Crescent-shaped bedforms on submarine volcanic flanks: the case of Salina (Aeolian Islands, Italy)

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ABSTRACT: Salina is the highest island of the Aeolian Archipelago, representing the upper part of a large submarine stratovolcano. The submarine eastern flank of Salina is morphologically dominated by different bedforms fields located between ~50 and ~600 m water depths. Bedforms have wavelengths ranging from some tens to few hundreds of meters and wave heights of some meters at maximum. Their crestlines are roughly parallel to the isobaths, with sinuous to arcuate/crescentic shape in plan-view, while their cross-sections are commonly asymmetric downslope, with short and steep lee sides. Bedform size tend to increase with water depth, especially in correspondence of marked break-in-slopes or within wider channels developed at the base of the edifice. Based on their similarities in size and geometry with bedforms found in other submarine volcaniclastic systems, canyons and fan-deltas, these features have been interpreted as migrating cyclic steps.

1 INTRODUCTION

In the last few decades, extensive seafloor mapping studies performed on the submarine portions of insular volcanoes and seamounts have exponentially increased our knowledge on the geological processes shaping their flanks. However, most of these studies mainly focused on the characterization of large-scale geomorphic features associated with sector collapses or caldera eruptions (e.g., Mitchell et al. 2002; Wright & Gamble 1999), often overlooking smaller-scale features associated with more frequent mass-wasting processes. This bias is also due to the rapid decrease in resolution with depth of hull-mounted multibeam systems as well as to the paucity of shallow-water surveys around volcanic islands (Casalbore et al. 2021 and reference therein). Seafloor mapping of shallow-water areas is, in fact, a time-consuming and expensive task because of the limited lateral coverage of multibeam swath in the first hundreds of meters. On the other hand, the available studies in shallow-waters areas (also through time-lapse surveys) have evidenced widespread small-scale landslide scars, erosive channels and bedform fields, indicating a highly dynamic environment in terms of mass-wasting processes and associated sedimentary gravity flows (e.g., Babonneau et al. 2013, Clare et al 2018; Casalbore et al. 2020, 2021 and reference therein).

In this study, we describe and discuss the main features of small-scale bedforms fields recently identified along the eastern submarine flank of Salina Island (Aeolian archipelago) between few tens of meters down to over 400 m water depths (Casalbore et al. 2016, 2021). The analysis is based on high-resolution multibeam bathymetries, integrated by seafloor grabs, collected during the 2010 "EOLARC" and 2013 "Thygraf" cruises onboard the R/V Urania (National Research Council).

2 STUDY SITE

Salina is the highest island of the Aeolian archipelago, reaching a maximum elevation of 962 m above sea level (asl, herafter) at Monte Fossa delle Felci (MFF in Fig. 1). continuation of the regional "Tindari-Letojanni" strike-slip fault system (Ventura, 2013). The subaerial volcanic activity of Salina spans between ~244 and 15.6 ka, displaying an overall E-W migration of active vents through time (Lucchi et al. 2013). The NE part of Salina is mostly characterized by basaltic lava flows and strombolian scoriae belonging to the Pizzo Capo composite volcano (~244-226 ka, PC in Fig. 1). South of Pizzo Capo, basaltic to dacitic pyroclastic successions and lava flows, emplaced between 160-121 ka, formed the eastern flank

