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The seafloor geomorphology of Boka Kotorska Bay

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***Abstract* – One of the most intriguing feature along the entire Adriatic coast is the bay of Boka Kotorska, where the sea enters inland for over 20 km. The Bay is located along the Montenegro margin and is part of a ria coastal system surrounded by high mountains that are part of the Dinaric range. The Bay is composed by three major basins, connected by two narrow straits with a maximum depth of 67 m. Despite its historical and geostrategic role the morphology and geology of the Bay is poorly known. New high resolution multibeam and seismic reflection data reveal unknown details of present-day morphologies and sedimentary infilling geometries. Several processes are involved in shaping the bay and its seafloor. Our results show that the observed morphologies are due to the interaction at different timescales of climate, water circulation, sealevel changes, erosion, sedimentation and tectonics constrained by the geological and structural setting of the area.**

I. INTRODUCTION

The interactions between climate, sealevel changes, erosion, sedimentation and tectonics determine littoral morphology worldwide. The eastern border of the Adriatic Sea is characterized by fragmented coastlines, islands, coastal bays, that interact with the main basin influencing it and being influenced by it in terms of circulation patterns and freshwater supply. One of the most important feature along the entire Adriatic coast from both historical and economical viewpoint is the bay of Boka Kotorska, where the sea enters inland for over 20 km. The Bay is located along the coast of Montenegro and is composed by three main basins: Herceg Novi, Tivat and Morinj-Risan-Kotor; connected by two narrow straits: Kumbor and Verige straits ~350 m wide (Fig.1). The Bay is surrounded by high mountains that are part of the Dinaric range and for this reason is improperly considered as the southernmost fjord in Europe, although its origin is not related to glacial processes [1,2]. Instead, Boka Kotorska Bay is part of a ria coastal system, where the valleys were formed mainly during sealevel low-stands allowing regressive erosion of the landscape since the Messinian Salinity Crisis (~5 Ma). This resulted in a very deeply incised morphology below modern sealevel by a river flowing NE-SW, orthogonal to the orientation of the main tectonic structures, with its tributaries, parallel to them. In the hard limestone formations, narrow and steep valleys were incised while in the soft flysch layers, the river and tributaries formed wide valleys, causing the NW-SE orientation of the major basins [2,3]. The area is the richest region for precipitations in this part of the Mediterranean and represents one of the most highly karstified areas in the world.

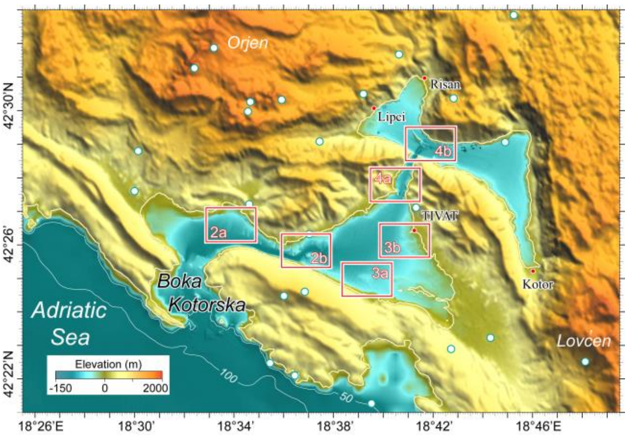

Fig. 1. Topography of the Boka Kotorska Bay. White dots, earthquake epicentres with magnitude > 4 since 1976 from International Seismological Data Centre. The numbered white boxes refer to the area displayed in figures 2, 3 and 4.

Despite the historical and geostrategic role of Boka Kotorska, little is known on the morphology of the submerged portion of the area. Here, we report on the first detailed multibeam morphological and bathymetric mapping of the entire Bay resulting from high resolution seismic reflection profiles, magnetics and swath bathymetry data collected during several geological-geophysical cruises from 2008 to 2013.

