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Volcanic geomorphology and tectonics of the Aeolian archipelago (Southern Italy) based on integrated DEM data

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Abstract The geomorphological and morphometric analysis of the sea floor topography surrounding the Aeolian Islands, South Tyrrhenian Sea, Italy, provides insights into the relationships between the volcanological evolution of the islands and their tectonic features. We constructed geomorphological maps of the submarine portions of the seven large edifices constituting the islands on the basis of a DEM with a 5 m resolution step. These maps include constructional and destructional landforms such as submarine volcanic vents located west of Lipari and north of Alicudi, and hummocky surfaces recognised north of Lipari and Salina. The latter landforms, together with the occurrence of large scars affecting the main edifices on land, suggest that sector collapses affected some islands. Geomorphological data indicate that the location of sub-aerial and submarine vents is strongly controlled by local tectonic structures striking WNW-ESE (Alicudi-Filicudi sector), NNW-SSE (Salina-Lipari-Vulcano sector) and NE-SW (Panarea-Stromboli sector). The islands can be divided

into two groups on the basis of some morphometric parameters: a first group with a pancake-like shape, D_p/D (abrasion platform diameter/basal diameter) higher than 0.40 and H/D (total height/basal diameter) lower than 0.13, and a second group with a conical shape, characterised by D_p/D lower than 0.34 and H/D higher than 0.14. These ratios and other morphometric parameters reflect the different volcanological and structural evolution of the Aeolian Islands. The pancake-like shaped complexes have been created, in addition to their submarine stage, by extrusive and highly explosive activity, whereas the cone-shaped edifices have been characterised by effusive or moderate explosive activity.

Keywords Volcanic geomorphology · Morphometric analysis · Tectonics · Evolution of volcanism · Sector collapse · Marine geology

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Introduction

The Aeolian volcanoes are located between the Southern Tyrrhenian Sea backarc basin (Marsili oceanic basin) and the Calabrian Arc forearc region (Fig. 1), a Hercynian belt affected by Late Quaternary extensional tectonics and uplift (Boccaletti et al. 1984). The volcanoes emplace on a 15 to 20 km thick continental crust, and their products, which ages between 1.3 Ma and the present (Gillot 1987), belong to the calc-alkaline, high-K calc-alkaline, shoshonitic and alkaline potassic associations (Barberi et al. 1973; Keller 1982). The geochemical affinity of these rocks and the occurrence of deep seismicity (up to 550 km; Milano et al. 1994) below the Southern Tyrrhenian Sea led many authors to interpret the Aeolian Islands as a volcanic arc related to the active subduction beneath the Calabrian Arc (e.g. Barberi et al. 1973; Beccaluva et al. 1985; Ferrari and Manetti 1993; Mantovani et al. 1996). However, some authors suggest that subduction ceased about 1 Ma, since when a general uplift coupled with extensional tectonics has affected both the Calabrian Arc and the Aeolian

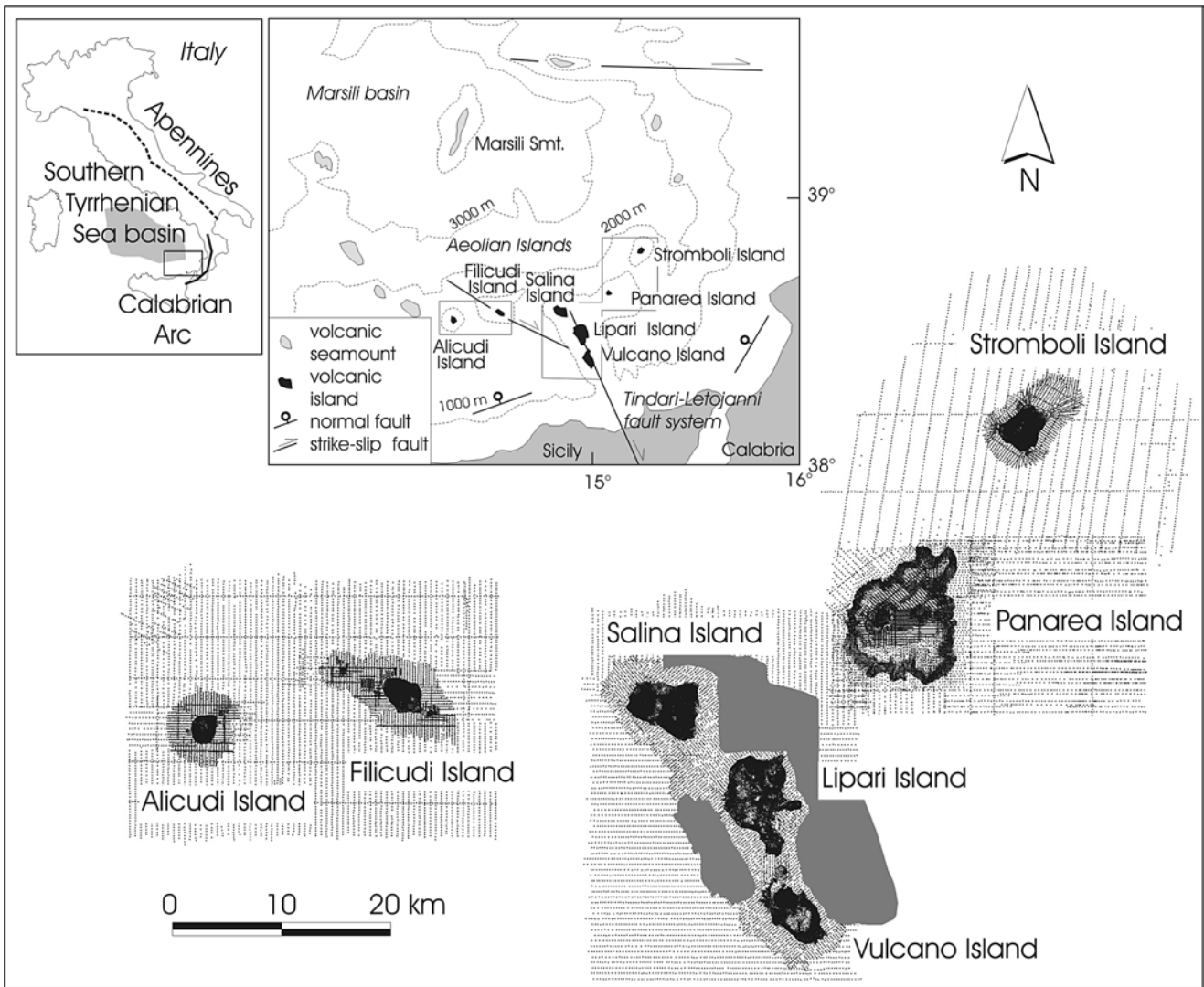


Fig. 1 The Aeolian Archipelago, Sicily, Italy, showing the main tectonic trends (De Astis et al. 2003). The density of the DEM input data as collected by monobeam and multibeam echo sounders is

reported in the bottom and right sketches. Higher density input data in the two grey patches around Vulcano, Lipari and Salina are from Gamberi et al. (1997a)

Islands in the last 0.5–0.7 Ma (Westway 1993; Hippolite et al. 1994; Milano et al. 1994; Carminati et al. 1998).

