Mem. Descr. Carta Geol. d'It.
XLIV (2004), pp.109-126
15 figg.

Distribution and nature of submarine volcanic landforms in the Tyrrhenian Sea: the arc vs the backarc

Distribuzione e natura della morfologia del vulcanismo sottomarino nel Mar Tirreno: l'arco e retro-arco

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ABSTRACT - Based on morphological characters, different varieties of submarine volcanic landforms typify the arc and back-arc portions of the Tyrrhenian Sea. The arc volcanoes. develop both to the northeast and west of the emergent Aeolian Islands are isolated, more or less longlived vent centres as shown by the geochemical variety of collected rock types. Primarily cone shaped, several of the volcanoes display morphologies related to incipient flank instability. Stronger, more developed instability is found in the easternmost volcano of the Palinuro volcanic complex.
In contrast, the back-arc basins of the Tyrrhenian are characterised by the development of large volcanic complexes that occupy their axial parts. The flanks of the volcanoes display a variety of volcanic constructs including flat topped and conical seamounts, volcanic terraces and, less commonly cratered edifices.
It is shown that the morphologies of the volcanoes can offer clues to their origin and subsequent development.

KEY WORDS: seafloor morphology, submarine volcanoes, arc and backarc edifices, Tyrrhenian Sea

RIASSUNTO - Dal punto di vista morfologico, esiste una netta diversità di forma fra i vulcani sottomarini di arco e quelli di retroarco nel Mar Tirreno. I vulcani sommersi che si sviluppano sia a nord-est sia ad ovest delle isole dell'arco Eoliano sono centri di alimentazione isolata, come evidenziato dalle differenze geochimiche delle rocce costituenti e hanno principalmente forma conica. Alcuni dei vulcani di arco mostrano morfologie riconducibili ad incipienti eventi di instabilità. Questi eventi sono invece in fase matura nell'edificio all'estremità orientale del complesso vulcanico di Palinuro.
I bacini di retroarco del Tirreno sono caratterizzati dallo sviluppo di grandi complessi vulcanici posizionati nelle loro porzioni assiali. I fianchi di questi vulcani presentano una varietà di morfologie vulcaniche, fra i quali edifici a sommità piatta, edifici conici, terrazzi di lava ed alcuni vulcani con crateri.
Sulle basi della sola morfologia, si dimostra comunque che possono essere avanzate alcune ipotesi circa l'origine dei vulcani sottomarini ed il loro successivo sviluppo.

PAROLE CHIAVE: morfologia dei fondali, edifici vulcanici sottomarini, arco e retro-arco, Mar Tirreno

1. - INTRODUCTION

Submarine volcanic landforms have been shown to result, in part, from processes similar to those commonly observed in terrestrial volcanic settings. All land-based lava flow morphologies have been recognized in the marine environment, while the products of the range of explosive eruption styles have been documented; even from the deep ocean at >3000 metres water depth (HEAD & WILSON, 2003).

However, submarine conditions dictate the development of unique lava flow morphologies and landforms that are absent from terrestrial counterparts. Higher lava viscosity or lower extrusion rates at the seafloor give rise to the ubiquitous pillow or tube lavas that form small edifices and ridges, observed in all submarine geological settings, and also in the fossil

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record (GREGG & FINK, 1995). Landforms typical only to the submarine environment are low aspect ratio flat top volcanic seamounts, the origin and modes of formation of which are much less understood. In part explained by the faster cooling rates, varying eruption styles and greater pressure ranges of the marine ambient (CLAGUE *et alii*, 2000; BRIDGES, 1997), much data is lacking in terms of the controlling parameters due to the impossibility of directly observing their formation.

