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A morphometric model of the Aeolian Islands (Italy)

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Summary. — A Digital Elevation Model (DEM) of the Aeolian Islands (Southern Tyrrhenian Sea, Italy) is presented, with a 5 m horizontal resolution, derived from photograms at a relative medium scale of 1:35000, collected during an aerophotogrammetric flight in 1994-5. The sea data come from a hydrographic survey (1996-1997) of the seabed topography, carried out in accordance with present international standards. The sounding density of the bathymetric survey varies: it is more accurate near the coasts and in areas of structural interest. Previous bathymetric surveys, when available, were limited to small areas. The present DEM is enclosed in a rectangle with limits of longitude 14°16′32″-15°22′51″E and latitude 38°20′55″-38°53′50″N. The DEM of the islands and of the seabed, merged together, is presented here for the first time. The shadowed raster images of the DEM clearly outline the structural and volcanological features of the archipelago.

PACS `91.10.Jf` – Topography; geometric observations.
PACS `91.50.Ga` – Bathymetry and noncoastal underwater morphology.
PACS `91.40.-k` – Volcanology.

1. – Introduction

Digital Terrain Models (DTM) or gridded topographic data (Digital Elevation Models: DEM) are a powerful instrument in the study of the morphometric aspects of volcanic areas. They define the dimension, shape and position of objects of varying sizes [1-4]. In a volcanological context, depending on elevation errors, these tools can be applied in particular i) to study the structural and volcanological evolution of the area of interest; ii) to evaluate ground deformation; iii) to estimate volcanic product volumes; iv) to provide suitable geometric georeferenced maps to use as a basis to store and manage geological information in a GIS [3-6].

Different techniques can produce surface topography on a regular grid. Ground surveying (either by EDM or GPS) is very accurate but precarious, arduous and slow over wide areas. Traditional satellite remote-sensing mapping techniques are rapid, but the data may not be accurate enough for some applications (*i.e.* volume estimates from data spot). Topographic mapping can also be produced from radar interferometry or laser altimetry, which have future potential benefits. The more traditional, well-established, aerial photogrammetry produces spot heights and contour lines, from which regular data can be obtained if appropriate interpolation techniques are used [2-4].

Here a DEM of the Aeolian Islands (Southern Tyrrhenian Sea, Italy) is presented. No previous DEMs of the islands are available with the exception of a detailed digital photogrammetric topography of La Fossa Cone at Vulcano [5] and a preliminary DEM of the emerged and submerged portions of Vulcano [7].

We have computed the DEM from contour lines and spot heights reconstructed from stereo-photograms at a scale of 1:35000, dated 1994-1995. The flight altitude was about 6000 m, with a variation, depending on relief, of $\pm 10\%$. A suitable interpolation algorithm resamples elevations on a regular grid (at 5 m resolution), starting from input topographic information. With respect to digital photogrammetry, which processes data in automatically, our approach has the advantage that the input points can be selectively chosen as belonging to natural features, so that man-made structures are excluded.

The terrain data came from a bathymetric survey in 1996-1997. The surveys were performed by the Monobeam echosounders ATLAS KRUPP DESO 20 and DESO 25 (Istituto Idrografico Marina) along parallel routes as perpendicular as possible to the coastlines, with each-other distances of 250 m, 125 m or less, and by Multibeam Echosounder ELAC with 100% coverage of the sea bottom, beyond the 500 m bathymetric line. The results are presented here for the first time. Other bathymetric surveys have previously been available, but were limited to specific sectors (north-west of Sciara del Fuoco, Stromboli, same areas around Vulcano, Lipari, Salina and Panarea [8-10, 7])

2. – Geological framework

The Aeolian Archipelago (fig. 1) lies on the south-eastern Tyrrhenian continental slope and it is the emergent edge of the broad, largely submarine, Aeolian Volcanic Structure (AVS). The AVS is an extensive complex Quaternary volcanic arc (see [11] and references therein), extending for about 200 km. It consists of seven main islands with some major composite volcanoes (Vulcano, Lipari, Stromboli, Alicudi, Filicudi, Panarea, Salina) and several scattered seamounts, along an approximately ring-like structure (fig. 1). The arc lies on a 15 to 20 km thick continental crust [12] and it is related to the subduction of the Adriatic plate beneath the African plate [13].

The volcanic activity and structural trends in the arc are strongly controlled by the regional stress fields. Three distinct sectors can be recognised:

– the western sector (Alicudi and Filicudi Islands) with predominantly NW-SE oriented tectonic alignments [14];

– the central sector (Vulcano, Lipari and Salina Islands) aligned along an important regional transcurrent fault with a NNW-SSE oriented trend;

– the eastern sector (Panarea and Stromboli Islands) characterised by prevailing NE-SW oriented tectonic alignments [15].

The Arc formed from about 1 Ma to the present day [16]. The oldest documented volcanic activity (1.3 Ma) in the Arc is testified by a dredged sample coming from the Sisifo seamount (in the submarine western portion of the arc). The Vulcano and Strom-

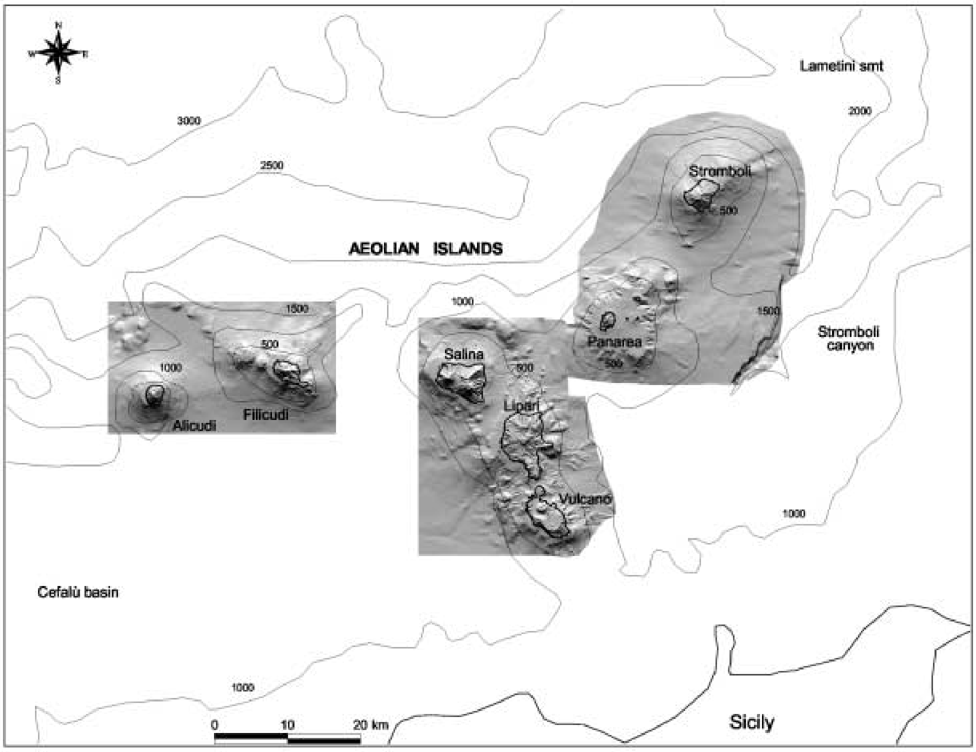


Fig. 1. – General map of the Aeolian Arc. The shadowed portion represents the area where the DEM has been reconstructed.

boli volcanoes are still active; eruptions occurred at Lipari in historical times and on Salina and Panarea during the very late Pleistocene (< 15 ka before present).