The Aeolian Islands (maximum altitude 987 m a.s.l. on Salina Island) represent emerged portions of extended submarine volcanic complexes that rise from 1,000–1,500 m b.s.l. The volcanoes are characterised by composite structures. Effusive and explosive activity from a number of vents produced thick lava flows and domes as well as thick (up to 70 m) pyroclastic sequences. In contrast to the well-known geological and petrological evolution of the subaerial portions of the volcanic edifices, the submarine portions of the volcanic edifices are surprisingly poorly identified. A number of studies on some offshore sectors of volcanic edifices (e.g. Vulcano and Lipari: Gamberi 2001; Panarea, Salina: Savelli et al. 1999; Stromboli: Romagnoli et al. 1993) are available, but a complete data set of the bathymetry and a geomorphological study on the offshore features of the volcanic edifices are lacking. In addition,

correlations between subaerial and submarine landforms, volcanic activity, and tectonic features have not been made.

In this paper, we present new results on the Aeolian Islands based on newly compiled DEM data constructed from various sources (cf. Bisson et al. 2003; Favalli et al. 2003). On the basis of the DEM images and geological features of the main volcanic structures outcropping on land (Keller 1980; Crisci et al. 1991; Mazzuoli et al. 1995; Ventura et al. 1999) we compiled geomorphological maps of the offshore sectors of the islands, complete with major structural-geomorphic elements. These maps allow us to: (1) characterise the morphology of submarine volcanic structures and deposits; (2) define the main submarine tectonic structures and relate them to those on land; (3) analyse the relationships between tectonics and volcanism in the Aeolian Islands. Finally, the collected data allow us to put constraints on the evaluation of the volcanic hazard in the Aeolian active volcanic region.

On-land tectonic structures and volcanic centres

Three main fault systems affect the Aeolian Islands (Fig. 1; Calanchi et al. 1993; Mazzuoli et al. 1995; Lanzafame and Bousquet 1997; Ventura et al. 1999; Tibaldi 2001): (1) a WNW-ESE striking fault system characterises the western sector; (2) a NNW-SSE striking fault system (Tindari-Letojanni system) affects the central sector; (3) a prevailing NNE-SSW to NE-SW striking fault system affects the eastern sector. In the western sector (Alicudi and Filicudi), the outcropping faults show morphological features (scarps) consistent with dip-slip movements. In the central sector, the faults affecting the islands of Salina, Lipari and Vulcano follow three main strikes: a prevailing NNW-SSE to NW-SE strike and second-order N-S and NE-SE strikes. Fault-slip data indicate that the NNW-SSE to NW-SE striking faults are characterised by right-lateral to normal movements. The N-S and NE-SW striking faults, which splay out from the main strike-slip segments, show normal movements. The NNW-SSE faults represent the main shear zone, while the N-S and NE-SW striking faults represent tensional structures associated to the shear zone.

In the eastern sector, faults with a prevailing NE-SW strike occur. Minor N-S, E-W and NW-SE faults are also present at Stromboli (Falsaperla and Spampinato 1999), but they are related to local deformations induced by the sector collapses that affected the northwestern sector of the edifice (Tibaldi 2001).

The subaerial volcanoes of the western sector align along the WNW-ESE faults, whereas the volcanoes of the central and eastern sectors align along the NNW-SSE and NE-SW faults, respectively.

Data and methods of analysis

The digital elevation models of the islands

The DEMs of the Aeolian Islands have a 5 m resolution step and have been obtained from a Triangulated Irregular Network (TIN), which approximates the terrain surface as a network of planar triangles (Favalli and Pareschi 2004). The vertex of the TIN are points of known elevation (i.e. isolated points or points belonging to contour lines) from a topographic survey. The topographic survey of the Aeolians (scale of airborne photographs 1:23,000) was carried out in December 1994–February 1995 (Bisson et al. 2003). The maximum altimetric error is lower than 1.8 m. For the cone of Vulcano (La Fossa), data came from a more accurate topographic survey (August 1993; scale of airborne photographs 1:8,000), with an altimetric error lower than 50 cm (Achilli et al. 1998).

The triangulation of the input points is based on a modified version (Favalli et al. 1999) of the Delaunay algorithm, which is able to reconstruct gullies and ridges (DEST algorithm, Favalli and Pareschi 2004). Starting from a set of input points, the Delaunay approach provides triangles (with vertexes on the input points) approximating the

topographical surface as a network of planar triangular facets. The triangles satisfy the maximum minimum angle criterion (the minimum angle of each triangle is the maximum over all the possible triangulations; Macedonio and Pareschi 1991). To avoid artificial features introduced by the Delaunay algorithm when input points are not random (in our case aligned along contour lines), the DEST algorithm reconstructs ridges and gullies along the skeletal axes of the contour lines.

The bathymetric grid

The newly combined bathymetric data came from various sources:

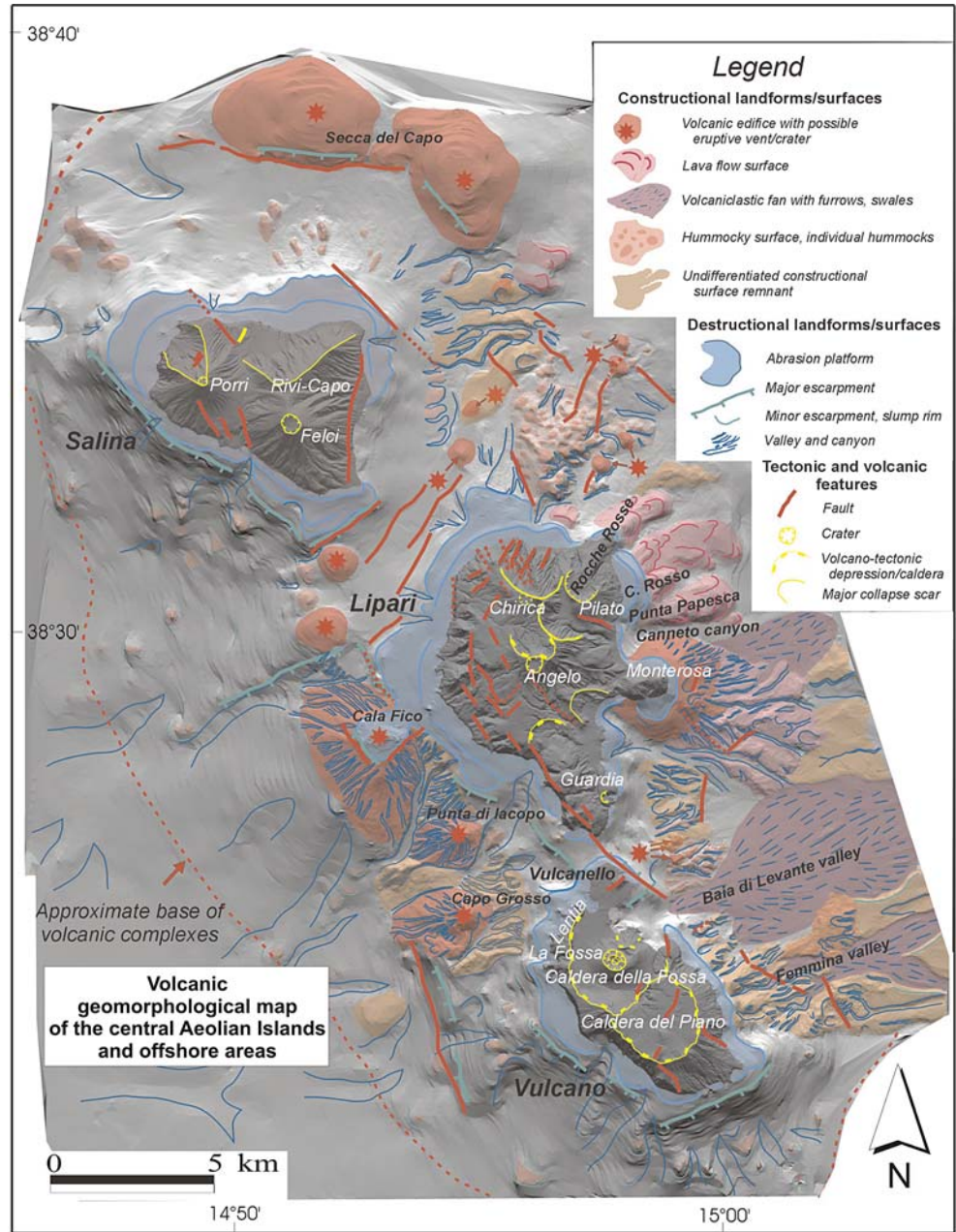
1. Between the coastline and the 500 m bathymetric line, from the 1996–1997 hydrographic survey of IIM (Istituto Idrografico della Marina, Genova, Italy). During this campaign, detailed data were also collected close to the berths and small harbours of the islands. A higher density of sounding was used where the sea bottom showed irregular features (see grey area around Salina, Lipari and Vulcano in Fig. 1);
2. Far from the coasts, in some areas northeast and southwest of Vulcano-Lipari-Salina, by the Italian Navy Survey ship ‘*Amm. Magnaghi*’ in 1994–1995;
3. Near the Vulcano-Lipari-Salina coasts, from a survey by the Italian National Council of Research ship ‘*Urania*’ (Gabbianelli et al. 1993; Gamberi et al. 1998, and references therein), along parallel routes as perpendicular as possible to the coastline;
4. Northwest of Stromboli, from a detailed bathymetric survey by Romagnoli et al. (1993).