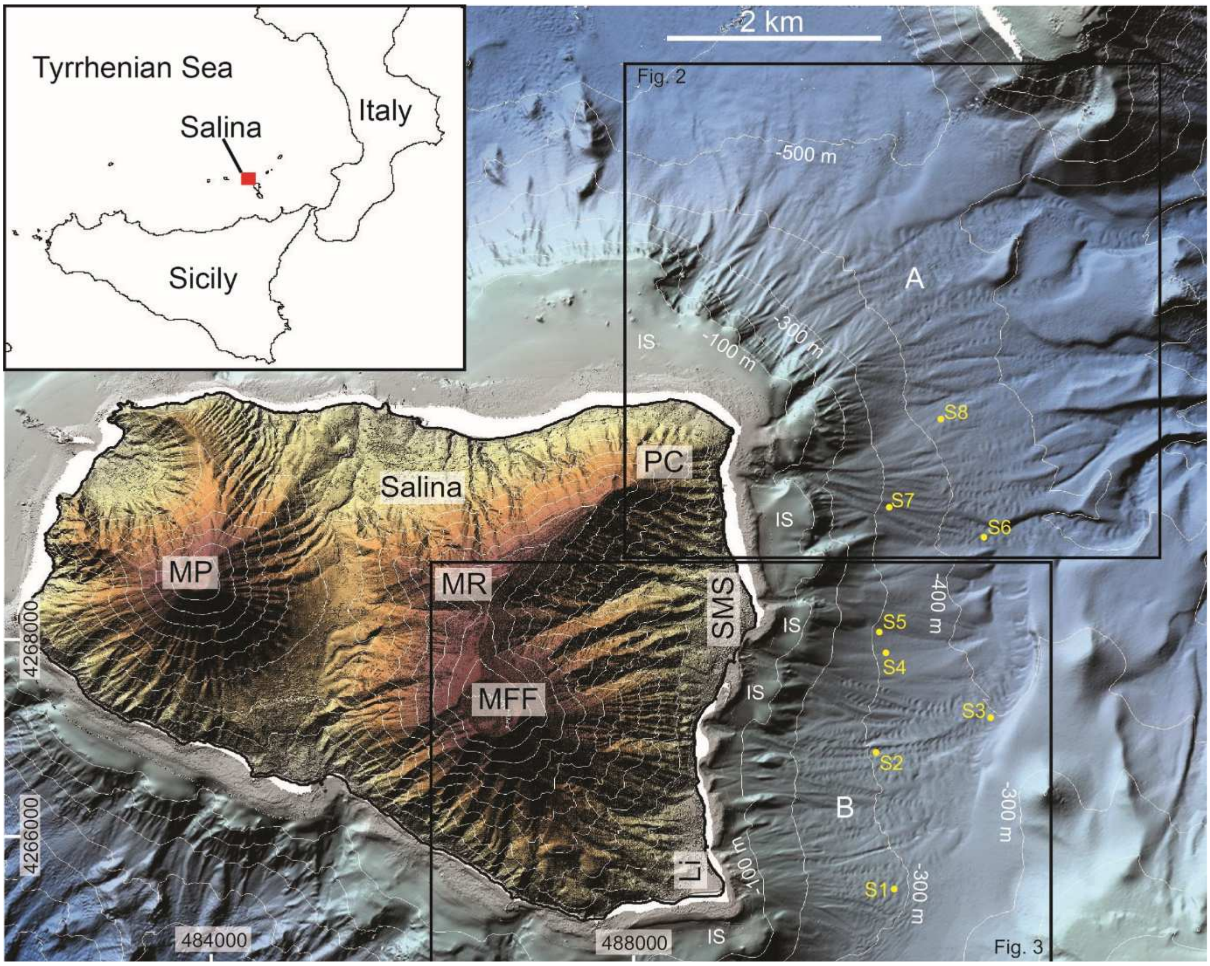

Figure 1 Shaded relief map (artificial light from NW) and contour lines (equidistance of 100 m) of Salina Island and its eastern and north-eastern submarine flanks, with the location of the described features and seafloor grabs (S1-S8, see also Table 1). MP: Monte dei Porri, MFF: Monte Fossa delle Felci, MR: Monte Rivi, PC: Pizzo Capo, SMS: Santa Marina Salina, Li: Lingua; IS: insular shelf. Coordinates are in UTM WGS84 33N.

The island is the tip (~16% as surface) of a large submarine volcanic edifice, extending down to 1300 m water depth (Casalbore et al. 2016). Together with Lipari and Volcano, Salina is part of an NNW-SSE elongated volcanic belt linked with the offshore

of Monte Rivi (MR) and Monte Fossa delle Felci stratocones. Three orders of raised marine terraces, located at 50, 25-30 and 10-12 m asl and attributed to the Last Interglacial peaks, cut the lower part of the early stratocones, witnessing a general uplift since (at least) 124 ka, with average rates of 0.35 m/ka (Lucchi et al. 2019 and reference therein).

