lines on SSS mosaic indicate the 2013 ROV tracks.

The latter, rough seabed shapes correspond to hard substrate covered by fine sediment draping: evidence of structural relief with a tabular shape, possibly relict reef structure. An example from a site at 382 m depth, that appeared on both the SSS and ROV surveys, is shown in Figure 16-3a. In other areas the seabed backscatter is less strong, bedform morphologies are evident in the ROV sonograms as sharp "ridges" around 0.5 – 1 m in height above the surrounding bottom (Figure 16-3b).

They were located exactly in the area of the historical coral sites mapped by Admiral Fusco in 1967. These ridges likely indicate buried bio-constructions at 380 – 400 m that are covered by very fine sediment. Furthermore, the SSS revealed widespread footprints of intensive trawling activities, and different types of tracks produced by trawl doors were recorded (Figure 16-3c)

3.4.1. Multiple focusing

A multiple scale methodology approach was chosen in accordance with instruments and software available on board the Italian Navy Hydrographic Ship Magnaghi. MBES data acquired were processed by CARIS HIPS&SIPS software and compared with the IIM database. At first a seabed map of the area with high detail of the seafloor shapes was obtained, and used for other similar sectors of the canyon catchment area. The canyon is characterized by a gully network with a dendritic pattern.

At a metric scale (medium scale), acoustic backscatter analysis permits to accurately describe drainage canyon system (with variable slope up to 30% in the channel sectors) and its geomorphic variability in relation with seabed nature. HR maps permit the identification of sites of interest for substrate dislocation and benthic features. These were investigated at a larger scale (sub-meter) by SSS Klein 3000, 100-500 kHz. SSS operation was planned in accordance with seafloor canyon morphology and optimising recording data operations on board. In fact SSS lines were recorded in a selected area from 510 to 370 m depth (Figure 17), where the seafloor morphology showed variable and interesting features characterized by different size, shape and slope.

Finally, the integration between MBES and SSS data, morpho-bathymetric analysis and acoustic characterization of the sub bottom allowed for the individuation of a large scale feature to be calibrated by ground - truthing. Figure 18 shows the section, chosen for its morphology, and used for higher resolution analysis with SSS. The presence of round structures (mound) of multi-meter dimensions inside the drainage system must be remarked. MBES and SSS data show higher acoustic backscatter in the deepest sections of the canyon than in the interfluve and the changes in the seabed nature on the mounds are highlighted as areas of variable intensity characterized by high level of reflectance typical of substrate. Besides that, SSS images show flat heterogeneous seabed with signs of trawling fishing (Figure 18).

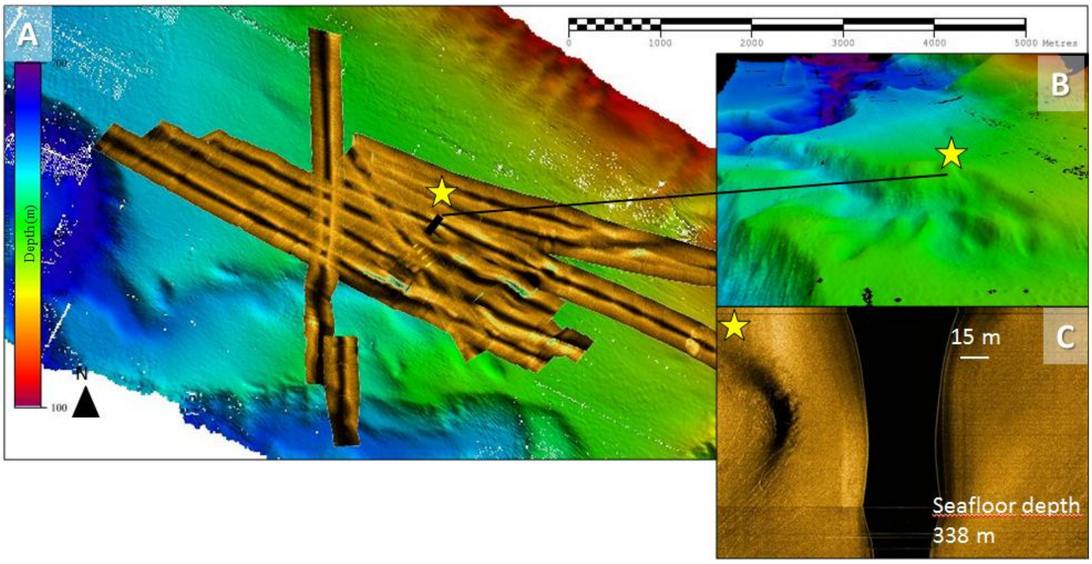

Figure 17 – (a) SSS images overlapping MBES data; (b) 3D MBES, from the westernmost upper channel down to the deepest part of the Levante Canyon, and the star indicates the site of C image; (c) SSS acoustic image of the interest seabed referring to a mound structure showing hard and mixed nature bottom (sandy/muddy sediments and small coral colonies) with clear signs of trawling fishing.

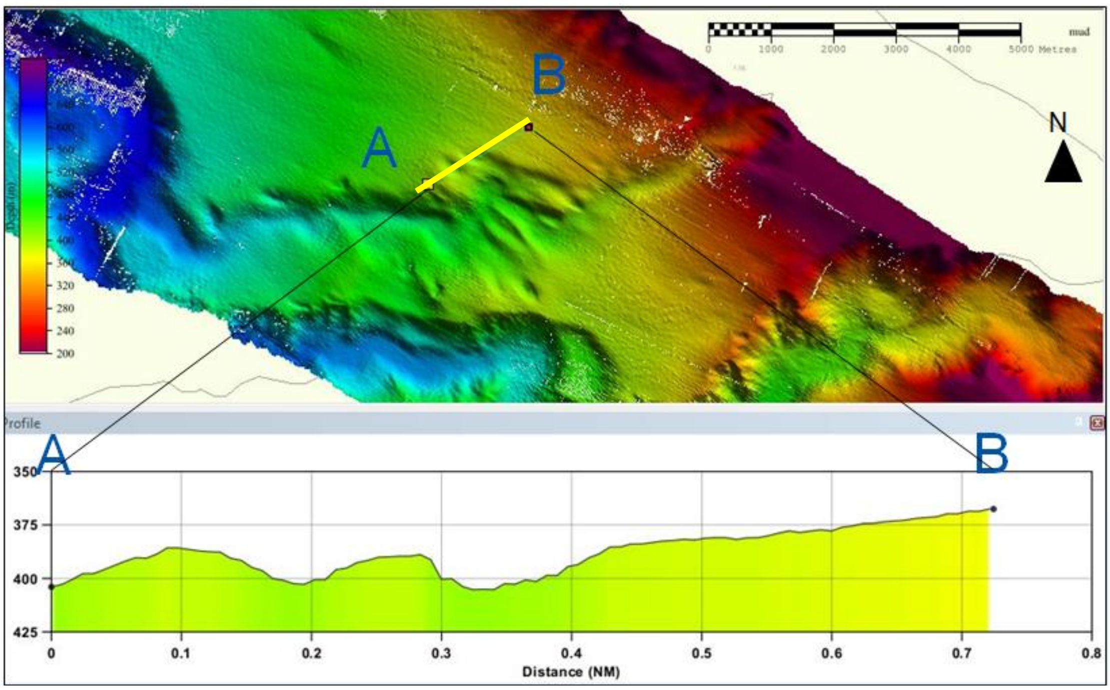

Figure 18 - Detail of MBES study area; AB is a cross profile of a canyon flank and a mound.

In conclusion, the direct sampling bottom data collected on the mounds displayed the presence of biological communities, mainly typical of deep muddy bottom and small cold water coral colonies, possibly identified as *Madrepora oculata*. The hard bottom, probably constituted of buried coral banks, is also present (Delbono *et al.*, 2014).

3.5. Concluding remarks

The integrated approach used in this study (MB, SSS, ROV video surveys) provided new and important information on the occurrence and status of the CWC of the Eastern Ligurian Sea, specifically those in the Levante Canyon. The surveys conducted on one of the 'historical' coral banks identified by Fusco (1967) in the tributary Punta Mesco Canyon showed a complex sea-bottom, consisting of a rugged morphology with a tabular relief and several small-scale "ridges" with fine sediment draping at around 380-400 m. These small, sharp, ridge-like features cannot be bedform morphologies only due to sedimentation processes; they likely indicate the presence of bio-constructions, those mapped in 1967, rising around 0.5 – 1 m above the seabed. Small coral colonies of around 0.1 m height covered by fine sediments but emerging from the mud were also recognized (Fanelli et al., 2016). ROV evidence of reefs confirms the active role of the canyon as an efficient conduit for terrigenous inputs, sediments and likely nutrients from the inner continental shelf down to considerable depths. Furthermore, the chaotic structure of the deposits observed at an ROV site at 398 m probably indicates intermittent slides and gravitational mass movements down the Levante Canyon, as already shown in the canyon head by Delbono (2007).

The sharing of knowledge and instruments is the basis of this integrated work focused on the study of seafloor features with particular reference to morphology of the proximal area of the canyon system. Maps revealing the geophysical characteristics of the seabed represent an essential tool for the effective management of the marine environment, because they allow for the wide-scale geology and present-day (Holocene) sedimentary processes to be determined and understood. Furthermore, the integration of different maps, resulting from the use of different equipment and data processing methods, allowed for the research to focus on the best possible area.

Operating with SeaBeam 1050 (MBES) and Klein 3000 (SSS), seabed morphological characterization, sediment type discrimination and processes dynamic description, on broad-scale (>1 km^2) were carried out. Besides that, small-scale habitat classification (<1 km^2 up to centimetre) was achieved thanks to SSS images analysis integrated with direct sampling methods such as grab sampler or underwater camera.

During the real time survey processing, the establishment of a confidence level to each feature of interest, at the different scales, justified the multiple focusing and HR investigation of the seabed variability and nature with different instruments.

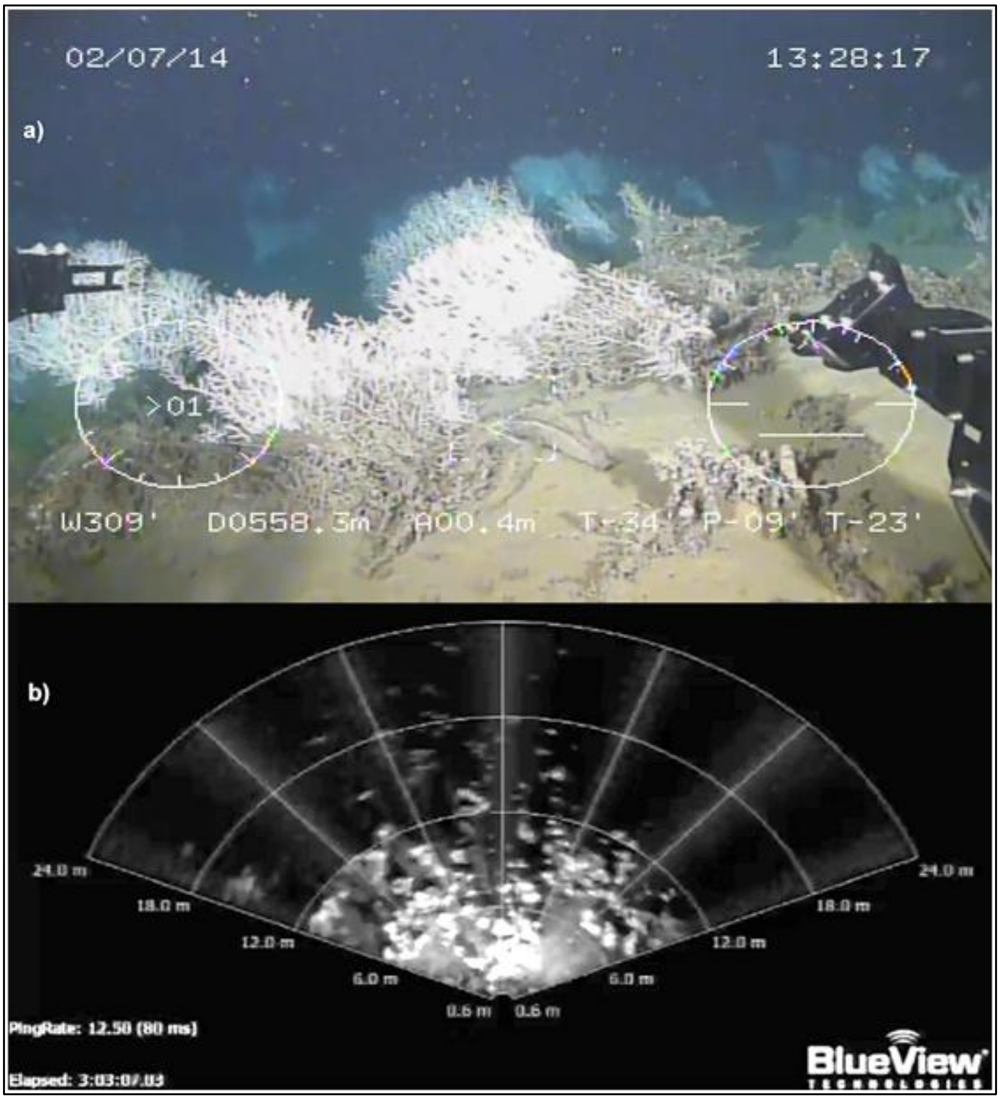

Figure 19 – (a) CWC image taken by ROV Pegaso camera at 558 depth, showing widespread and thriving colonies of Madrepora oculata; (b) The correspondent image of Blue View 2D imaging sonar.

Finally, it is highly recommended that appropriate biological ground-truthing is undertaken where remote sensing technologies are to be used for habitat mapping purposes. In fact the ground truth confirmed the area ecological interest (Figure 19). Thanks to Italian Navy resources, the survey provided not only a detailed mapping of the variable morphology of the proximal area of the Levante Canyon at different scales, but it also investigated the seabed nature and the biological communities in the canyon system for the assessment of a potential Site of Community Importance under the European Commission Habitats Directive (92/43/EEC).

Finally, this particular approach and scientific results obtained prove the power of “dual use” purposes in order to make HR maps that can be used by different stakeholders with different aims but only one standard (Pratellesi et al., 2014).

4. Acoustic seabed analysis of Panarea hydrothermal area

4.1. Aim of the study

Acoustic instruments have already been used in hydrothermal systems to measure gas (Heinicke et al., 2009) and fluids (Jackson et al., 2003; Tudino et al., 2013). The integrated analysis based on high resolution acoustic data is conducted in Panarea island (Aeolian arc, Italy), characterized by high hydrothermal activity.

The hydrothermal activity represents an evidence of high-energy submarine processes related to active or recent volcanism. Shallow hydrothermal vents represent a unique study opportunity due to the easy access to the vented fluids. The hydrothermal fluids released off the coast of Panarea Island have been intensively investigated since mid 80s. The sudden unrest of submarine volcanic activity occurred on November 2002 with a submarine low-energy explosion, dramatically changed the geochemical features and the degassing rate of the submarine hydrothermal vents and pushed the scientists to develop new methods to monitor the venting activity.

The acoustic characterization of the seabed of such a peculiar environment is a challenge. According with the frequency being used, the BS intensity measured can be affected by the scatter of the gas particles in the water. Despite that, high resolution acquired allowed seabed morphology and nature analysis. The study focused in two main areas: Basiluzzo island and the islets (Dattilo, Panarelli, Lisca Bianca, Bottaro, Lisca Nera) (Figure 21).

4.2. Material and methods

4.2.1. Study area

Panarea Island is located in the Southern Tyrrhenian Sea and is part of the volcanic arc of the Aeolian Islands that is made up of seven islands, some minor islets and several seamounts (Figure 20). The area is characterized by a complex geodynamics being affected by shallow to deep seismicity due to a slab deepening under the Calabrian Arc, active crustal deformation, active volcanoes (Lipari, Vulcano and Stromboli) and hydrothermalism (Anzidei et al., 2005). It is now considered inactive, since last documented activity is 20 Ka old. However, on 2002-11-03, gas started to flow violently from the seafloor in an area E of the Island, mainly along NE and NW structural lineaments, and lasting up to 2003-2004 with a consistent flux, orders of magnitude larger that 'steady-state' fumarolic activity documented there in historical times (Bortoluzzi et al., 2011).

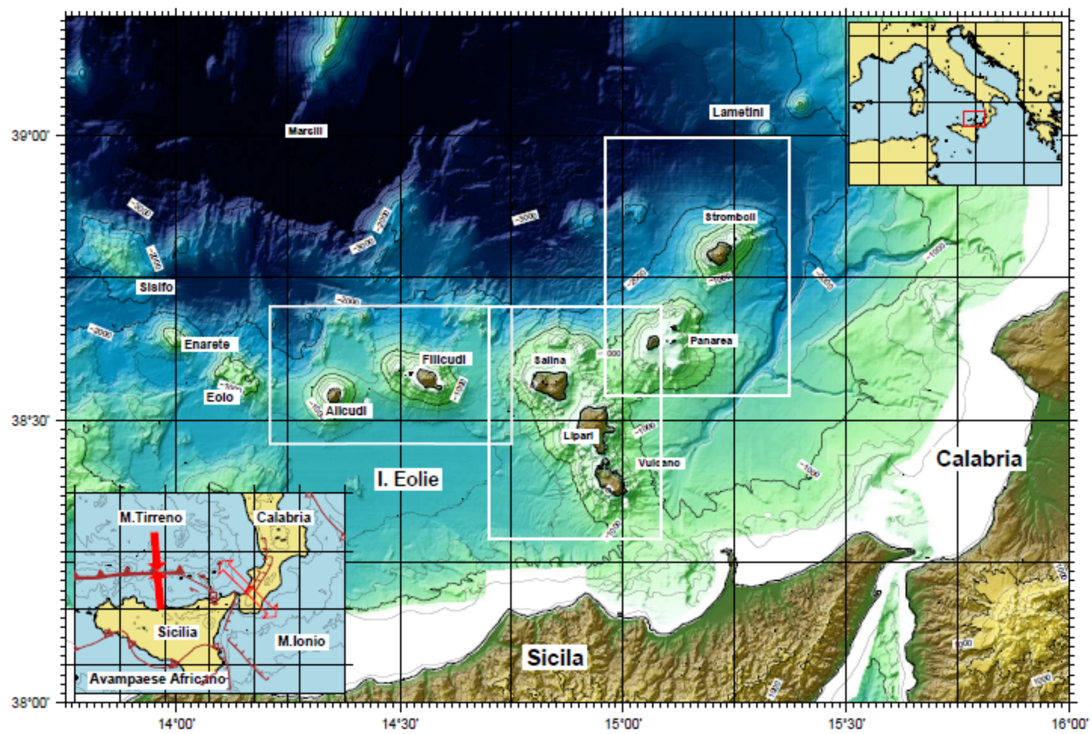

Figure 20 - Eolian Volcanic Arc (Grassi et al., 2013)

The exhalative area, surrounded by the islets of Dattilo, Panarelli, Lisca Bianca, Bottaro and Lisca Nera (Figure 21), has been known since historical times for the hydrothermal activity related to the Panarea volcanic complex. Due to the exceptional characteristics of the phenomenon, different geological, geochemical, geophysical and studies started immediately to monitor this event from geological and geochemical point of views, also in the light of volcanological surveillance and risk (Anzidei, 2005), and on the possible connection to regional tectonics.

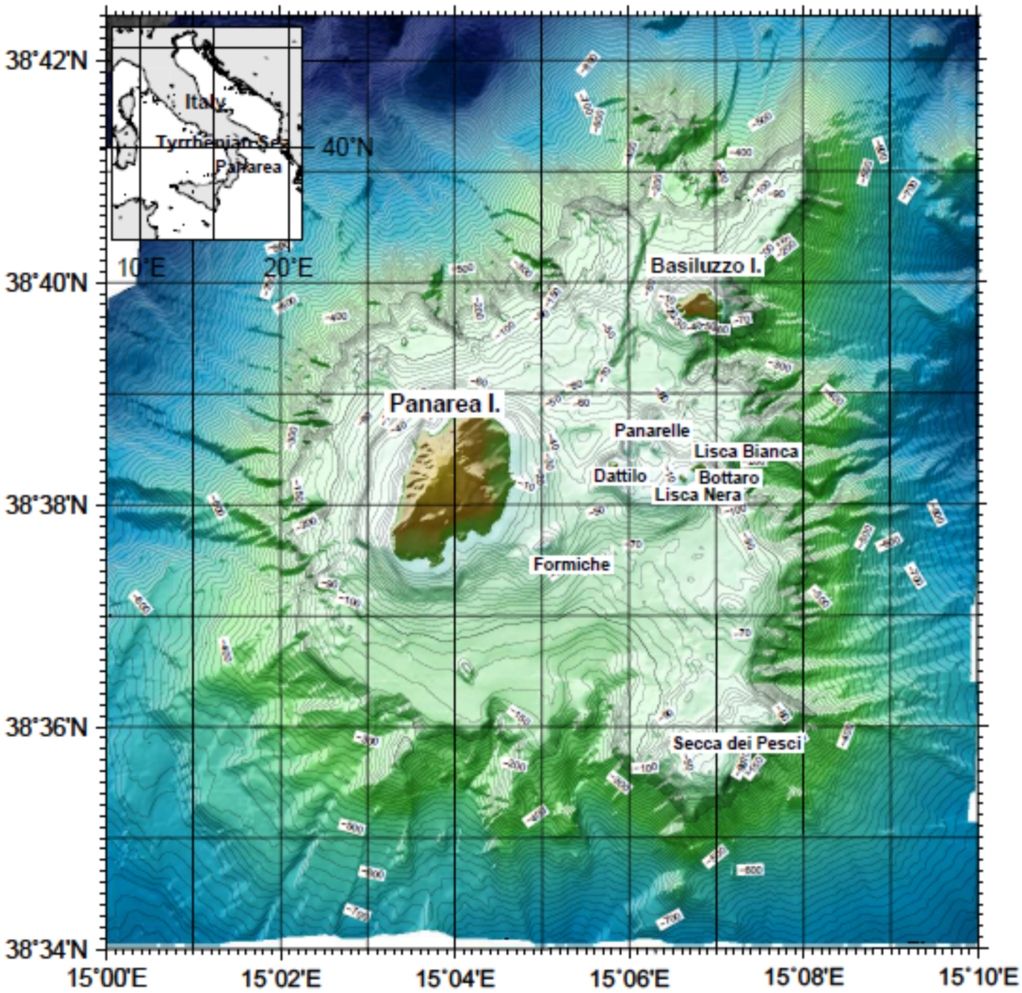

Figure 21 – Panarea complex morphology (Grassi et al., 2013)

Boiling of the sea-water has been described since historical times in the Aeolian Islands by Titus Livius, Strabo, Julis Obsequens, Orosius Palulus, Posidonius and Plinius the Elder (SGA, 1996). An event that produced sudden changes in the sea level, hot steam from sea surface, stinky air, death of fishes, mud emerging from seafloor occurred on 126 b.C. This event is likely referred to the formation of Vulcanello, nowadays linked to Vulcano Island. The exhalative activity at Panarea has been described by Houel (1782), Dolomieu (1783), Ferrara (1810), Spallanzani (1825), Dumas (1860), Mercalli (1883), Luigi Salvatore d'Austria (1895), Romano (1973), Italiano and Nuccio (1991), Gabbianelli et al. (1990), Calanchi et al. (1995), Anzidei (2000), Caliro et al., (2004), Caracausi et al. (2005). At the beginning of

November 2002, during the eruptions of Etna and Stromboli volcanoes, a submarine gas eruption started in a shallow area up to 30 m water depth and 2.3 km^2 of surface, bordered by the Islets. The event occurred suddenly, without significant seismicity (Saccarotti et al., 2003) and reached an intensity level never observed before during the last century (SGA, 1996). The gas output was estimated to be 109 l/day, two orders of magnitude higher than that previously measured (Caliro et al., 2004) (Bortoluzzi et al., 2014).

