The Bathymetry of the Adriatic Sea

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Abstract

The Istituto di Scienze Marine (ISMAR-CNR) conducted several research projects in the Italian side of the Adriatic Sea over more than 15 years collecting bathymetric, geophysical, and sediment core data and performing multidisciplinary studies to reconstruct paleoenvironmental changes and sediment dynamics during the last eustatic cycle. A key issue in any marine dataset is the construction of a detailed bathymetry. The Adriatic Sea bathymetry is unique because, due to the shallow water depth of large areas of the basin, standard hydrographic surveys to obtain a comprehensive Multi Beam bathymetry are not applicable. The Adriatic Sea bathymetric map is necessarily based on heterogeneous data with uneven spatial distribution and includes both Single Beam echo-soundings and Multi Beam surveys in key study areas. The main objectives of this work are to illustrate the methodology applied to compile a new bathymetric map of the Adriatic Sea integrating Single Beam and Multi Beam data, to describe the morphological units reflecting the main geological features, and to discuss the limits of reliability of the data when a bathymetric map is to used by oceanographic modellers

1 Introduction

The bathymetry plays a key role not only in geological, geomorphological and geophysical studies, but also in the fields of physical oceanography and habitat mapping in submarine areas. In particular, the bathymetry represents a crucial constrain for oceanographic models in basin-scale circulation and in bottom-boundary-layer studies, and for the simulation of tsunami propagation across continental margins and in shallow areas. The seafloor morphology has been investigated for more than a century, but only with the technologies developed during the last decades it revealed world-wide scale physiographic features such as mid-ocean ridges, transform faults and deep-sea trenches [2]. Heezen et al. [2] represented the morphology of the seafloor in a semi-pictorial way based on continuous echosoundings profiles together with an intelligent interpretation of the seafloor features to fill-in areas where no such soundings existed. Their purpose was to illustrate the morphology rather than to offer a precise measure of the water depth at any given point.

In 1922, De Marchi provided the first representation of the Adriatic Sea bathymetry giving, in particular, a conceptual image of the network of fluvial valleys incising

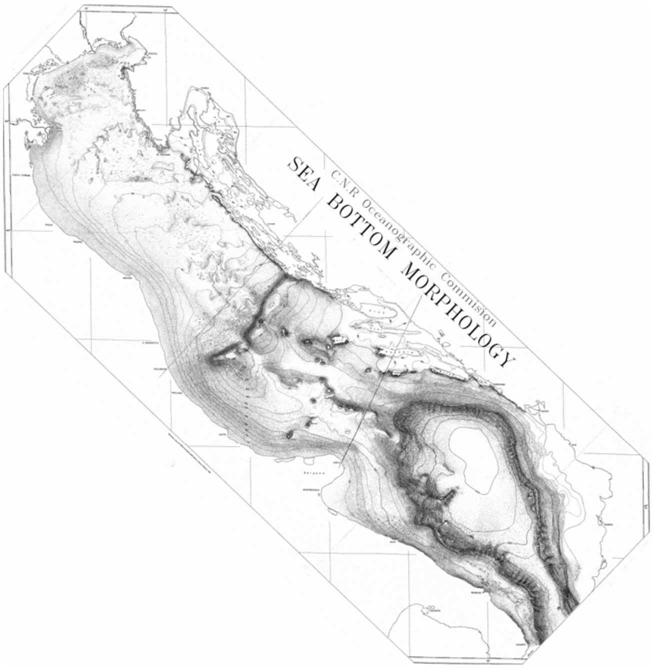

Figure 1: General morphology of the Adriatic Sea from Giorgetti and Masetti [1] (Mercator Projection - Scale 1:750.000). Compiled from O.G.S Trieste from 1966-67 cruises with the CNR oceanographic vessel ”Bannok” and integrated with I.I.M published data.