II. GELOGICAL SETTING

Montenegro is part of the thrust-and-fold system forming the Dinaric Alps. Relative movements between the European plate and the Adria microplate during the Mesozoic and the Tertiary controlled the evolution of Montenegro and of the adjacent areas. The Mesozoic rifting phase related to extension, was followed by continental convergence from the Late Cretaceous/Early

Eocene to the Upper Pleistocene, that formed a series of thrust-and-folds belts and associated foreland and back-arc basins [4]. The 200 km-long plate boundary along Montenegro consists of a WNW trending thrust, cut by N-S and rarely ENE oriented strike-slip faults, which laterally segment the major thrust front [5]. Starting from the Adriatic Sea, four NW-SE trending geomorphological provinces can be distinguished onshore: “Coastal Montenegro”, “Budva-Cukali”, “High Karst” and “Durmitor Zone”.

The Coastal Montenegro Zone is the innermost part of the Ionian-Adriatic Thrust Zone, build up by Cretaceous limestones, anhydrites and dolomites, and Eocene-Oligocene flysch deposits. Thrust-folded over this tectonic unit is the Budva-Cukali Zone consisting of Triassic flysch deposits and carbonates, Cretaceous limestones and Paleocene flysch. Budva-Cukali tectonic unit is overthrust by the High Karst Zone made mainly of Mesozoic limestone and dolomites with thickness reaching several kilometres due to reverse faulting and overthrusting that duplicate the carbonate series. Along the northern sector of Kotor Bay from Morinj to Kotor, across Risan and Perast, this unit is in direct contact with the sea. The northernmost tectonic unit is the Durmitor Zone consisting of different thrust sheets build up by Late Paleozoic and Lower Triassic sedimentary deposits (clay, marl and sand beds), and Jurassic diabases and cherts rock [6,7].

III. DATA AND METHODS

Data were collected during several geological-geophysical cruises from 2008 to 2013 with the *R/V Dallaporta*, *R/V Urania* and *R/V Maria Grazia* of the Consiglio Nazionale delle Ricerche (CNR), under the framework of ADRICOSM-STAR and MEDPOL projects. Oceanographic cruises ADR08, ADR02_08, MNG01_09, MNG02_09, and MNG03_10 were carried out in 2008, 2009 and 2010, respectively, in order to explore the area with high resolution seismic reflection profiles, magnetics and swath bathymetry data.

Bathymetric data were acquired during the *R/V Urania* cruises using a SEABAT-8160 RESON multibeam system (50kHz, 126 beams with a resolution of 0.5° and a 150° aperture) in 2008; and an EM710 Kongsberg-Simrad multibeam system (~70 kHz, 400 beams with a resolution of 1°x2° and a 150° aperture), in 2009. During the R/V Maria Grazia cruise in 2009, the multibeam system was a Kongsberg EM3002D Dual Head (~300 kHz, 508 beams with a resolution of 0.5° and a 170° aperture). Continuously surface water acoustic velocity data for beam-forming was recorded by a sound velocity probe, located 1 m above the sonar head. Sound velocity profiles within the water column were determined by a conductivity-temperature-depth (CTD) *SeaBird SBE 911* probe. Positioning was provided by a High Precision differential GPS. Multibeam data were processed using Kongsberg NEPTUNE software including tide corrections based on the Split and Durres tidal reference stations, lines adjustments, removal of coherent and incoherent noise. Cartographic data homogenization to WGS84 of digitized maps (with coordinates referring to the Zone-7 of the MGI/Balkans cartographic system) was carried out using DIGMAP and DATUM software [8,9]. Spatial analysis and mapping were performed using the PLOTMAP package [10]. Digital terrain models were produced down to a horizontal resolution of 0.5 m.

A dense grid of single channel seismic reflection profiles was carried out using a Benthos CHIRP-III SBP system (operating with 16 hull-mounted transducers). The system generates a 0.02 s-long signal with frequency linearly varying from 2 to 7 kHz. Maximum sub-bottom penetration is 50-60 m with a vertical resolution of about 0.2-0.5 m. The seismic dataset was processed using SeisPrho software [11], applying time variant gain, automatic gain control and band-pass filters. Seismic data interpretation was carried out through the Kingdom Suite software and the seismic dataset was merged together with the high resolution DEM to allow integrated interpretations.