4.2.2. Panarea-13 survey campaign

Several cruises were performed in the area for obtaining geophysical and oceanographic data and to monitor the geomorphological features of the seabed and the evolution of the gas outflow after the 2002 crisis (Bortoluzzi et al., 2014). In this scenario the oceanographic and geophysics campaign PANAREA-13 (3-8 June 2013) was carried out with the synergic effort of the Institute of Marine Sciences of the National Council of Research and the Italian Hydrographic Institute. The main object was to achieve the environmental characterization of the seabed and water of Panarea, with particular reference to the islets area (Figure 21). In particular, different type of surveys were performed throughout different instruments:

- Multibeam (Konsberg EM3002);
- Magnetometer (Seaspy);
- Benthic chamber with CH4, pH, Conducibility, Temperature, CO_2 flux;
- Seabed samplings with van veen buckets and a CARMACORING SW-104 corer;
- Rosette water sampler (General Oceanics).

Data integration allowed morphological characterization of the seabed supported with ground truth and gas emissions census with measure of water/sediment fluxes.
Emission areas of main interest are PEG1 (12,5 m), PEG2 e Black Point (Figure 22). These spot are characterized by a strong flux of gas and relevant morphological changes over time (PEG1) and high temperature water sources and CH_4 and other gas spills (Black Point, 24 m; PEG2, 17 m; PEG25).

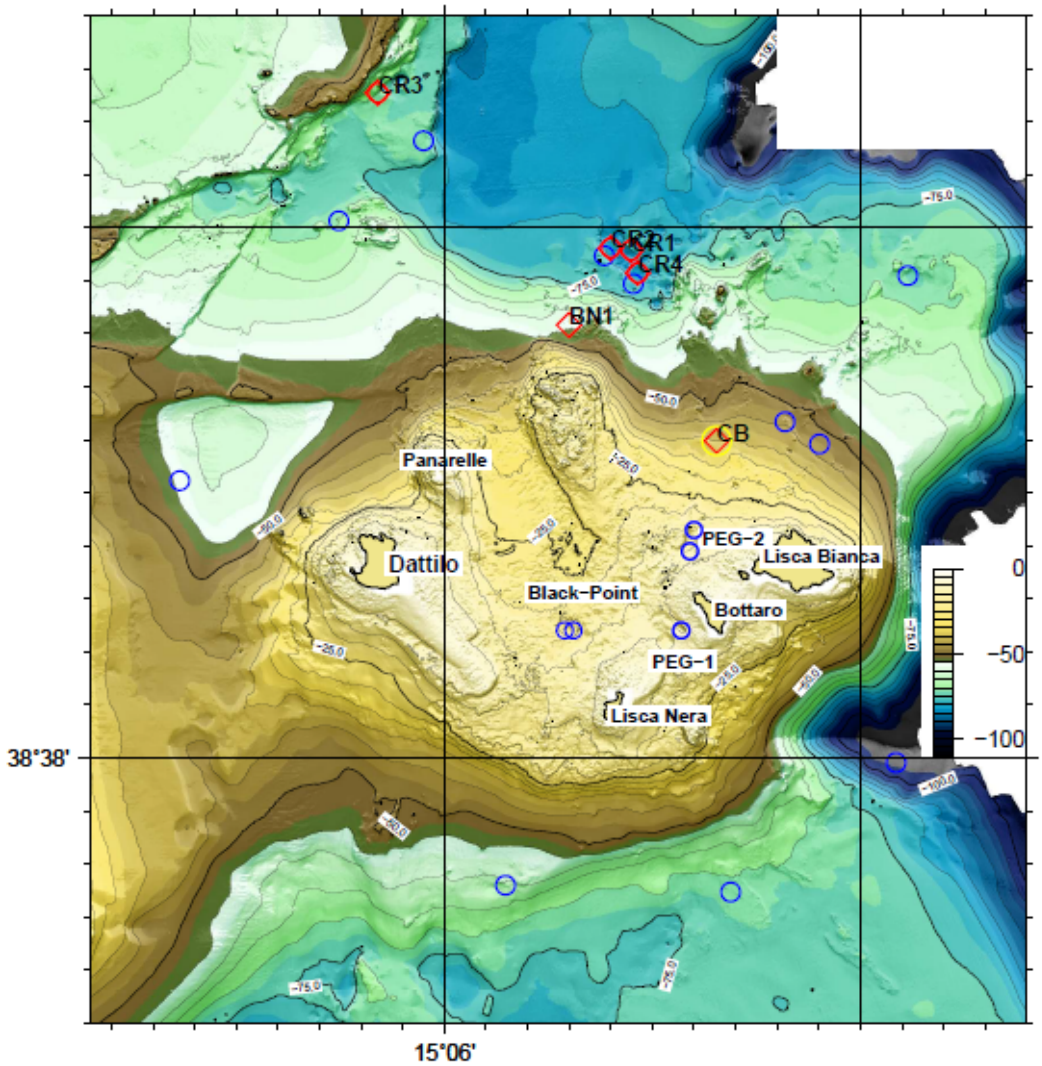

Figure 22 - Emission areas of main interest are PEG1, PEG2 e Black Point; blue spot represent the CTD cast sites, red point represent coring sites, yellow circles represent benthic chamber measure sites (Grassi et al., 2013)

4.2.3. Bathymetric survey

High resolution bathymetric data (S-44, 2008; C-13, 2012) were collected between Dattilo, Lisca Bianca and Lisca Nera islets with a Kongsberg EM3002 multibeam following S-44 IHO (2008) standards for hydrographic surveys (Figure 23). Tide correction was applied to raw data using the Stromboli Island tide gauge (www.mareografico.it).

In order to increase resolution, the survey was conducted with 40% swath overlay. A 0.3 m resolution digital terrain model was obtained. Data were processed with

CARIS suite of software (www.caris.com).

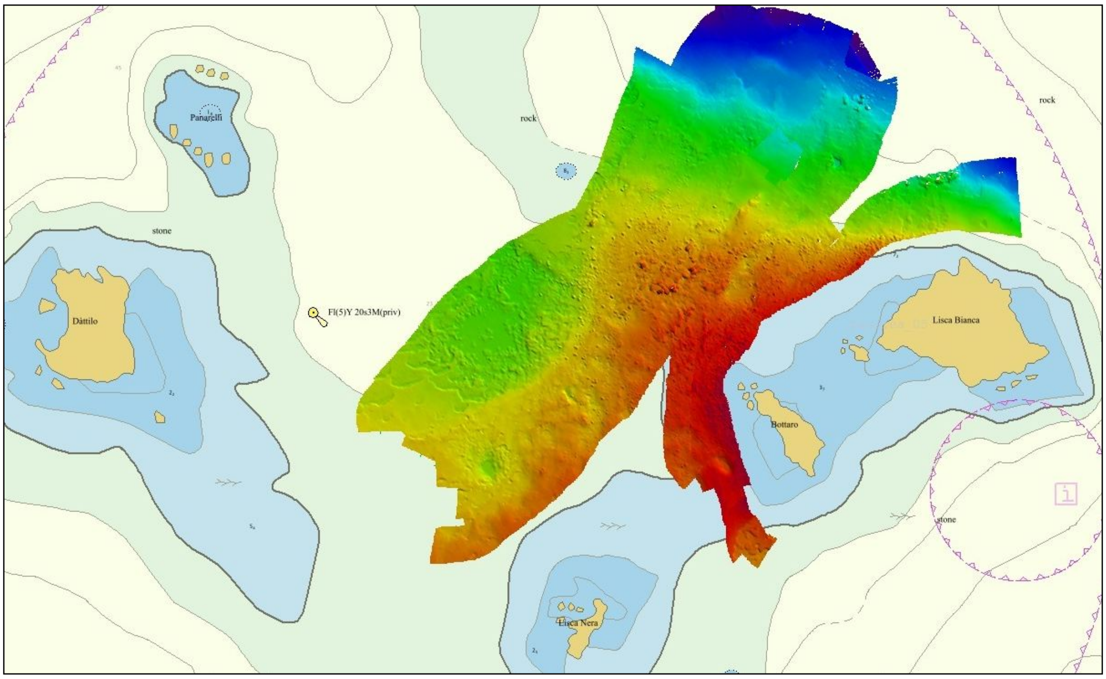

Figure 23 – PANAREA-13 bathymetric survey

Multibeam data collected in 2013 were compared with a 2012 survey following the same hydrographic standard. Even if the activities were carried out with different instruments the surveys are fully comparable as it is shown in Figure 24.

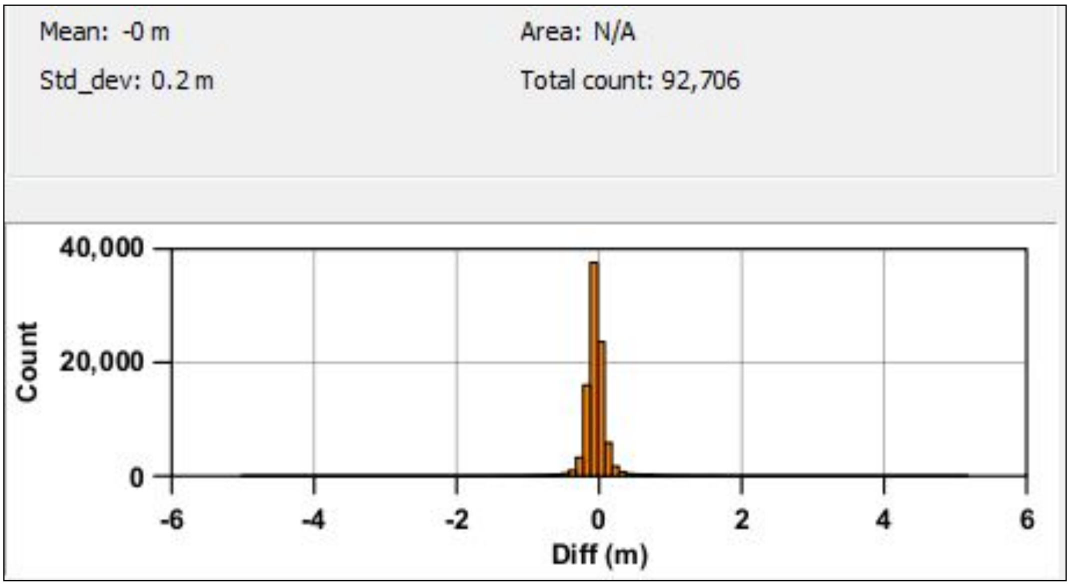

Figure 24 – Statistic results comparing 2013s and 2012s Digital Terrain Model (mean 0 m, standard deviation 0,2 m)

The EM2002 provides a measure of the instantaneous backscatter strength that has been measured. It was analysed throughout QTC suite of software allowing seabed classification (see Chapter 1).

This process is called image compensation and it consists in suppressing as much as possible the instrument and survey effects, thus isolating the seabed effects. The more complete the compensation, the more accurate the classification (Preston, 2008).

The backscatter that appears in a compensated image is, ideally, determined only by the nature of the seabed sediments. The image has been compensated for the amount by which variables such as transmission power, receiver gains, range, and grazing angle differ from some baseline values. The next step in acoustic seabed classification is to capture backscatter characteristics into some statistical variables, which are called features. Features are calculated from portions of a sonar image. Mean, standard deviation, and other first-order statistics can be calculated for pixels from an image sub-sample of any shape.

4.3. Integrated data analysis and seabed classification

The volcanic system of Panarea is mainly characterized by structures directed SW-NE (Figure 25 and Figure 27). At small scale, the system is delimited by 100 m bathymetric with low gradient (abrasion platform configuration). Inside this main structure, analysing at a larger scale, the emerged main structures develop (Panarea and Basiluzzo islands) and another one with an elliptic shape and volcanic-tectonic origin with low depth (< 20 m) and low slope (probably another abrasion surface upon where circular structures are visible covered by sediment. This area is delimited by the islets called “Lische”, characterized by an intense volcanic activity (gas emissions, vents, substrate with biostructures).

4.3.1. Small scale Analysis – Panarea complex and Basiluzzo

Data set analysis, whose result is shown in Figure 25, as follows:

- The principal structure has an oval shape with an extension toward NE. It is constituted by an inner platform with SW-NE aligned structures. Moreover, it is visible the one along Panarea – Basiluzzo direction (A-C) with a depth variation of about 30/40 m. Along that one, slope model shows circular structures at different scale, from kilometres to metres, filled with sediment, highlighted by the slope variation. (Figure 25).
- Est of Basiluzzo island there is a sector characterised by high slope (40-60%). This is the limit of the sector analysed, characterized by drainage channels.

Backscatter analysis obtained with QTC software shows the homogeneity of seabed nature class – medium sand of volcanic origin - that characterize especially in the inner part of the system (low slope). This was confirmed by ground truth. As example, Basiluzzo Island morphology and seabed classification is shown in detail in Figure 26.

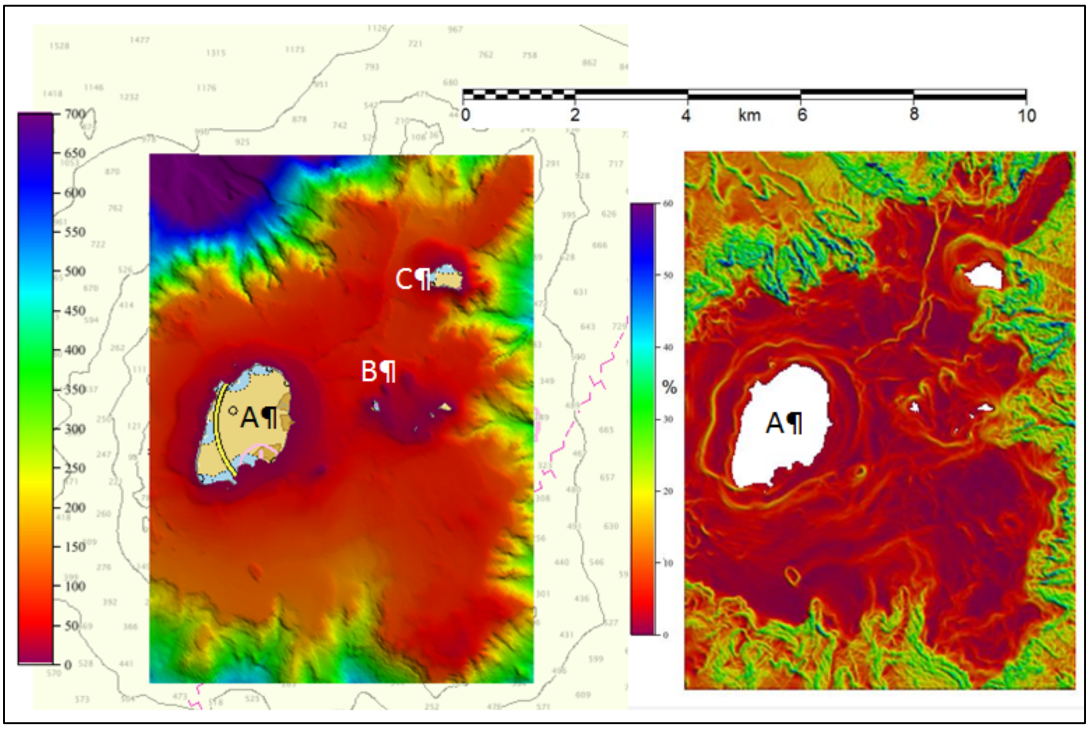

Figure 25 – Study area. On the left the 2D bathymetric DTM overlapping the electronic nautical chary: A Panarea Island, B Lische islets, C Basiluzzo island; Depth is expressed in metre. On the right the slope model expressed in percentage (5) Panarea Island.

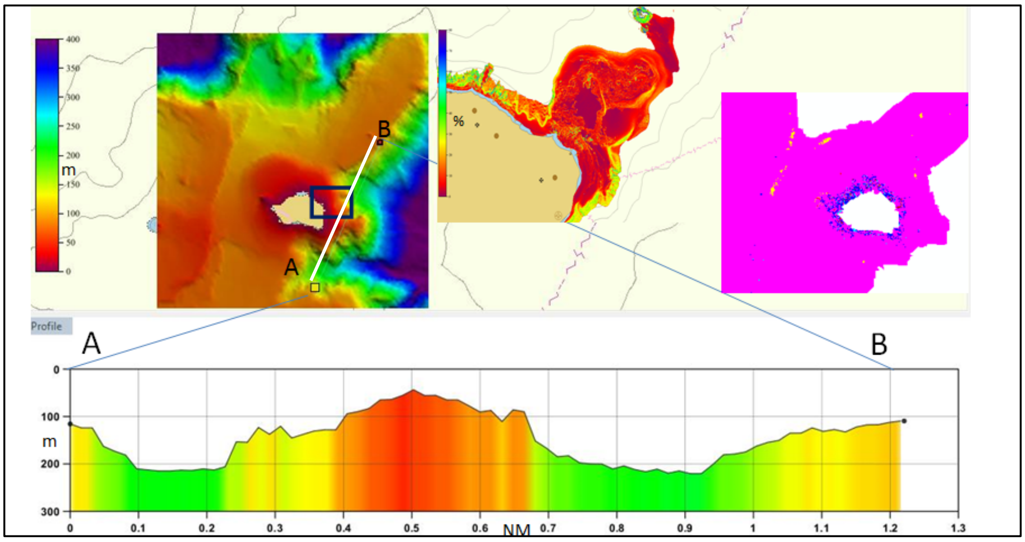

Figure 26 – Particular of Basiluzzo Island; On the top left there is visible the 2D bathimetric model where A-B section is represented, in the centre the slope model and on the top right the seabed classification obtained with QTC software (right). In the bottom an example of section (A-B), depth is expressed in metres and distances in nautical miles. Slope as follows: red 0-20%, yellow 20-30%, green 30-50%, light blue 50-60% e blue 60-80%).

4.3.2. Large scale Analysis – Islets “Lische”

During multibeam survey in the islets area, gas emission activity sport were recognized (large scale). The “Lische “system, as previously anticipated, is inside the circular larger one that comprehend Panarea and Basiluzzo. It is constituted by an oval shaped volcanic-tectonic depression with axes oriented E-W. As shown in Figure 27 it is characterized by reduced slope, atypical of an abrasion platform with sedimentary deposits. Gas emission are still significant in this area (Bortoluzzi, 2011).

The mobile sediment of the inner part of the “Lische” has both terrigenous and chemical origin. Acoustic BS signal analysis shows the presence of circular and sub-circular structures.

There is a strong correlation between morphology and seabed nature (Figure 27, Figure 28 and Figure 29):

- Medium- coarse sand with a non-significant soft section (magenta colour) in low slope areas, inside the “lische” and more significat externally.

- Hard substrate with moderate presence of sediment (blue) in correspondence stronger gas emission and hard substrate (red) without sediment inside “lische” sector.

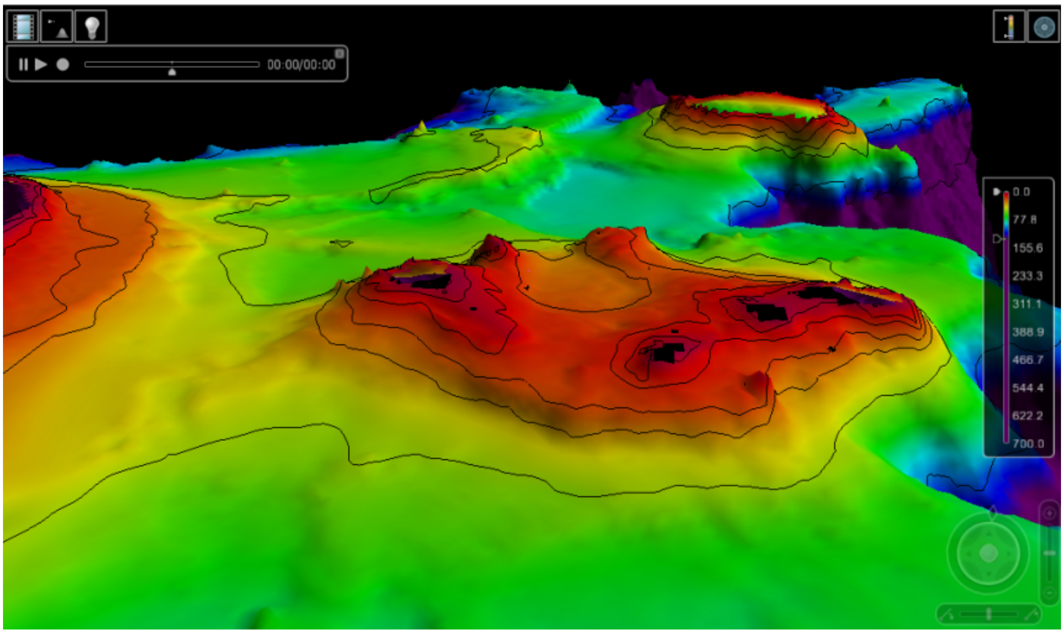

Figure 27- 3D bathymetric model of the study area showing the “Lische” apparatus and on the left the NE sector of Panarea Island.