2˙1. *Alicudi*. – This is the westernmost island of the Aeolian Archipelago (figs. 2a, b; see also fig. 9). The island has an area of about 5 km^2 and attains a maximum elevation of 675 m a.s.l. Like almost all the Aeolian Islands, Alicudi is the uppermost part of a submerged stratocone. With the exception of scree deposits and coastal sediments, it is mainly made up of volcanic rocks (lava domes, lava flows, pyroclastic deposits). The evolution of the island is characterised by several important volcano-tectonic episodes. Each cycle has a new volcanic cone on the top of the previous one. The oldest outcroppings are the "Lave di Galera", younger than 90 and 87 ka. During 60–55 ka, normal faulting and erosion deeply dissected this volcano, and the position of its central vent is hardly identifiable [17] (figs. 2a, b). The younger portion of Alicudi begins with the lava flows and the tephra deposition of the Malopasso System. Its main eruption center was located at about 900 m north-west of the present top of the cone and successively collapsed southward. Mainly in the amphitheatre originated by the collapse, a new cone, the Bazzina system, was built up and successively collapsed. The last period of volcanic activity took place and lasted until about 28 ka BP. The products (lava domes and flows) are grouped under the Montagnole system [17].

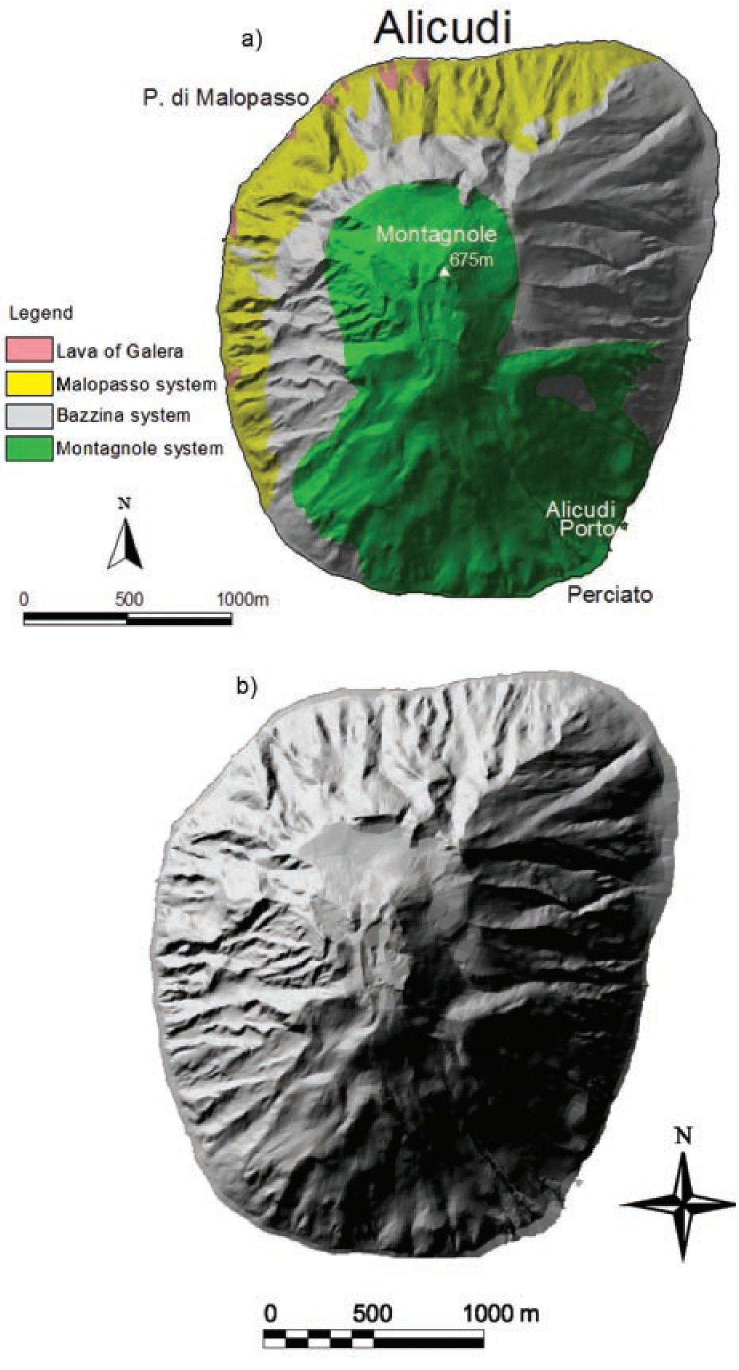


Fig. 2. – a) Schematic geological map of the Island of Alicudi (after [17]) "draped" on the shaded relief image. b) Shaded relief image of the DEM.