the alluvial plain during the Last Glacial Maximum and drowned during the following sea level rise. Later, Giorgetti and Mosetti [1], constructed a map of the general morphology of the Adriatic basin based on a great number of echosounder records taken during several geophysical cruises that covered nearly the entire Adriatic Sea. The morphological map of Giorgetti and Mosetti [1] was drawn with the purpose of representing a pictorial view of the seafloor structures (Figure 1). Over the last 15 years, the Istituto di Scienze Marine (ISMAR-CNR) conducted several research projects in the Italian side of the Adriatic Sea collecting bathymetric data in order to obtain a high resolution map of the seafloor features [3]. This map represented a key step for multidisciplinary studies aimed to reconstruct paleoenvironmental changes and sediment dynamics during the last glacial-interglacial cycle. The bathymetric map is necessarily based on heterogeneous data with uneven spatial distribution and includes both Single Beam echo-soundings and variable-frequency Multi Beam surveys in key study areas such as the South West Adriatic Margin and part of the continental shelf on the Italian side. The aim of this paper is to present the new bathymetric map of the Adriatic Sea compiled by CNR-ISMAR for the Italian side of the Adriatic Sea and to illustrate the main geological features of the

Western Adriatic Basin. In this framework, we will examine the methodological approaches applied to process and to integrate single beam and multi beam echosoundings and we will discuss the limits of reliability of the data when the bathymetric map is to used by oceanographic modellers interested either in basin-scale circulation or in bottom-boundary-layer studies.

2 Methodology

2.1 Single Beam bathymetry - Data acquisition and processing

Single Beam sonar data were collected using an hull mounted Echo sounder (Atlas Deso25 operating at frequencies of 12, 100, 33 and 210 kHz) along about 17.830 km of seismic profiles during 22 cruises performed by ISMAR from 1991 to 2005 on board R/V Urania in the Italian side of the Adriatic Sea (Figure 2). The echo sounding profiles are unevenly distributed and the seafloor coverage is within the range of one sounding every 20-40 m, along track. The Echo sounder Atlas Deso25 was merged with the navigation system NAV PRO from Communication Technology and with DGPS positioning system with metrical accuracy. The sound speed was set at 1500 $\mathrm{m \cdot s^{-1}}$. In areas where the sound speed profiles were highly variable, as for example in front of the Po River Delta, local values obtained from CTD (Conductivity, Temperature, and Depth) measurements were applied. The navigation and water depth data were stored every 2 seconds in a Database and filtered to correct positioning errors and to delete null values using filtering procedures implemented by ISMAR (e.g. Kalman filter). Afterwards, the bathymetric data were migrated in a GIS (Geographic Information System) Database and plotted as water depth points in maps at different scale depending on the soundings density, dividing the Adriatic in subset areas from north to south. The bathymetric contours were manually drawn and digitised as vector data in a GIS, with variable space according to water depth range (contour every 1 m from 5 to 150 m and every 20 m from 150 m to 1200 m). The contours were used to generate a uniform grid (200 m) applying computing technology (KRIGING algorithm with variable resolution depending on the soundings density) in order to give a more flexible product for visualisation and manipulation of data.

2.2 Multi Beam bathymetry - Data acquisition and processing

The Multi Beam data were collected with a variety of Multi Beam Echo. with variable frequency, beam number and beam angles, according to the scientific objectives or to the instruments available. The Multi Beam acquisition strategy comprised a full coverage survey of the entire South Adriatic Continental slope on the Italian side (from 200 to 1200 m) and the investigation of selected areas of the continental shelf (from 10 to 150 m) characterised by complex seafloor morphology. Table 1 summarizes the Multi Beam Echo. technical characteristics and the water depth range surveyed. The Multi Beam data processing was carried out using both PANGEA Multi Beam System and CARIS HIPS and SIPS 7.0. The processing methodology applied implies the creation of a 2D and 3D best-fit interpolated surface using dif-