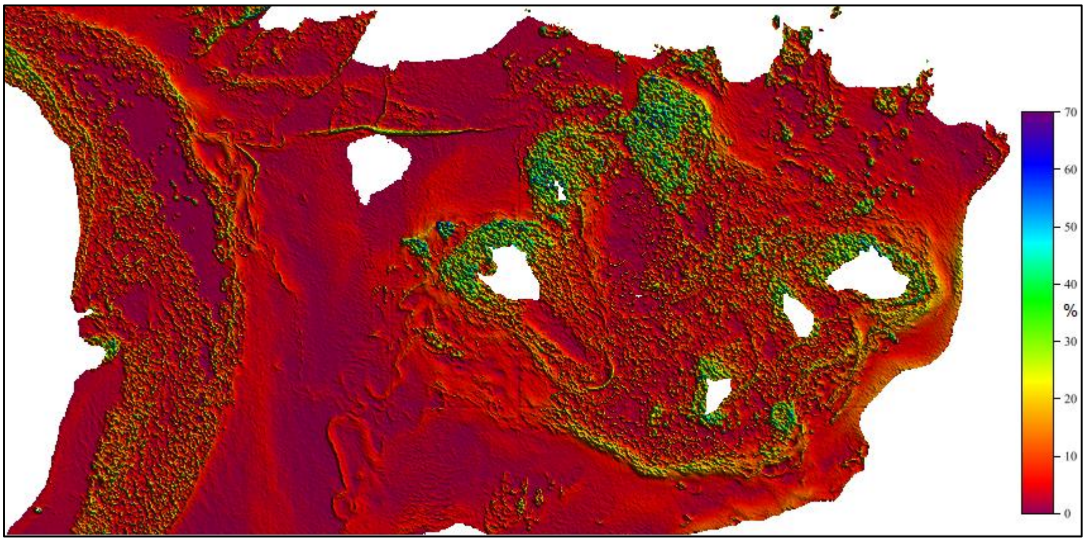

Figure 28 – 2D slope model of Panarea islets area: in red slope <20%, in yellow-green between 20-45%, blue >45%.

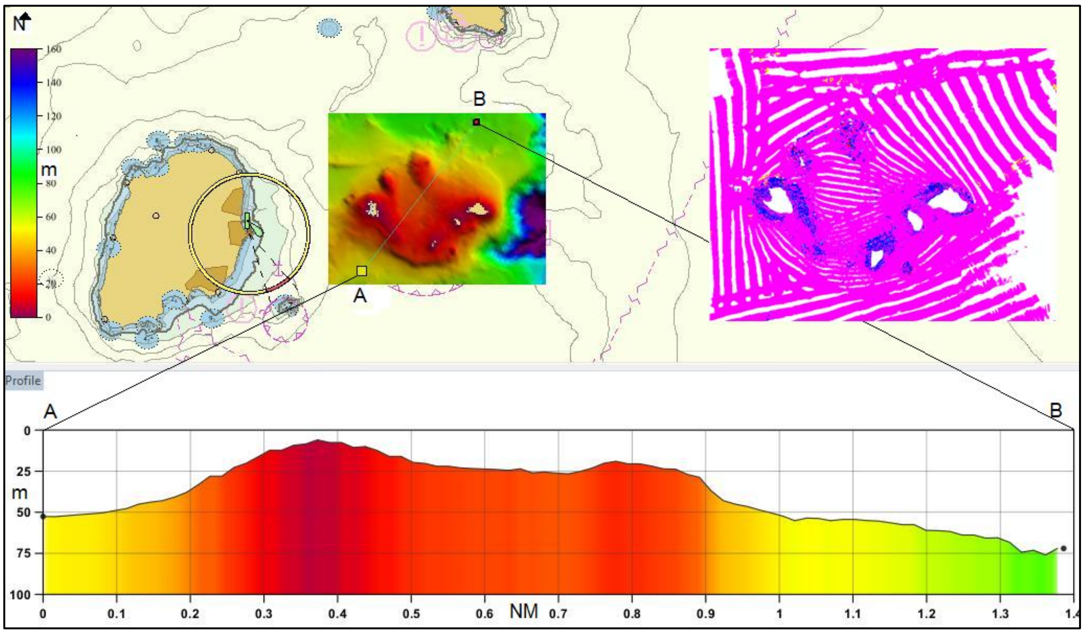

Figure 29 – Nautical chart Panarea complex with 2D bathymetric model of “Lische” islets (left) and seabed classification with QTC software(right). AB is a generic bathymetric section, depth is in metre and distances in nautical miles.

4.4.Observations

The high resolution multibeam technique provided a 3D detailed bathymetric map of the seafloor at 0.3 m resolution and confirmed the location and distribution of the exhalation centres, during the crisis that has affected the Panarea area since November 2002. These data are useful to improve and support the geological, volcanological, geochemical, geophysical research and monitoring of this volcanic area of high interest. Moreover, they represent an accurate and inter-discipline record of data whose value is maximised through different sensor data integration.

The DTM shows that the area of Panarea Archipelago represents a positive geomorphic feature which is defined by the the coalescence of individual volcanic edifices. This is an asymmetric structure sloping at high angle in its southeastern flank while the others flanks display smoother slopes. The area within the Islets is characterised by a shallow seafloor platform, bewteen 0 and –30 m, gently slooping to NW. Lisca Bianca, Bottaro and Lisca Nera islets are NE-trending coalescent structures. The Dattilo structure shows an elongated tongue-like marine abrasion platform, SE trending, for 0.8 km at depths between 5 and 8 m.

The area within the Islets is dotted by hundreds of circular or horseshoe-shaped depres- sions up to several metres deep and wide, large- ly distributed especially surrounding Dattilo, Lisca Nera and Bottaro. The high frequency relief of coarse textured morphology, at metre to decimetre size pinnacles and troughs, is well developed between Lisca Bianca, Bottaro and Secca dei Panarelli. In the area between

Panarelli and Secca dei Panarelli the map re- veals large lava flow surfaces, smooth and lobed.

The deepest sector displays evident morphological structures such as those located in the northwest area, NE- NNE- NNW- and E-trending lineaments. The southwest sector displays a sub-elliptical shape wide depression probably due gravitative movements

The location of the gas vents, mapped on the bathymetric maps, revealed the existence of preferential alignments NE-SW and NW-SE trending and along which the gas eruption took place. These directions are the main pathways for the up-welling of hydrothermal fluids.

The maximum number of exhalation centres was located in a limited extended zone, west of Bottaro and Lisca Bianca islets, whereas clusters of minor centres were sparse in the area. The largest and most active exhalation centre is located a few tenths of metres south of Bottaro. The ellipsoidal crater rim spans between 8 m and 15 m. Its main axis, NW-oriented, is 40 m long and the minor axis is 25 m long. The hundreds of depression features identified on the seafloor can be related to fossil exhalation centres.

5. Geomorphological changes over a 135-year period of a small Mediterranean estuary: The Magra River

5.1. Background

5.1.1. Aim of the study

The same high resolution analysis method was finally applied in shallow waters and in particular in an area with high anthropic impact and subjected to risk of flooding.
The morphological and volumetric changes of the delta system at the mouth of the Magra River (Western Mediterranean) were studied using hydrographic data. The data series were collected during several hydro-oceanographic surveys carried out from 1882 to 2014, processed following the hydrographic international standards (IHO S-44) and stored in the Italian Navy Hydrographic Institute database. In particular, high resolution bathymetric data characterized by the same standard and accuracy were collected using different devices such as lead lines, singlebeam and multibeam acoustic systems.

5.1.2. Estuaries and Delta

Deltas are geomorphologic features resulting from interactive river and marine dynamics and because of that they can be considered as transitional environment. The former essentially supplies sediment to the coastal system whereas the latter basically mobilize and transport the sediment molding the riverine deposits. The strength of both factors determine the dominant processes governing the evolution of the deltaic system. When the river supply is larger than the sediment removal capacity by littoral dynamics, the delta can be considered dominated by processes. On the other hand, when the river supplies are small compared to the marine transport capacity, the corresponding coastal dynamic factors are able to remove not only these riverine supplies but also part of the sediment forming the deltaic fringe. Under this scenario, the deltaic coast is subjected to reshaping and reduction processes. Reshaping and reduction processes, such as Ebro delta, one are genetically related, since they are linked to the sediment redistribution along the coast by the action of marine factors (Jiménez et al., 1997; Jiménez et al., 1999). Reshaping does not imply a significant loss in sediment volume with balance of erosion and accretion of the delta and coastal systems whereas reduction indicates the dominance of littoral erosion (Pranzini and Farrell, 2004). Moreover, these processes are associated with different temporal scales (yearly, decadal, secular). Reshaping is the first action to appear just after the decrease of river sediment supply, being its natural temporal scale from years to decades, whereas reduction generally implies temporal scales, from decades to centuries (Jiménez et al., 1997).

The modern estuaries and deltas form a continuous series where the degree of evolution is determined principally by the importance of the rivers terrigenous load. Well-developed estuaries are typical of river systems of low terrigenous load. Deltas are characteristic of river systems of very high terrigenous load, and their morphology may vary with the importance of the tides and the action of the waves. The accumulation of sediment at or near river mouths is principally the consequence of interaction (mixing) between fluvial and marine waters and energy decreasing (Robert, 2009).

The transport of sand or gravel as bedload creates on the bed a variety of riverine and undersea features differencing for size, form and relative orientation, which depend through complex interactions on the density, shape and coarseness of the sediment particles, and on the strength, uniformity and steadiness of the current (Goudie, 2003).

Wave, tide and river processes, eventually influenced by human intervention, control the location of marine and river sediments in the estuary and the morphology of the sedimentary deposits (Galloway, 1975). Conceptual models of estuarine morphology classify estuaries according to the relative contribution of these processes and are based, in part, on regional studies of estuarine sedimentation and morphology (Figure 30) (Boyd et al., 1992; Goudie, 2003; Anthony, 2013).

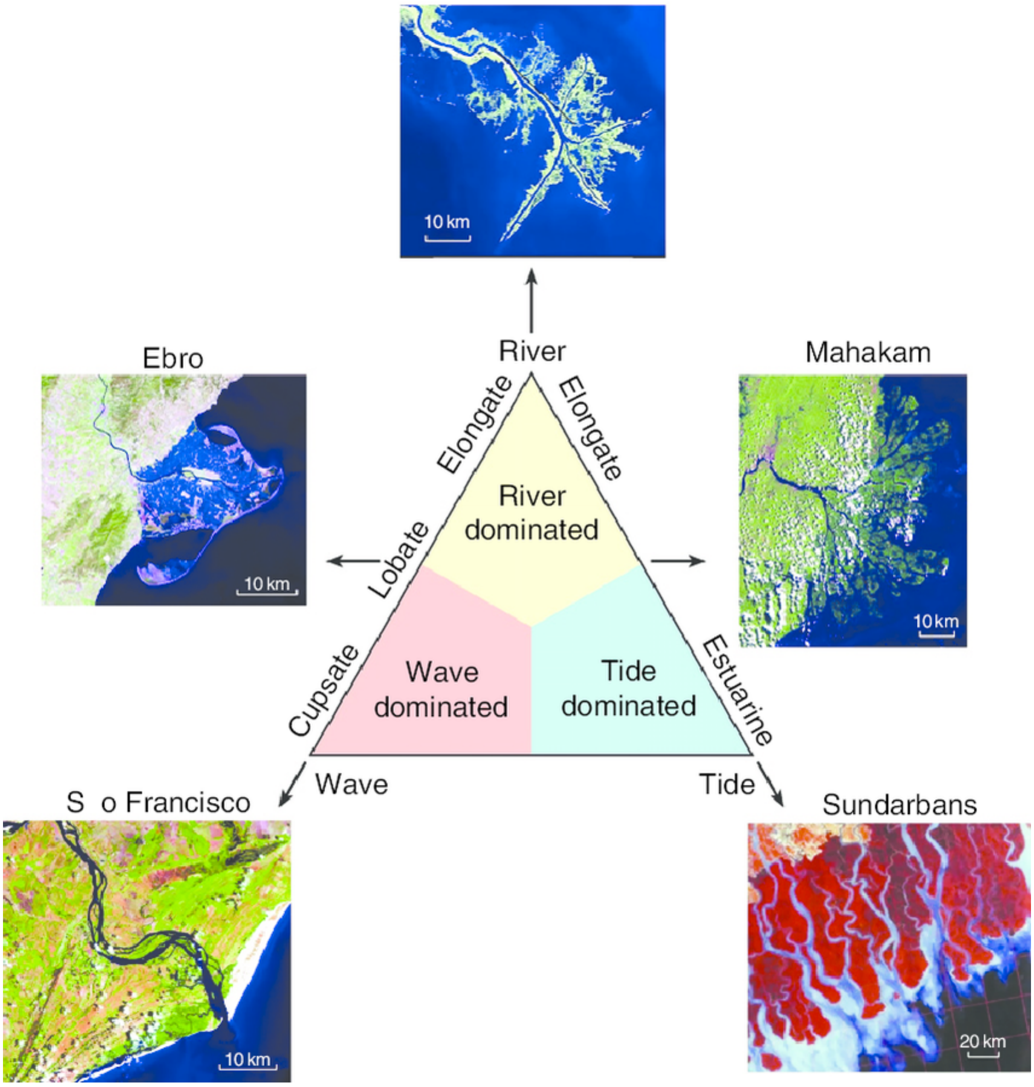

Figure 30 - A ternary diagram indicating the relative balance between river, wave, and tide processes, illustrated by Landsat satellite images. The modern (Balize) lobe of the Mississippi Delta represents a river-dominated elongate delta; the Ebro in Spain is a lobate delta, whereas the São Francisco in Brazil is cuspate and wave-dominated. The Mahakam Delta in Kalimantan, Borneo, is intermediate in a more tidally dominated setting, whereas the Passur River and neighbouring systems in the Sundarbans are extremely tide-dominated. Based on Galloway, W.E., 1975. Process framework for describing the morphologic and stratigraphic evolution of delta in depositional systems.

There are numerous definitions of “estuary” in the literature, but the geological definition “a drowned river valley that receives sediment from both landward and seaward sources” is more closely linked to geomorphology than other definitions. Wave and tide-dominated estuarine environments both receive sediment from rivers and from the adjacent sea, but they exhibit contrasting arrangements in marine habitats (Harris and Baker, 2012). Tide-dominated estuaries (macro-tidal environment with tide range >4 m), are generally funnel-shaped with wide mouths and high current velocities (Goudie, 2003). In the centre of tide-dominated estuaries, tidal sand banks are aligned with their long axes normal to the overall trend of the coast (onshore–offshore alignment) (Harris and Baker, 2012).

By contrast, wave-dominated estuaries are generally found in micro-tidal environment (tidal range <2m). In general, these estuaries have an upper sector near the head, where river processes, sediments and bedforms dominate, a lower sector near the mouth, where wave and tidal processes and marine sediments dominate, and a middle sector, where tidal currents dominate and both river and marine sediments are present. High wave and tidal energies at the mouth of an estuary can deposit sediment and restrict or completely prohibit exchange of water between the ocean and the estuary (Harris and Baker, 2012). The central muddy basin is the deepest part of the estuary, bounded on its seaward side by a sandy barrier composed of marine-derived sediments. The barrier is cut by a tidal inlet, which supports ebb and flood-tidal deltas on its seaward and landward sides, respectively (Goudie, 2003).

Mixed wave-tide estuaries (such as those in meso-tidal environments with a tidal range of 2–4m) can be found behind barrier islands. The dominant sand bodies in meso-tidal estuaries are the deltas (ebb and flood) formed by tidal inlet processes. Within the estuary are meandering tidal channels and point bars and marsh deposits (Goudie, 2003).

Estuarine shoreline environments often occur in small isolated reaches with different orientations and with great variability in morphology, vegetation and rate of erosion. This variability results from regional differences in fetch characteristics, exposure to dominant and prevailing winds, wave energy, variations in subsurface stratigraphy, irregular topography inherited from drainage systems, differential erosion of vegetation or clay, peat and marsh outcrops on the surface of the subtidal and intertidal zones, small-scale variations in submergence rates, effects of varying amounts of sediment in eroding formations and effects of obstacles to longshore sediment transport, such as headlands and coves, that define drift compartments (Goudie, 2003).

Terrigenous sediments are dominant in coastal areas near river mouths. When the terrigenous load of the river is important a delta develops, progressively creating a coastal plain and expanding the shelf (Lambeck et al., 2004). In other areas the terrigenous input is low, restricted to local erosion and reworking of nearshore sediments and substrates (Robert, 2009).

A driving force of continental weathering, rainwater is also a major agent of erosion of terrigenous particles to the marine basin. As the velocity of the flow increases it may transport sand- to gravel-sized particles as bedload, which are used as abrasives for further eroding the substrates. Erosion principally characterizes the upper section of the drainage basins. It decreases with slope gradient and flow velocity. Flow velocity is minimum on the sides of the river channel where particles may lay down and build a succession of channel levees through time. Slope gradients are very low, and the related stream velocity reduced, in the lower section of the drainage basins. Water may flow over channel levees during high floods and expand in the floodplains where a fraction of the terrigenous load is released. However, the vast majority of the suspended load is released at the river mouth and river systems are currently the most efficient agent of erosion and transport of terrigenous particles to the ocean (Robert, 2009). For river systems of high discharge and terrigenous load characterized by a delta, sedimentation processes are principally controlled by the dynamics of the fluvial outflow.

Whereas asymmetric jets expand at constant angles in theory, fluvial outflows may not be able to expand in all directions, depending on the morphology of coastal areas and continental shelves. In areas where the water depth does not constrain the expansion of the plume, the angle of expansion remains narrow and velocities decrease slowly with distance from the outlet. In this case, fluvial waters and their terrigenous load are transported relatively far into the ocean/sea. In areas where the expansion of the plume is constrained by shallow water depths, important shear stress forces develop on the seafloor. As a consequence, the velocity of the flow decreases rapidly and the plume expands on the inner shelf, where most of the terrigenous load accumulates. Other factors controlling the sedimentation processes are the magnitude of the tides and the action of the waves. Their relative importance shapes the morphology of the deltas (Robert, 2009).

Estimation of long-term sediment transport rates is often carried out as part of the determination of the littoral sediment budget for a section of coastline. The littoral sediment budget is often linked to the concept of a littoral drift cell and together they provide a coastal management framework for the assessment of the potential impact of human actions on clastic shorelines (Bird, 1996; Anthony, 2005). In fact, the littoral sediment budget is an accounting technique in which the volume (or mass) of all sediment inputs (termed sources) and outputs (sinks) to and from the beach and nearshore zone are assessed for a section or reach of the shoreline (Davidson-Arnott, 2010). Many now make use of littoral cell (i.e. Davidson-Arnott, 2010). Magra River sediment delivery and adjacent coast evolution was studied with a cell segmentation approach (Anfuso et al., 2011).

Low-lying coasts in general and deltas in particular are among the most affected coastal erosion systems due to natural reasons but, more importantly, to human influence (Antonelli et al., 2004; Rinaldi et al., 2009; Anthony et al., 2014).

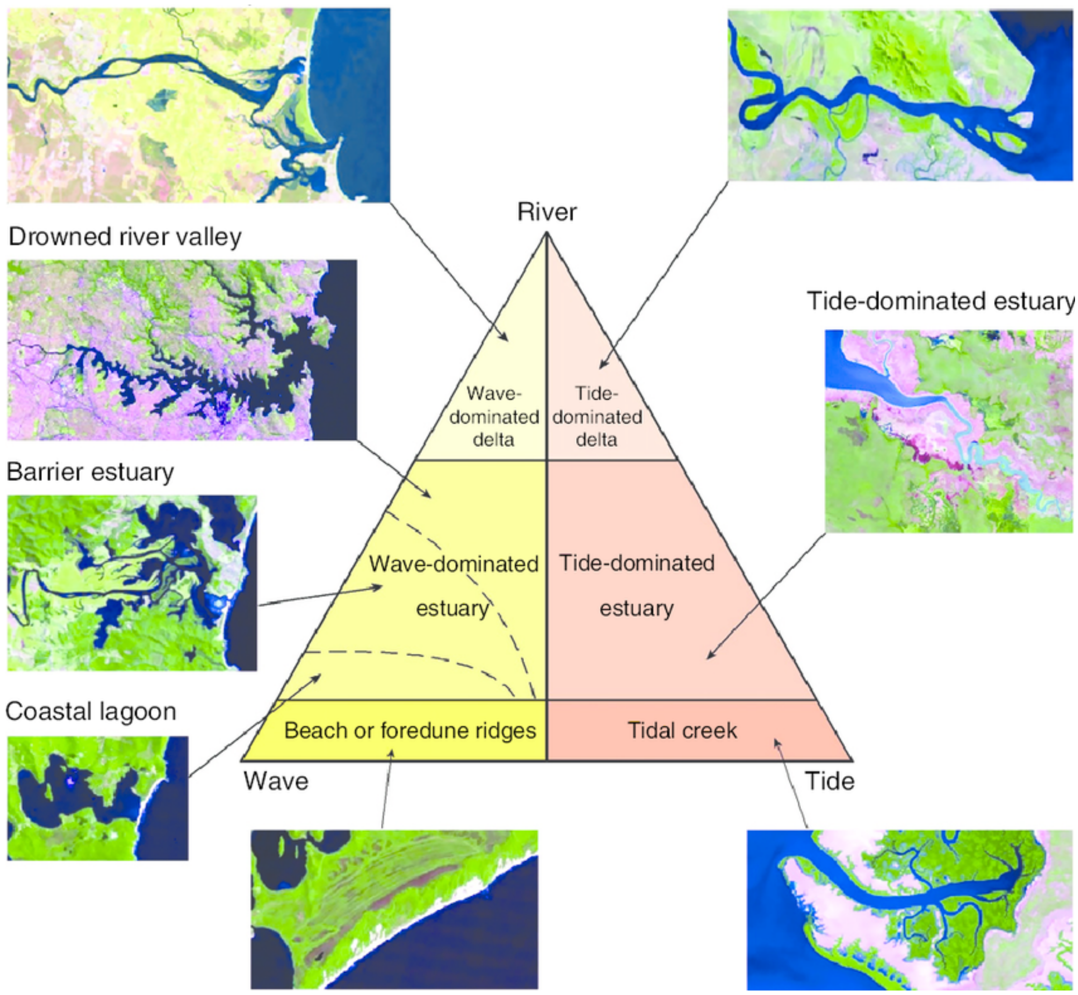

Figure 31 - Classification of deltas and estuaries, together with other coastal depositional landforms, illustrated with satellite images of selected coastal waterways in Australia. (Boyd et al., 1992).