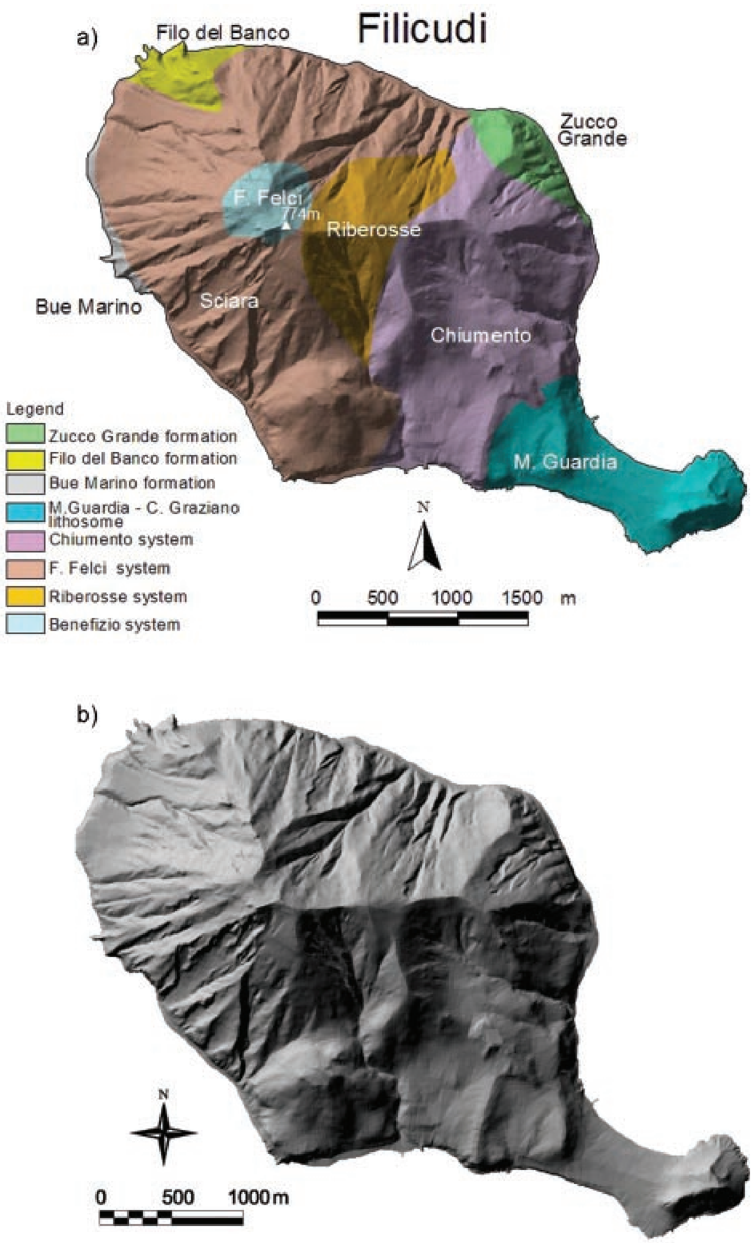


Fig. 3. – a) Schematic geological map of the Island of Filicudi (after [18]) "draped" on the shaded relief image. b) Shaded relief image of the DEM.

2˙2. *Filicudi*. – The island (figs. 3a, b; see also fig. 9) has an area of 9.5 km^2; the maximum elevation (774 m a.s.l.) is represented by the stratocone Fossa Felci. Most of the several volcanic centres are aligned in a NW-SE trend, creating a shape lengthened in this direction. The volcanic evolution of the island begins with the formation of the Zucco Grande system (lava flows and pyroclastic deposits, 1.02 Ma [19]). The second volcanic period, following a long period of erosional activity producing a flat surface, is located in the western and north-western part of the island (Filo del Banco and Bue Marino). After another quiescent period, the volcanic Centres of Fossa Felci, Chiumento and Riberosse formed. The last volcanic active period (> 50 Ka [18]) was characterized by the formation of the Benefizio System.

2˙3. *Panarea*. – The eastern sector of the Aeolian Volcanic Structure is characterized by a broad submarine volcanic belt, extending for more than 45 km in a NE-SW direction (fig. 1). The major features of the belt are the Panarea and Stromboli polygenetic stratovolcanoes. Panarea (figs. 4a, b; see also fig. 10), with an area of 3.3 km ^{2}, reaching a subaerial height of 421 m a.s.l. at Punta del Corvo, is the smallest island of the archipelago. Its dominant structural trend is NNE-SSW, shown by its elongated shape [20]. Gabbianelli *et al.* [15] suggest that Panarea is the subaerial remnant of an old volcanic complex, together with some nearby islets. The island is one of the oldest of the whole Aeolian Structure (the subaerial volcanic activity developed between 211 ka and < 10 ka [16]). The oldest lavas and domes are located to the north-west (Punta del Corvo) and south (Punta Tribunale); the middle products are to the south (Punta Milazzese) and east (Punta Falcone). The last event seems to be represented by the extrusion of the dome of Basiluzzo.

2˙4. *Stromboli*. – Stromboli is the northern island of the Aeolian arc (figs. 5a, b; see also fig. 10). With a surface area of 12.2 km^2 and a coastal contour of 14.4 km, it is the fifth in size of the seven major islands of the Archipelago. Like the other islands, it is entirely volcanic, and, together with Vulcano, it is still active. The Stromboli cone, steep and rather uniform, rises from a depth of about 2000 m in the Tyrrhenian Sea, to reach a subaerial height of 924 m a.s.l. at I Vancori. The island displays a NE-SW elongation, in accordance with the general tectonic framework of the area, starting from Strombolicchio, the remnant of an older volcano NE of Stromboli, connected with the submarine cone of Stromboli. The subaerial activity, spanning from about 100 ka BP to the present strombolian activity of Sciara del Fuoco, has the same spatial pattern. The old structures (Paleostromboli and Vancori cycles), characterized by pyroclastic products and lava flows, are located in the eastern part of the island. The younger cycle (Neostromboli and Recent Stromboli), including the present activity, is located in the western side [21].

2˙5. *Salina*. – Salina, the second largest island of the Aeolian Arc, has a surface area of 26.75 km ^{2} (figs. 6a, b; see also fig. 11). At present, two steep volcanic cones characterise the island (Fossa delle Felci, 962 m a.s.l., and Monte dei Porri, 860 m a.s.l.), separated by a deep valley (290 m a.s.l.). In its history, five main subaerial eruptive centers can be detected, ranging in age from 430 to less than 13 ka [16,22,23]. These formed during two main eruptive cycles. Monte Rivi, Serro del Capo (on the East) and Pizzo Corvo (on the West), dissected and eroded by marine abrasions, and the better preserved, younger Fossa delle Felci belong to the older cycle. The younger cycle (100-13 ka) built up Monte dei Porri, displaying a youthful morphology with a well-preserved summit crater, and ended with the explosion crater of Pollara, on the north-western side of Salina.

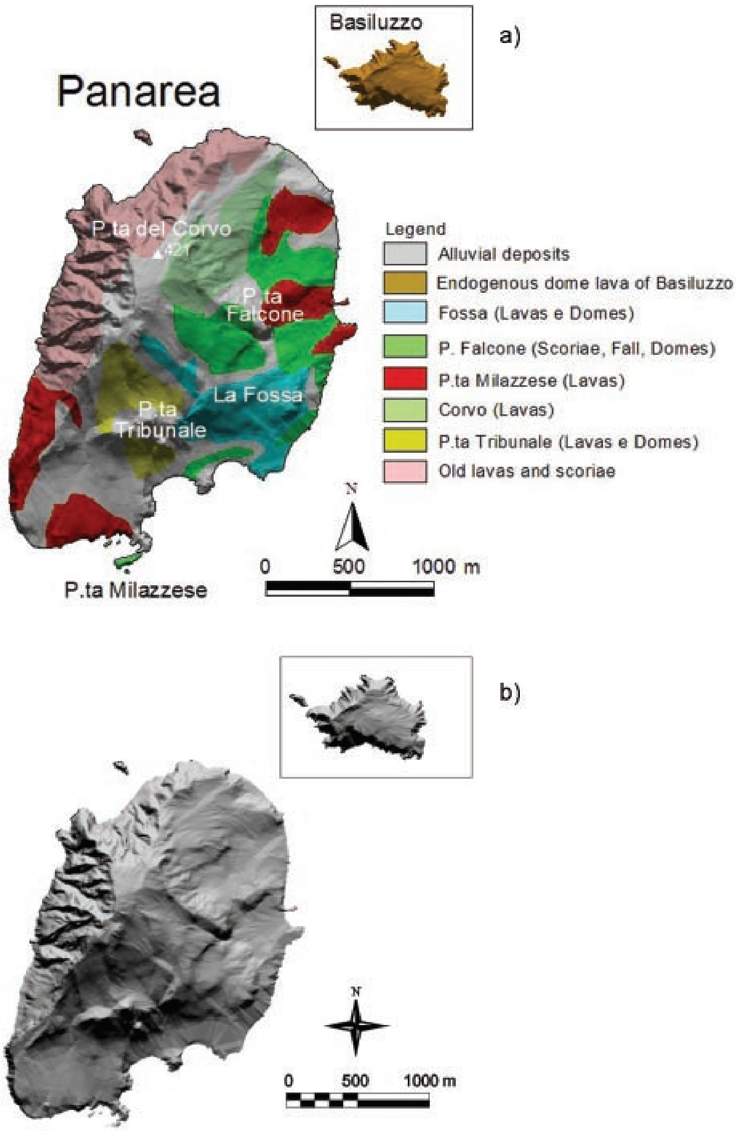


Fig. 4. – a) Schematic geological map of the Island of Panarea (after [20]) "draped" on the shaded relief image. b) Shaded relief image of the DEM.