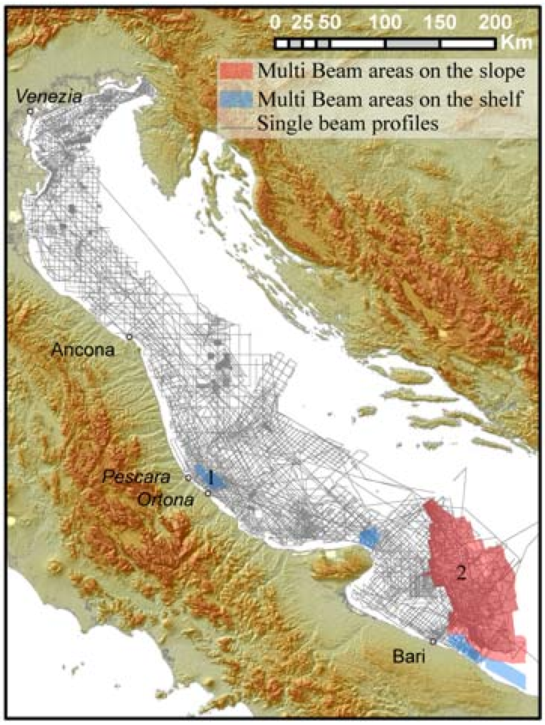

Figure 2: Single Beam data (grey lines) collected by ISMAR from 1991 to 2005 on board R/V Urania in the Italian side of the Adriatic Sea. The blue boxes represent the areas surveyed with high frequency Multi Beam systems on the continental shelf, the red boxes represent the areas surveyed with low frequency Multi Beam systems on the Adriatic continental slope.

ferent algorithms and grid resolutions. The first processing step is the analysis of the data errors and the definition of a strategy to solve them. The latter includes: 1) the correction of the sensor angles (multi beam patch-test); 2) the sound speed correction applying the ray-tracing technique after data acquisition; 3) the manual cleaning of the spikes (beam remove) only in the area where they are visible on the 2D and 3D surface; 4) the automatic filtering for a depth window, by beam number or slope between points. The second processing step is the creation of a new surface after the data correction and cleaning using a different resolution grid for a given water depth range and for geologically relevant seafloor features. The processing methodology applied is based on an interpretative approach instead of a traditional line to line cleaning system. The role of the data processing is to understand the reliability of the seafloor features detected on the grid surface and to identify all kinds of

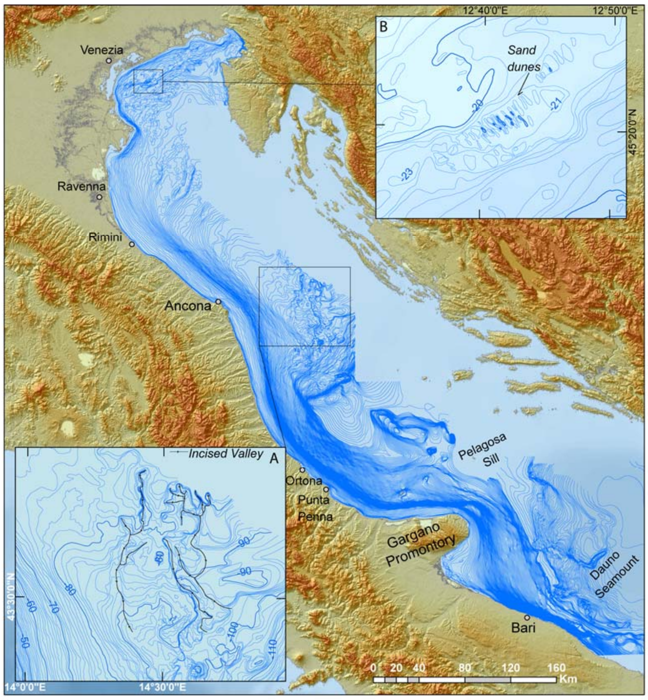

Figure 3: Single Beam bathymetry contour map of the Italian side of the Adriatic (contour lines every 1 m from 5 to 150 m and contour every 20 m from 150 to 1200 m). A) Incised valleys on the north Adriatic shelf, offshore Ancona, between 75 and 100 m of water depth formed during the subaerial exposure of this area during the Last Glacial Maximum and the early stages of the post-glacial sea-level rise; B) Sand dunes on the north Adriatic shelf are located 20 km SE of Venice between 20 and 24 m water depth.

noise and their origin. The interpretative approach leads to achieve a high resolution bathymetry focusing the processing effort in revealing the geologically most significant seafloor features. This method is less time consuming in terms of manual data cleaning and implies a change in the perspective of the entire processing work flow.