5.1.3. River mouth sedimentary processes

Relation between river dynamics and coastal changes in the Mediterranean were previously investigated (Frihy and Khafagy, 1991; Jiménez et al., 1995; Pranzini, 2001; Poulos and Collins, 2002; Antonelli et al., 2004; Sabatier et al., 2006; Frihy et al., 2008; El Banna and Frihy, 2009; Anthony, 2013; Anthony, 2014) also with an integrated approach using remote sensing (Ciavola et 44al., 1999) and studying historic series of data (Frihy and Lawrence, 2004; Maillet et al., 2006b; Longhitano and Colella, 2007, Burningham and French, 2011). Recently Syvistki and Saito (2007) reviewed 51 deltas around the world using all remotely sensed information they could find, to build up a database of the landform characteristics considering their seasonal as well as yearly evolution. They concluded that these systems are almost everywhere heavily engineered by man, avoiding the occurrence of floods that supply sediment essential to counteract coastal erosion and favor delta progradation across the shelf. Notably a definition of "deltaic evolution in the Anthropocene" was proposed by the authors.

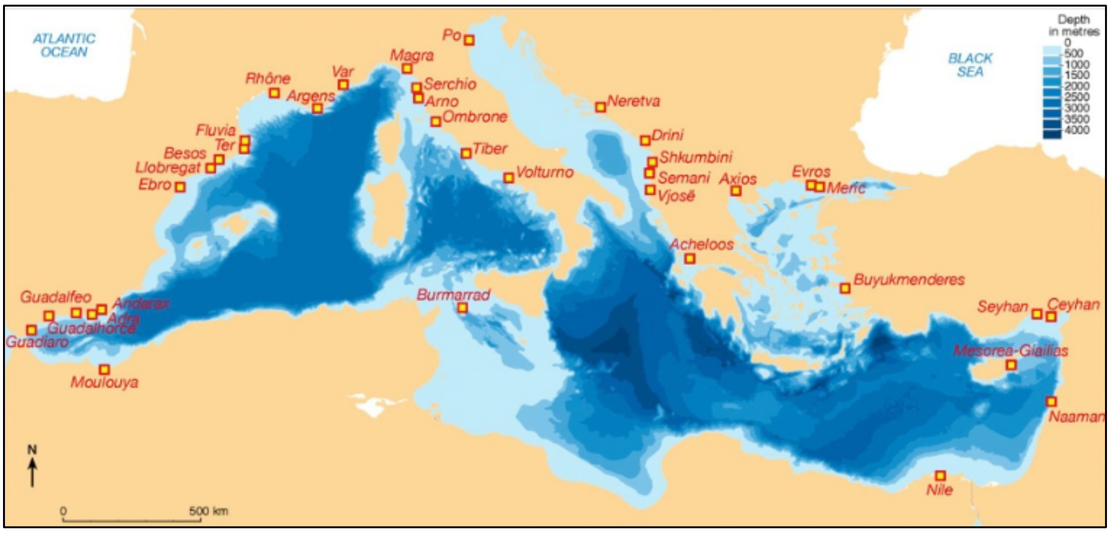

Figure 32 – The particularity large concentration of river deltas in the Mediterranean (Anthony et al., 2014)

On a world wide scale, human stress on the decrease in river sediment discharge is well known. However, this impact is not clearly defined such in the case of the Rhône River, one of the largest fluvial systems of the Mediterranean Sea which is affected by significant erosion (Maillet et al., 2006a and 2006b). According to Maillet (2006) studies, the variations in the position of the coastline at the Rhône mouth have been controlled by two independent factors. The first is the consequences of external forcing mechanism, which constrain sediment inputs and control load grain size. The second factor is authocyclic and linked to marine processes (Maillet et al., 2006b). Deltas cyclical shifting tendency of the river mouth over the centuries, is characterized by a prograding and retrograding pattern. Moreover, given a constant wave energy through time, changes in river input will result in the delta exhibiting several levels of dominance and acquiring different shapes which may be permanently recorded in its morphology (Pranzini, 2000). Low-lying coasts, in general and deltas in particular, are among the most affected coastal erosion systems due to natural reasons but, more importantly, to human influence (Frihy et al., 2008; Antonelli et al., 2004; Rinaldi et al., 2009; Anthony et al., 2014). The Rosetta Promontory, derived by Rosetta Nile branch sediments, has been subjected to some of the most severe shoreline erosion of all the world's delta coastlines during the twentieth century. The erosion and bed scour is the result of a limited sediment supply that has developed from the placement of control structures on the Nile River. Besides that, the shoreline and seabed changes reflect the natural processes of wave-induced longshore, coastal currents and sediment transport in the alongshore and cross-shore (Frihy et al., 2008).

A Mediterranean case history is the Ebro delta. After several centuries of growth, the seaward development of the Ebro Delta, in the NW Mediterranean coastline of Spain, changed a few decades ago mainly as a response to the decrease in riverine sediment supply due to river damming (Jiménez et al., 1997; Jiménez et al., 1999; Lavoie et al., 2014). The coastal response showed both highly vulnerable sediment depleted stretches and areas that are experiencing sediment accretion. Overall, those studies illustrate the recent disequilibrium of the system at different timescales under a general frame of intensifying socio-economic stresses and conflicts, as the Ebro Delta sustains a valuable ecosystem with high environmental, fishing and tourist values, in addition to an intensive agricultural use (Lavoie et al., 2014).

5.2. The study area

The Magra River (Figure 33) is situated in the Northern Apennines and its basins covers a total area of over 1700 km^2, partly in Eastern Liguria and partly in Northern Tuscany (Italy). The alluvial aquifer of the lower Magra Basin is mainly recharged by two main rivers of the region, Magra and Vara. Moreover, it experiences the contribution from rain waters infiltrating in the eastern horst adjacent to the graben of the lower Magra River (Brozzo et al., 2011). The Magra River originates in the Apennines chain, it has a length of about 64 km and flows with an average slope of 2% into the Tyrrhenian Sea following a dentritic pattern. Until the XIX Century the lowland was largely a swamp area and after human intervention most of it has been reclaimed by artificial drainage systems (Aiello et al., 1975; Raggi and Sansoni, 1993; Cappucci et al., 2011).

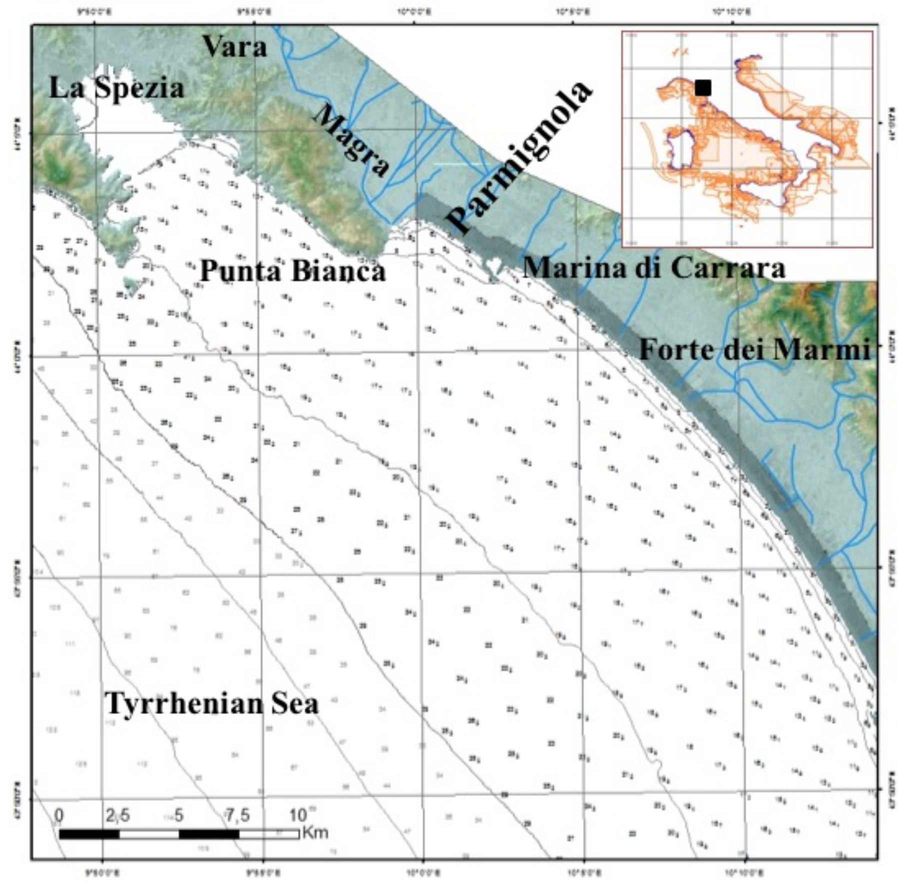

Figure 33 - Map of the study area obtained merging the electronic nautical chart (ENC IT400115 – Istituto Idrografico della Marina, Ed. 2012) and 1 m resolution Lidar data from Geoportale Nazionale (www.pcn.miniambiente.it). Depth values are in metres. Blue color lines represent water courses. Inset Italian Hydrographic Institute database. Black square study area.

Moreover, the Magra deltaic system is delimited at west by a rocky promontory (Punta Bianca), corresponding to a tectonic line, and at east by an alluvional plane (Geological Map of Italy, 2011). Coastal orientation varies from NE to SW, in the northern sector, from NW to SE, in the southern part. The total length of the sandy beach that stretches south-eastern ward, from the Magra River mouth to the Marina di Carrara harbor, is about 4.2 km (Cipriani et al., 2001; Pranzini, 2004; Pranzini and Farrell, 2004; Anfuso et al., 2011; Cipriani, 2013).

5.2.1. Geology

The study area is located in the Apennines chain that consists of a series of nappes which override each other from west to east. These nappes are either sedimentary and ophiolitic deposits (Sub Ligurian and Ligurian Units) or exclusively made up of sedimentary formations (Tuscan Nappe) while the Apuan Alps constitute the low grade metamorphic basement over which, at place, the Nappes have been tectonically emplaced (Geological Map of Italy, 2011).

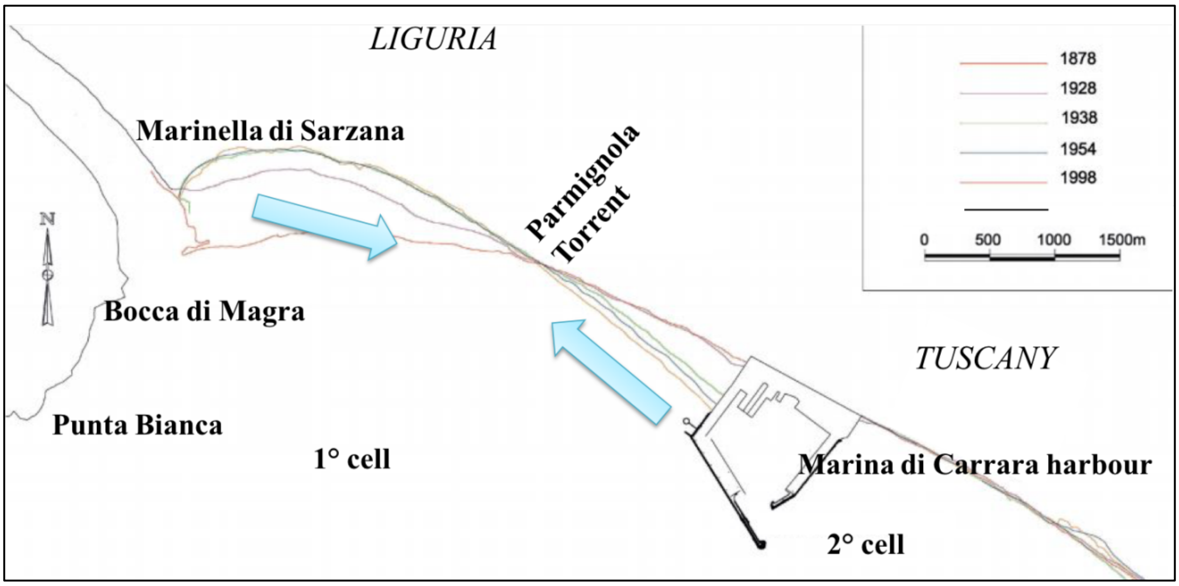

Figure 34 – Shoreline changes between 1878 and 2015 (Cipriani and Pranzini, 2014 modified). Arrows represent proximal drift directions north of Carrara harbour, with Parmignola torrent representing the reverse point. Numbers are the distant circulation subcells (Anfuso et al., 2011).

The Magra River develops through the sedimentary formations of the Tuscan Nappe and, in particular, in its upper and middle courses before meandering in the alluvial plain, it flows within a widespread and thick Oligocene stone sand formation known as “Macigno”, which represents the top of the Tuscan Nappe. As a matter of fact the sand which constitutes the beaches of the area under consideration is almost entirely the result of the “Macigno” erosion, transport and sedimentation by the Magra River (Rosi and Di Paola, 2001).
Except for the northern sector, which consists of mixed sand and gravel, the coast is mostly composed of sandy beaches of varying width, rich in quartz and carbonates, but also containing feldspars and heavy minerals (Gandolfi and Paganelli, 1975; Garzanti et al., 2001; Cipriani, 2013; Cipriani and Pranzini, 2014).

5.2.2. Climatology

The prevailing winds in this area blow from the west and the south-west during spring and summer, while in autumn and winter, north-north-east winds progressively increase in frequency (Melito et al., 2006). Wave climate is almost mono- directional and all the incoming relevant waves come from 220 N to 240 N, as a result of the geographical fetch distribution, as swell are sheltered by the Corsica and Elba islands to the south and by Ligurian and Tuscan coast to the north and east (Cappucci et al., 2011). Extreme events with significant heights wave (H_s) larger than 6 m are from 235 N (Aminti et al., 2002).
The Mediterranean basin and consequently the study area have a microtidal behavior, with an astronomical tidal range of about 30 cm (database of Istituto Idrografico della Marina - IIM), to which an atmospheric component of +20 cm and −18 cm must be added according to possible pressure values in this part of the Tyrrhenian Sea. Atmospheric pressure ranges between 994 hP and 1031 hP, with 1% and 99% of the frequency distribution based on 64988 observations at Marina di Carrara harbor from January 2006 to October 2009 (Anfuso et al., 2011). Due to the limited tidal variations, waves and wave-induced currents can be considered the mainly driving forces for Magra mouth and coastal changes.

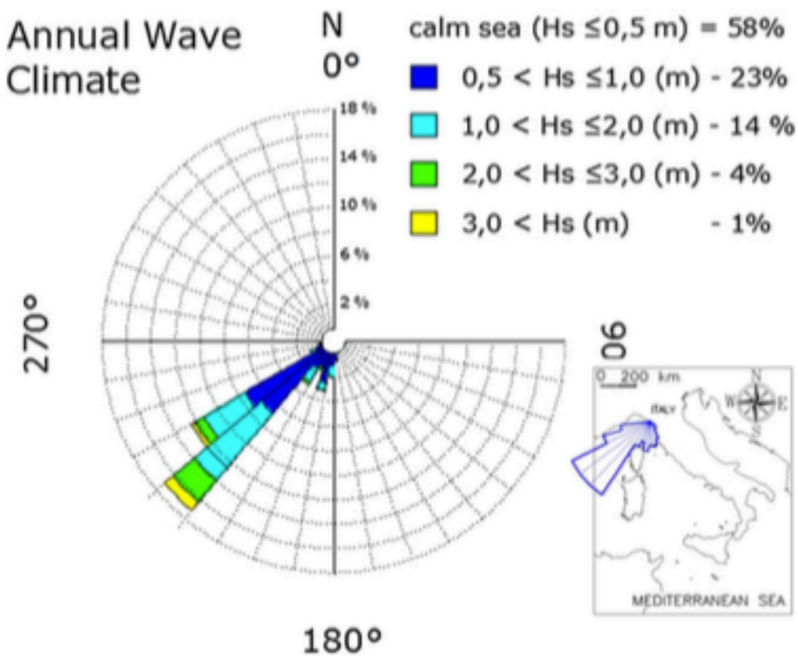

Figure 35 –Annual wave climate and geographical fetch on Carrara Coast (Cappucci, 2011)

5.2.3. Coastal physical processes

For a better understanding of the present morphological and sedimentary dynamics it is necessary to consider the physiographic sub-unit between the Magra mouth and Marina di Carrara harbor (south-easternward), part of main physiographic unit between Punta Bianca Promontory and Arno River mouth (Anfuso et al., 2011) (Figure 36).

The 64 km-long coastal physiographic unit (Figure 33 and Figure 34), located in the northern littoral of Liguria and Tuscany, recorded significant erosion problems in recent decades due to reduction in sediment input from rivers (Pranzini, 2004) and to the effect of the Marina di Carrara harbor, the Bocca di Magra marina and shore protection structures (groynes, island platforms, breakwaters, submerged groynes made of sand-filled polypropylene geo-containers) (Cipriani et al., 2001; Cipriani and Pranzini, 2014).

Geomorphological studies in this area (Aiello et al., 1975; Anfuso et al., 2011) supported by mineralogical and petrographic evidences (Gandolfi and Paganelli, 1975) identified a proximal and a distal drift inside this physiographic unit. The first one is directed north-south and is prevalently pumped by river transported sediments

(Figure 34). The second one is associated with three different cells inside which sedimentary transport occurs.

In fact, along the northern part of the coast, where Marina di Carrara harbor is located, the net sediment transport is directed southward, whereas along the southern section, net transport is directed northward. The local sediment distal drift reverse point is located south Marina di Carrara harbor (Anfuso et al., 2011) while the Parmignola Torrrent (Figure 34) is the reverse point for the proximal one (Cipriani and Pranzini, 2014).

The analysis of the three distal sedimentary drift cells allow the definition of the shoreline and its trend during time. The coast line is historically characterized by evident changes (littoral retreat and growth) due to sediments input variation from the rivers (Cipriani and Pranzini, 2014). That is caused by anthropic factors such as sediment withdrawal, land reclamation, dams and embankments construction (Pranzini, 2004).

The Magra River sediments represent the main natural nourishment for the beaches between the Magra River mouth and Marina di Carrara, as demonstrated by beach sediment petrography (Gandolfi and Paganelli, 1975; Basin Authority, 2000). The Magra River mean sediment load was estimated to be of approximately 50.000 m3/yr (EUROSION, 2004).

All of the studies performed so far ascribe the NW-SE direction to the distal drift, while the proximal drifts -which are the cause for the re-distribution of the sediments along the coast- show variable directions (Figure 34). These various directions are linked to the presence of different types of defence structures which determine local inversions of the longshore sediments transport direction (Anfuso et al., 2011; Cipriani and Pranzini, 2014).

The beaches of Marinella di Sarzana (Figure 34) have been experiencing severe erosion since the XIX Century (Pranzini and Farrell, 2004; Basin Authority, 2005; Rinaldi, 2006; Rinaldi and Simoncini, 2006). The beach of Carrara experienced accretion due to the presence of Marina di Carrara harbor which intercepts the longshore sediment transport directed southwards while the erosion processes were taking place around the Magra River mouth. In fact, the sectors near the Magra River mouth suffered the strongest damage in terms of loss of subaerial beach surface

(Cipriani et al., 2001). Moreover, Marina di Carrara harbour defines a clear boundary, indicating that the sediment plume from the Magra River moves mainly towards north-west, following the direction of the major Ligurian current (Delbono et al., 2016).

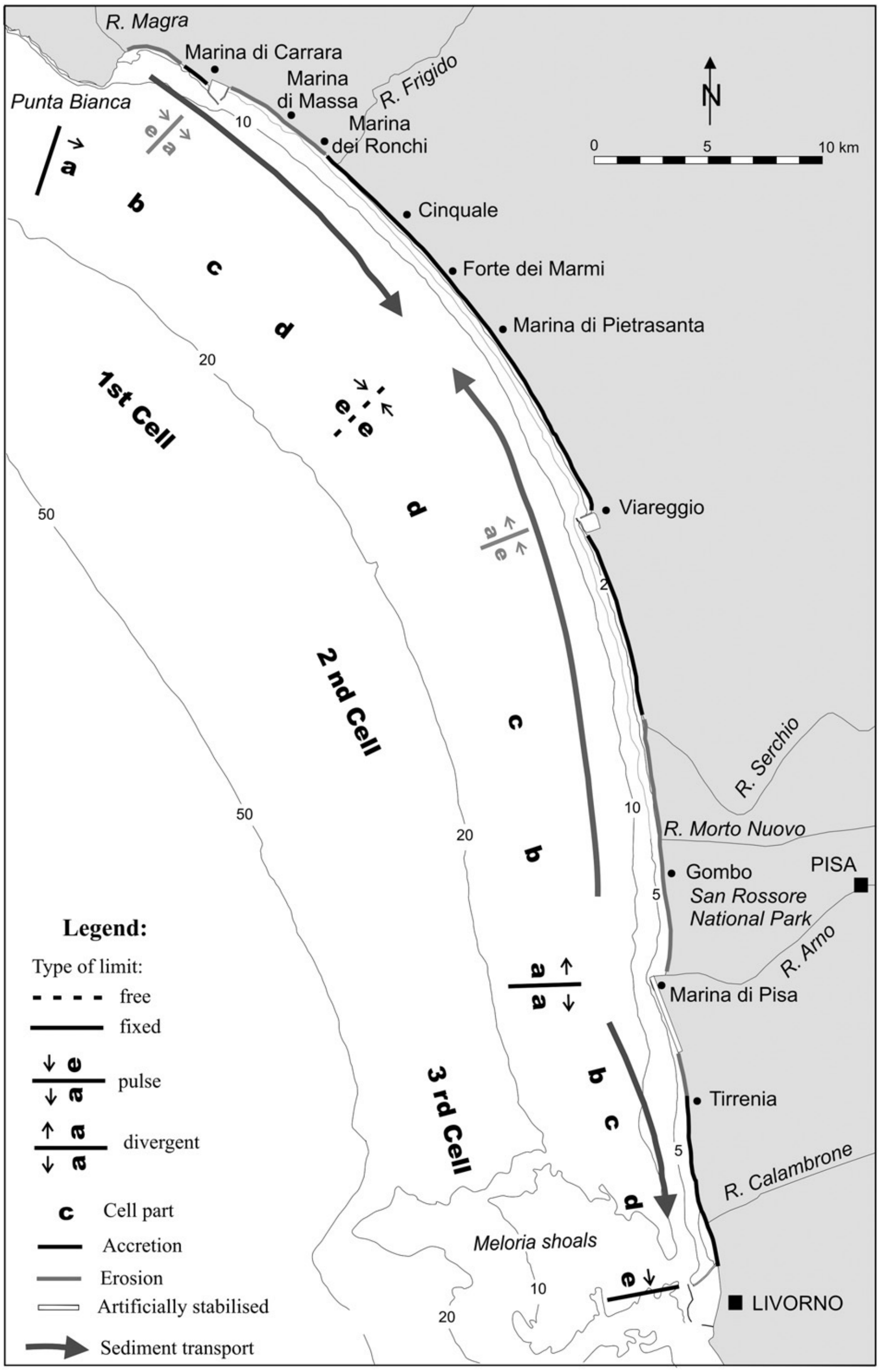

Figure 36 - Erosion/accretion areas, sediment transport, characteristics of limits and parts of major cells—limits of secondary cells in grey (Anfuso et al., 2011).