2·6. *Lipari*. – Lipari, the main island of the Aeolian Archipelago (figs. 7a, b; see also fig. 11), has an area of 38 km^2. It consists mainly of volcanic rocks. Some alluvional deposits and a conglomerate marine terrace, on the western coast, are the only sedimentary rocks of Lipari. Stratigraphic reconstructions based on field and geochronological data indicate that the volcanic activity can be subdivided into two main stages, ranging in time from the 223 ka up to 580 AD [24]. The first stage, from 223 to 42 ka, consists of six eruptive cycle and the second one of four cycles [24]. All ten cycles began with

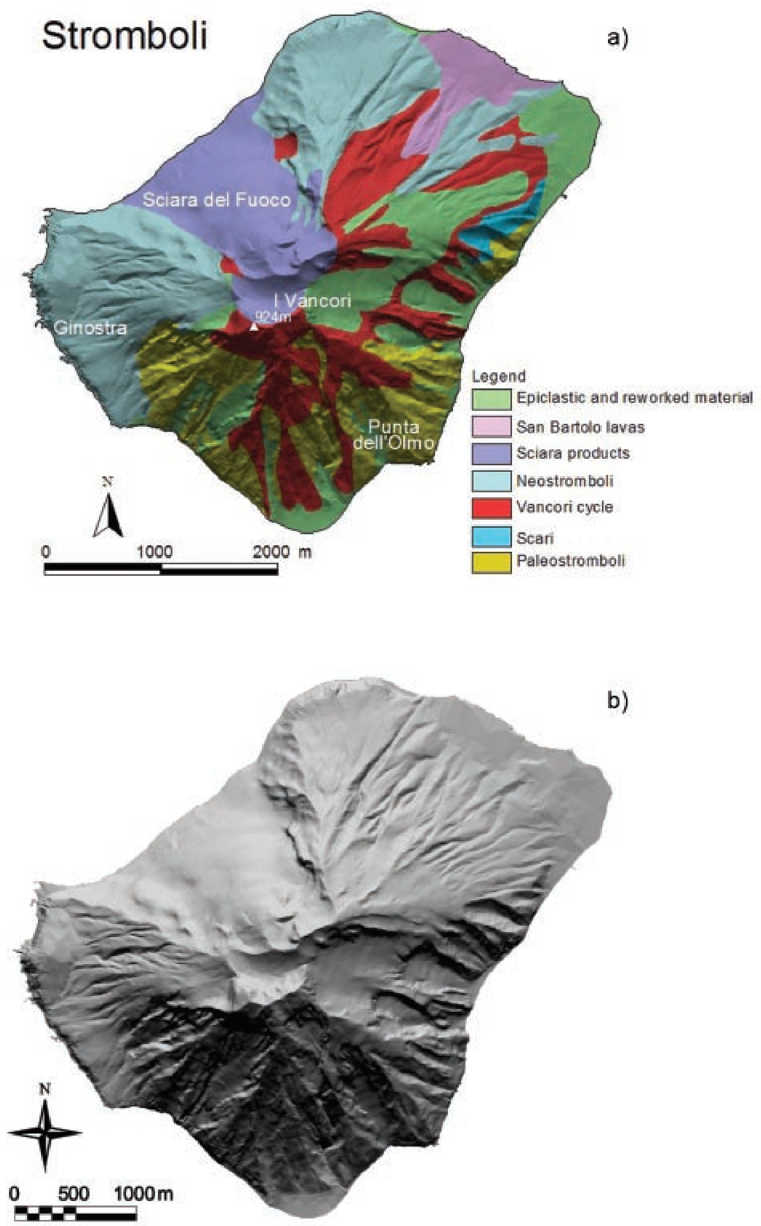
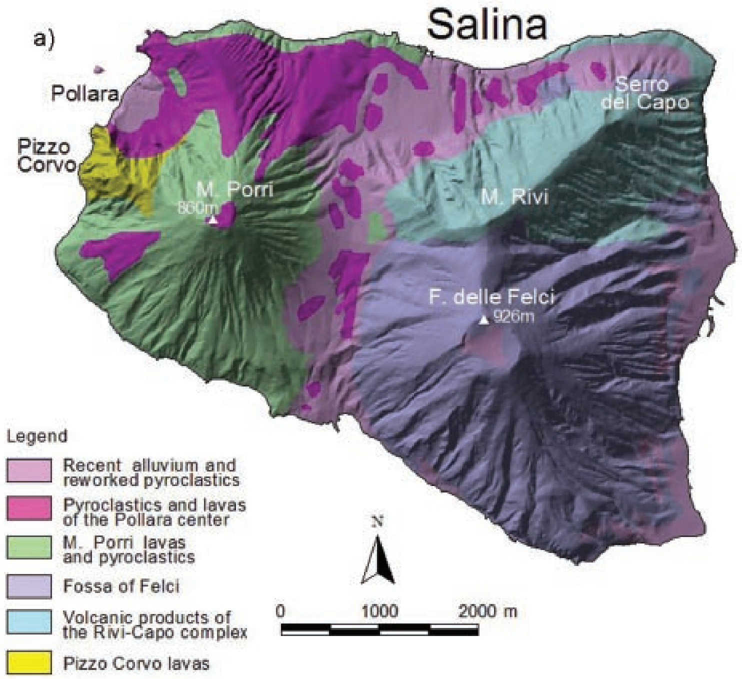


Fig. 5. – a) Schematic geological map of the Island of Stromboli (after [21]) "draped" on the shaded relief image. b) Shaded relief image of the DEM.



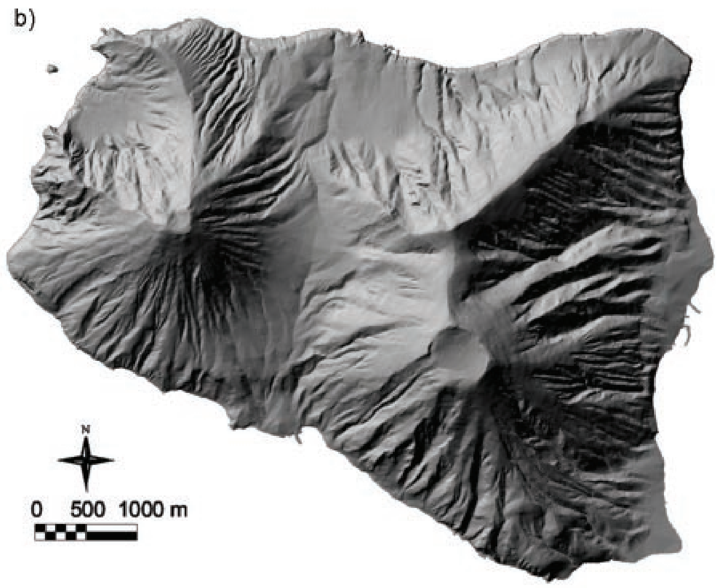


Fig. 6. – a) Schematic geological map of the Island of Salina (after [22]) "draped" on the shaded relief image. b) Shaded relief image of the DEM.