Data of campaigns i) and ii) were collected by the echosounders single beam (ATLAS KRUPP DESO 20 and DESO 25 and ELAC LAZ47100), with an accuracy of 10 cm to the depth of 100 m and 0.1% of sea depth for increasing depths. Data of campaigns iii) and iv) were collected by multibeam echosounders with the same accuracy of single beam. The surveys cover the sea-floor around all the islands up to a distance of 12–15 km offshore, with a total area of 2,700 km².

Landforms and geomorphological maps

The geomorphological maps (Figs. 2–4) of the submarine portions of the Aeolian Islands have been produced on the basis of (a) interpretation of the new DEM images; (b) the already recognised subaerial structures (craters and volcano-tectonic collapses, depression rims, landslide scarps and fault scarps; Keller 1980; Crisci et al. 1991; Mazzuoli et al. 1995; Ventura et al. 1999) and reconstructed offshore geomorphic features of the archipelago (in general: Gamberi et al. 1997a; Vulcano: Gabbianelli et al. 1991; Lipari: Gamberi and Marani 1997; Vulcano, Lipari: Gamberi 2001; Panarea: Gabbianelli et al. 1990;

Fig. 2 Geomorphological and structural map of the central sector of the Aeolians (Vulcano, Lipari, Salina) displayed on a shaded relief image. Here, Vulcano is the only active volcano



Marani et al. 1997; Panarea, Salina: Savelli et al. 1999; Panarea, Stromboli: Gabbianelli et al. 1993; Stromboli: Romagnoli et al. 1993); (c) worldwide analogies of submarine landforms with special reference to the landforms related to landslides and volcano-tectonic collapses (Moore et al. 1989; Masson and Watts 1995; Marti et al. 1997; Urgeles et al. 1999; Hürlimann and Marti 2000; Gee et al. 2001). Due to the higher resolution of the new images in some sectors of the archipelago, a number of previous interpretations of submarine geomorphic features have been modified. In these cases, the new interpretation is discussed. In the following, we describe the categories of the recognised geomorphic features displayed in the maps.

Constructional landforms

These are positive geomorphic features that have been built by constructive, accumulative volcanic and/or sedimentary processes such as lava or pyroclastic flows and debris flows/avalanches. In the case of individual eruptive vents, the origin of these landforms is subaqueous, whereas other accumulation features may typically result from subaerial volcanic flows entering the sea.

Volcanic edifice with possible eruptive vent/crater

Circular, relatively large (1–5 km in diameter), positive geomorphic features, the size of which is comparable to

individual edifices on land. An example of analogies to define such landforms is Monterosa in Lipari, the basal flanks of which are under water (e.g. Gamberi 2001) and show a well-developed submarine, quasi-radial canyon system originating probably from high-energy volcanoclastic flows. The same morphology characterises the seamount of Cala Fico bay (about 4 km westward of Lipari), which is connected to the island by a flat surface and bordered by similarly dissected flanks. Several of the possible subaqueous edifices are of this size, but some are of smaller order in volume, similar to the largest individual hummocks (see below; examples are found northward offshore from Lipari). Uncertain features have been indicated in the geomorphological maps.

Lava flow surface

Subaerial, historical lava flows (i.e. Rocche Rosse, Lipari Island) can easily be followed under water. These surfaces are relatively smooth, extended downward, lobed, and have a steep front. In addition to previous delimitation of lava flow boundaries (e.g. Gamberi and Marani 1997), we detail lava flow morphology, for instance northward and eastward offshore from Lipari.

Volcanoclastic fan with furrows and swales

Detailed submarine bathymetry (e.g. Gabbianelli et al. 1991; Gamberi et al. 1997a) have revealed extended, large fans showing densely dissected topography. These fans consist of fine-grained furrows and coarser-grained swales (Gamberi 2001), the most typical example being the Baia di Levante fan, eastward offshore from Vulcano. Persistent, small- to moderate-scale volcanoclastic mass-flow activity originating from recent eruptions may have partly built these landforms.

Hummocky surface, individual hummocks

Similarly to the Canary Islands (e.g. Masson and Watts 1995; Urgeles et al. 1999; Paris and Carracedo 2001), the present-day erosional scarps of some ridges can be connected to huge landslides entering the sea (Keller 1982; Ventura et al. 1999). Eastward offshore from Salina, northward from Lipari and northeastward from Vulcano, there are hummocky areas comprising small (up to 100–150 m-high), positive, circular landforms, most of which were previously interpreted as pillow lava cones (“seamounts”: e.g. Gamberi et al. 1997a, b). In some larger cases these features indeed exhibit a crater-like hollow on top; however, in most cases their topography is irregular, of variable size and are found downslope of the scarps. Therefore, we postulate most of these surfaces to be related to landslides. Conversely, the area northward of Lipari is characterised by hummocky landforms associated with small volcanic cones aligned along scarps probably of tectonic origin.

Undifferentiated constructional surface remnant

Due to low resolution, the character of some surfaces (i.e. lava flow, volcanoclastic fan, hummocky terrain) cannot be unequivocally defined. For example, northeast of Salina, there are large areas of unambiguous volcanic flow morphology (with lobes and fronts). However, in the resolution available, the bathymetry does not reveal sufficient detail to differentiate lava flow or hummocky surface. There is also some uncertainty west of Lipari and Vulcano possibly related to older volcanic edifices covered by younger products.

Destructional landforms/surfaces

These are formed by destructive, erosional processes, abrasion and mass movements. As a result, various types of submarine surfaces have been produced.