The shoreline trend shows that the mouth of the Parmignola Torrent (administrative border between the Regions of Tuscany and Liguria) is a stable area with no evident erosional-depositional phenomena from 1878 to nowadays (Figure 34). Therefore, representing the point around which the entire physiographic sub- unit shoreline rotated clockwise (Pranzini, 2004; Anfuso et al., 2011; Cipriani and Pranzini, 2014).

5.3.Method

The morphodynamics evolution of the Magra River mouth was studied throughout processing and exploitation of a palaeographic reconstruction overview and hydrographic data stored in the database of the IIM integrated by aerial photographs and coastline profile obtained from Liguria District.

5.3.1. Palaeogeographical reconstruction

Several geological, geomorphological, topographical and archaeological studies were carried out about the historical evolution of the Magra River mouth (Delano Smith, 1986; Delano Smith et al., 1986; Raggi and Sansoni, 1993; Bini et al., 2006; Bini et al. 2012).

At the beginning of Holocene (10000 BC) sea level was 7-8 m lower than the actual one and the last portion of the Magra River flew throughout a sandy and pebble plain more spaced from the western hills and Punta Bianca (Figure 33) promontory than it is now. These sedimentary material constituting the coastal plain was transported by the river ad its western tributaries because of the frequent precipitations. After a cold period (2000 BC) the local sea level raised and became 4 m higher than the actualposition. This determined the sea ingression inside the plain, and the reduction of sediment supply from the tributaries due to precipitation reduction determined the formation of a swampy area and a gulf (Raggi and Sansoni, 1993).

During the first millennium BC, as consequence of a cold and rainy period, sea level regressed again determining a bar system closing part of the gulf. During the I century BC the Magra River developed inside a large inlet and the plain between the hills and the Parmignola Torrent was 1 km wide (Delano Smith,1986; Raffellini, 2000). the city of Luni was built on its dendritic fan.

In fact the Magra River is strongly connected with the Roman colony of Luni foundation and development over centuries. The port of Luni, from which the marbles quarried in the Apuan Alps, used to build most of the monuments in Rome, were delivered, was never precisely localized, although it is supposed to be located inside the present day coastal plain built by the Magra River since the Early Middle Ages (Delano Smith, 1986; Bini et al., 2006).

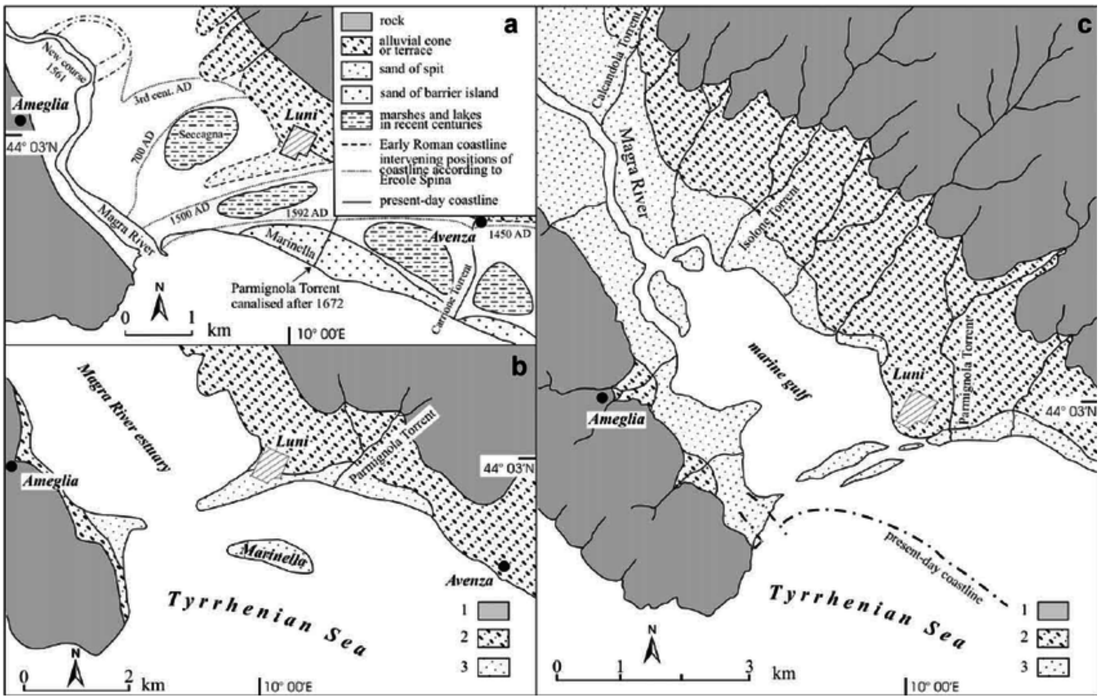

Figure 37 – The area of Luni at Roman times in the view

During the I century BC sediment input from the river deposited on the left side of the river and the wave action pushed the bars toward the lagoon, determining the progressive disappearance of the roman port named Saccagna. Lastly, around 1000-1200 BC, the lagoon infilled creating the fusion of sandy beaches and terrain inlet, determining a coastal lagoon. During the following years the river huge terrigenous supply caused the complete lagoon closure, and the mouth movement in west direction until the actual position delimited by the rocky promontory of Punta Bianca.

Magra deposits created a sandy bar directed E-W determining a bay surrounded by

swamp Saccagna. These scenario is shown in 1592 Ercole Spina's painting. Moreover, it is also visible another sandy bar on the right side of the estuary where will be constructed Bocca di Magra and finally, in front of the mouth, a sandy barrier parallel to the coast called "Isola di Marinella". These sandy structures surrounded by the swamp where used as docking facilities (Bini et al., 2006).
Therefore, this accretion of the littoral zone continued since the second half of XVIII century. The plain was still an uncontaminated area, with only a few buildings, delimited by local torrents as Parmignola one. The map of Matteo Vinzoni (1773) gives an image of the river mouth and surrounding area (Figure 38). While the presence of several lakes and pounds showing the drainage system and the channels are really similar to the actual one, the Magra River mouth is very different than nowadays, with long bars testimony of the huge sedimentary input. The effects of this terrigenous supply are also visible in 1829 topographic map of the area: sandy deposits and lagoons are seaward limited by the Magra mouth.
Moreover, during the centuries, the riverbed axis migrated towards Punta Bianca Promontory with a parallel setting. Starting from 1878, with the first reclamation activities in order to increase agriculture in the area experiencing a trend inversion: a progressive erosion with the consequent recession of the coast line at east of the Magra mouth.
At the beginning of the XX century human constructions appeared around river banks, announcing the intense urbanisation of the plain. Thanks to legislative measures, reforestation and riverbanks adjustment activities were carried out. In fact, the updrift beach, adjacent to the port breakwater, has experienced accretion of approximately 400 m since the 1920, when port construction began (Cipriani and Pranzini, 2014). Around 1930-1950 three dams were built for hydroelectric purposes along Magra tributaries (Delbono et al., 2016). These interventions caused bed reduction, and the river tendency to alter the meandered morphology for a more linear one. This tendency accentuated during 1960-1970 due to the excavation activity: sediments were used to build neighbouring highways. These excavations ended in the beginning of 1990s showing a high reduction of the river bed depth along its course, and moreover its shrinkage (Rinaldi, 2005; Rinaldi, 2006; Rinaldi et al., 2009). In order to halt erosion, which affects only the Ligurian sector, several

coastal defence structures have been built (groynes, island platforms, breakwaters and submerged groynes made of sand-filled polypropylene geo-containers). These have intercepted the small volume of longshore sediment transport coming from the Magra River mouth.

Figure 38 - La Marinella, M. Vinzoni 1773, Archivio di Stato, Genova

A new coastal defence intervention was made at Marinella di Sarzana in 1999, inducing moderate accretion locally, in the Ligurian side. After that, modifications to existing defence works were also made, which included extending groynes with submerged parts. This was followed by beach nourishment using sediments that had been dredged in the lower section of the Magra River and, recently, by the input of sand coming from quarries located in the Po river alluvial plain (Cipriani and Pranzini, 2014).

5.3.2. Hydrographic data analysis

The hydrographic data stored in IIM database were collected since 1882s (Table 3) and they are representative of all the data set analyzed. This database covers a 135-yrs period, expression of the evolution of hydrographic survey methods and technology. All data stored were acquired to be used for navigational purposes and because of that they follow the hydrographic standards of the survey time. As consequence of the data quality, the data and their processing products, such as Digital Terrain Model (DTM), are naturally comparable. Survey equipments and methodology are the discriminating factor and thanks to the standards they did not influence data quality but increased resolution.

Year	Number	Survey Denomination	Scale	Survey System
1882	IIM-2105	DAL TINO A PUNTA CORVO	1:10.000	Lead line
1882	IIM-2205	DA PUNTA CORVO A FORTE DEI MARMI	1:25.000	Lead Line
1954	IIM-7309-2	DALLA SPEZIA A MARINA DI CARRARA	1:10.000	Singlebeam
1972	IIM-8287-1	DA MONTE CASTELLANA A COLONIA	1:20.000	Singlebeam
2000	IIM-8961	FOCE DEL FIUME MARA	1:2.500	Singlebeam
2000	IIM-8961	CORSO DEL FIUME MAGRA	1:5.000	Singlebeam
2014	Regione Liguria	FIUME MAGRA	1:2.500	Multibeam

Table 3 - IIM Bathymetric Database

Depth values acquired with different systems (lead line, acoustic singlebeam and multibeam) were analyzed together with metadata (positioning system, vessel type, tide correction, sound velocity correction, systems accuracy) and processed in order to obtain digital products.

The DTM is a numerical representation of seabed topography, which is widely used throughout hydrographic, geomorphologic and environmental studies. In coastal areas, DTMs have been utilized in many analyses such as topography, seafloor slope, estimation of scour and/or fill volumes semi-quantitatively (Taaouati et al., 2011).

Besides that, the aim of this study is to analyze the morphodynamic of the study area exploiting high resolution bathymetry data output, the use of DTM is fundamental. In fact, this investigation was achieved through a number of steps based on temporal spatial scaled DTM and their comparability permitted seabed and coastal change monitoring.

For all data set, which have nearly a 50-yrs interval (1882, 1954, 2000, 2014), a 1 m grid resolution DTM was obtained and 150, 50, 10-yrs period analysis was carried out. The processing was made by means of CARIS software (www.caris.com) in order to obtain 2D and 3D DTM, slope model and difference surfaces.

In particular slope model is obtained taking into account the direction of TIN nodes and it in each point gives information about maximum slope and aspect. Finally, difference surfaces enable sediment volume analysis because they give an exhaustive representation of seabed dynamics over time.

Bathymetric DTM are representative also of the coastline due to the connection between 0 m depth with the interface land/water. So integrated analysis among different years gives information about study area changes over time.

5.3.3. Bathymetric data analysis and processing

In order to analyze 1882s data using modern hydrographic software and make assertions about seabed morphology evolution over more than a century period of time, sounding were digitalized throughout the following procedure: bathymetry graph (Figure 39) was scanned and geo-referenced to the world geodetic datum (WGS84 UTM32N) by trigonometric point of IIM database used in 1882s as reference point for the survey line (Figure 39). These trigonometric points belong to the 4^{th} order network and have a relative uncertainty of ±50 cm. Calculating total budget error, graphicism was also considered: at 1:100.000 scale is 2 m. Using Gauss error quadratic propagation law, horizontal uncertainty is about 2.3 m.

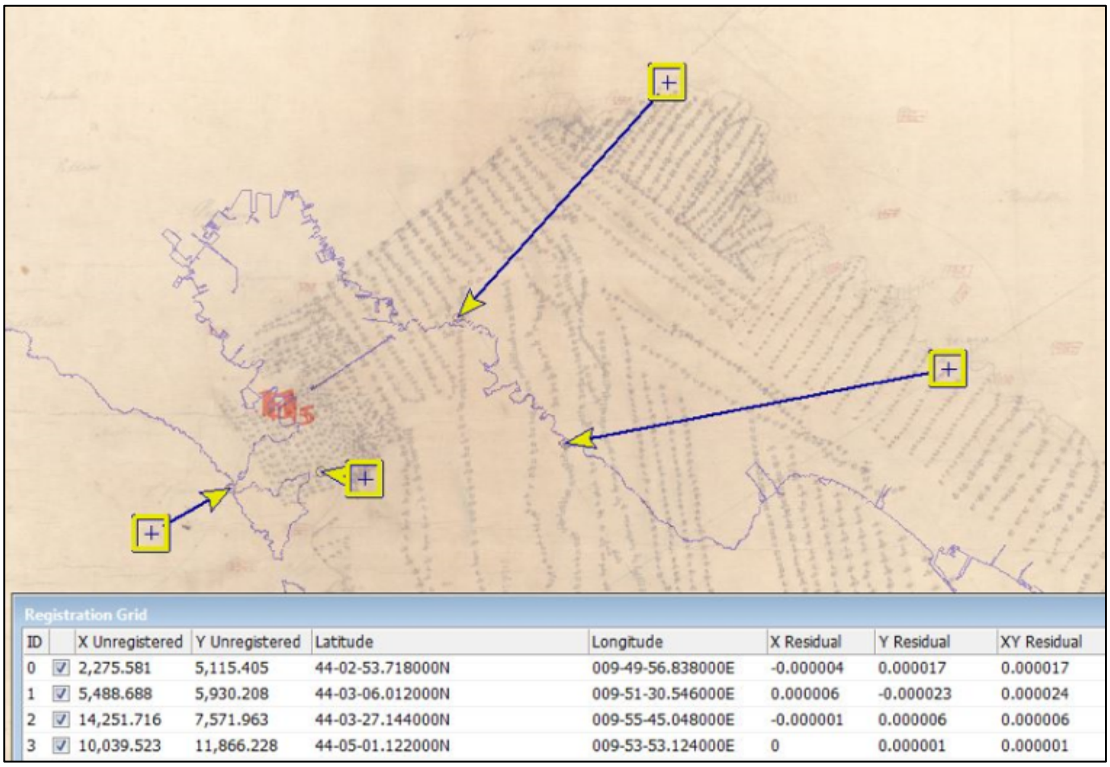

Figure 39 - Bathymetric survey (lead line) survey sheet IIM No, 2105 (1882); Arrows indicate trigonometric points used for georeferencing process.

Finally, 1882s depth values were digitalized using the geo-referred image, obtaining as final output a XYZ file comprehensive of the coastline witch correspond to 0 m depth head of the survey line. 1882s data were already corrected by tide and referred to local mean sea level.

In order to model, visualize and better understand 1882s scattered bathymetric dataset, interpolation was performed implementing point cloud to grid conversion so to estimate the value of an attribute at locations without sample obtaining a DTM representative of the continuous bathymetric surface. Natural neighbor interpolation technique based on Voronoi polygons was applied to the Triangulated Irregular Network (TIN) obtained by soundings digitalization. Final output is shown in Figure 40.

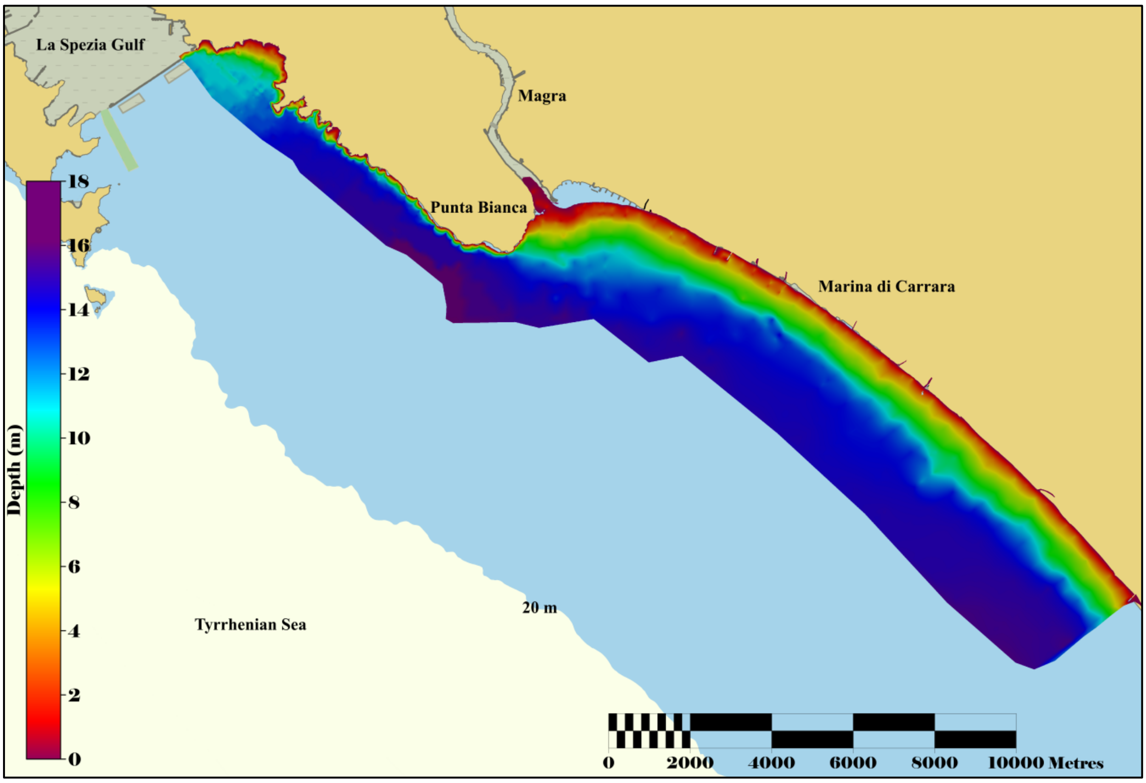

Figure 40 - Interpolated surface (1m x 1 m Grid) from 1882s sounding chart overlaying electronic nautical chart (ENC IT400115).

1954s (data set depth from 1 m to 15 m) and 1972 single beam data set (data set depth from 1 m to 20 m) were already digitalized by IIM but they did not cover coastline. In order to make coastline evolution assumption throughout different years DTM integrated analysis, 1954 topography graph was geo-referred and digitalized extrapolating a XYZ file comprehensive of 0 m depth. Finally, a unique dataset with singlebeam data and coastline (0 m) was created and processed with CARIS HIPS&SIPS software in order to obtain a 1m resolution introduced grid, natural neighbor interpolation method (Figure 40).

The same process was applied to 2000 bathymetric data set. In this case coastline (0 m) was obtained thanks to aerial photographs digitalization. Latest dataset was acquired in 2014 with multibeam echo sounder. This survey covers Magra riverbed and was made before a dredging activity.

Bathymetric data exploitation was carried out through slope analysis and difference surfaces. In particular slope surfaces were calculated from each DTM. Slope data give information about bottom stability and their comparison highlight Magra River

delta system features evolution. Moreover, the volume computation was made digitalizing erosion/ accretion areas and comparing difference surfaces.
1182 survey graphs also contained information about seabed type. These data were digitalized. The result of such elaboration is shown in Figure 41. The distinction about mud (East Magra River) and sandy mud (West Magra River) may be due by a change in the surveyor.

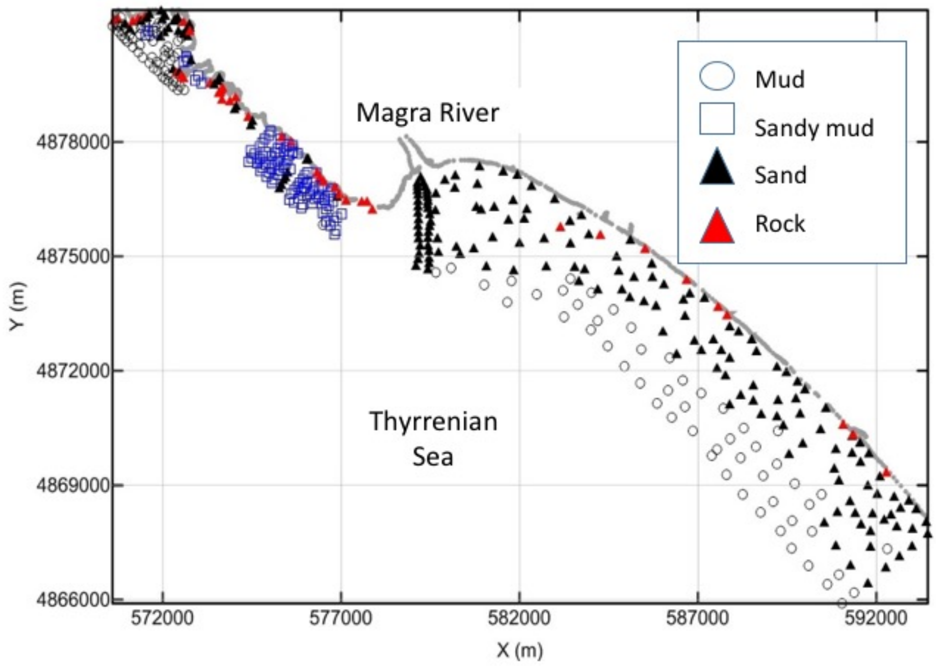

Figure 41 – Sediment chart obtained from 1882 data

5.4.Observations

During the last decades the most apparent response of the Magra mouth and close beaches has been an intense reshaping of the delta system, seabed and shore sedimentary deposits with significant coastline changes. This behavior is assimilable in the Mediterranean to the Ebro delta one (Jiménez et al., 1997; Jiménez et al., 1999).
Data Magra River mouth evolution was centered on three main periods defining secular, 50-yrs and 10-yrs trend. In particular, these temporal frames are characterized by natural and anthropic processes combination as sediment supply,

marine factors principally wave action and fluvial and coastal structures. In detail the studied area is characterized by:

i. 1882-2000: a long period that highlights the delta geometry destruction both in its subaerial and submerged part with significant erosion of the seabed and N-E beaches accretion and clockwise rotation of the coastline. In particular, between 1882 and 1954 the shore protection structures and harbors were constructed. This period allows medium term evolution studies characterizing longshore sediment transport pattern;
ii. 1954–2000: when no important projects were implemented by the sea but sedimentary budget was influenced by human activity along the river for analysis of current trends; river mouth experienced a significant erosion;
iii. 2000-2014: strongly influenced by the dredging activity to the mouth, for analysis of current trends DTMs comparison produced difference surfaces (Figure 45 and Figure 44) obtained overlaying earlier to the older surface (1882-1954; 1954-2000; 2000-2014; 1882-2000), clearly highlighting accretion and erosional sectors with the consequent coastline modification, and disappear, creation and migration of undersea features.