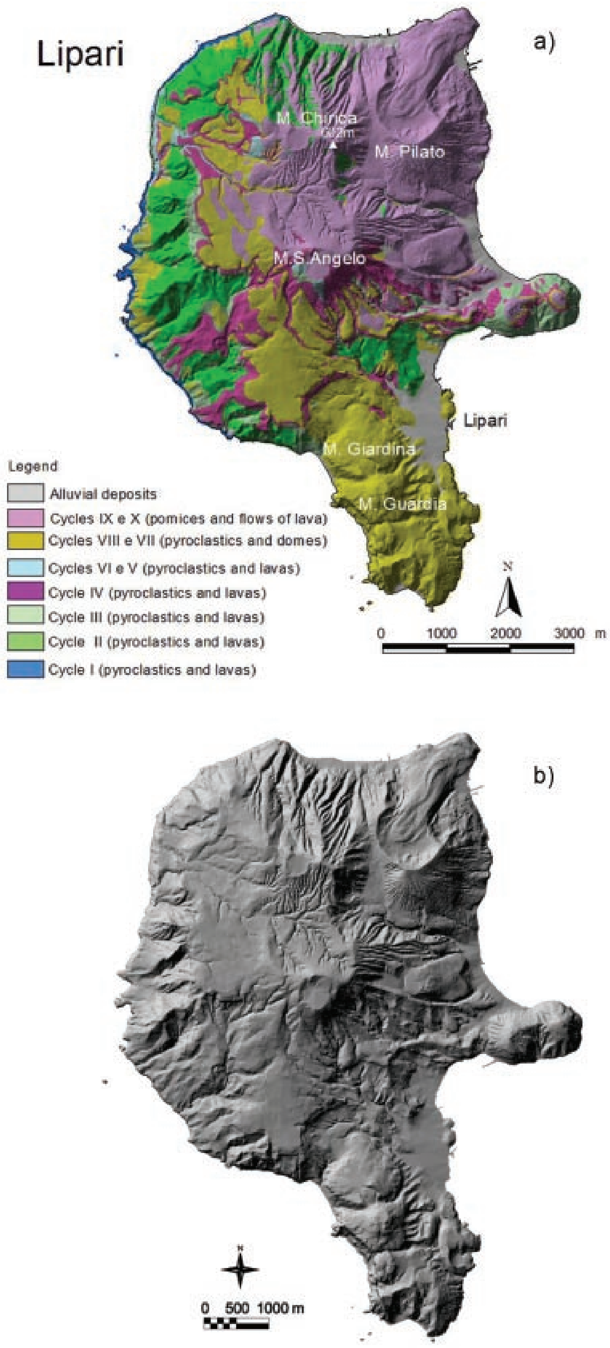


Fig. 7. – a) Schematic geological map of the Island of Lipari (after [24]) "draped" on the shaded relief image. b) Shaded relief image of the DEM.

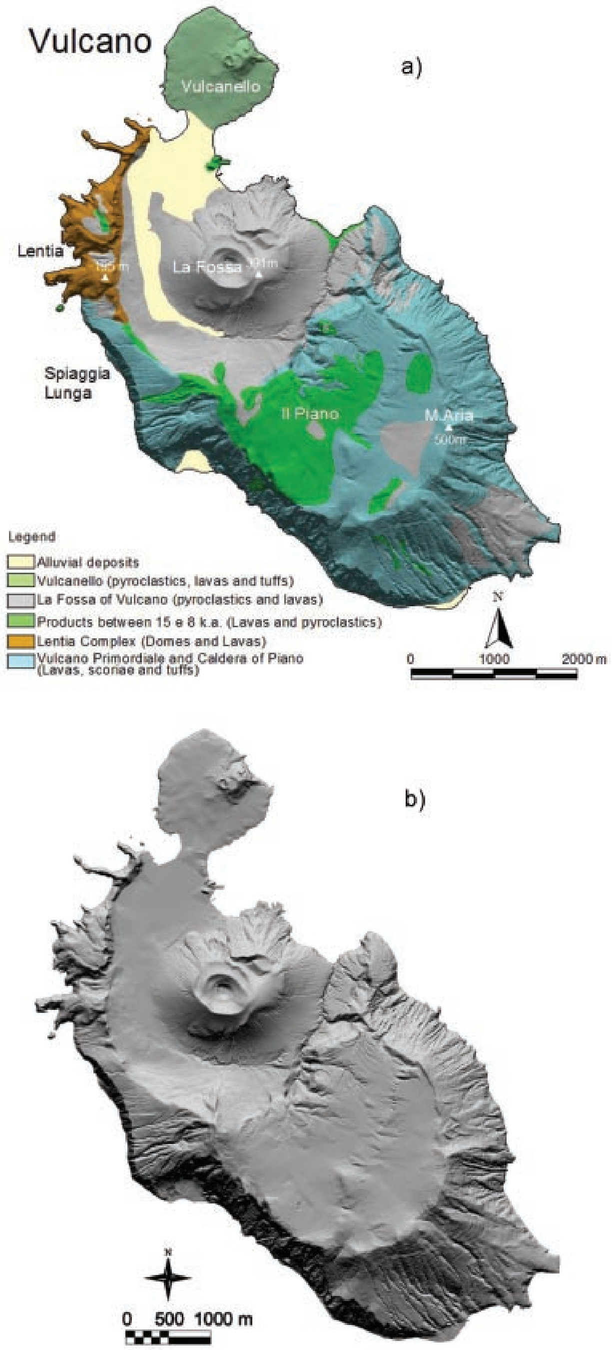


Fig. 8. – a) Schematic geological map of the Island of Vulcano (after [25]) "draped" on the shaded relief image. b) Shaded relief image of the DEM.

an explosive phase and ended with effusive activity. In addition, they were separated by significant quiescent intervals, indicated by large geochronological gaps, stratigraphical unconformity and, sometimes, by abrupt compositional changes. The final prehistoric and medieval activities occurred in the north-eastern part of the island. The maximum height of the island (602 m a.s.l.) is represented by Mt. Chirica volcano.