Abrasion platform

Most Aeolian Islands are surrounded by a more or less extended, relatively flat surface at shallow depth (<150 m b.s.l.). These erosive shelf plateaus have been interpreted as Late Pleistocene abrasion platforms by Gabbianelli et al. (1990). This platform is missing on areas of more recent activity: e.g. northeastward offshore from Vulcano (last eruption 1888–1890) and westward offshore from Sciara del Fuoco in Stromboli (active). Around most islands, these platforms are divided into two levels by a steep escarpment, reflecting at least two cycles of Pleistocene glacio-eustatic changes. The age of the deeper platform may correspond to the cold period at about 200/180 ka (6th isotopic stage); the shallower platform could be formed at around 20 ka (2nd isotopic stage; Shackleton 1987).

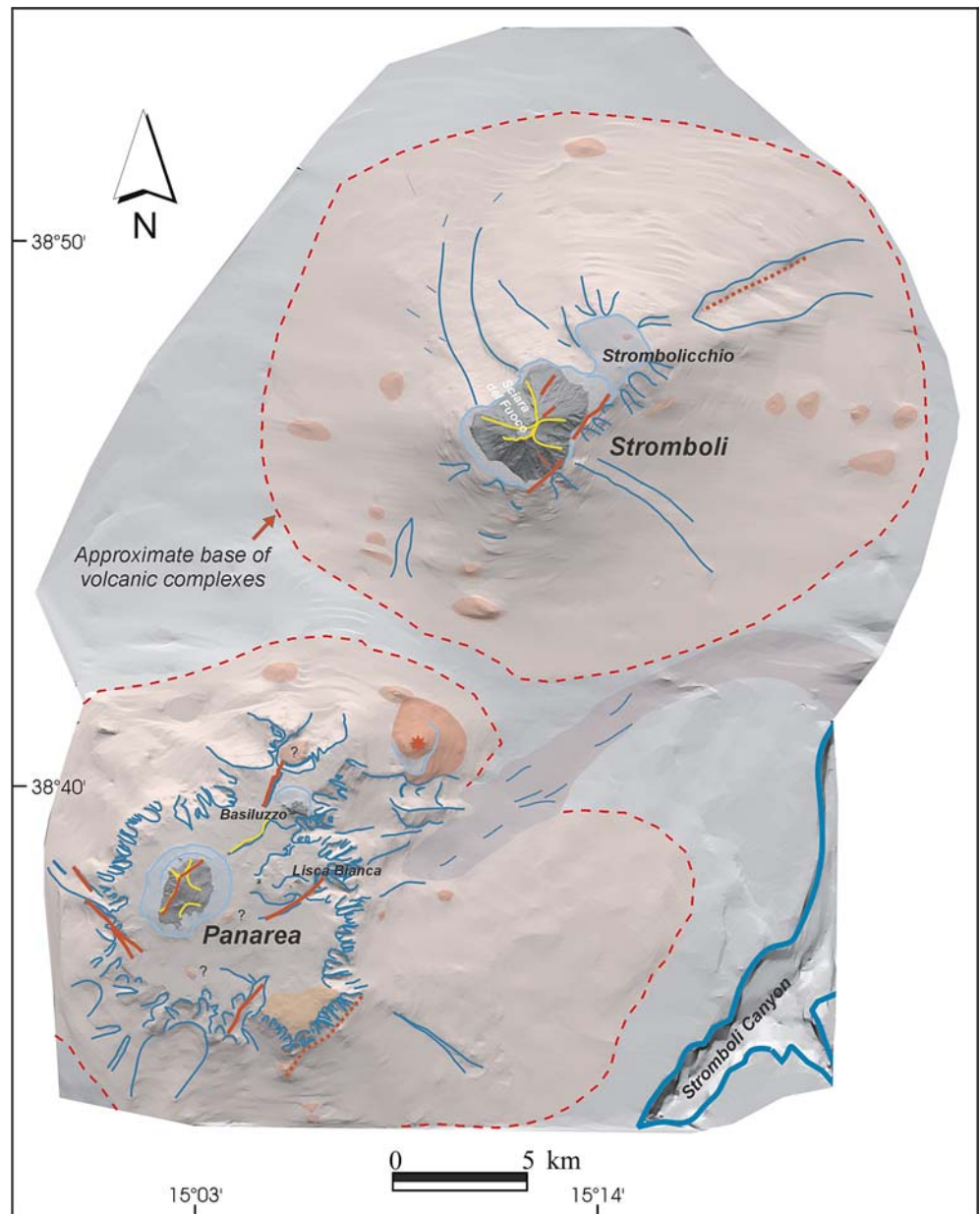
Major escarpment

The flat abrasion platforms are typically cut at their outer edge by almost rectilinear scarps from which the flank is continuing downward with a steep (20–30°) slope. In addition to these landforms, major slope breaks and steep morphology also occur at deeper sections, e.g. westward of Lipari and Vulcano. The rectilinear scarps follow the strike of the main fault segments on land.

Minor escarpment, slump rim

Rugged topography characterises the steep lower portion of the western slopes of Lipari and Vulcano, where the surface is broken by minor escarpments, possible slump rims. However, a higher-resolution bathymetry is needed to verify this interpretation.

Fig. 3 Geomorphological and structural map of the eastern sector of the Aeolians (Panarea, Stromboli) displayed on a shaded relief image. The legend is the same as in Fig. 2. The pink coloured area corresponds to the extension of the volcanic edifices. Recent activity occurs on Stromboli and east of Panarea



Valley and canyon

These were the first recognised submarine landforms (e.g. Gabbianelli et al. 1991), ranging from narrow incisions (e.g. on the submarine flanks of Monterosa in Lipari, or on the southern and eastern submarine flanks of Panarea) to larger, up to 200–400 m wide valleys (e.g. the submarine extension of Sciara del Fuoco in Stromboli, or the Canneto canyon eastward offshore from Lipari). The largest canyon system, not dealt with in this paper because of the lack of DEM cover, is the northern continuation of the Stromboli Canyon (Volpi et al. 1997), ca. 1 km wide, eastward offshore from Panarea (see Fig. 3). Given their various sizes, the submarine valleys canalise transport processes from small-scale gravity flows to larger-scale debris

flows/avalanches. Slope gradient may vary from a few to 15–20°, the higher values being more frequent.

Geomorphological maps: interpretation and discussion

In the following, we describe the main on land and offshore geomorphic features of each Aeolian island. In the interpretation, we also used representative morphometric parameters of the main edifices determined on the basis of DEM data (see Table 1). In Figs. 2–4 and Table 1, the submarine extension of the edifices as well as their abrasion platforms have been defined using previous data (e.g. for Stromboli and Panarea: Gabbianelli et al. 1993;

Table 1 Main morphometric parameters of the Aeolian Islands. For Panarea, second values in the last four rows refer to the large plateaus. “H min” and “H max” are the lower and upper elevations

	Stromboli	Alicudi	Filicudi	Fil. SM	Panarea	Vulcano	Lipari	Salina
H min (m)	-2,085	-1,365	-1,487	-1,487	-1,176	-1,240	-1,240	-1,240
H max (m)	924	683	773	-45	421	481	602	962
H total height (m)	3,009	2,048	2,476	1,442	1,597	1,739	1,841	2,204
A total area (km ²)	385	104	166	52	240	188	270	239
D average diam. (km)	22.1	11.5	14.5	8.2	17.5	15.5	18.5	17.4
V total volume (km ³)	198.1	45.6	91.8	19.8	114.6	119.8	196.7	179.6
V _i island vol. (km ³)	3.78	1.41	2.41		0.48	4.08	8.34	8.30
A _i island area (km ²)	12.6	5.2	9.3		3.8	21.0	37.4	26.1
V _i /V	0.019	0.031	0.026		0.004	0.034	0.042	0.046
H/D	0.14	0.18	0.17	0.18	0.09	0.11	0.10	0.13
A _p platform area (km ²)	19.6	8.8	18.7	2.0	9.4/56.0	29.7	59.3	43.8
D _p platform diam. (km)	5.0	3.3	4.9	1.6	3.5/8.4	6.2	8.7	7.4
D _p /D	0.23	0.29	0.34	0.20	0.20/0.48	0.40	0.47	0.43
A _p /A _i	1.56	1.70	2.02		2.50/14.83	1.42	1.59	1.68

of the volcanic edifices with respect to the sea level. “Fil. SM” refers to the Seamount NW of Filicudi (see Fig. 4)