The NE coastal area is generally characterized by steep and up to 65-m high sea cliffs, engraved on a thick succession of strombolian scoriae around Pizzo Capo (Romagnoli et al. 2018). Differently, sea cliffs are markedly lower (< 26 m) or totally absent along the eastern flank of Monte Fossa delle Felci. This volcanic flank is largely carved by a network of narrow and steep subaerial creeks, locally forming thick epiclastic slope fans at its foot, where Santa Marina Salina and Lingua small villages are built (SMS and Li in Fig. 1).

The submarine morphology of the eastern Salina flank is characterized by a narrow insular shelf (around Pizzo Capo, Fig. 1) being almost absent on the eastern flank of Monte Fossa delle Felci) (Romagnoli et al. 2018). A network of submarine erosive channels indents the shelf edge at variable depths: a) around 80-100 m wd in the NE part (Pizzo Capo), where the shelf is larger and better preserved, b) up to 5-10 m wd in the SE sector, where the shelf is almost absent or dismantled (Casalbore et al. 2016).

3 RESULTS

Morpho-bathymetric data allow us to recognize two main areas (A and B in Fig. 1) characterized by bedforms fields located on the submarine flanks of the Pizzo Capo and Monte Fossa delle Felci stratocones, respectively (Fig. 1).

In area A, coaxial trains of arcuate or crescent-shaped bedforms are recognized at depths higher than 320 m, down to over 600 m (Fig. 2). They commonly start as narrow (50-150 m wide) and shallow (a few meters deep) channelized features that erode an overall convex-downward morphology related to the presence of one or more (coalescent) fan-shaped deposits. These deposits are, in turn, associated upslope with erosive channels that mainly indent the insular shelf edge around 80-100 m wd, (locally up to 15-25 m wd). The recognized bedforms have wavelengths of ~20-150 m and wave heights of ~0.5-5 m; their wave parameters generally increase downslope, especially when the narrow channels merge within wider and flat-bottomed, more sinuous channels. The latter develop at the base of the submarine flank, in correspondence of a marked decrease of slope gradients from 7°-8° to value less than 4°. In cross-section, bedforms are generally symmetric or (mostly) downslope asymmetric, with a gently sloping stoss side followed by a shorter and steeper lee side. In area A, three grabs (Table 1) recovered sandy sediments (S6 and S7 in Fig. 1) or silty sand (S8).

In area B, bedforms are present from ~45 to ~430 m wd, displaying a larger variability in size and plan-view shapes (Fig. 3). Shallower bedforms start as isolated coaxial trains in the first 150-200 m wd, forming narrow channelized features within the main erosive channels that carve the steep (> 10°) volcanic flank from shallow-water (up to 5-10 m wd). These bedforms are mostly arcuate or crescent-shaped in plan-view and downslope asymmetric in cross-section; they have wavelengths of few tens of meters and wave heights < 1 m. At greater depths, bedforms are widespread and commonly tend to increase their wave parameters downslope. The maximum concentration of bedforms is observed-between 150-200 m and 300-340 m wd, where they display sinuous or arcuate/crescentic shape in plan-view. The sinuous bedforms are mainly associated with the development of fan-shaped deposits at the foot of erosive channels, in correspondence of an abrupt decrease of slope gradients to values less than 6°-8°. Differently, arcuate or crescent-shaped bedforms are commonly related to narrow and erosive channelized features superimposed on the fan-shaped deposits (Fig. 3). At depths greater than 300-340 m wd, the coaxial trains of bedforms merge downslope within a wider and flat-bottomed channel running at the base of the volcanic flank. Here, bedforms are arcuate or crescent-shaped in plan-view, reaching wave lengths of ~200 m and wave heigh of ~6 m; their lateral extent largely increase, extending on almost all the channel’s width. In the area