2˙7. *Vulcano*. – The Island of Vulcano (figs. 8a, b; see also fig. 11) has an area of 22 km^2. It rises from a depth of about 1000 m in the Tyrrhenian Sea, to reach a maximum subaerial height of 500 m a.s.l. at Mt. Aria [26]. Radiometric measurements confirm an age of 120 ka [16]. Since its emersion, the volcanic activity has migrated from SSE to NNW, resulting in a composite structure, with four main eruptive centres and two poliphasic calderas [27, 25]. They are in chronological order: the Old Stratovolcano (or Vulcano Primordiale); the Caldera del Piano; the Lentia Complex; the Caldera of La Fossa; the Fossa di Vulcano; Vulcanello [25]. The Vulcano Primordiale, characterized by steep slopes, occupies the southern part of the island, extending to the West as far as the Spiaggia Lunga, south of Mt. Lentia. The summit part of the cone disappeared as a consequence of the formation of the Caldera del Piano, about 100 ka BP. The Lentia Complex (20–15 ka), made up of thick lava flows, reaches a maximum height of 195 m a.s.l. The Caldera of La Fossa occupies the central part of the island, as the result of a differentiated and poliphasic collapse. In the central part of the Caldera La Fossa, there is the Fossa Cone, a tuff cone, 391 m high, with a base diameter of 1 km. Its activity initiated about 6000 years BP; the last eruption occurred in 1888-1990 [25]. Vulcanello, formed in 183 AD, and connected with the main southern part of the island in 1550, is made up of a lavic platform and three scoria cones.

3. – Photogrammetric survey of the Aeolian Islands

3˙1. *The land photogrammetric survey*. – The topographic survey of the Islands was carried out in December 1994-February 1995. The 253 photograms (230 mm × 230 mm) of the flight were obtained by a camera equipped with a 150 mm lens and black and white panchromatic Kodak film; the photograms were taken at a scale of 1:23000. The maximum planimetric error of the contour lines reconstructed from the stereo models is less than 3.5 m. Since error in the vertical position of a contour line is proportional to the tangent of the local slope [28], for steep slopes we expect on contour lines a maximum altimetric error lower than 2 m. The maximum altimetric error on isolated topographic points is less than 1.8 m. For the cone of Vulcano, data come from a more accurate topographic survey (August 1993), assuring an altimetric error lower than 50 cm [5].

3˙2. *The digital elevation model of the islands*. – The DEMs of the Aeolian Islands have been obtained by computing, on a regular grid, the elevations provided by a Triangulated Irregular Network (TIN), approximating the terrain surface as a network of planar triangles. The vertexes of the TIN are points of known elevation, *i.e.* isolated points or points belonging to contour lines, both coming from the topographic survey. Table I reports, for each island, the number of input points of the triangulation and the number and the average dimension of the triangles. For La Fossa Cone on the Island of Vulcano, as already mentioned above, the input points of the cone come from a more detailed survey, based on photograms 1:8000 [5]. Here the original DTM has a 1m horizonthal resolution.

The triangulation used to reconstruct the TIN is based on a modified version [2, 4]

TABLE I. – *Eolian Islands.*

Island	Surface (km^2)	No. of points along contour lines	No. of isolated points	No. of triangles	Triangle average dimension (m^2)
Alicudi	5.194	48533	27	108759	48
Filicudi	9.231	57459	77	126952	73
Lipari	37.565	136239	715	356982	105
Panarea	3.811	24828	35	65295	58
Salina	26.229	144694	330	329175	80
Stromboli	12.597	63526	186	140987	83
Vulcano	21.083	80553	244	218384	96
La Fossa Cone	3.005	572082		1273548	16.5

of the Delaunay algorithm. Starting from a set of input points, the Delaunay approach [29-31] provides triangles (with vertexes on the input points), reconstructing the topographical surface as a network of planar triangular facets. The triangles are "as equilateral as possible", since they satisfy the maximum minimum angle criterion (the minimum angle of each triangle is the maximum over all the possible triangulations). Since the points (vertexes of the triangles) are not random in space, because they belong to contour lines, some problems can arise in correspondence to sharp contour bends. There the Delaunay triangulation commonly suggests flat triangles built on the same contour line (instead of narrower triangles with vertexes on different contour lines). In the modified triangulation techniques adopted here, these kinds of problems are avoided by introducing lines across which triangulation is not allowed. These lines, automatically evaluated, join points of maximum curvature of the digital contour lines [2-4].

The vertical error of the DEM is the same as the input points coming from the photogrammetric survey (maximum error below 2 m). In the area of the La Fossa Cone we have compared the DEM derived from the photograms 1:23000 with the more accurate data coming from [5]. Using the data from Achilli *et al.* [5] as the reference topographic matrix, the root-mean-square error in the DEM derived from the 1:23000 photograms is:

– 1.8 m in the area of La Fossa Cone (text area of 1 km^2 with average slope 26.3°);

– below 1 m, in the flat area of Vulcano Porto.

The DEMs are georeferenced, the step is 5 m, the coordinate system is Gauss Boaga and table II reports the dimension of the rectangles including the Alicudi-Filicudi islands, Stromboli-Panarea and Salina-Lipari-Vulcano. Figures 2a, 3a, 4a, 5a, 6a, 7a, 8a show the shaded relief images of the DEM of the islands. The illumination is from the north.

3˙3. *The bathymetric grid*. – In 1996 and 1997 new hydrographic surveys were performed around the major Aeolian islands by the IIM (Istituto Idrografico della Marina, Genoa, Italy), in order to produce the new Nautical Chart n° 248 at a scale of 1:30000. These data are presented here, integrated with the land orographic information. The impetus for the surveys was the structural importance of the sea-bottom around the islands and the fragmentary bathymetric data previously available. Data far from the coasts were already available in some areas NE and SW of Salina-Lipari-Vulcano, collected during an IIM oceanographic campaign in 1994-5 by the Italian Navy Survey Ship Amm. Magnaghi

TABLE II. – *Eolian Islands DEM characteristics.*

Island	Step (m)	x-coordinate 1st point top-left (m) (GB-east)	y-coordinate 1st point top-left (m) (GB-east)	x-coordinate last point bottom-right (m) (GB-east)	y-coordinate last point bottom-right (m) (GB-east)
Alicudi/Filicudi	5	2457133.22	4279072.54	2488520.26	4260880.87
Stromboli/Panarea	5	2520363.14	4305224.37	2553227.12	4267403.86
Salina/Lipari/Vulcano	5	2499868.92	4276870.98	2527116.02	4244174.47

(EOCUUM Project) (integrated with our data where available at a greater detail). Other data near Vulcano, Lipari, Salina were collected by the National Research Council (CNR) ship Urania along routes perpendicular to the coast (see [8,7] and references herein). NW of Stromboli, a detailed bathymetric survey was performed [9]. This bathymetric survey, given its great detail, has been integrated into our DEM.