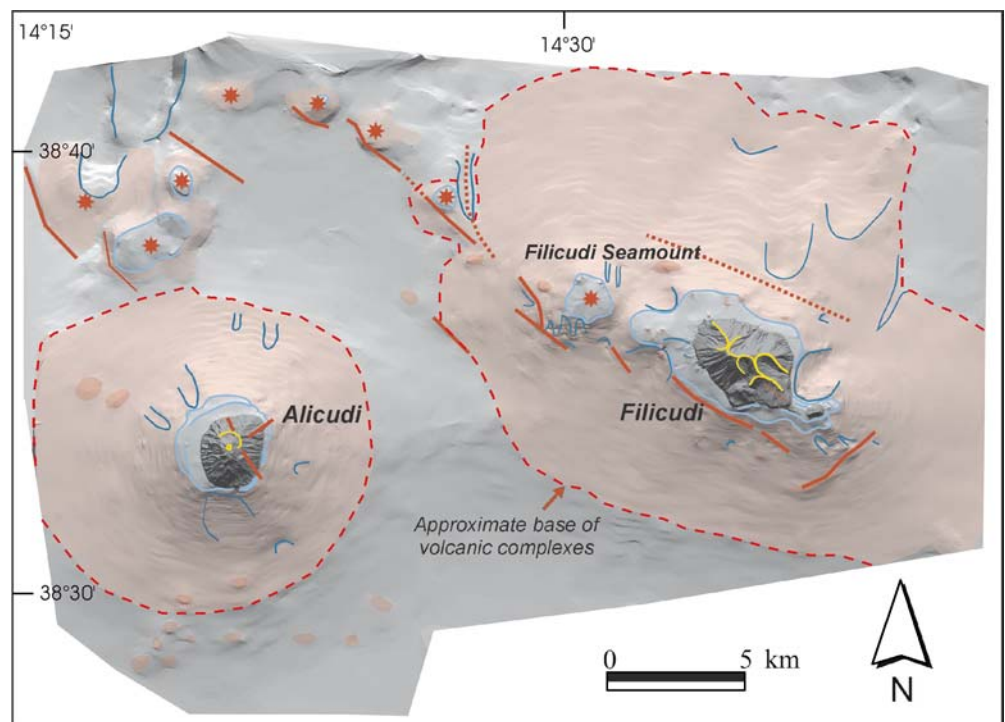
for Vulcano: Gabbianelli et al. 1991), and on the basis of significant breaks in slope.

Central Aeolian Islands (Salina, Lipari, Vulcano)

In these islands (Fig. 2), previous studies have described a number of volcano-tectonic and geomorphic features (Gabbianelli et al. 1991; Gamberi and Marani 1997; Gamberi 2001). These works show that westward offshore from these islands and their well-developed abrasion platforms, a coalesced, uniformly-dipping slope can be found,

reaching the sea bottom (i.e. the Cefalú basin: Gabbianelli et al. 1991) at about 1,000–1,200 m b.s.l. Eastward offshore the islands, the abrasion platforms are less developed and, below a steep slope section, the basal flanks are more gentle and affected by accumulation processes. This latter feature may be due to the fact that the more recent volcanism (about <100 ka) concentrated in the eastern sectors of the islands, whereas the older volcanism (>100 ka) mainly developed in the western parts. Eastward offshore, along with the giant Panarea submarine edifice, the base of Vulcano merges with the Gioia basin (e.g. Gabbianelli et al. 1993).

Fig. 4 Geomorphological and structural map on of the western sector of the Aeolians (Alicudi, Filicudi) displayed on a shaded relief image. The legend is the same as in Fig. 2. The pink coloured area corresponds to the extension of the volcanic edifice



Salina

Three composite central volcanoes dominate the morphological setting of Salina: Rivi-Capo, Felci and Porri cone (Fig. 2). Geological data (Keller 1980, 1982; Ventura 1994) and the shaded relief DEM image indicate that Rivi-Capo and Porri volcanoes were affected by landsliding. Rivi-Capo volcano, dated to 430–127 ka (Gillot 1987; Ventura 1994), has an apparent amphitheatre depression open to the north and formed as a consequence of a large landslide. Vent structures and feeding dykes cut and destroyed by the landslide (Keller 1982) are field evidence that a large part of the cone collapsed northwards. Offshore, in front of the scarp on Rivi-Capo flank, a gently sloping abrasion platform (locally 1.5 km wide, with almost constant 3.5° slope, 100–110 m maximum depth) could cover any trace of the debris avalanche deposits. However, to the north of the terrace, at about 6 km from the coast, a hummock-like morphology could represent part of the Rivi-Capo debris avalanche deposits. Other landslides recognised on Salina (Calanchi et al. 1993; Ventura et al. 1999) occur on the northwestern side of the 100–66 ka old Porri volcano, where the vent of the last volcanic activity, which occurred between 24 and 13 ka, is located (Calanchi et al. 1993). Offshore, the sea bottom shows traces of hummocky deposits, again at a distance of about 5–6 km. Near the coast, the platform has smoothed the sea bottom and no deposits can be detected. To the east of Felci volcano, the platform is missing and the shaded relief DEM image reveals undifferentiated constructional surfaces (including lava flows) that apparently come from Salina. This may imply tectonic activity or erosional processes on the Felci eastern flanks, as also shown by Critelli et al. (1993). In the same sector, two small highs on the offshore constructional surfaces are interpreted as individual volcanic cones on the basis of small crater-like summit depressions.

Lipari

The largest of the central Aeolian volcanic complexes, Lipari, has one of the highest-resolution bathymetries revealing spectacular submarine features. The subaerial volcanic activity started at 223 ka; the last eruption (Pilato) occurred in 580 AD in the northeastern corner of the island (Cortese et al. 1986; Crisci et al. 1991; Esperança et al. 1992). The field data (Crisci et al. 1991) and DEM image (Fig. 2) indicate that the most ancient volcanic structure (Chirica), which is located in the northern part of the island, is affected by a large amphitheatre-like scar. About 7 km northward offshore from Chirica, at 800 m b.s.l., some hundred-metres scale topographic highs can be interpreted as deposits from the Chirica collapse, even if some of these have the morphology of volcanic cones (with crater-shaped hollows on top). Just offshore to the north, the hummocky morphology is masked by abrasion platform levels at about 100 m b.s.l.

The northeastern offshore of Lipari has been carefully investigated and described by Gamberi and Marani (1997), but correlations with the on-land deposits have only been

rarely presented. On the basis of the surface volcanological units, a correlation between subaerial and submarine lava flows has been made (e.g. Rocche Rosse), and a number of exclusively submarine lava flow units have been recorded in the northern, northeastern and eastern offshore sectors of Lipari (Gamberi and Marani 1997). Lava flow lobes are depicted in the geomorphological map (Fig. 2), and the volume of the submarine lava flow units is at least five times larger than that of the subaerial flows.