5.4.1. Submerged delta system changes

Despite the artifacts due to data interpolation the comparison of 1954 slope and bathymetric surfaces (Figure 42) shows an evident seabed erosion. In fact, there are two submarine channels indicating a relevant sedimentary flux (Figure 40 and Figure 42). Moreover, is also visible a bar system that was not present in 1882s DTM (Figure 39).

The comparison of 1882s and 1954s DTM highlights a coastline clockwise rotation toward SE with consequent movement of sedimentary deposits (Figure 43). In detail there is a progradation of the coastline and the advance of subaerial beaches in the north-eastern sector and an infill in the southern sector with a depth decreasing in correspondence of Marina di Carrara harbor that was built between 1922 and 1954 and represented a barrier against sediments drift (Cappucci et al., 2011; Cipriani and Pranzini, 2014).

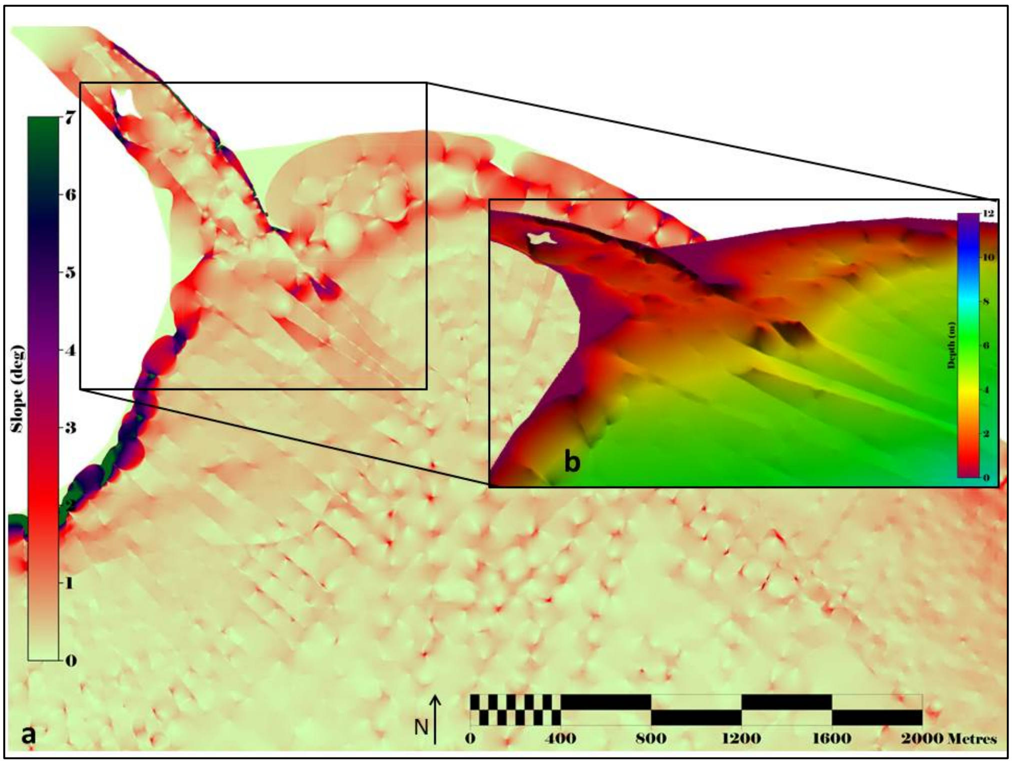

Figure 42 - (a) 1954s Slope Surface; (b) 3D bathymetric model with enhancement 10 showing submarine channels

Sediments deposited besides the north pier of this port determined 200 m accretion of the beach as is shown in Figure 43 (around 8 m) where the black line and the purple line are respectively 1882 and 1954 coastline. Opposing to this accretion activity in correspondence of the harbor, the Magra River delta became estuary, experiencing an erosion activity probably caused to the decreasing of the sedimentary budget associated with the river excavations and land reclamation (Rinaldi et al., 2009). These erosion phenomena determined the depth increasing close to the river mouth (maximum value calculated 4.5 m) and the rotation of the coast line with the advancement of the subaerial beaches (about 350 m). The rotation occurred around Parmignola Torrent, as is shown in Figure 34 and above in detail discussed (Cipriani and Pranzini, 2014).

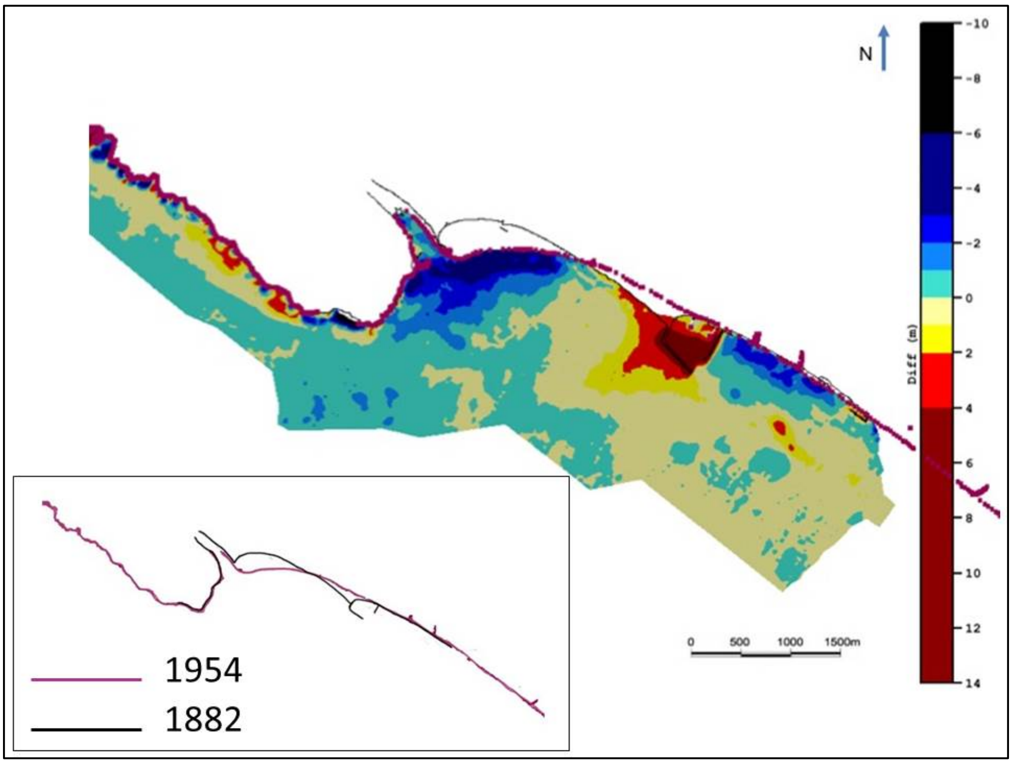

Figure 43 - Difference surface between 1882 and 1954 bathymetric data set; Erosion areas are represented in blue and accretion one are in red (values are expressed in metres). Black line represents 1882 coastline, purple line represent 1954 coastline.

The comparison of 1954 and 2000 DTM shows the continuous trend with sensible reshaping of Magra mouth in estuary. In this period several defense structures and human facilities were constructed along the river mouth and the beaches such as piers, embankments, river banks and groins. Elongated seabed features shown in Figure 44 recorded a S-E oriented erosion trend toward sea, particularly evident phenomena in correspondence of the eastern mouth pier. These elongated geometries are representative of submarine drainage systems (channels) and bar systems creating the estuary. The pier construction represented a barrier for the S-N sediment drift becoming an artificial barrier for fluvial and marine processes, in addition to the natural barrier (tectonic line) represented by Punta Bianca promontory that delimits the western side of the Magra River mouth (Rinaldi et al., 2009). Moreover, a beach accretion is visible N of it analyzing the very shallow water and subaerial portion of the studied sector as above mentioned.

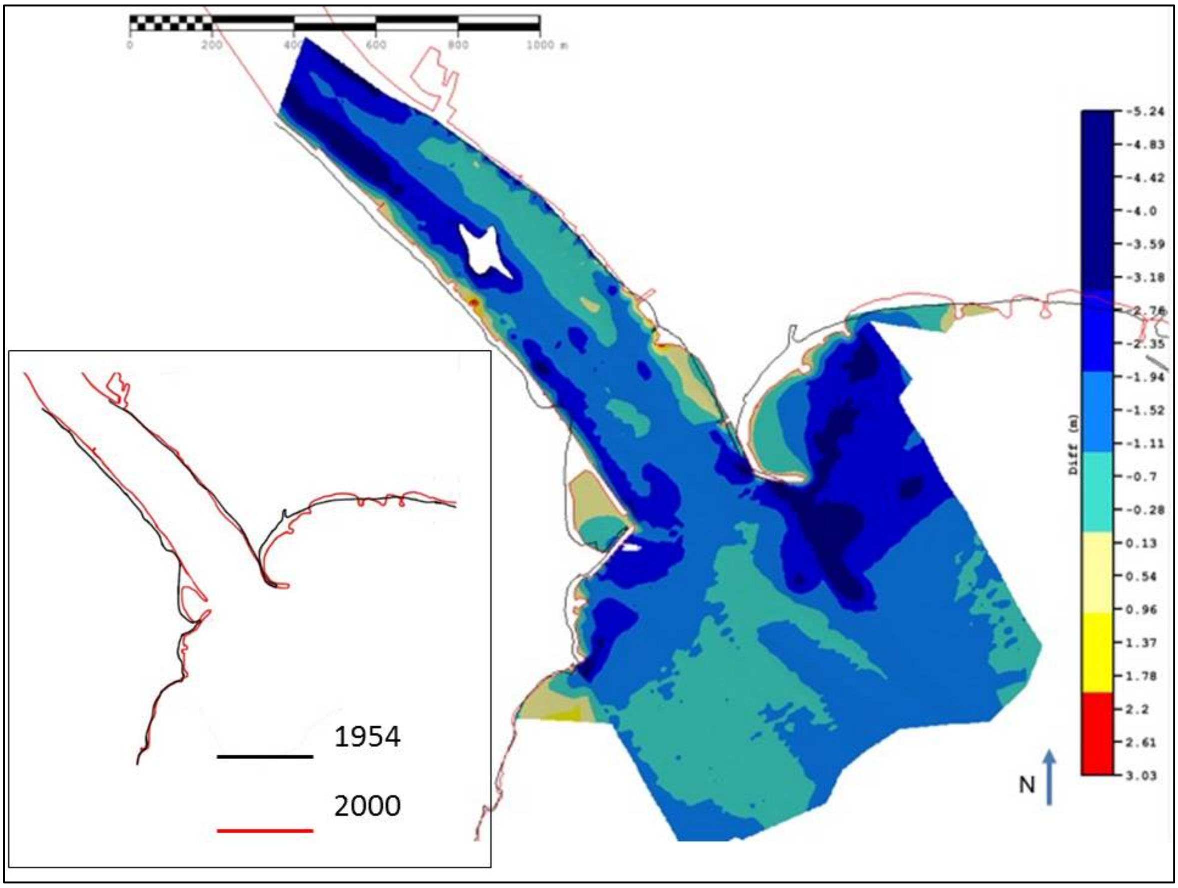

Figure 44 - Difference surface between 1954 and 2000 bathymetric data set. Erosion areas are represented in blue and accretion one are in red (values are expressed in metres); the red line indicates the 2000 coastline and the black line the 1954 one. Positive values indicate net vertical accretion

Furthermore, riverbed sediment supply decreasing is a consequence of dredging activities over this period. In fact, this trend is mainly caused by a strong reduction of the sediment input coming from the river whose material was highly used for highways constructions (Cappucci et al., 2011).

The decadal trend obtained by 2000-2014 DTM comparison gives the confirmation of the riverbed dredging. The west side of the river experienced higher erosion phenomena due to the increasing of the current intensity and the sediment flux changes its direction constrained by the river defence structures. On the other hand, on eastern river side there is a huge sediment deposition with submerged elongate bars formation typical of an ebb delta (Figure 45).

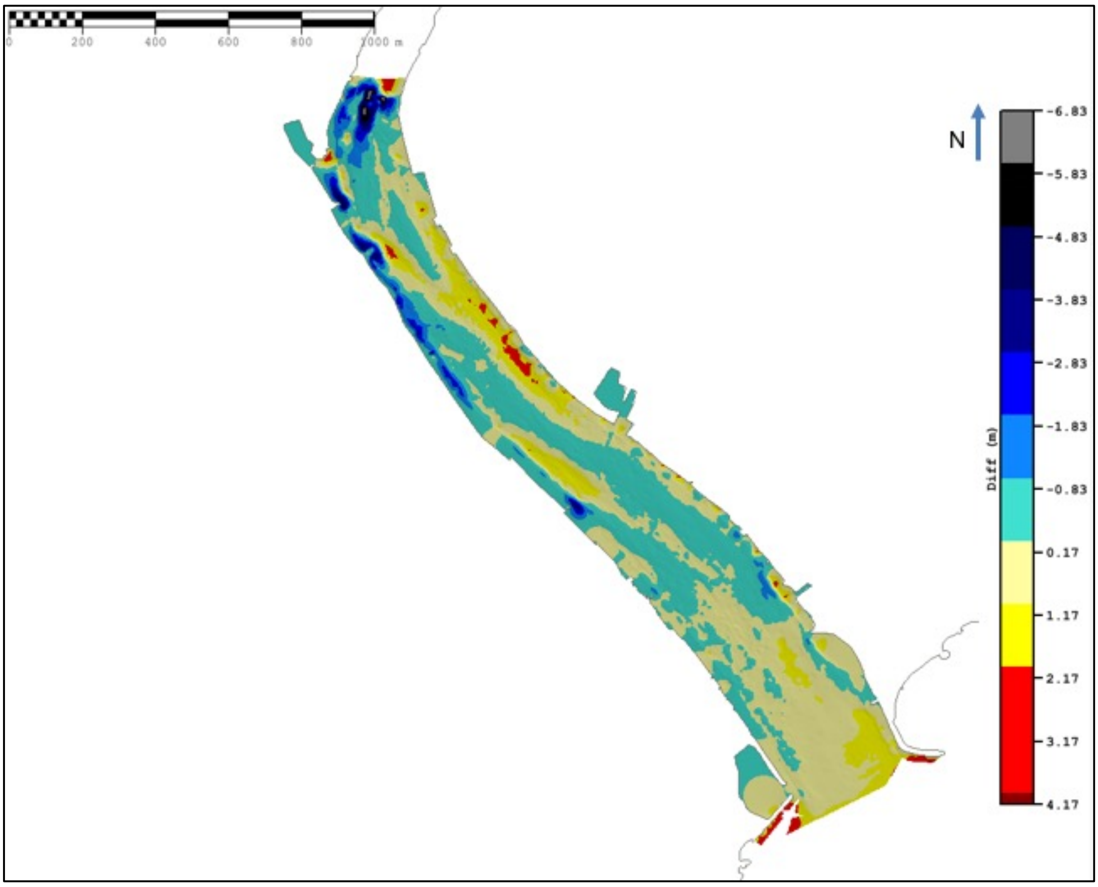

Figure 45 - Difference surface between 2000 and 2014 bathymetric data set; Erosion areas are represented in blue and accretion one are in red (values are expressed in metres).

The secular trend is showed by the 1882-2000 difference surface that also in this case allows a quantitative estimation of the erosion over 118-yrs period of time. As is shown in Figure 46 (a) there is 300x400 m area where the erosion reached 6 m. An area of accretion is also evident in correspondence of the western mouth side (Promontory of Punta Bianca).

Between 1954 and 2000 the riverbed showed in Figure 46(b) and the bar, totally disappeared due to the erosion combined with the sensitive lack of terrigenous sediment input. This a confirm that the continuous reshaping of the Magra River mouth over time is mostly influenced by sediment input and longshore sediment pattern both induced by human activity. In fact, until the first half of the XX century (1882-1954 data analysis) the Magra River mouth was characterized by emerged structures typical of deltas such as bars and a structured riverbed axes. In this period alongshore alternation of accretive and erosive stretches did not determine a

significant change in the overall deltaic subaerial surface. Although the study area is a microtidal one, and waves are the main agent forcing coastal evolution at yearly scales, the Magra mouth is well structured as estuary system.
It is important to highlight that in this area sediment transport is mainly influenced by wave direction, principle responsible for short-term and seasonal changes. In fact, wave action on deltas produces a local modification of river mouth processes on one hand, and the reworking/redistribution of river supplied sediments along the coast, on the other hand. Sediment reworking along the coast is not independent of the river influence because sediments are mostly of riverine origin and is strongly influenced by wave characteristics which drive the reshaping and reduction of deltaic body and local bathymetry which controls wave propagation towards the coast. The eastern jetty construction at the mouth concurred to the directionality of the seabed features Figure 46 (b) created by marine processes whose probably energy consequently increased. The long-term scale, from 1882s to 2000s better shows the disappearance of the visible delta system, westerly constrained by the tectonic line, to the nowadays visible Magra estuary Figure 46 (a).
Despite the significant erosion process that lead to the estuary formation in Figure 46 (a) is in fact clearly recognizable a submerged delta. The ebb structure depicted by DTMs is the result of submarine sedimentary processes occurred in the second half the XX century in the meantime of the emerged estuary shaping. This structure, as result of the data quality and the method of analysis applied, evidences the reduction of the deltaic system and the complete destruction of its subaerial portion during centuries while these hydrographic data permit the quantification of the sediment volumes using seabed data analysis and processing.
In fact, as anticipated, the difference surface resulted from 1882 and 2000 DTMs were compared in order to obtain quantitative assessment about sediment evolution. This volumetric calculation at different time scales supports literature semi-quantitative assumptions (Cappucci et al., 2011). The calculated volumes resulted by this computation at the Magra River mouth are: 3Mm^3 in the last 100-yrs, 1,8Mm^3 in the last 50 yrs and 1Mm^3 in the last 10 yrs. In particular, the sedimentary loss trend, confirms the delta system destruction, in particular during the first half of the XX century. Both emerged and submerged delta progressively modified their typical

morphology evolving into an estuarine system with its characteristics features (elongated bars, directionality of sedimentary deposits). The submerged delta, appeared after 1954 as previously discussed, contrasts with the normal delta's trend evolution (Galloway, 1975; Boyd et al., 1992; Anthony et al., 2014).

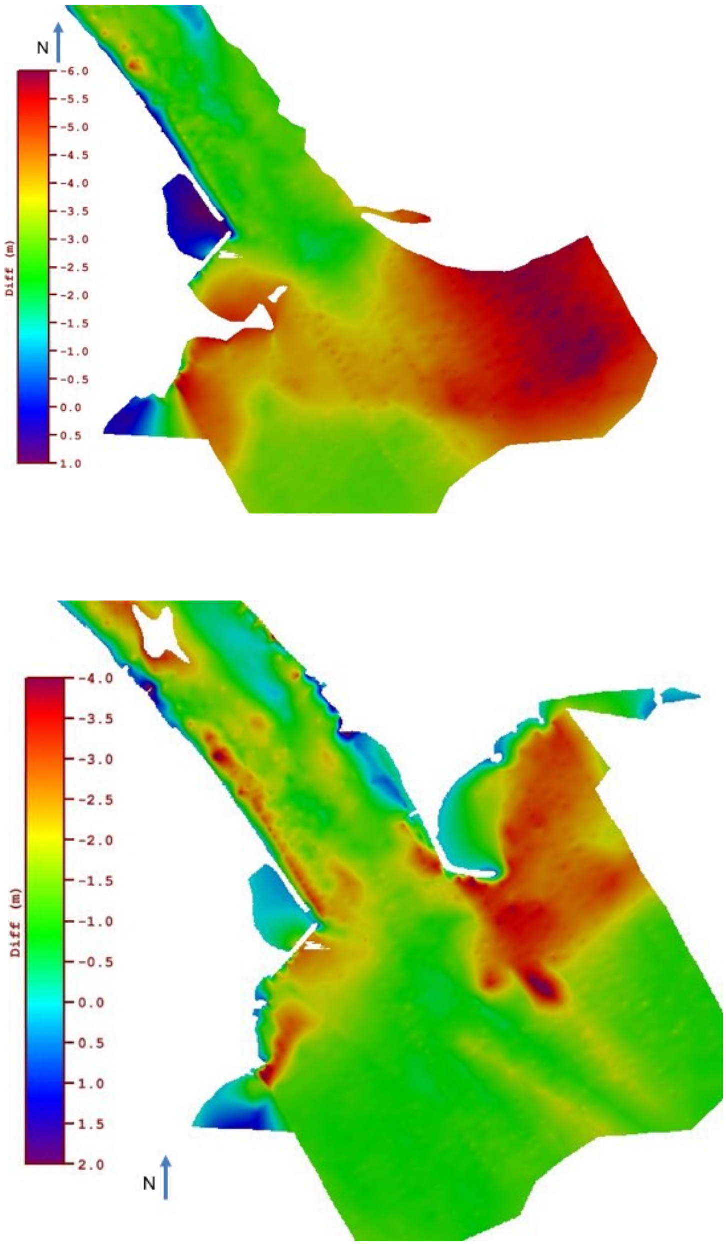

Figure 46 – (a)Difference surface between 1882s and 2000s bathymetric data set; (b) Difference surface between 1954s and 2000s bathymetric data set

About this, there is no comprehensive typology of Mediterranean estuaries, however, the geomorphic classification is largely studied and it is characterized by the transition from a strongly nature-dominated to an increasingly human-dominated environment (Delano-Smith, 1986; Anthony et al, 2014) at different time and local scales.