The surveys presented here cover all the sea-floor around all the islands for up to a distance of 12–15 km offshore, for a total area of 2700 km^2. The outer boundaries have the following geographical limits respectively in longitude and latitude: 14°16′32″-15°22′51″E and 38°20′55″-38°53′50″N. The surveys were conducted along parallel routes as perpendicular as possible to the coastline, while the distances in meters between such routes were respectively 125 m, 250 m, 500 m, depending on the offshore distances (0–100 m, 100–500 m, > 500 m), and parallel to the bathymetric lines beyond the 500 m bathymetric line (when executed with the Multibeam echosounder). Very detailed data were collected close to the berths and small harbours of the islands, and in general from

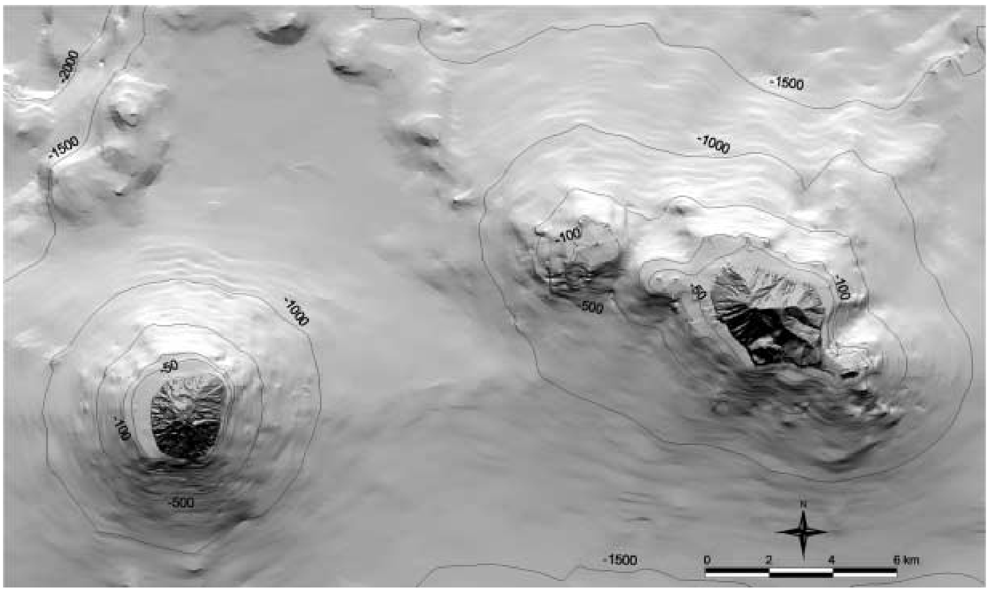


Fig. 9. – Shaded relief image of the DEM of Alicudi and Filicudi area.

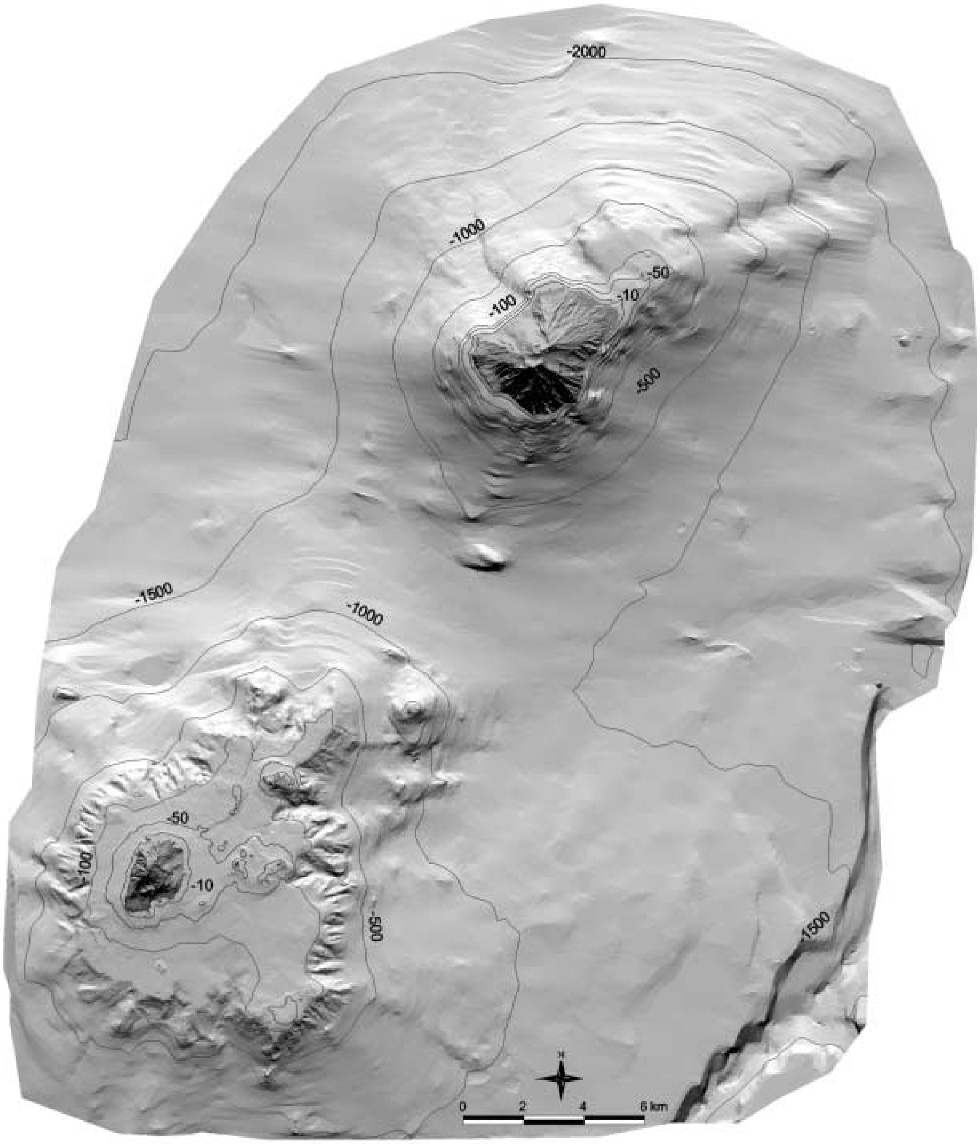


Fig. 10. – Shaded relief image of the DEM of the Panarea and Stromboli system.

the coastline to the 500 m bathymetric line.

A higher sounding density was performed where the sea bottom showed anomalies, due to irregular trends and peaks. In these cases, divers were sometimes used, to determine depths accurately. Among these zones we note:

– The "Secca del Capo", located at latitude 38°37′21″N and longitude 14°54′48″E, north-east of the Island of Salina, where a depth of 8.2 m was verified.