The eastern submarine portion of Lipari is dominated by the Monterosa cone, the base of which shows a less developed lava flow morphology and heavily dissected upper flanks. A deep and wide canyon (the Canneto canyon) can be found north of Monterosa. On land, the apex of this canyon departs from a 1 km wide land slide scar. At the base of the canyon, the morphology widens and flattens, and an accumulation area of a volcanoclastic fan can be inferred.

Westward offshore from Lipari, the morphology is dominated by a steep escarpment that bounds the southern edge of the archipelago. The escarpment follows a NW-SE strike, the main trend of the Tindari-Letojanni faults, and is interrupted by valleys with a NE-SW main direction. At least five small- to moderate-scale submarine volcanic edifices are found along the escarpment. Only the southernmost of these edifices, which is located 4 km southwest from Lipari, has been described (Gabbianelli et al. 1991). After shoreline names, the largest three (including the latter) can be named as Cala Fico, Punta di Iacopo, and Capo Grosso seamounts. All these edifices are separated from the island by a well-developed, extended abrasion platform, suggesting a relatively old age of their volcanic activity. In their surroundings, slope morphology displays volcanic flow patterns, but individual lava flows cannot be distinguished.

Vulcano

This island is the southernmost Aeolian volcanic complex located on the Tindari-Letojanni fault. This structure cuts the northeastern sector of Vulcanello and the southwestern lava domes of Lipari (Ventura 1994). The island is characterised by the still active La Fossa cone, developed during the last 6 ka inside the Caldera della Fossa (Gioncada et al. 2003). The last eruptions occurred in 1739 and 1888–1890. At present, the Fossa crater and the northern sea sector of the island are affected by fumarolic activity (Pareschi et al. 1999). The northeastern sector of the Vulcanello platform is sharply cut in NW-SE direction. NW-SE trending escarpments influenced by the Tindari-Letojanni fault system also affect the western side of the Vulcano.

Along with Lipari, the offshore features of Vulcano have been described by Gamberi (2001). Our high-resolution DEM revealing fine details of landforms is available only on the eastern sector of the submarine edifice. Major offshore features east of Vulcano are constructive surfaces, probably old lava flows, and large volcanoclastic fans in between. To the northeast, hummocky surfaces and some scattered cones can be recognised. The occurrence of

hummocky surfaces and the lack of an abrasion platform in the sea sector of the Caldera della Fossa suggest that these deposits may represent remnants of the collapsed portion of the Lentia complex. This collapse may have occurred during the later phases of caldera formation dated between 6 and 15 ka (Ventura 1994). The extended fan originating from the sea sector of the La Fossa Cone and a similar fan southward (named Femmina valley) may have formed by high-energy mass movements related to small-scale slides and persistent sediment transport from the La Fossa cone and caldera. These mass movements seem to cut into older, constructional surfaces, possibly lava flows, of the Vulcano submarine edifice. In accordance with Volpi et al. (1997), these fan areas could feed the southernmost tip of the N-oriented large Stromboli Canyon (see Fig. 3). Gamberi (2001) described an “eccentric” volcanic construct between the two fans, but the morphology instead suggests a possible lava flow surface. Further southward, Vulcano Island is bordered by a steep ENE-WSW striking escarpment, and its submarine slopes to the W are also affected by NW-SE striking escarpments. These scarps may represent the submarine morphological expression of the NW-SE and NE-SW to ENE-WSW fault systems affecting Vulcano on land.

Eastern Aeolian Islands (Panarea, Stromboli)

The two large submarine edifices of Panarea and Stromboli (Fig. 3), following a ENE-SSW direction, are separated by a 1,200 m deep saddle.

Panarea

This island represents a small emerged volcanic complex set on a large platform at a depth of about 100 m (Fig. 3). This abrasion surface may have formed, as for the other islands, about 180–200 ka ago. The subaerial volcanism on the island developed in four main cycles between 149 and <13 ka (Calanchi et al. 2002). The island is characterised by a collapsed area open towards the sea. Gabbianelli et al. (1993) linked this structure to an elliptical caldera collapse bordered by the northeastern part of the island and, eastward, by a submarine structure forming the Lisca Bianca islet. The submarine image, however, does not show a caldera-like structure. Instead, the on land rims could represent lateral collapses. The western segment of the island, probably also of collapse in origin, is affected by a NNE-SSW fault system. Faults belonging to this system are clearly detectable on the shaded relief DEM image of the submarine platform (Fig. 3).

A striking feature of the Panarea area is the relatively large plateau, well exceeding the island size, which has been mentioned (Gabbianelli et al. 1993) but not explained so far. Because Panarea, and Basiluzzo islet too, are also surrounded by an abrasion platform, similar in size to that of other islands, the submarine plateau seems to be not

only due to erosion (abrasion) processes. We propose that it should have existed as a flat top of a seamount. Subsequently, late-stage volcanic activity produced rhyolitic lava domes and flows (Gabbianelli et al. 1990, 1993). The large plateau is flanked by heavily dissected, steep slopes that cannot be followed in detail downslope due to poorer resolution. In the northeastward base of the submarine edifice, a volcanoclastic fan filling a NE-SW striking valley is inferred. It may be fed by gravity mass flows from the valley system of northeast Panarea and is likely connected to the large Stromboli Canyon appearing in the east. On the plateau surface, northeastward of Panarea Island and across Basiluzzo, there is a shallow graben-like structure. Recent volcanic manifestations consist of an intense hydrothermal activity on the eastern plateau surfaces (<http://www.ingv.it/panarea/panarea.html>).

Stromboli

This is the northernmost island of the Aeolians (Fig. 3) and is currently active. It is the emerged part of a complex volcanic structure elongated, along with Strombolicchio, in a NE-SW direction. Many sector collapses affected the island from approximately 60 ka (Francalanci et al. 1989, 1993; Pasquaré et al. 1993). The more recent collapse, which resulted in the formation of the present-day Sciara del Fuoco depression, occurred in the last 13 ka. Minor collapses have affected both the submerged and subaerial part of Sciara del Fuoco up to now (Tibaldi 2001). The shaded relief image clearly shows these collapse structures (Fig. 3). The Stromboli edifice, considering also its submerged part, is one of the largest in volume of the Aeolian Islands (Table 1), but the subaerial portion, as well as the surrounding abrasion platform, is not so much extended. The platform including the old (ca. 200 ka) Strombolicchio construct is almost rectilinear at its northeastern edge and follows a NE-SW strike. The most impressive feature of the submerged part of Stromboli is the graben-like, relatively flat western extension of Sciara del Fuoco (Romagnoli et al. 1993), formed by complex sector collapses induced by magma intrusions along a NE-SW structural discontinuity and by gravity sliding. A NE-SW elongated chute appears on the submerged flank of the volcanic complex. This chute is comparable in size to the continuation to Sciara del Fuoco. Towards the base of the submarine edifice, small positive forms could be hummocks or slid masses. According to the available geochronological data (Francalanci et al. 1989), the poorly preserved scars affecting the eastern sector of Stromboli indicate that the landslides originating from this flank are older than those on the northwestern part.

Western Aeolian Islands (Alicudi, Filicudi)

The smallest edifices of the Aeolians, the Alicudi and Filicudi submarine constructs (Fig. 4) are separated from each other by an extended, flat saddle.