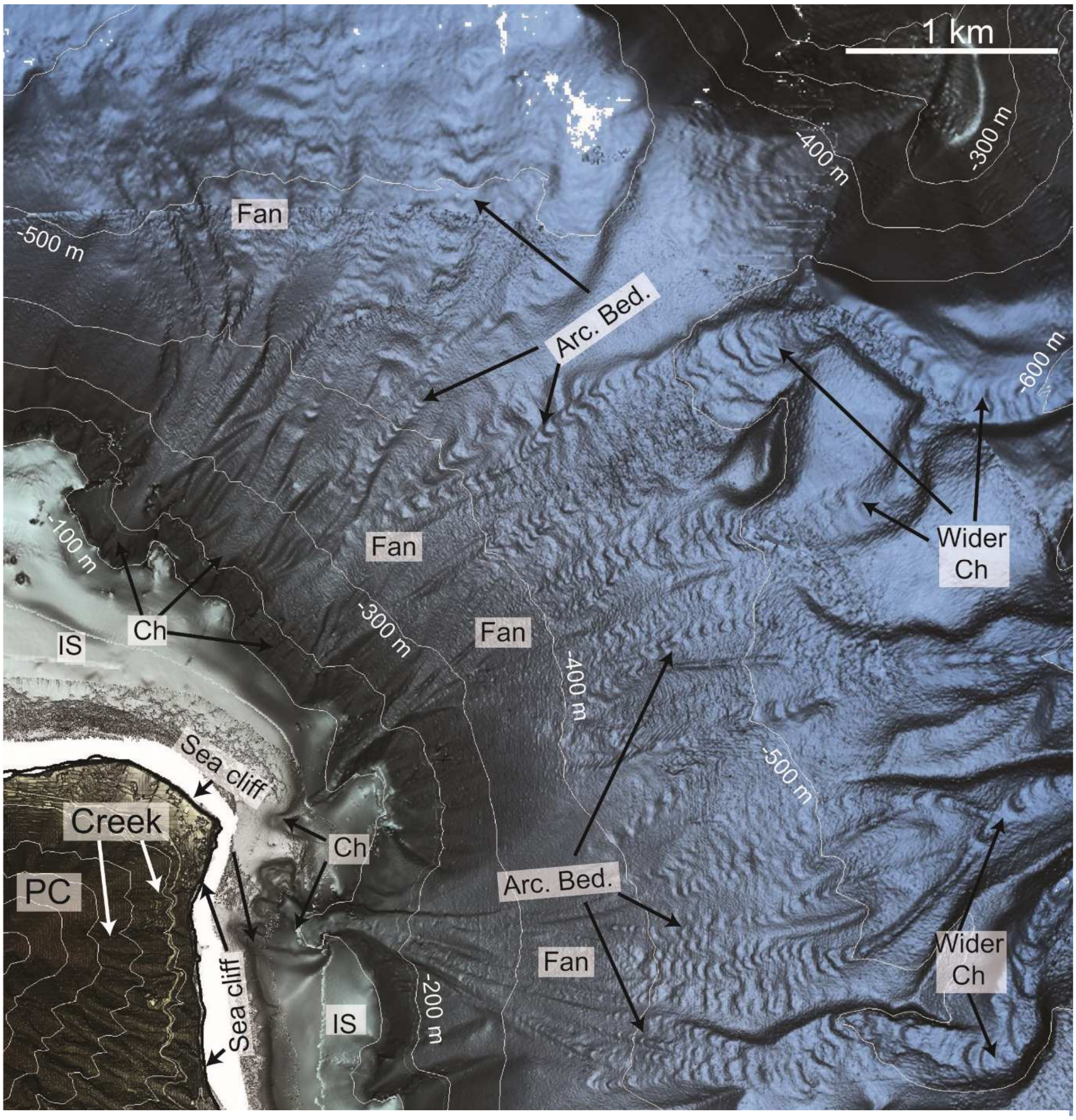

Figure 2 Shaded relief map (azimuthal artificial light) and contour lines (equidistance of 100 m) of area A (location in Fig. 1) in front of Pizzo Capo (PC), where minor creeks hanging on steep and high sea cliffs are present. In the facing marine area, the insular shelf (IS) is indented by channels (Ch), passing downslope to fan-shaped features and wider channels, locally characterized by coaxial trains of arcuate bedforms indicated by arrows (Arc. Bed.).

B, five grabs recovered sandy sediment, with variable percentage of silty or gravelly component (S1 to S5 in Fig. 1 and Table 1).