IV. RESULTS

Boka Kotorska Bay hosts a large number of species of seabed fauna which has adapted to specific environmental conditions [12]. The seafloor and sub-bottom are mostly covered by well stratified sedimentary layers of fine mud interbedded to clay loam, clay sand, silt and sand. These unconsolidated sediments, deposited during the last sealevel high stand (Holocene), rest on an erosional surface in direct contact with the Mesozoic-Early Cenozoic basement or above alluvial and/or marine syn- and pre-LGM deposits, and reach their maximum thickness of about 25÷30 m in the depocenters [13]. Boka Kotorska can be divided into three major basins based on morphological and structural differences (Fig. 1): Herceg Novi Bay; Tivat Bay and Morinj-Risan-Kotor Bay.

A. Herceg Novi Bay

This basin has a sub-triangular shape and lies almost entirely within the “Coastal Montenegro Zone” with basement mostly represented by Early Cenozoic flysch deposits. It shows a flat seafloor with an average depth of ~42 m reaching the maximum depth of ~48 m in the channel entering from the south along the narrow passage to the Boka Kotorska Door (Fig. 1). The steepest flanks are located in the south, toward the Lustica peninsula that is made by Cretaceous and Early Cenozoic limestones and presents slopes ranging from 10° to 20°. The northern flanks show more gentle slopes ranging from <1° to 3°.

Despite this, these flanks are affected by several ~5 m-high 150 m-wide linear ridges running perpendicular to the coast between Melijine to Zelenika in the lower part of the slope (Fig. 2a). The seismic profile shown in figure 2c, suggests that they are relicts of older marine sediments cut by V-shape deeply incised valleys, formed during the LGM and filled by the recent marine deposits.

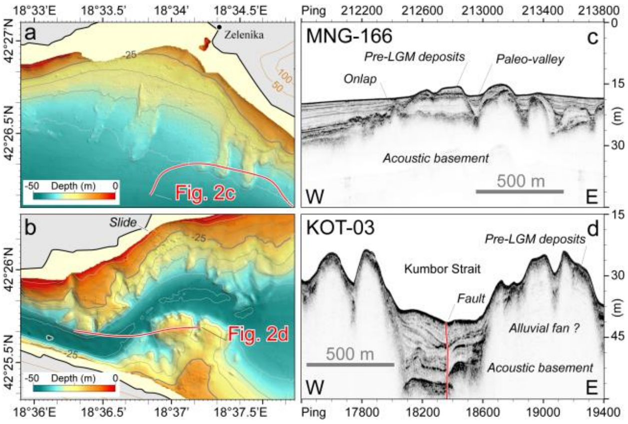

Fig. 2. Multibeam bathymetric details of selected areas. ***(a)*** *Northern slope of Herceg Novi Bay.* ***(b)*** *Eastern sector of Kumbor Strait. Red lines indicate location of high resolution seismic profiles (CHIRP III).* ***(c)*** *Herceg Novi Bay: profile running parallel to the coastline across the northern slope of the basin.* ***(d)*** *cross-section of Kumbor Strait. The SW-NE fault located in the middle of the strait cuts the entire sedimentary sequence.*

Herceg Novi Bay is connected to the east with Tivat Bay through the ~800 m-wide ~3.5 km-long Strait of Kumbor (Figs 1 and 2b). The narrow passage shows steep flanks cut by several deeply incised valleys and a central ~100 m-wide ~50 m-deep channel that follows three short linear segments running along and perpendicular to the major tectonic lineaments. A seismic profile crossing the SW-NE segment is shown in figure 2d. The seismic cross-section shows a ~300 m–wide valley with depth ranging from 40 to 45 m, filled by ~20 m of sediments. The acoustic basement across the strait presents a flat reflector, slightly dipping toward east, offsets by a ~5 m step with overlying sediments broken and discontinuous suggesting an active fault.