– The "Banco del bagno", located at latitude 38°27′54″N and longitude 14°47′12″E, west

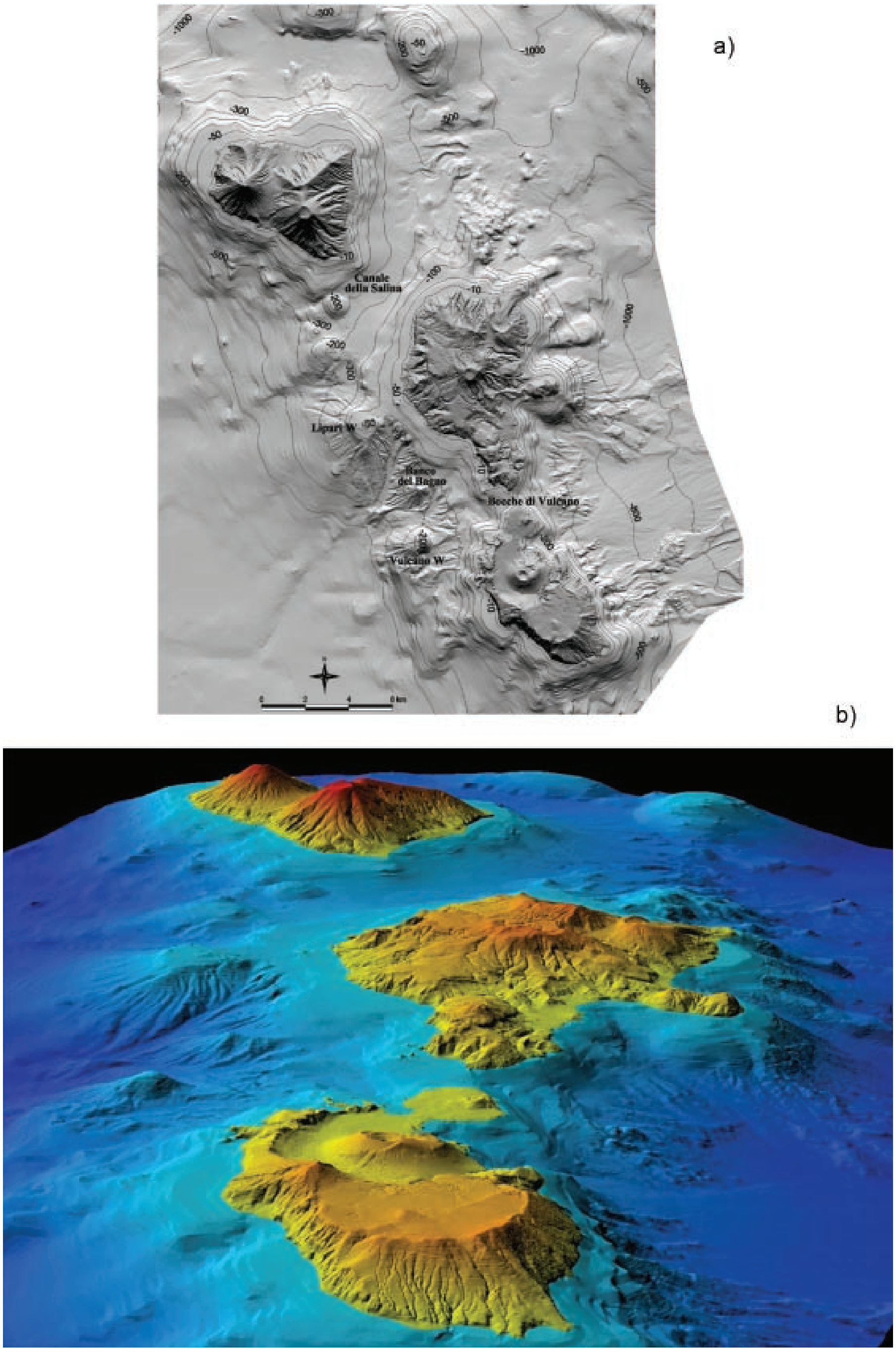


Fig. 11. – a) Shaded relief image of the DEM of the Vulcano, Lipari and Salina system. b) 3D perspective view.

of the Island of Lipari, where a depth of 12.5 m was verified.

The following means and equipment were in general employed:

– Differential GPS.

– Multibeam echosounder ELAC.

– Monobeam echosounders ATLAS KRUPP DESO 20 and DESO 25.

– Total Station AGA 540.

– Italian Navy Survey Ships "Ammiraglio Magnaghi" and "Mirto".

– 7 m long survey boat.

– Automatic hydrographic data acquisition system.

Sound velocity and tide corrections were applied to the depths measured. Sound velocity corrections were taken from IIM Depth Correction Tables (I.I. 3126) and from local CTD measurements. A digital tide-gauge was used to record tide oscillations for a period of two months. These corrections do not exceed a few centimeters, according to the Z0 (CHART DATUM) of the Nautical Chart n° 248. Figures 9-11 show the shadowed images of the DEM for the islands and the surrounding sea floor. The illumination is from the north.

4. – Discussions and conclusions

Digital Elevation Models can supply important information for the the study of volcanic structures since they provide a basis for the extraction of terrain-related attributes and features. Information may be extracted in two ways: by qualitative visual analysis or graphic representations (through visualization) or by quantitative analysis of digital terrain data (through interpretation).

In this work we have presented a DEM for the lands and the submerged portion of a sector of the Aeolian Arc, including the Aeolian Islands, obtained by photogrammetric data and bathymetric surveys. The data (emerged and submarine topographies) are combined together to form a continuous grid.

Detailed analyses of the structural features of the area are beyond the aim of this work and they will be studied in other/feature works, integrating our DEM information with volcanological and geophysical analyses (for example volcanic information, earthquake distribution, etc.).

However, some very brief comments can be made here. The DEM shows a complex topography with several eruptive centres, oriented E-W, N-S, NW-SE and NE-SW.

The Panarea-Stromboli complex defines a major SW-NE alignment (fig. 10) separated by a saddle (about 1280 m deep). Both the volcanoes, bordered by the Stromboli Canyon visible in our DEM in the bottom right portion, have a large submarine portion (the emerged volume is about 3% (Stromboli) and 1% (Panarea) of the total one), rising from a depth of 1200–1700 m b.s.l. The Panarea complex, with a maximum diameter of 20 km, shows an erosive submarine shelf (related to the Late Pleistocene glacio-eustatic sea-level fluctations [15]), bordered by an approximately 100 m deep, 17° slope, edge. With respect to the older Panarea stratovolcano, the younger and still active Stromboli shows steeper slopes (20–25°) and partial collapses with a submarine continuation.

The Salina-Lipari-Vulcano system shows a main NNW-SSE trend (figs. 11a, b). Channels are present between the three islands, with different characteristics from each other. The northern channel (between Lipari and Salina), called "Canale della Salina", goes down to a depth of 300 m; the southern one (between Lipari and Vulcano), called “Bocche di Vulcano”, is much shallower, about 35 m in its central part, suggesting a former continuity between the two islands through a partially buried eruptive centre [32].

Notable asymmetry of the flanks of the Salina-Lipari-Vulcano system is detectable in the DEM. Especially in the areas of Lipari and Vulcano, the strip between the 100 m and 200 m bathymetric lines appears rather levelled with a strong gradient in proximity to a depth of 200 m. The westward-facing slopes are more extensive, relatively regular and less steep than the eastern ones (fig. 11b). The asymmetry is partially due to their older age and the successive eastward migration of the main crustal axes [33], as also confirmed by an almost total absence, along the eastern edge of the vulcanic system, of a marine abrasion platform associated with the late-Quaternary glacial-eustatic variations in sea level [7]. On the western submarine flanks of Vulcano and Lipari, the DEM gives clear evidence of the relationship between tectonics and vulcanism. Along a NNW-SSE alignment, characterized by high seismicity [34], there are some secondary eruptive structures (Vulcano W, Banco del Bagno and Lipari W), other minor submarine structures (SW of Salina between 200 and 800 m b.s.l., figs. 11a, b) and abrupt scarps aligned with emerged structures [35, 36].

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