Alicudi

It has the simplest, most regular cone shape of all edifices. A subcircular rim characterises the top of the cone. This rim, which is interrupted southward, may represent the morphological expression of a collapse structure. A small crater occurs within the collapse rim. The circular island is surrounded by a double-stepped abrasion platform, which, possibly due to tectonic activity, is missing to the east. The fault possibly responsible for this feature is that departing from the summit crater. The steep submarine flanks are relatively well preserved. At the base of the southern sector, however, small morphological highs can be interpreted as hummocks, originating from slope failures on the submerged flank of Alicudi. Possible contours of minor slide scars both on the island and on the upper flanks are faintly visible. A group of never described, small-scale seamounts can be recognised, to the north of the edifice. Due to the poor resolution, real extension and features of these centres can only be roughly marked. However, the top of at least two of these centres presents a flat morphology, possibly indicating the occurrence of an abrasion platform.

Filicudi

This island and its submerged portion form a WNW-ESE elongated volcanic complex with an elliptical shape. This feature can be due to the existence of at least three, or even four, volcanic centres located beside each other. The top of the southernmost centre forms a peninsula, whereas the centre located northwest of Filicudi is marked by emerged islets. The submarine centre Filicudi Seamount has a flat abrasion platform on top similar in size to the Cala Fico centre, which is located west of Lipari. As well as the elongated Filicudi itself, all these submarine edifices show regular flanks reflecting relatively simple growth history. The Filicudi complex, in the available resolution, is dissected by at least four major slide scars. Some small (<100 m) morphological highs recognised on the flanks could represent part of the deposits of the slides. In the submerged part of the island, amphitheatre-like ridges occur, mainly in the northern periphery. These ridges may represent submarine slide scars.

Morphometry: implications for the volcanic and tectonic activity

The main morphometric parameters of the Aeolian Islands calculated from the DEM presented here are summarised in Table 1 and Fig. 5. These data allow us to characterise the individual volcanic edifices of the Aeolian Islands and to obtain some indications on their evolution. In the morphometrical calculations, dimensional parameters such as area (A), average diameter (D), island height (H_i) total height (H), total and subaerial (i.e. island) volumes (V and V_i , respectively) as well as basal and abrasion platform average diameters (D and D_p , respectively), have been measured,

along with the adimensional parameters V_i/V , H/D and D_p/D .

In Fig. 5a, the island height (H_i) is plotted against the total height (H) of the edifices. The plot shows that there is a positive correlation between the two parameters. This figure and Table 1 demonstrate that the Stromboli edifice has a total height comparable with Etna volcano (3,300 m), and the small islands of Alicudi and Filicudi also have a total height between 2,000 and 2,500 m. On the other hand, Fig. 5b–d show that two groups of edifices can be identified: the first includes Alicudi, Filicudi, and Stromboli, the second includes the islands of the central sector (Vulcano, Lipari, Salina). At Panarea, the existence of the large flat plateau and the small abrasion platform poses some problems as discussed later. In the first group, a direct relationship between H and the V, A, H_i and D as well as the D_p is recognised. This relation does not hold for the second group (Vulcano, Lipari, Salina) probably due to the nature of their more complex submarine and subaerial (island) growth.

In order to characterise the different trends, it is useful to plot the D_p/D ratio against the H/D ratio (Fig. 6). In this plot, the two above-mentioned groups are also well-defined. The first group is characterised by higher H/D and lower D_p/D , and includes Alicudi, Filicudi, Stromboli. The second is characterised by lower H/D and higher D_p/D , and include Vulcano, Lipari, Salina (and Panarea with the associated larger scale plateau).

These two groups define volcanic complexes characterised by different morphologies. The more voluminous volcanoes of the central sector (Vulcano, Lipari, Salina) show a pancake-like morphology, whereas those of the eastern and western sectors have a more conical shape (Fig. 6). The contrasting morphology can be explained in the light of the available volcanological and structural data. These data indicate that the volcanoes of the central sector are characterised by significant volumes of <42 ka dacitic to rhyolitic and trachytic domes and pyroclastics related to explosive eruptions (e.g. in the southern sector of Lipari at 24 ka and in the northwestern corner of Salina at 24 and 13 ka). The entire northern sector of Vulcano and the southern and southeastern parts of Lipari consist of rhyolitic/trachitic viscous lava domes and lobe-like rhyolitic lava flows. These extrusive and effusive products are responsible for the pancake-like morphology. On the contrary, the volcanic complexes of the W and E sectors mainly consist of less evolved, thin lava flows and products of strombolian/lava fountain activity. Both effusive and strombolian activity produce cone-shaped morphologies.

In addition, the volcanoes of the central sector were emplaced on the major discontinuity crossing the Aeolian Islands (the strike-slip Tindari-Letojanni fault system), whereas the volcanic complexes of the W and E sectors were emplaced on WNW-ESE and NE-SW normal faults, respectively. In fact, the morphological features of the two groups evidenced on the basis of morphometric parameters reflect a different structural and volcanological evolution of the volcanic complexes. As proposed by some