B. Tivat Bay

The southern and the central sector of the Tivat triangular basin lies within the Coastal Montenegro Zone, while the northernmost area, north of the village of Bijela, lies within the Budva-Kukali Zone (Fig. 1). The Bay present a wide-almost flat central area with depths > 35 m, with a maximum depth of 45 m reached close to Kumbor Strait. The northern and the south-western slopes are steeper than the eastern and south-eastern slopes that gently grade toward the deepest central area with gradients < 0.5°. A narrow elongated ridge, along the alignment of the Ostrvo Cvijeca peninsula and of the Sveti Marko (1.5 km-long) and Gospa od Milosrda (200 m-long) islands, divides the south-eastern corner area of the Bay in two shallow sub-basins (max depth of 20 m). On the two islands conglomerates, sandstones and marls of the Early Cenozoic flysch unit outcrop. The Chirp profile shown in figure 3c, crosses an elongated structural high parallel to the southern coast and aligned along the prosecution of the narrow ridge formed by Sveti Marko and Gospa od Milosrda islets (Fig. 3a). The seismic section reveals a very thin sedimentary sequence (thickness < 10 m) onlapping basement rocks in sub-vertical strata.

Hummocky terrains with huge (>5 m–high) blocks mark the eastern upper slope of Tivat Bay, just south the town of Tivat (Fig. 3b). The seismic section crossing this feature shows that blocks are free of sediments, suggesting a very recent mass wasting event (Fig. 3d).

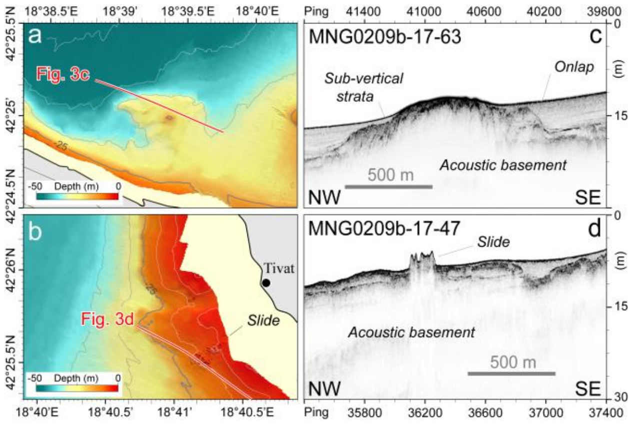

Fig. 3. Multibeam bathymetric details of selected areas. ***(a)*** *Southern flank of Tivat Bay, to the west of Sveti Marko and Gospa od Milosrda islets.* ***(b)*** *Eastern flank of Tivat Bay. Red lines indicate location of high resolution seismic profiles.* ***(c)*** *Tivat Bay, southern slope. The seismic line crosses the structural high in front of Bjelila village.* ***(d)*** *Tivat Bay, eastern slope. The profile crosses the small slide located just south of Tivat.*

Tivat Bay is connected to the Morinj-Risan-Kotor Bay by the Verige Strait. The Strait striking SSW-NNE, forms a 400 m-narrow passage within the Mesozoic carbonates of the Budva-Kukali Zone and shows very steep flanks. In the central part, two deeper channels (max depth of 45 m), bounding a few meter-high central dome, develop. The southern and northern 200 m-wide central domes are dominated by linear sediment wave fields (Fig. 4a). The sediment waves run almost perpendicular to the axis of the valley, with a wavelength of 25 m and heights ranging from 1 m up to 3 m. The seismic profile in figure 4c shows that the mobilized sediment layer, represented by acoustically transparent material without internal coherent reflections, can reach the thickness of 10 m. This layer overlays a lower sequence with coherent reflectors sub-parallel to the top of the acoustic basement.