2.3 Multi Beam and Single Beam data integration

The Single Beam and Multi Beam data were integrated at regional scale using the software PANGEA MB Manager and its “Tuning filter” tool. The “Tuning filters” represent special areas, drawn by the operator as polygons with variable shapes, where it is possible to apply a specific resolution. The software assigns an ID number to each Tuning filter with its associated resolution value. The Single Beam

Multi Beam systems	Water depth range surveyed	Frequency kHz	Beam width	N° of Beams	Total area surveyed
Reson Seabat 8160	100-1200m	50	1.5°X1.5°	126	7700 km^2
Kongsberg EM300	100-1000m	30	1°x 2°	135	
Kongsberg EM710	100-900m	70-100	1°X1°	258	
Konsberg EM3000	30-100	300	1.5° x 1.5°	127	
Konsberg EM3002D	30-100 m	300	1.5° x 1.5°	508	1600 km^2
Reson Seabat 8125	30-100	455	0.5°x1°	240	

Table 1: Technical characteristics of the Multi Beam echo sounders used to survey the South West Adriatic Margin and some selected areas of the Adriatic continental shelf.

and the Multi Beam DTM (Digital Terrain Model, respectively 200 m and 20 m resolution) were loaded in the software as soundings. According to the sounding density, at a given water depth range, the operator drawn Tuning Filters including areas with homogenous characteristics. For each areas a different resolution was assigned in order to emphasize the most relevant seafloor features and to maintain the details of the Multi Beam DTM. At the border between the Multi Beam surveys and the Single Beam ones, several Tuning filters were drawn increasing progressively the resolution, going from the Single Beam to the Multi Beam data, in order to minimize the differences between the two areas and to avoid the creation of morphological steps. The Tuning filters allowed the creation of a DTM with variable resolution depending on the operator choice, permitting to merge Single Beam and Multi Beam data maintaining the high resolution of the area surveyed with Multi Beam E.

3 Results and discussion

3.1 Single Beam bathymetry of the Western Adriatic Sea

The new contour map of the Western Adriatic Sea resulting from the acquisition, processing and interpretation of data collected by ISMAR over the last 15 years shows in detail the seafloor morphology of the Adriatic from the northern shelf to southern slope (Figure 3). The bathymetry shows that the Northern Adriatic has a low longitudinal topographic gradient (ca 0.02°), whereas the maximum shelf gradient along the central Adriatic is on the order of 0.5°. The central Adriatic is characterised by a narrower shelf and localised bathymetric irregularities that are the expression of structural highs offshore Punta Penna, the Tremiti Islands and the Gargano promontory, and reaches a maximum depth of 260 m in two remnant slope basins aligned in a SW-NE direction. The Southern Adriatic, beyond the Pelagosa Sill, reaches the depth of ca 1200 m and is flanked by a steep slope. In this area, the shelf is generally narrow except in the Gulf of Man-

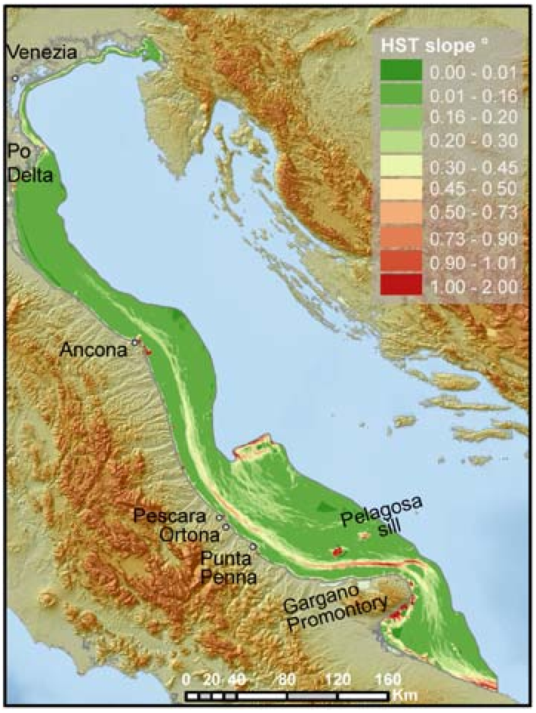

Figure 4: Slope map of the Late Holocene clinoform on the Adriatic shelf. The offlap break (yellow and red slope values) occurs in progressively deeper waters from the Po Delta (few meters water depth) to the area offshore Gargano The geometry of the clinoform varies between Ancona and Ortona where the gradient gradually increases.