The impacts of the changes in river sediment budget on the Mediterranean deltas (Anthony, 2014) and their adjacent shores have been documented in many case studies, notably concerning the deltas of the Nile (Frihy and Khafagy, 1991; Frihy and Lawrence, 2004; El Banna and Frihy, 2009), the Rhone (Antonelli et al., 2004; Maillet et al., 2006a and 2006b; Sabatier et al., 2006), the Ebro (Palanques et al., 1990; Jiménez et al., 1997; Jiménez et al., 1999; Lavoie et al., 2014) and the Po (Jiménez, et al., 1995; Simeoni and Corbau, 2009). In particular, Ebro experienced a significant reshaping process mainly due to limited sediment supply and wave action. In Ebro case, the main agents caused a series of erosive and accretive coastal stretches without a significant change on the subaerial surface of the delta (Jiménez et al., 1997; Lavoie et al., 2014).

As anticipated, models and classification schemes in coastal studies are used to explain, generalize and simplify complex landscapes and the processes affecting its. The most classic classification schemes are the tripartite divisions of wave/tide/river dominated deltas by Galloway (1975) and the wave/tide dominated estuaries and their tripartite zonation structure by Dalrymple *et al*. (1992); both categorize coastal water bodies into end members in the morphologic spectrum on the basis of the relative dominance of wave, tidal or fluvial (in deltas) processes (Litcher et al. 2011).

The dynamic morphology of Mediterranean rivers mouths and their spatial and temporal deflection patterns are subjected to the influence of numerous factors such as the topographic setting of the beach (Anthony, 2014: Antonelli et al., 2014), vegetation cover, river discharge, wave climate, shoreline position, and anthropogenic factors. Processes and changes in one or more of these factors trigger change in the morphology of a river mouth. These processes occur in different temporal scales (Litcher et al. 2011)

Under stable tectonic and sea level conditions, the gross geomorphology of coastal waterways is principally determined by the relative influence of wave, tide, and river power, with each coastal waterway containing a distinctive suite of geomorphic and sedimentary environments relating to each sediment supply and developing new classifications (Boyd et al., 1992, Dalrymple et al., 1992). In fact, in accordance with fluvial power and wave and tide action, deltas tend to estuary differencing themselves by the dominating factor (wave or tide dominated estuary) with an embayed shape characterised by mixed sediments source (intermediate condition) or strand plains and tidal plains, with minimum fluvial power, and prograding marine sediment source.

So the classification link estuaries and deltas (Boyd et al., 1992), the former normally tending to evolve into the latter over time if sediment supply is adequate.

This research has used 135-yrs bathymetric data in order to study Magra River mouth evolution over time, taking also into account its history and human influence and considering stable tectonics and sea level conditions. Data analysis and the difference surface comparison clearly show us an opposite tendency than the normal evolution trend of deltas described by Boyd: despite the poor fluvial power and sedimentary discharge a submerged delta is appearing.

In fact, in Magra River case, the subaerial changes are the product of sediment supply and marine processes, in accordance with the other Mediterranean deltas. Besides from seabed data set emerged that undersea features and morphology are typical of estuarine body. Therefore, the secular monitoring of the River Magra delta system, demonstrate that this mouth has a different and anomalous evolutionary trend in comparison to the other Mediterranean deltas because the subaerial retreat is associated with a new submerged deltaic body transforming from delta to estuary in a microtidal condition.

There is no evidence in literature about this tendency. In fact, the anomaly is represented by the delta transaction into estuary of the Magra River mouth that experienced a retreat of the emerged part mainly caused by erosion and a total destruction of the submerged one.

5.5. Conclusions

The study of the morphological evolution of the Magra mouth over 135-years period of time, carried out through high resolution bathymetric data, allowed to define the submerged delta system changes over secular, decadal and yearly time scale frame.

DTMs of 1882, 1954, 2000, 2014 show the seabed morphology during time and their comparison permit to follow coastal dynamics with accretion or erosion conditions. In fact, bathymetric data collected from 1882 to 2014 with different survey systems but following the same international standards (IHO S-44, 2008) are completely comparable. They allow to assess and quantify the seabed morphodynamics in relation with the river sedimentary budget and covering different time scales (secular, half-century and decade). Thanks to data series stored in the historical database of the IIM, digital bathymetric dataset used for the nautical charts highlights changes in the geometry of Magra River mouth from delta to estuary. In fact, its bottom features and the coastline changes primarily due caused by sedimentary budget variation and secondarily by wave dynamics. This result was gained thanks to standard high resolution data and using sophisticated software for data exploitation and modeling.

Difference surfaces DTMs show that Magra delta riverbed during the last century maintained its position while previously was characterized by migration and progradation. This high deltaic morphodynamic is recorded during time since the I century BC. In fact, the Magra River was described by a well structured deltaic system in advancement. While the area was developing the riverbed was migrating towards west and stopping at the tectonic line of rocky Punta Bianca Promontory. As consequence the river mouth continued in its progradation phase and followed by a decreasing due to human intervention over centuries. In particular, reclamation activities, reforestation and urbanization caused a significant sediment supply reduction that lead to deltaic system erosion. Moreover, jetties represented an additional barrier to the sediment drift, constraining the river flux and preventing the normal, outflow and expansion of the plume eastward whose angle of expansion remained narrow confined in the riverbed alignment and velocities decreased slowly with distance from the outlet determining the bar system formation.

Magra River mouth evolution, probably, is the first case study of monitoring change from delta to estuary system with decrease of sediment supply. This situation may have been influenced again by the tectonic line west Magra River, acting as a block in delta development.

In fact, during the last century, it was recorded a passage from fluvial-dominated to wave-dominated processes because of the significant decrease of the sediment supply creating two different situations: 1) delta subaerial morphology weak retreat with clockwise rotation and progradation of the eastern coastline; 2) well structured submerged delta transforming itself in a wave-dominated estuary in a microtidal environment. In addition, besides the disappearance of the typical constructive seabed delta morphology into the current small estuary, a submerged delta appeared after 1954.

6. Concluding remarks

During this study I provided a harmonised and integrated approach to seabed characterisation, in order to achieve a classification of relevant geomorphic structures of different interest (biological, geological, hydrographical, engineering, etc). In particular, this research has reviewed how the identification of undersea features with seabed mapping of ecologically relevant geomorphic structures relies heavily on automated or semi-automated classifications which can be taken further to a true geomorphic classification. The results depend on the scale of bathymetry used, the programs/algorithms used, data quality integration and generally on methodology to be applied. There is a need for a harmonisation of the resolution of the data sets, and the used tools for the analysis. Standardised scales like 500 m – 50 m – 5 m and corresponding map scales of 1:1.000.000 – 1:100.000 – 1:10.000 can be one option but not a general solution as shown during the analysis.

Geomorphic structures identified from acoustic data contribute significantly to the knowledge base needed both in coastal and deep waters.

Acoustic fundamentals are the basis for this approach leading to different acoustic responses generated by different seabed features. Responses for various orientations of the survey track, and these structures can change with time. This phenomenon is referred to as the "directionality" of the seabed. Such different responses are particularly apparent in Side Scan Sonar. They also occur in single-beam and multibeam data, but they are seldomly measured. This directionality can be overcomed thought a multi-focusing approach and data integration such in the Levante Canyon seabed characterisation undertaken in this thesis.

Moreover, the resolution of the acoustic data to be used for seabed mapping should be directly linked to the scope of the analysis. High resolution bathymetry and historical dataset comparability allow the morphological evolution study of specific features such as in the Magra River estuary characterization.

The resolution currently provided by open portals (eg. GEBCO[6], EMODNET[7],

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[6] http://www.gebco.net/data_and_products/gridded_bathymetry_data/

[7] http://www.emodnet-hydrography.eu

NOAA[8], etc…) is suitable for broad classifications at a basin-wide scale. Less than 50 metre resolution is necessary to define medium-scale features like canyons and associated possible habitats (as cold water corals in the Levante Canyon). When fine-scale classification is the scope, bathymetric data from multibeam echo sounders with a resolution of 5 metre or better is required.

The natural world is hierarchically structured, and processes within natural regions operate across a number of spatial and temporal scales. Variability is present at all temporal and spatial scales, and this should be handled properly with a survey-design strategy adapted to the required seabed-classification scheme. More consideration needs to be given to survey designs plans that are weighted towards systematic line transects with no randomization and little or no prior knowledge; or to acoustic multibeam surveys based on the need to sample along bathymetric contours to obtain a uniform swath width and to minimize outer-beam variability.

The use of multiple frequencies increases the ability to classify seabed, because both surface (near nadir) and volume backscatter vary with frequency. Lower frequencies penetrate the seabed to greater depths, whereas higher frequencies can resolve smaller spatial structures. Frequency palette may also penetrate seabed for approximately centimetres, or possibly up to 1 m, depending on substratum. Combining frequencies is equivalent to optical-satellite remote sensing, where multiple wavelengths measuring different physical characteristics are combined to classify and map land and ocean areas. Currently, during the analysis, different frequencies and echosounders have been combined to improve seabed classification.

In the framework of my research the application of the same methodological approach to three different areas (deep, medium and shallow waters) with different environmental characters (biological interest, volcanic and hydrothermal activity, river mouth evolution and management) allowed the following considerations:

- The Levante Canyon case study showed that classification of ecologically relevant geomorphic structures can be based on a multi-focusing approach using different sensors and multiscale bathymetry data sets. Broad-scale features can be defined using coarse data sets, such as a 10 metre grid. On the

[8] https://maps.ngdc.noaa.gov/viewers/bathymetry/

other hand, it is critical to have very high resolution data sets from multibeam echosounders in deep waters and in areas with complex geomorphic structures such as canyons. Data integration overcame this issue, allowing mound identification and deep corals banks localisation. The bathymetric grid was suitable for defining canyons, with a wide range of topographic/geologic features such as ridges, terraces, sediment waves, slump scars and channels. These features provide the physical environment for corals habitat, including hard substrate suitable for cold water coral banks. In conclusion this application also provided an overview of seabed mapping using multibeam echo sounder and integration with other instruments such as side scan sonar and ROV.

- The case study from Panarea complex used bathymetric data from a hydrographical campaign targeted to hydrothermal activity analysis and seabed characterisation of this peculiar volcanic area. It showed that high resolution acoustic data and slope diagrams are very useful to define submarine structures and characterize the substrate. Different scale approaches allowed the identification of a strong correlation between morphology and seabed nature. The use of backscatter acoustic data and seabed classification supported the identification of particular targets such as seabed structures and sediment deposits by recent gas and hydrothermal activities in very shallow water.
- The case study from the Magra River mouth demonstrated how historical datasets can be comparable thanks to data quality, defined standards and a rigorous processing methodology. A 1 metre grid was obtained for each dataset available, temporally spaced in 135-years of time, from 1882 and 2014. High resolution data analysis demonstrated how the river mouth evolved at different time scale (secular, decadal, yearly). The results highlighted changes in the geometry of the Magra River mouth, of the coastal profile and bottom features primarily due to variations of the sedimentary budget (medium time scale) and secondarily to wave dynamics (short time scale). It also showed how river sediment discharge changed over the years and, besides the geological characteristics of the area, determined the

evolution of the deltaic system. The morphodynamics were studied through two different approaches: the first one taking into account the sediment delivery, the second one the energy of the system. The aim of this work was to study this processes throughout bathymetric data acquired in secular time scale with different survey systems. Sedimentary volumes budget computation obtained from DTMs difference surface analysis was the expression of this great variability with about 3 Mm^3 lost in the last 100-yrs, 1.8 Mm^3 in the last 50-yrs and 1 Mm^3 the last 10-yrs. This behavior was characterized by the transformation from a fluvial-dominated to a wave-dominated processes river mouth. In fact, during the last century, the Magra River mouth was characterized by the disappearance of the typical fluvial-dominated delta prism and the transformation into the current wave dominated small estuary, with microtidal condition. This estuary has an upper sector where river processes, sediments and bedforms dominate, a lower sector near the mouth, where wave and tidal processes and marine sediments dominate, and a middle sector, where tidal currents dominate and both river and marine sediments are present. This is an anomalous trend, opposite to the Mediterranean deltas system behavior, with a decreasing sediment supply and human interventions that caused a reshaping of the seabed sedimentary and outer Magra in a tectonic line constrained scenario.

As revealed during my study this approach allowed to reach significant results in different scenarios, with variegate instruments and factors of interest.

References

Aiello, E., Bartolini, C., Caputo, C., D'Alessandro, L., Fanucci, F., Fierro, G., Gnaccolini M., La Monica, G.B., Lupia Palmieri, E., Piccazzo, M., Pranzini, E., 1975. Il trasporto litoraneo lunga la costa Toscana tra la foce del Fiume Magra ed i Monti dell'Uccellina. Bollettino della Società Geologica Italiana, 94, 1519-1571.

Aminti, P., Cammelli, C., Pelliccia, F., Pranzini, E., 2002. Beach response to a submerged groin field (Marina dei Ronchi, Italy). In: Ozhan, E. (Ed.), Proceedings of the International MedCoast Workshop on Beaches of the Mediterranean and the Black Sea: Dynamics, Regeneration, Ecology and Management, Kusadasi, Turkey, 71-82.

Anderson, J.T., Van Holliday, D., Kloser, R., Reid, D.G., Simard, Y., 2008. Acoustic seabed classification: current practise and future directions. ICES Journal of Marine Science 65, 6, 1004–1011.

Anfuso, G., Pranzini, E., Vitale, G., 2011. An integrated approach to coastal erosion problems in Northern Tuscany (Italy): Littoral morphological evolution and cell distribution. Geomorphology, 129, 204–214.

Anthony, E.J., 2005. Beach erosion, In M.L. Schwartz (ed.), Encyclopedia of Coastal Science, Springer, Dordrecht, 140-145.

Anthony, E.J., 2013. Deltas. In: Masselink, G., Gehrels, R. (eds.), Coastal Envirnments: Dynamics, Climate Change and Management. Wiley Springer, 299-337.

Anthony, E. J., 2014. The human influence on the Mediterranean coast over the last 200 years: a brief appraisal from a geomorphological perspective. Géomorphologie: relief, processus, environnement, 3, 219-226.

Anthony, E. J., 2015. Wave influence in construction, shaping and destruction of river deltas: A review. Mar. Geol., 361, 57-78.

Anthony, E. J., Marriner, N., Morhange, C., 2014. Human influence and the changing geomorphology of Mediterranean deltas and coasts over the last 6000 years: from progradation to destruction phase? Earth-Science Reviews, 139, 336-361.

Antonelli, C., Provansal, M., Vella, C., 2004. Recent morphological changes in a deltaic environment. The case of Rhone River, France. Geomorphology, 57, 385-402.

Applied Physiscs Laboratori, University of London, 1994. High-Frequency Ocean Environmental Acoustic Models Handbook (APL-UW TR 9407). Seattle, WA: Applied Physics Laboratory, University of Washington.

Anzidei, M., Esposito, A., Bortoluzzi, G., Degiosa, F., 2005. The high resolution map of the exhalative area of Panarea (Aeolian Is., Italy). Annals of Geophysics, 48(6), 899– 921.

Barnhardt, W.A., Andrews, B.D., Ackerman, S.D., Baldwin, W.E., and Hein, C.J., 2009. High-resolution geologic mapping of the inner continental shelf; Cape Ann to Salisbury Beach, Massachusetts: U.S. Geological Survey Open-File Report 2007-1373, variously paged, DVD-ROM and available online at http://pubs.usgs.gov/of/2007/1373/, 47 pp.

Bartholomä, A., 2006. Acoustic bottom detection and seabed classification in the German Bight, southern North Sea. Geo-Marine Letters 26, 177–184.

BASIN AUTHORITY -Autorità di Bacino del Fiume Magra- 2000. Studio per il Piano Stralcio di Bacino del Fiume Magra: Elaborazione statistica dei dati di portata finalizzata alla valutazione della portata idrica. Rapporto Tecnico, 68 pp.

BASIN AUTHORITY -Autorità di Bacino Interregionale del Magra- 2005. Messa in sicurezza idraulica delle aree prospicienti il tratto focivo del fiume Magra. Rapporto Tecnico, 51 pp. Ortega-Sánchez, M., Masselink, G., Losada, M.A., 2016. Implications of delta retreat on wave propagation and longshore sediment transport - Guadalfeo case study (southern Spain). Marine Geology, 382, 1-16.

Bini, M., Chelli, A., Pappalardo, M., 2006. Geomorfologia del territorio dell'antica luni (La Spezia) per la ricostruzione del paesaggio costiero in età romana. Atti della società toscana di scienze naturali, 111, 436 pp.

Bini, M., Brückner, H., Chelli, A., Pappalardo, M., Da Prato, S., Gervasini, L., 2012. Palaeogeographies of the Magra Valley coastal plain to constrain the location of the Roman harbour of Luna (NW Italy); Palaeogeography Palaeoclimatology Palaeoecology, 337-338, 347-355.

Blanc J.J., 1959. Recherches sur les vases du Golfe de Génes (Région de Portofino). *Annales de l'Institut Oceanographique* 37, 274-287.

Bird, E.C.F., 1996, Beach Management. Wiley, Chichester, 281 pp.

Bortoluzzi, G., Aliani, A., Ligi, M., D'Oriano, F., Ferrante, V., Riminucci, F., Carmisciano, C., Cocchi, L., Muccini F., 2011. Multidisciplinary Investigations at Panarea (Aeolian Islands) after the Exhalative Crisis of 2002; Volume DTA/06-2011.

Boyd, R., Dalrymple, R., Zaitlin, B.A., 1992. Classification of clastic coastal depositional environments. Sedimentary Geology, 80, 139–150.

Brown, C.J., Blondel, P., 2009. Developments in the application of multibeam sonar backscatter for seafloor habitat mapping. Applied Acoustics 70 (10), 1242–1247.

Brown, C.J., Smith, S.J., Lawton, P., and Anderson, J.T., 2011. Benthic habitat mapping: A review of progress towards improved understanding of the spatial ecology of the seafloor using acoustic techniques. Estuarine, Coastal and Shelf Science, 92(3), 502-520.

Brozzo, G., Accornero, M., Marini, L., 2011. The alluvial aquifer of the Lower Magra Basin (La Spezia, Italy): conceptual hydrogeochemical–hydrogeological model, behavior of solutes, and groundwater dynamics. Carbonates Evaporites, 26, 235–254.

Broussard, M.L., 1975. Deltas: Models for Exploration. Texas Geological Society, Houston, pp. 87–98.

Calanchi, N., Capaccioni, B., Martini, M., Tassi F., Valentini, L., 1995. Submarine gas-emission from Panarea Island Aeolian Archipelago: distribution of inorganic and organic compounds and inferences about source conditions, Acta Vulcanol., 7, 1, 43-48.

Caliro, S., Caracausi, A., Chiodini, G., Ditta, M., Italiano, F., Longo, M., Minopoli C., Nuccio, P.M., Paonita, A., Rizzo, A., 2004. Evidence of a new magmatic input to the quiescent volcanic edifice of Panarea, Aeolian Islands, Italy, Geophys. Res. Lett., 31, 1-5.

Cappucci, S., Scarcella, D., Rossi, L., Taramelli, A., 2011. Integrated coastal zone management at Marina di Carrara harbor: sediment management and policy making. Ocean and Coastal Management 54, 277–289.

Caracausi, A., Ditta, M., Italiano, F., Longo, M., Nuccio, P.M., Paonita, A., 2005. Massive submarine gas output during the volcanic unrest off Panarea Island (Aeolian arc, Italy): inference for explosive conditions. Geochemical Journal, Vol. 39, 459-

467.
Ciavola, P., Mantovani, F., Simeoni, U., Tessari, U., 1999. Relation between river dynamics and coastal changes in Albania: an assessment integrating satellite imagery with historical data. International Journal of Remote Sensing, vol. 20, nr.3 561-584.
Cipriani, L.E., Ferri, S., Iannotta, P., Paolieri, F., Pranzini, E., 2001. Morfologia e dinamica dei sedimenti del litorale della Toscana settentrionale. Studi Costieri 4, 119–156.
Cipriani, L.E., 2013. Coastal Erosion Monitoring. Results from RESMAR project. Nuova grafica fiorentina, Firenze, 247 pp.
Cipriani, L.E., Pranzini., 2014. Beach erosion and protection in Tuscany. Monitoring results: a Capitalization tool from COASTGAP project. Nuova grafica fiorentina, Firenze, 93 pp.
Cochrane, G.R., and Lafferty, K.D. (2002) Use of acoustic classification of sidescan sonar data for mapping benthic habitat in the Northern Channel Islands, California. Continental Shelf Research, 22(5): 683- 690.
Cordes E., Arnaud-Haond S., Bergstad O., Da Costa Falcao A.P., Freiwald A., Murray Roberts L., Bernal P. 2016. Cold water corals. In: The first global integrated marine assessment. Division for ocean affairs and the law of the sea, United Nations, 28 pp.
Corradi, N., Fanucci, F., Fierro, G., Firpo, M., Piccazzo, M., Ramella, A., Tucci, S. 1987. Importance des canyons sous-marins dans la dynamique sédimentaire de la Mer Ligure. *Quaderni Istituto di Geologia dell'Università di Genova* **8** (3), 73-104.
D'Onghia, G., Maiorano, P., Sion, L., Giove, A., Capezzuto, F., Carlucci, R., Tursi, A. 2010. Effects of deep-water coral banks on the abundance and size structure of the megafauna in the Mediterranean Sea. *Deep-Sea Research II* 57, 397-411.
Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1992. Estuarine facies models; conceptual basins and stratigraphic implications. Journal of Sediment Research, 62, 6, 1130-1146.
Davidson-Arnott, R., 2010. Introduction to Coastal Processes and Geomorphology. Cambridge University Press, 156-176.
Davies, A.J., Roberts, J.M., Hall-Spencer, J.M. 2007. Preserving deep-sea natural heritage: emerging issues in offshore conservation and management. *Biological*

Conservation 138, 299–312.

Delano Smith, C., 1986. Changing environmental and Roman land- scape: the ager lunensis. Papers of the British School at Rome, 56, 123-140.

Delano Smith, C., Gad, D., Mills, N., Ward-Perkins, B., 1986. Luni and the Ager Lunensis the rise and fall of a Roman town and its territory. *Papers of the British School at Rome,* 56, 82-140.

Delbono, I., Barsanti, M., Schirone, A., Conte, F., Delfanti R., 2016. 210Pb mass accumulation rates in the depositional area of the Magra River (Mediterranean Sea, Italy). Continental Shelf Research, 124, 35–48.

Delbono, I., Ivaldi, R., Pratellesi, M., Fanelli, E., Peirano, A., Cocito, S., Dialti, L., Delfanti, R., 2014. Seafloor morphology: nature of the seabed and the cold water corals of the Levante Canyon (eastern Ligurian Sea, NW Mediterranean). Geophysical Research Abstracts 16, EGU2014-14732.