C. Morinj-Risan-Kotor Bay

This Bay represents the innermost basin of Boka Kotorska and straddles the overthrust zone between the High Karst Zone to the north and the Budva-Kukali zone to the south. It displays a hour-glass shape (Fig. 1) and can be divided into two major sub-triangular embayments to the NW and to the SE (Morinj-Risan and Kotor bays, respectively). The deepest part (~45 m) of the entire basin is found at the northern mouth of the Verige Strait, where the two channels, that come out from the narrow outlet, impact against a structural high, and join together following a semi-circular path (Fig. 4b). The structural high is formed by a narrow ridge parallel to the northern coastline, with steep flanks and a roughly simmetric cross-section, that rises above sea-surface at Gospa od Skrpjela and Sveti Dordje islets (Fig. 4b).

The central area connecting the Risan-Morinj and Kotor bays, in correspondence of the northern foot slope near Perast, displays a large number of circular to elliptical depressions at depths ranging between 27 and 41 m (Fig. 4b). Isolated circular depressions are the most representative of the area and occur in a wide range of depths, with diameter ranging from 10 to 100 m. These depressions display a well-developed, funnel-shape vertical section, that can locally cut the entire sedimentary sequence (Fig. 4d).

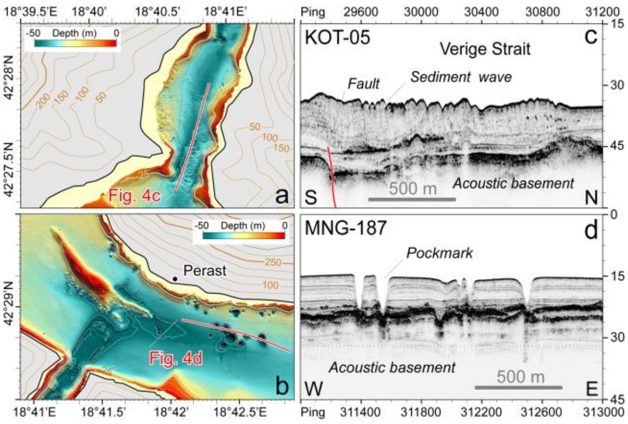

Fig. 4. Multibeam bathymetric details of selected areas. ***(a)*** *Southern end of Verige Strait.* ***(b)*** *Northern end of Verige Strait and central sector of Morinj-Risan-Kotor Bay including Gospa od Skrpjela and Sveti Dordje islets. Red lines indicate location of high resolution seismic profiles.* ***(c)*** *Verige Strait, along axis profile.* ***(d)*** *Morinj-Risan-Kotor Bay: seismic profile running paral-.lel to the northern coast in front of Perast.*

V. DISCUSSION

Past sealevel changes together with the geological setting of the area played an important role in shaping the modern Bay morphology. Incised valleys across continental margins represent the response of fluvial systems to changes in their equilibrium dynamics, mainly driven by base level fall forced by glacial-eustatic cycles [14]. Given that the maximum depth of present day sill toward the open Adriatic Sea is 37.6 m (Fig. 1), the bottom floor of Boka Kotorska was exposed during Late Pleistocene glacial maxima, when global sea level fell more than 100 m [15-18]. The pronounced upstream deepening of the valleys related to river/stream incisions of MIS5e and older highstand deposits, forms relict ridges perpendicular to the coastline (Figs 2a and 2c). Sea level rise reached Boka Kotorska during the Early Holocene, drowning the Bay and leading to the formation of an embayment confined toward land. At this time, part of the incisions remained under-filled with a marked bathymetric expression; the Bay was then rapidly filled by highstand deposits. Also the lobate structures on the southern flank of Kumbor Strait, interpreted as fan-deltas, would have been deposited sub-aerially during sealevel lowstands. Channels cutting the present-day fan surface and extending for several hundred metres down are clearly visible in the bathymetric imagery (Fig. 2b). This suggests that these channels were incised subaerially, and have since been submerged by rising sea level and subsidence of Boka Kotorska Bay [19]. Along the steepest upper slope of Boka Kotorska flanks, hummocky terrains (Figs 2b and 3b) suggest mass-wasting events probably related to slope failure triggered by the strong earthquakes affecting the region and enhanced by overpressure induced by gas and fluids.