fredonia, south of the Gargano Promontory, where it broadens to about 80 km. The main morphological features detected on the Single Beam bathymetry reflect the following main geological elements of the area:

- The Late Holocene mud wedge clinoform extending over 600 km along the coast of Italy from the modern Po Delta to the area south of the Gargano Promontory, with a characteristic subaqueous offlap break, marking the transition between topset and foreset deposits (Figure 4). The Late Holocene clinoform on the Adriatic shelf reaches up to 35 m in thickness with a volume of 180 km^3 and rests above the maximum flooding surface (mfs), a regional downlap surface dated ca. 5.5 cal kyr BP [4, 5, 6];
- Several incised valleys on the North Adriatic shelf, offshore Ancona, between 100 and 75 m of water depth formed during the subaerial exposure of this area during the Last Glacial Maximum and in the early stages of the post-glacial sea level rise (Figure 3A). The valleys are

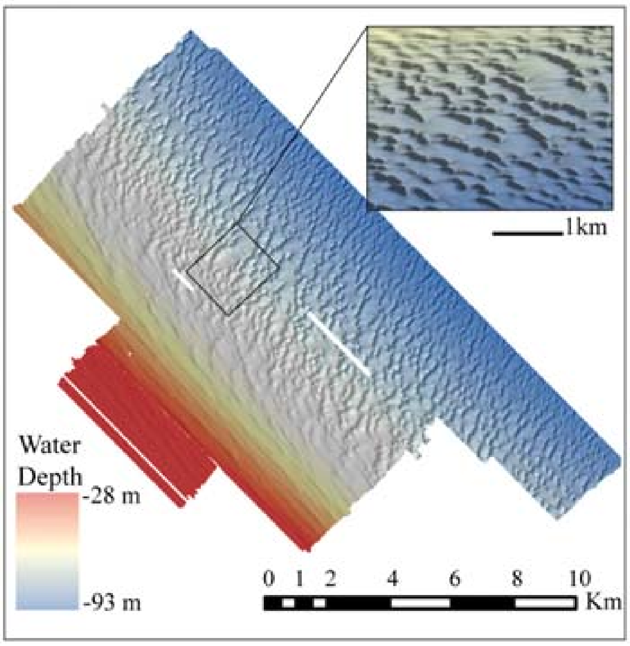

Figure 5: Subsurface undulations between 28 m and 93 m water depth the foreset region of the late Holocene progradational clinoform in the area offshore Ortona (Location in Figure 2 - Area 1). The undulations (maximum slope of 2°) are associated with mud reliefs that occur further seaward (60 m water depth).

up to 20 km long, several hundred metres to a kilometre wide and between 4 and 15 m deep. The orientation of the valleys is predominantly north-south and their sinuosity is low [7]. The valleys are spatially associated to preserved barrier-lagoon deposits, which originated during the Late Pleistocene and Holocene sea-level rise [8, 9];

- Sand dunes on the North Adriatic shelf are located 20 km SE of Venice between 20 and 24 m water depth (Figure 3B) [10]. The sand dunes rest on a broad shore-parallel mound bounded landward by an elongated trough. The dunes are up to 2 km long, characterised by low sinuosity and extend across the entire width of the underlying mound to the edge of the shoreline parallel trough [10]. The sand dunes off shore the Venice Lagoon are formed from the reworking of a drowned coastal lithosome accompanied by secondary erosion in the troughs and recycling of low stand fluvial sand [10].