Dolomieu, D., 1783. Voyage aux Iles de Lipari Fait en 1781 ou Notice sur les Iles Aeoliennes, Paris, pp. 208.

Dumas, A., 1860. Dove il Vento Suona. Viaggio nelle Isole Eolie (Ed. Pungitopo, Marina di Patti, Messina).

Eidem, E.J., Landmark, K., 2013. Acoustic seabed classification using QTC IMPACT on single-beam echo sounder data from the Norwegian Channel, northern NorthSea;

Continental Shelf Research 68, 1–14

El Banna, M., Frihy, O.E., 2009. Human-induced changes in the geomorphology of the northeastern coast of the Nile delta, Egypt. Geomorphology, 107, 72-78.

Ellingsen, K.L., Gray, J.S., Bjørnholm, E., 2002. Acoustic classification of seabed habitats using the QTC VIEW system. ICES Journal of Marine Science 59, 825–835.

EUROSION, 2004. http://copranet.projects.eucc-d.de/files/000134_EUROSION_Marinella_di _Sarzana.pdf

Fanelli, E., Delbono, I., Peirano, A., Ivaldi, R., Pratellesi, M., Niccolini, A., Dialti, L., Pellegrini, M., Cocito, S., Delfanti, R. 2014. Re-discovery of cold water corals in the Eastern Ligurian Sea (NW Mediterranean). *Deep-Sea Life* **4**, 16-17.

Ferrara, F., 1810, Campi Flegrei della Sicilia e delle Isole che le sono intorno

(Messina), pp. 424.

Fonseca, L., Mayer, L., 2007. Remote estimation of surficial seafloor properties through the application Angular Range Analysis to multibeam sonar data. Marine Geophysical Researches, 28, 119-126.

Freitas, R., Silva, S., Quintino, V., Rodrigues, A.M., Rhynas, K., Collins, W.T., 2003. Acoustic seabed classification of marine habitats: studies in the western coastal-shelf area of Portugal. ICES Journal of Marine Science 60, 599–608.

Freiwald A. 2002. Reef-forming cold-water corals. In: *Ocean Margin Systems* (eds G Wefer, D Billett, D Hebbeln, BB Jørgensen, M Schlüter, TCE van Weering), pp. 365-385, Springer, Heidelberg.

Frihy, O.E., Khafagy, A.A., 1991. Climatic and human induced changes in relation to shoreline migration trends in the Nile delta promontories. Catena, 18, 197-211

Frihy, O.E., Lawrence, D., 2004. Evolution of the modern Nile delta promontories: development of accretional features during shoreline retreat. Environmental Geology, 46, 914-993.

Fusco N. 1967. Il fondo del mare da Sestri Levante alla foce dell'Arno, con annessa carta di pesca n 6. Ministero Marina Mercantile, Direzione Generale della Pesca Marittima.

Gabbianelli, G., Gillot, P.Y., Lanzafame, G., Romagnoli, C., Rossi, P.L., 1990. Tectonic and volcanic evolution of Panarea (Aaeolian Island, Italy), Marine Geology, 92, 312-326.

Galloway, W.E., 1975. Process framework for describing the morphologic and stratigraphic evolution of delta depositional systems. In Deltas: Models for exploration. Edited by M.L. Broussard, Texas Geological Society, Houston, 87-98.

Gandolfi, G., Paganelli, L., 1975. Il litorale pisano-versiliese (Area campione Alto Tirreno). Composizione, provenienza e dispersione delle sabbie. Bollettino della Società Geologica Italiana 94, 1273–1295.

Garzanti, E., Canclini, S., Moretti Foggia, F., Petrella, N., 2001. Upraveling magmatic and orogenic provenances in modern sands: the back-arc side of the Apennine thrust - belt (Italy). Journal of Sedimentary Petrology 72, 2–17.

Geological Map of Italy – 1:1.000.000, 2011. ISPRA – Dipartimento Difesa del Suolo. SELCA

Goudie, A.S., 2003. Encyclopedia of geomorphology. Routledge, Taylor and Francis Group, 1202 pp.

Guerra-García JM, Sorbe JC, Frutos I (2008) A new species of *Liropus* (Crustacea, Amphipoda, Caprellidae) from the Le Danois Bank (southern Bay of Biscay). Organisms, Diversity & Evolution **7**, 253–264.

Hall-Spencer, J.M., Allain, V., Fosså, J.H. 2002. Trawling damage to Northeast Atlantic ancient coral reefs. Proceedings of the Royal Society of London B: Biological Sciences 269, 507–511.

Haris, K., Chakraborty, B., Ingole, B., Menezes, A., Srivastava, R., 2012. Seabed habitat mapping employing single and multi-beam backscatter data: a case study from the western continental shelf of India. Continental Shelf Research 48, 40–49.

Harris, P.T., Baker, E.K., 2012. Seafloor Geomorphology as Benthic Habitat. Elsevier, 890 pp.

Heinicke, J., Italiano, F., Maugeri, R., Merkel, B., Pohl, T., Schipek, M., Braun, T., 2009. Evidence of tectonic control on active arc volcanism: the Panarea–Stromboli tectonic link inferred by submarine hydrothermal vents monitoring (Aeolian arc, Italy), Geophysics Research Letters, 36, L04301.

Henry, L.A., Roberts, J.M. 2007. Biodiversity and ecological composition of macrobenthos on cold-water coral mounds and adjacent off-mound habitat in the bathyal Porcupine Seabight, NE Atlantic. Deep-Sea Research I 54, 654–672.

Houel, L., 1782. Voyage pittoressque des Isle de Sicilie de Malte et de Lipari ect., Paris.

Hughes Clarke, J.E., Mayer, L.A., and Wells, D.E., 1996. Shallow- water imaging multibeam sonars: A new tool for investigating seafloor processes in the coastal zone and on the continental shelf. Marine Geophysical Researches, 18(6), 607- 629.

Hughes Clarke, J.E., Danforth, B.W., and Valentine, P., 1997. Areal seabed classification using backscatter angular response at 95 kHz. High Frequency Acoustics in Shallow Water, NATO SACLANT Undersea Research Centre, Lerici, Italy, 30 Jun- 4 Jul 1997.

Huvenne, V.A.I., De Mol, B., Henriet, J.-P. 2003. A 3D seismic study of the morphology and spatial distribution of buried mounds in the Porcupine Seabight. Marine Geolology 198, 5–25.

IHO, 2008. Standards for Hydrographic Surveys, Special Publicazion n. 44, Published by Internatinal Hydrographic Bureau (IIB) Monaco, 36 pp.
IHO, 2012. Manual on Hydrography (C-13), Published by Internatinal Hydrographic Bureau (IIB) Monaco, 501 pp.
Jackson, D., Richardson, M., 2007. High Frequency Seafloor Acoustic. Springer, N.Y., 616 pp.
Italiano, F., Nuccio, P.M., 1991. Geochemical investigations of submarine volcanic exhalations to the eat Panarea, Aeolian Islands, Italy, J. Volcanol. Geotherm. Res., 46, 125-141.
Jackson, D.R., and Briggs, K.B., 1992. High-frequency bottom backscattering: Roughness versus sediment volume scattering. Journal of the Acoustical Society of America, 92, 2, 962-977.
Jackson, D.R., Jones, C.D., Rona, P.A., Bemis, K.G., 2003. A method for Doppler acoustic measurements of black smoker flow fields. Geochem. Geophys. Geosyst. 4, 11, 1–12.
Jiménez, J.A., Capobianco, M., Suanez, S., Ruol, P., Fraunie, P., Stive, M.J.F., 1995. Coastal processes along Ebro, Po and Rhone Deltas. In: Proceedings of the Second International Conference on the Mediterranean Coastal Environment, MEDCOAST'95, Tarragona, , E. Ozhan (Ed.), 827-840.
Jiménez, J. A., Sànchez-Ancilla, A., Valdemoro, H. I., Gracia, V., Nieto, F., 1997. Processes reshaping the Ebro delta, Mar. Geol. 144, 59-79.
Jiménez, J.A., Guillén, J., Gracia, V., Palanques, A., Garcia, M.A., Sànchez-Arcilla, A., Puig, P., Puigdefàbregas, J., Rodriguez, G., 1999. Water and sediment fluxes on the Ebro Delta shoreface: on the role of low frequency currents. Mar. Geol., 157, 219-239.
Kenny, A. J., Cato, I., Desprez, M. Fader, G., Schuttenhelm, R.T.E., Side J., 2003. An overview of seabed-mapping technologies in the context of marine habitat classification. ICES Journal of Marine Science 60, 411–418.
Kostylev, V.E., 2012. Benthic habitat mapping from seabed acoustic surveys: do implicit assumptions hold? In: Sediments, Morphology and sedimentary Processes on Continental Shelves, Li, M.Z., Sherwood, C.R., Hill, P.R. [eds.]; Wiley Blackwell, IAS Spec. Pub., 44, 405-416.

Lambeck, K., Antonioli, F., Purcell, A., Silenzi, S., 2004. Sea-level change along the Italian coast for the past 10,000 yr. Quaternary Science Reviews, 23, 1567–1598.

Lavoie, C., Jiménez, J. A., Canais, M., Lastras, G., De Mol, B., Amblas, D., Liquete, C., De Batist, M., Hughes Clarke, J. E., 2014. Influence on present-day coastal dynamics and evolution of a relict subaqueous delta lobe: Sol de Riu lobe, Ebro Delta. Continental Shelf Research, 74, 94–104.

Le Chenadec, G., Boucher, J.M., and Lurton, X., 2007. Angular Dependence of K-Distributed Sonar Data. IEEE Transactions on Geoscience and Remote Sensing, 45(5), 1224-1235.

Litcher, M., Klein, M., Zviely, D., 2011. Dynamic morphology of small south-eastern Mediterranean River mouths: a conceptual model. Earth Surface Processes and Landforms, 36, 547-562.

Luigi Salvatore D'Austria, 1895. Die Liparischen, Inseln vierter Heft: Panaris (new edition by P. PAINO, Lipari (ME), 1977).

Lumsden, S.E., Hourigan, T.F., Bruckner, A.W. & Dorr, G. (eds.). 2007. The State of Deep Coral Ecosystems of the United States: 2007. U.S. Department of Commerce, NOAA Technical Memorandum CRCP-3, Silver Spring MD, 365 pp.

Lurton, X., Lamarche, G., Verdier, A. L., Augustin, J. M., Wright, I.C., Rowden, A.A., Orpin, A., Dunkin, M., 2008. Analysis of Backscatter and Seafloor Acoustical Properties for Geosciences and Biodiversity Mapping Studies in Cook Strait, New Zealand. Journal of the Acoustical Society of America, Acoustic, 92, 2, 962-977.

Lurton, X., 2010. An Introduction to Underwater Acoustics. Principles and Applications. 2nd edition. Springer Praxis Books & Praxis Publishing, UK, 346 pp.

Lurton, X.; Lamarche, G., 2015. Backscatter measurements by seafloor-mapping sonars. Guidelines and Recommendations, 200 pp.

Kasalos, J.G., Chayes, D.N., 1983. A portable system for ocean bottom imaging and charting, Proc. Oceans 83, 649-656.

Kinsler, L.E., Frey, A.R., Coppens, A.B., and Sanders, J.V. (1999) Fundamentals of Acoustics, 4th. John Wiley, New York, 560 pp.

Maillet, G.M., Sabatier, F., Rousseau, D., Fleury, T.J., 2006a. Connections between the Rhone River and its deltas (part 1): Changes in the Rhone delta coastline since the mid-19th century. Geomorphologie: relief, processus, environment, 2, 111-139.

Maillet, G.M., Vella, C., Provansal, M., Sabatier, F., 2006b. Connections between the Rhone River and its deltas (part 2): evolution of the Rhone river mouth since the beginning of the 18th century. Geomorphologie: relief, processus, environment 2, 125-139.

Mastrototaro, F., D'Onghia, G., Corriero, G., Matarrese, A., Maiorano, P., Panetta, P., Gherardi, M., Longo, C., Rosso, A., Sciuto, F., Sanfilippo, R., Gravili, C., Boero, F., Taviani, M., Tursi, A. 2010. Biodiversity of the white coral bank off Cape Santa Maria di Leuca (Mediterranean Sea): an update. Deep Sea Research II 57, 412- 430.

Medialdea, T., Somoza, L., León, R., Farrán, M., Ercilla, G., Maestro, A., Casas, D., Llave, E., Hernández-Molina, F.J., Fernández-Puga, M.C., Alonso, B., 2008. Multibeam backscatter as a tool for sea-floor characterization and identification of oil spills in the Galicia Bank. Marine Geology 249, 93–107.

Melito, I., Cuomo, G., Bellotti, G., Franco, L., 2006. Field measurements of harbor resonance at Marina di Carrara. In: Proceedings of 30th International Conference on Coastal Engineering, ICCE 2006, San Diego, California, USA, 1280 - 1292.

Mercalli, G., 1883. Vulcani e fenomeni Vulcanici, in Geologia d'Italia, edited by G. NEGRI, A. STOPPANI and G. MERCALLI (Milano), 3rd part, 374 pp.

Myers, A.A., Hall-Spencer, J., 2004. A new species of amphipod crustacean, *Pleusymtes comitari* sp. nov., associated with gorgonians on deep-water coral reefs off Ireland. *Journal of the Marine Biological Association UK* 84, 1029–1032.

Morelli D. 2008. La cartografia marina: ricerche ed applicazioni orientate ai rischi geologico-ambientali in aree campione. Tesi di Dottorato di ricerca in Scienze Ambientali (Ambiente fisico, marino e costiero; XX Ciclo) dell'Università Degli Studi di Trieste [Ph.D. thesis in Marine Environmental Sciences (physical, marine and coastal environment, XX Cycle), University of Trieste (Italy)].118 pp.

Morelli D. 2008. La cartografia marina: ricerche ed applicazioni orientate ai rischi geologico-ambientali in aree campione. Tesi di Dottorato di ricerca in Scienze Ambientali (Ambiente fisico, marino e costiero; XX Ciclo) dell'Università Degli Studi di Trieste [Ph.D. thesis in Marine Environmental Sciences (physical, marine and coastal environment, XX Cycle), University of Trieste (Italy)], 118 pp.

Morri, C., Bianchi, C.N., Damiani, V., Peirano, A., Romeo, G., Tunesi, L. 1986. L'ambiente marino tra Punta della Chiappa e Sestri Levante (Mar Ligure): profilo

ecotipologico e proposta di carta bionomica. Bollettino dei Musei e degli Istituti Biologici dell'Università di Genova 52 (suppl.), 213-231.
Mortensen, P.B., Fosså, J.H. 2006. Species diversity and spatial distribution of invertebrates on deep–water Lophelia reefs in Norway. Proceedings of 10th International Coral Reef Symposium, 1849-1868.
Palanques, A., Plana, F., Maldonado, A., 1990. Recent influence of man on the Ebro margin sedimentation system, northwestern Mediterranean Sea. Marine Geology, 95, 247-263.
Poulos, S.E., Collins, M. B., 2002. Fluviatile sediment fluxes to the Mediterranean Sea: a quantitative approach and the influence of dams. Sediment flux to basins: Causes, controls and consequences. Geological Society, London, 191, 227-245.
Pranzini, E., 2004. Caratteristiche morfologiche e sedimentologiche di una zona di convergenza del trasporto litoraneo (Versilia, Toscana). Studi Costieri, 8, 135-149.
Pranzini, E., Farrell, E. J., 2004. Shoreline evolution and protection strategies along the Tuscany coastline, Italy. Journal of Coastal Research, SI 39, Proceedings of the 8th International Coastal Symposium, 842-847.
Pratellesi, M., Ivaldi, R., Delbono, I. 2014. Dual use Hydrographic Surveys for Seabed Nature and Morphological Research. Integrated Mapping of Seabed Features. Hydro International 18 ,7, 26-29.
Preston, J., 2009. Automated acoustic seabed classification of multibeam images of Stanton Banks. Applied Acoustics 70, 1277–1287.
Raffellini, C., 2000. Archeologia e paleogeografia del *Portus Lunae*. L'Africa Romana XIV, 731-752.
Raggi, G., Sansoni, G., 1993. Variazioni storiche e tendenza evolutiva della linea di riva lunense. Memorie della Accademia Lunigianese di Scienze. «G. Capellini», 62-63, 3-43.
Ramírez-Llodra, E., Brandt, A. Danovaro, R., De Mol, B., Escobar, E., German, C.R., Levin, L.A., Martinez Arbizu, P. et al. 2010. Deep, diverse and definitely different: unique attributes of the world's largest ecosystem. Biogeosciences 7, 9, 2851 -2899.
Rinaldi, P. M., 2005. Studio geomorfologico dei principali alvei fluviali nel bacino del Fiume Magra finalizzato alla definizione di linee guida di gestione dei sedimenti

e della fascia di mobilità funzionale: Autorità di Bacino del Fiume Magra. Sintesi della relazione finale Convenzione di Ricerca tra Autorità di Bacino del Fiume Magra e Dipartimento di Ingegneria Civile, Università degli Studi di Firenze, 26 pp.

Rinaldi, P. M., 2006. Approfondimenti dello studio geomorfologico dei principali alvei fluviali nel bacino del Fiume Magra finalizzato alla definizione di linee guida di gestione dei sedimenti e della fascia di mobilità funzionale. Relazione Finale Convenzione di Ricerca tra Autorità di Bacino del Fiume Magra e Dipartimento di Ingegneria Civile e Ambientale, Università di Firenze, 152, 2009 pp.

Rinaldi, M., Simoncini, C., 2006. Studio geomorfologico del Fiume Magra e del Fiume Vara finalizzato alla gestione dei sedimenti e della fascia di mobilità. In: Atti Giornate di Studio “Nuovi approcci per la comprensione dei processi fluviali e la gestione dei sedimenti. Applicazioni nel bacino del Magra.”, Sarzana, 24-25 Ottobre 2006, Autorità di Bacino del Fiume Magra, 93-109.

Rinaldi, M., Simoncini, C., Piégay, H., 2009. Scientific design strategy for promoting sustainable sediment management: the case of the Magra River (Central-Northern Italy). River Research and Applications, 25, 607–625.

Robert, C. M., 2009. Global sedimentology of the ocean: an interplay between geodynamics and palaeoenvironement. Elsevier Amsterdam, 485 pp.

Roberts, J.M., Long, D., Wilson, J.B., Mortensen, P.B., Gage, J.D. 2003. The Cold-water coral Lophelia pertusa (Scleractinia) and enigmatic seabed mounds along the north-east Atlantic margin: are they related?, Marine Pollution Bulletin, 46, 7-20.

Romano, R., 1973. Le isole di Panarea e Basiluzzo, Riv. Miner. Siciliana, 139-141, 49-86.

Rosi, M., Di Paola, G.M., 2001. Informazioni di base inviate agli esperti internazionali. In: Proceedings of the International workshop “Strategie per la ricostruzione e la stabilizzazione delle spiagge turistiche lungo la costa apulo-versiliese”., 101-127.

Rossi, L. 1958. Contributo allo studio della fauna di profondità vivente presso la Riviera Ligure di Levante. Annali del Museo Civico di Storia Naturale di Genova “Andrea Doria”, 2, 1-13.

Rusby, J.S.M., Somers, M.L., 1977. The development of the GLORIA sonar system from 1970 to 1975, In: A Voyage of Discovery, Martin Angel, ed, Pergamon Press, N.Y., 611- 625.

Sabatier, F., Maillet, G., Fleury, J., Provansal, M., Antonelli, C., Suanez, S., Vella, C., 2006. Sediment budget on the Rhone delta shoreface since the middle of the 19th century. Mar. Geol., 234, 143-157.

Saccarotti, G., Galluzzo, D., La rocca, M., E. Del Pezzo, E., Patanè D., 2003. Monitoraggio dell'attività sismica a Panarea, in GNV General Assembly, 9-11 June, Roma, Italy.

Simeoni, U., Corbau, C., 2009. A review of the Delta Po evolution (Italy) related to climatic changes and human impacts. Geomorphology, 107, 64-71.

Soulet, Q., Migeon, S., Gorini, C., Rubino, J-l., Raisson, F., Bourges, P., 2016. Erosional versus aggradational canyons along a tectonically-active margin: The Norheastern Ligurian margin (western Mediterranean Sea). Marine Geology, 382, 17-36.

Spallanzani, L., 1825. Viaggi alle Due Sicilie e in Alcune Parti dell'Appennino (Milano), tomo I.

Spiess, F.N., 1980. Some origins and perspectives in deep-ocean instrumentation development, In: Oceanography: The Past, M. Sears and E. Merriman, Eds, Springer-Verlag, N.Y., 226-239.

Taaouati, M., El Mrini, A., Nachite, D., 2011. Beach Morphology and Sediment Budget Variability Based on High Quality Digital Elevation Models Derived from Field Data Sets. International Journal of Geosciences, 2, 111-119.

Tyce, R.C., 1986. Deep seafloor mapping systems – A review, MTS Journal, V. 20, No. 4, 4-16.

Tudino, T., Bortoluzzi, G., Aliani, S., 2014. Shallow-water gaseohydrothermal plume studies after massive eruption at Panarea, Aeolian Islands, Italy. Journal of Marine Systems 131, 1–9.

Tunesi L., Diviacco G., Mo G. 2001. Observations by submersible on the biocoenosis of the deep-sea corals off Portofino promontory (Northwestern Mediterranean Sea). In Proceedings of the First International Symposium on Deep-Sea Corals. Willison JHM, Hall J, Gass S, Kenchington ELR, Butler M, Doherty P eds. Ecology Action Centre and Nova Scotia Museum, Halifax, 76–87.

Urick, R.J., 1983. Principles of Underwater Sound (3rd edn). McGraw-Hill, New

York, 423 pp.

Vittorini, S., 1991. La diminuzione del trasporto torbido nei fiumi italiani tra il periodo prebellico e quello attuale. Geografia Fisica Dinamica Quaternaria, 14, 251-258.

Wienberg, C., Bartholomä, A., 2005. Acoustic seabed classification in a coastal environment (outer Weser Estuary, German Bight) - a new approach to monitor dredging and dredge spoil disposal. Continental Shelf Research, 25, 1143-1156.

Wyinn, R. B., Huvenne, V. A. I., Le Bas, T. P., Murton, B. J., Connelly, P., Bett, B. J., Ruhl, H. A., Morris, K. J., Peakall, J., Parsons, D. R., 2014. Autonomous Underwater Vehicles (AUVs): Their past, present and future contibutions to the advancement of marine geoscience. Marine Geology, 352, 451-468.