4 DISCUSSION AND CONCLUSIONS

The previous morpho-bathymetric analysis has shown how small-scale bedforms are widespread on the submarine E flank of Salina. Similar features were also observed on the northern submarine flank of Salina (Casalbore et al., 2021). They can be related to extensive mass-wasting processes and associated sedimentary gravity flows affecting the area, as testified by their linking with erosive channels and fan-shaped deposits. These features witness an efficient transport of volcaniclastic sediment (mostly

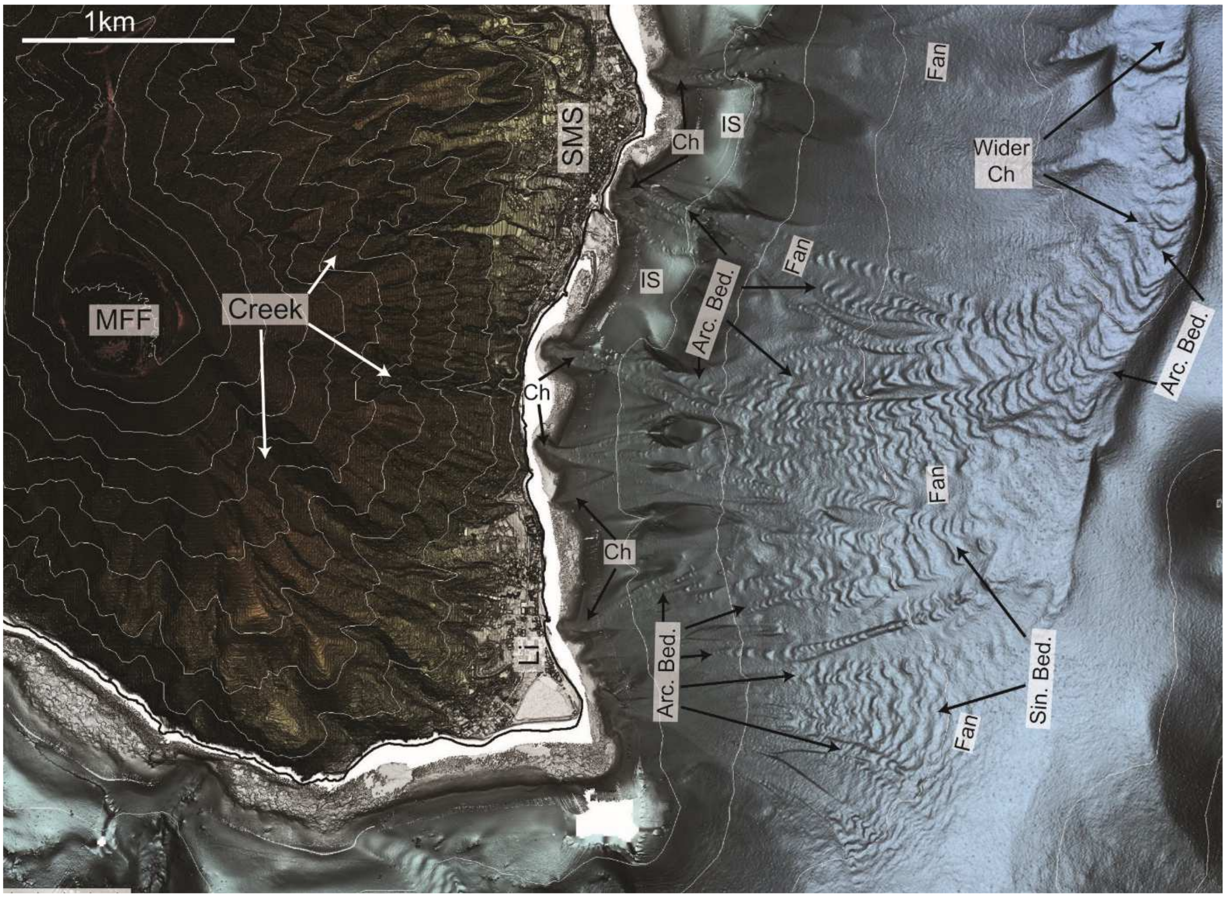

Figure 3 Shaded relief map (azimuthal artificial light) and contour lines (equidistance of 100 m) of area B (location in Fig. 1) along the eastern flank of Monte Fossa delle Felci (MFF), largely carved by a network of steep creeks, locally forming detrital cones at the coast. In the facing marine area, the narrow or totally absent insular shelf (IS)is indented by erosive channels (Ch) , passing downslope to fan-shaped features and wider channels. Both features are characterized by the occurrence of arcuate and sinuous bedforms (Arc. and Sin. Bed., respectively).

sandy) along the submarine flanks, where pyroclastic units crop out.