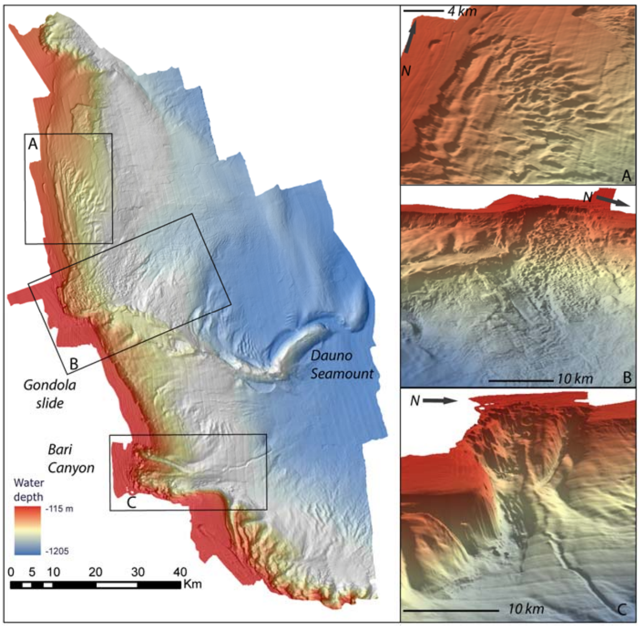

Figure 6: DTM (20 m grid) of the South West Adriatic Margin showing the extreme geological and morphological complexity of the slope. A) Areas with enhanced bottom-current features in the upper slope. B) The Gondola Slide representing the largest mass failure deposit on the SAM. C) The Bari Canyon System, the main sediment conduit active since the Last Glacial Maximum.

3.2 Multi Beam bathymetry of the Italian side of the central Adriatic continental shelf offshore Ortona

The Multi Beam map the Adriatic Continental shelf offshore Ortona (Figure 5. location in Figure 2) defines the seafloor expression of subsurface undulations between 30 m and 75 m water depth (typically 300 m wide, 2.5 m high, and several km long, parallel to the bathymetric contour) affecting the foreset region of the late Holocene progradational clinoform above a regional downlap surface (the mfs) in areas where it shows evidence of deformation and fluid escape [5, 11, 12, 13]. The undulations are associated with mud reliefs that occur farther seaward in elongated swarms perpendicular to the regional slope and to the crests of the undulations. Cattaneo et al. [11], suggested that these seafloor undulations evolved in response to sediment deformation and were successively amplified by differential deposition from bottom currents crossing an irregular seafloor. Recently Sultan et al. [14] demonstrated that the basal unit of the Holocene mud wedge immediately above the mfs has coarser grain size than the underlying and overlying units. The latter represents a weak layer where liquefaction can occur during earthquake of M1$\leq$4.5, typical of this area.

3.3 Multi Beam bathymetry of the South West Adriatic slope

The high resolution Multi Beam map of the South West Adriatic Margin (SAM) shows the extreme geological and morphological complexity of the slope and allows detailed description of the seafloor features (Figure 6). The SAM slope is generally characterised by: 1) widespread mass-failure features including slide scars up to 10 km wide and extensive slide deposits with runout distances greater than 50 km [15]; 2) a large variety of bottom-current features [16, 17]; 3) the Bari Canyon System (BCS), the main sediment conduit active since the Last Glacial Maximum interval [17]; 4) the Dauno Seamount, the main structural feature on the slope, with a clear morphologic expression. A large variety of bottom current features (Figure 6A) characterises a confined sub-triangular slope area suggesting the constructive interaction between two distinct southerly bottom water masses: the contour-parallel Levantine Intermediate Water and the North Adriatic Dense Water, cascading seasonally across the slope. By analyzing the large variety of bottom-current features, it was possible to identify areas in the upper slope strongly swept by bottom currents and characterised by predominant erosion. Seaward and eastward of the main current path, the bottom current progressively loses energy, through a field of progressively more continuous and aggradational sediment waves [16, 18]. The Gondola slide (Figure 6B) is one of the largest mass failure deposits on the SAM. It is 10 km wide on the slope, up to 35 m thick, it has a total runout of about 54 km [15] and a volume of the deposit of about 30 km^3. The evacuation zone includes a crescent-shaped headscarp located at the shelf edge with a maximum height of 250 m with several sub-parallel secondary scarps [15]. The morphological pattern reflects the interaction between the complex relief created by down-slope gravity flows and along-slope bottom currents [15, 18]. The Bari Canyon System (Figure 6C) is a peculiar erosional-depositional feature characterised by two main, almost parallel, conduits emanating from a broad crescent-shaped upper slope region [17]. This setting is consistent with the flow of bottom currents along the shelf from the North entering the canyon and interacting with its complex topography, leading to preferential deposition on the up-current side of pre-existing morphological relief [17]. Today, density-driven bottom currents cascade off shelf and flow both across the open slope and through the BCS, reaching velocities greater than 60 cm$\cdot$s^{-1} [19].