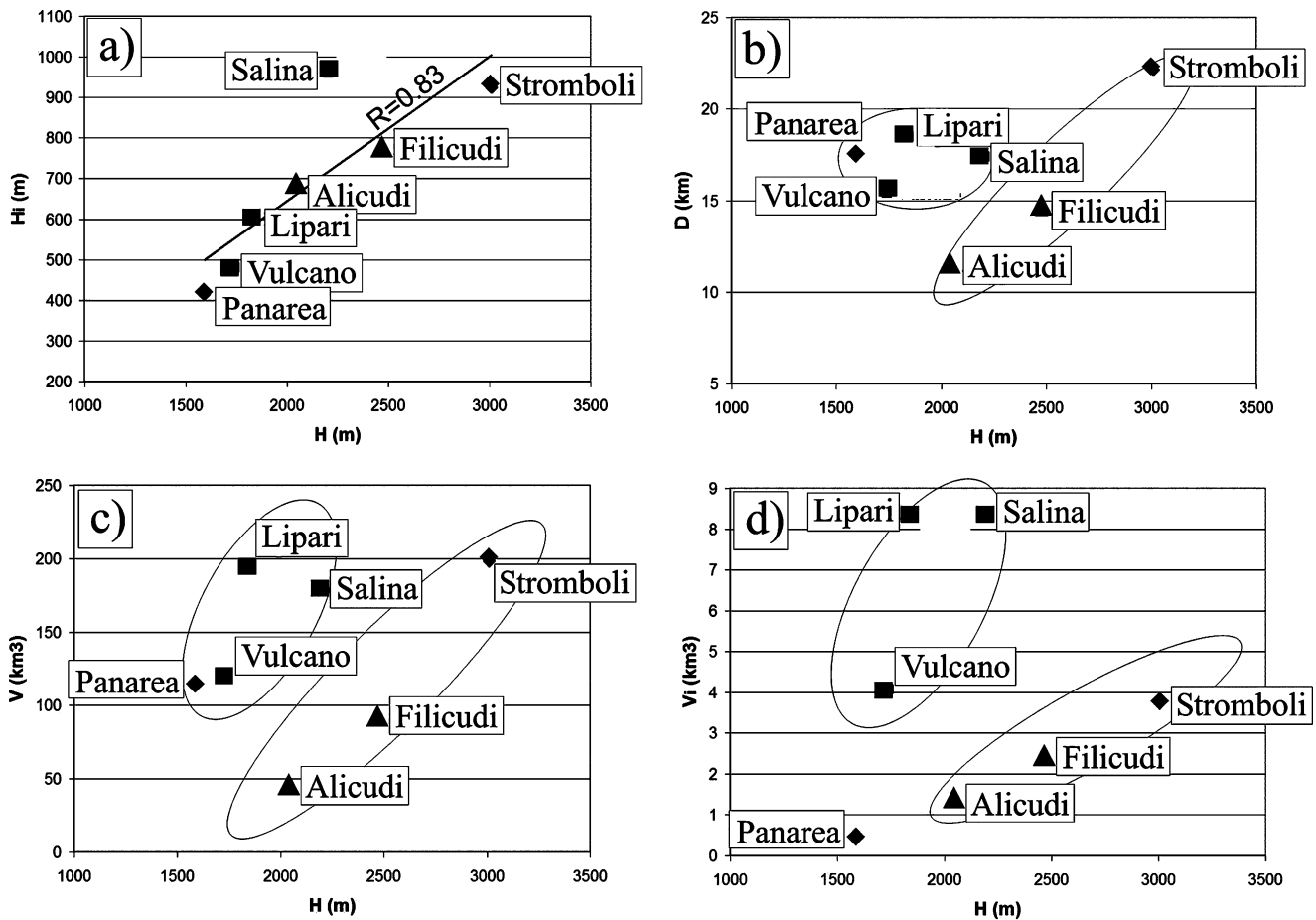


Fig. 5 Morphometric plots of **a** island height (H_i) vs. total height (H); **b** total diameter (D) vs. total height (H); **c** total volume (V) vs. total height (H) and **d** island volume (V_i) vs. total height (H)

authors (De Rosa et al. 2003; De Astis et al. 2003; Zanon et al. 2003; Gioncada et al. 2003), the volcanic complexes of the central sector erupted products that evolved in shallow magma chambers within the continental crust. These reservoirs are aligned along the strike-slip fault system that affects this sector of the Aeolian Islands (Fig. 1). On the contrary, the volcanoes of the W and E sectors erupted from WNW-ESE and NE-SW faults and deeper reservoirs, possibly located at the mantle/crust interface (De Astis et al. 2003).

At the same time, in the frame of the above considerations, it is more difficult to find the position of Panarea. As previously described, the Panarea edifice has a very large plateau, on which an abrasion platform developed around the present-day island. According to the plot of Fig. 6, if D_p refers to the large plateau, Panarea shows the same morphometric characteristics of the central island group. The only difference is that the island itself is much smaller than Vulcano, Lipari or Salina. In fact, when considering its size, real abrasion platform and morphometric parameters of the island, Panarea resembles the Alicudi-Filicudi-Stromboli group. Therefore, we conclude that Panarea may have had a complex submarine stage, similar to the extended central Aeolian edifices. Indeed, its plateau diameter unambiguously fits with their large platform size (Table 1). The mor-

phological parameters of Panarea Island and the associated smaller platform are consistent with those of the E and W islands. Accordingly, as we mentioned, Panarea Island mainly consists of lava flows and minor domes of dacitic and rhyolitic composition.

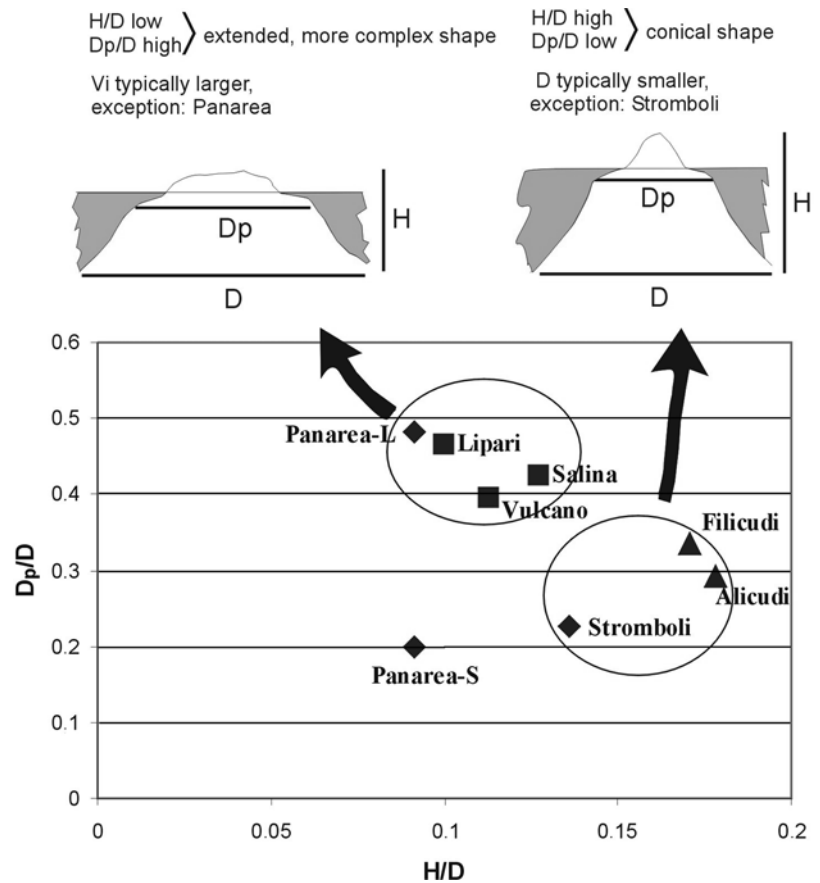
The morphometric trends of the two recognised groups of volcanic complexes also suggest that the edifices of the more conical group can evolve towards those of the other group if the emitted products increase their degree of evolution with decreasing time.

Conclusions

The presented data lead us to reach the following conclusions:

1. The geomorphic features of the Aeolian Islands, as well as the distribution of the volcanic vents, are strongly controlled by the local tectonic structures. WNW-ESE, NNW-SSE and NE-SW faults control the emplacement of the volcanoes in the western, central and eastern sectors, respectively. The main tectonic structure of the South Tyrrhenian Sea, the Tindari-Letojanni fault system, is clearly visible in the submarine portion of the central sector of the Aeolian archipelago. To the W of

Fig. 6 Morphometric plot of platform diameter/total diameter (D_p/D) vs. total height/total diameter (H/D). Panarea-S refers to the abrasion platform surrounding the island, Panarea-L corresponds to the large submarine plateau



- Lipari a series of submarine volcanic centres are aligned along the strike of this fault system.
2. Tectonics seems to control the degree of evolution of the erupted products as well as the eruptive style and, as a consequence, the large-scale morphology of the volcanic complexes (i.e. cone- or pancake-shaped edifices). The cone-shaped edifices (Alicudi, Filicudi and Stromboli) are characterised by poorly to medium evolved products related to effusive and moderate explosive activity. Pancake-shaped complexes (Vulcano, Lipari, Salina) are characterised, in addition to their submarine stage, by more evolved products related to extrusive activity and higher energy (up to subplinian) explosive eruptions. On the basis of the characteristics of the large plateau of Panarea, its submarine edifice belongs to the second group.
 3. The majority of the Aeolian Islands (Stromboli, Salina, Vulcano, Lipari, Alicudi, Filicudi) are affected by sector collapses whose products mainly produced hummock-like surfaces. This implies that sector collapses and the possible related tsunami events must be included in the evaluation of the volcanic hazard of both active and dormant Aeolian volcanoes.
 4. The abrasion platforms around all the islands suggests the occurrence of significant quiescence periods or periods with low activity in the Aeolian volcanism. These periods occurred around 200/180 ka (6th isotopic stage) and 20 ka (2nd isotopic stage).

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