The action of water currents is another important factor that contributes to determine the submerged morphology of Boka Kotorska Bay. The water circulation is mainly driven by meteorological condition and fresh water input, thus it suffers of a strong seasonality. Strong surface currents are due to the action of winds, while bottom currents are controlled by fresh water inputs [20]. The freshwater input from the numerous sources in the bays strongly modifies temperature, salinity and current patterns, with formation of density driven flows [20]. Bottom currents are stronger within the narrow passages connecting the several basins forming the Bay. In fact, most of the morphological features observed within the Kumbor and Verige straits can be ascribed to the action of bottom currents, such as: incised channels bounding the slopes of the straits (Figs 2b, 4a and 4b); contourites forming the lobate sedimentary geometries shown in the cross-section of Kumbor Strait (Fig. 2d); and sediment wave fields at the southern and northern end of the Verige Strait (Figs 4a, 4b and 4d).

Although precipitation in the catchment area of Boka Kotorska Bay is the highest in Europe (>5000 mm/a) [21], small watercourses are present in the Bay drainage area. Despite this, an enormous mass of freshwater flows into the basin through submarine syphons, springs and resurgences due to the karst environment [22]. Several springs are found along the edges of the Boka Kotorska Bay and are characterized by high variations in discharge due to intensively karstified rocks in the catchment area and an extremely fast propagation of rainfall. Some of those springs even dry out completely during summer, while after intensive rainfall or at the end of winter, some of them can discharge over 100 m^3/s [23].

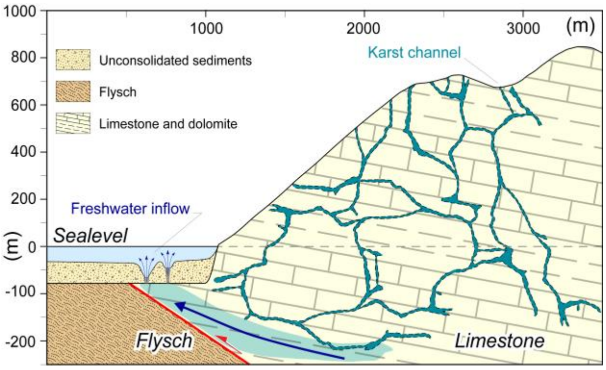

Fig. 5. Idealized hydrological cross-section from Morinj-Risan-Kotor Bay to Sanik mountain across Perast showing that the circular depressions observed in front of Perast are due to freshwater inflow at seafloor.

The deep circular depressions with sharp edges and smooth outer boundaries (Figs 1 and 4b) observed at the seafloor in several places across the Bay, are interpreted as pockmarks due to groundwater discharge (i.e., spring outlets) into the basin (Fig. 5). We count over 143 of these features across the entire Bay. Most of these circular depressions are located in Morinj-Risan-Kotor Bay close to the village of Perast. These spring outlets are aligned parallel to the coast, suggesting that they originate at the lateral ramp of the reverse fault between karstified limestone and dolomites of the Sanik mountain and the autochthonous Eocene flysch [13].

VI. CONCLUSIONS

High-resolution geophysical data reveal unknown details of present-day morphology and sedimentary infilling geometry of the Boka Kotorska Bay. Multibeam bathymetry combined with seismic reflection images suggests that the observed morphologies are due to the interaction at different timescales of climate, water circulation, sealevel changes, erosion, sedimentation and tectonics constrained by the geological and structural setting of the area. The Bay is composed by three major basins connected by two narrow straits and reaches the maximum depth of 67 m. It shows steep upper slopes and flat sub-basin central sectors lying at depths ranging from 35 to 45 m. Among the several morphological features shaping the seafloor, we note: deeply incised valleys and delta fans related to past sealevel falls; slope failures and mass wasting triggered by strong earthquakes; channels bounding the steep slopes of Kumbor and Verige narrow passages, and sediment wave fields in Verige Strait formed by strong bottom currents; karst morphologies developing at seafloor with submarine siphons, springs and resurgences (pockmarks) fed by karst hydrology of Boka Kotorska Bay's surroundings.

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