3.4 Bathymetry and Oceanographers - Multi Beam and Single beam combined map

In the case of basin scale circulation models, the Single Beam bathymetry of the Italian side of the Adriatic compiled by ISMAR can be applied in oceanographic numerical model as a uniform resolution grid. The main limitation in using this grid comes from the heterogeneity of the bathymetric data in terms of distribution and quality, and the possible errors generated during the interpolation procedures applied to derive a grid with homogeneous resolution. The Multi Beam bathymetry is more suitable for bottom boundary layer applications and for tsunami-propagation simulation models in specific areas. The reliability of Multi Beam data is higher because the Multi Beam Sys. guarantee a full coverage of the seafloor ensuring an homogeneous data quality. The processing of this kind of data leads to the reduction of instrumental noises and to the generation of a high resolution DTM where the uncertainty, given by the interpolation procedures, is extremely reduced. The integration of Single Beam with Multi Beam bathymetry, using a variable resolution grid, allows the generation of a complete bathymetric map functional at different scales. The resulting combined bathymetry is useful for the oceanographers in detecting areas of maximum strength of bottom-hugging currents and defining the regional morphological trends; for example in areas of flow restriction caused by the presence of narrow passageways or shallow shoals.

4 Conclusions

Due to its large extent (200 x 800 km) and its physiographic setting with a wide shelf area in the North and a slope basin in the South, the Adriatic bathymetric map is the result of a merger of dataset from numerous oceanographic surveys performed during the last decades with variable tools. In particular, large areas at shallow depth have been mapped with Single Beam tools and interpolated, because an extensive Multi Beam mapping would have been too time consuming in such conditions. The Single Beam contour map of the Italian side of the Adriatic Sea compiled by ISMAR-CNR shows, at basin scale, the following main geological features: 1) the coast-parallel extent of the late Holocene mud wedge; 2) the occurrence of incised valleys on the north Adriatic shelf; 3) the distribution of sand ridges and sand dunes of variable size on the north Adriatic shelf. The Multi Beam maps of the South Adriatic Continental slope on the Italian side (from 200 to 1200 m water depth) and of some selected areas of the continental shelf (from 10 to 150 m) show: 1) the complexity and variability of the progradational clinoforms of the late Holocene prodelta wedge; 2) widespread mass-failure features on the slope; 3) a large variety of bottom-current features; 4) the Bari Canyon System active during the Last Glacial Maximum, but still impinged by shelf density currents; 5) the Dauno Seamount, the main structural feature on the slope, with a clear morphologic expression. The Multi Beam data processing was based on an interpretative approach instead of a traditional line to line cleaning system. This approach allows to achieve a high resolution bathymetry focusing the processing effort in revealing the geologically most significant seafloor features. The integration of Single Beam with Multi Beam bathymetry using a variable resolution DTM (Tuning filter tool) allows the generation of a complete bathymetric map useful at different scales. The resulting combined bathymetry is useful not only for marine geologists, but also for oceanographers in detecting areas of maximum strength of bottom-hugging currents and defining regional morphological trends. In perspective, the methodology illustrated here could be furthered with the acquisition of the bathymetry on the East side of the Adriatic Sea, through international scientific projects in collaboration with eastern Adriatic countries such as Croatia, Slovenia, Montenegro and Albania.

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