The observed bedforms share similarities in size and geometry with those recognized within active canyons and fan-deltas in continental margins (e.g., Hughes-Clarke 2016) and other submarine volcanic settings (Casalbore et al. 2021), so they are similarly interpreted as upper-flow regime bedforms due to turbidity currents. Based on their different morphology and location, the arcuate or crescent-shaped bedforms found within channelized features may be tentatively interpreted as transportation or net-erosional cyclic steps, while the sinuous bedforms recognized on fan-shaped features as net-depositional cyclic steps, according to the recent aggradation-based classification of Slootman & Cartigny (2020). However, we are aware that seismic profiles able to image the inner geometry of the bedforms, coupled with more extensive seafloor sampling, should be required to better support such morphology-based inferences. Data also show a strong relationship between the development, change in size and/or geometry of the bedforms and marked variations in slope gradients along the submarine flank. These, in fact, can favour the development of hydraulic jumps in the sedimentary gravity flow, or locally change its parameters (e.g., Postma et al. 2009; Slootman & Cartigny 2020).

A further point of discussion deals with the different distribution of the bedforms in the two areas A and B, which can be related to a complex interplay between marine erosional retrogressive processes and the subaerial dismantling of pyroclastic materials from the

Sample	% gravel	%sand	% silt	% clay
S1	0,05	72,98	18,86	8,11
S2	8,6	85,01	4,80	1,59
S3	0,21	94,32	4,15	1,32
S4	1,07	55,62	30,41	12,9
S5	16,91	57,54	17,68	7,87
S6	0,8	89,26	7,15	2,79
S7	18,75	78,71	1,93	0,61
S8	0,1	39,23	42,38	18,29

Table 1 shows the percentages of gravel, sand, silt and clay in the recovered samples (location in Fig. 1)

E flank of the island through a network of narrow and steep creeks. In the NE area, where the shelf is wider and the few subaerial creeks hang above the high coastal cliffs, bedforms are mostly limited at greater depths and their formation is less directly linked to subaerial processes. They could be instead more likely associated with small-scale slope failures affecting the shelf edge. Alternatively, the formation of these bedforms could be related to past conditions, when the sea-level was lower than at present. Differently, along the E flank of Monte Fossa delle Felci, the morphological link between the subaerial and submarine drainage network is more evident and favored by the very limited extension (or lacking) of the insular shelf, the presence of lower sea cliffs or coastal detrital slope fans. Narrow and steep creeks are commonly considered prone to the development of hyperpycnal flows, especially in the case of sudden and heavy rains which may occur in the semi-arid climate characterizing Southern Italy (Sabato & Tropeano 2004). In addition, it should be considered that most of the submarine channel heads are located at 5-10 meters wd, so they can both intercept the longshore drift and/or be affected by storm-wave loading, thus increasing the probability of small-scale failures in coastal deposits.

In summary, the present study shows how the steep and uneven flanks of insular stratovolcanoes are very prone to the development of upper-flow regime bedforms. Particularly, those observed on the E flank of Salina show an impressive variability in size, plan-view geometry and cross-section at small spatial scale and can be considered a natural laboratory for identifying the main factors controlling the formation and development of small-scale bedforms.

5 ACKNOWLEDGEMENT

Multibeam bathymetry was collected in the framework of the Italian MaGIC (Marine Geohazards along the Italian Coasts) Project. We would like to acknowledge crews of R/V Urania (CNR) together with the researchers and students that have took part to the oceanographic cruises. We acknowledge Ministero dell’Ambiente e della Tutela del Territorio e del Mare-Geoportale Nazionale with license Creative Commons 3.0 Italy (CC BY-SA-3.0IT) for providing the terrestrial LIDAR data. Research activities of Daniele Casalbore were also supported by funding provided by the “Progetto di Ateneo 2021”, Sapienza University of Rome.

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