Volcanism at subducting plate boundaries represents about 25% of the Earth's magma production (SIGURDSSON, 2000), mainly developed within the volcanic arc environment. Convergent settings characterised by the subduction of ancient, dense oceanic lithosphere result in an extensional volcanic island arc due to the rollback of the oceanic slab and, ultimately, to the generation of further magmatism and new lithosphere in back arc basin (BAB) spreading environments. Thus, subduction zones are characterised by the development of large volcanic edifices both in island arc and backarc basin environments hosting 80% of the currently active volcanoes of the planet (CHESTER, 1993). Much of the volcanism occurs in the submarine environment.

This has been shown to be true by the increasing coverage worldwide of high resolution swath bathymetry targeting the development of submarine volcanism and associated processes. Recent examples include innovative studies of the morphology of submerged volcanoes carried out in the Mariana arc (BLOOMER *et alii*, 1989) and in the submerged sectors of Hawaii (PARFITT *et alii*, 2002; GREGG & SMITH, 2003). The use of swath bathymetric mapping as a remote sensing tool, augmented by steadily increasing ground truthing by means of sampling and direct observations, has profoundly increased our knowledge about the unique characters of submarine volcanism, concerning both edifice morphology and the structural instability of volcanic constructs inherent to the underwater environment.

A similar mapping effort has been undertaken in the Tyrrhenian Sea, a young backarc basin characterised by active arc volcanoes, where the primary morphologies of submarine arc and backarc volcanoes are preserved, and can thus contribute to the understanding of submarine volcanic processes.

2. – SETTING

The Tyrrhenian Sea, bordered to the east and south by the Apenninic-Maghrebides mountain belt and to the west by the passive Sardinian margin, formed as a consequence of rifting and backarc extension of the Alpine/Apennine suture above the north-westerly-subducting Ionian oceanic slab, (KASTENS *et alii*, 1988; KASTENS *et alii*, 1990; SARTORI, 1990; JOLIVET, 1991). An eastwards migration of crustal thinning and oceanic accretion affected the Tyrrhenian area since lower-mid Miocene (~15 Myr). E-W directed rifting in the northern Tyrrhenian and along the western margin of Sardinia (ZITELLINI *et alii*, 1986; KASTENS *et alii*, 1990) marks the initial opening of the Tyrrhenian basin leading to the formation of oceanic domains and associated volcanism in the Southern Tyrrhenian. First, production of oceanic crust occurred westward, during the Pliocene spreading of the Vavilov basin (4.3-2.6 Myr), where the large centrally located Vavilov volcano developed (KASTENS *et alii*, 1990). A subsequent change to ESE-directed extensional stress in Late Pliocene-Quaternary resulted in the emplacement of basaltic crust southeastwards, generating the Marsili backarc basin (2 Myr) also containing a large axial volcano, Marsili seamount, (KASTENS *et alii*, 1990).

To account for the eastwards migration of backarc basin development and active volcanism is the passive rollback of the Ionian plate (MALINVERNO & RYAN, 1986; SAVELLI, 1988). In step with backarc basin development, the subduction-related island arc volcanism of the southern Tyrrhenian basin migrated from west to south-east, from Sardinia (32-13 Ma) to the currently active Aeolian island arc (SERRI 1997 and references therein), developing the present-day arc-backarc configuration of the southern Tyrrhenian region (fig. 1).

The Aeolian arc consists of seven islands and a number of submarine volcanoes west and northeast of the emerged arc. The Aeolian arc, together with the Agean arc, represent the only still active island arcs of the Mediterranean. Available chronological data (BECCALUVA *et alii*, 1985) show that the beginning of activity took place in the Quaternary (~1-1.3 Ma) at Sisifo seamount and Filicudi. From ~0.8 Ma to the Present, dominantly shoshonitic and calcalkaline lavas, mainly consisting of basalts and basaltic andesites to rhyolites, were erupted in the different submarine and emerged edifices.

The northeastern submerged portion of the arc, positioned on the Calabrian margin, consists of isolated cones and the large, Palinuro volcanic complex. To the west of the emergent islands a number of submerged arc volcanoes are located on the Sicilian margin. The following discussion will describe the morphology of the submarine arc volcanoes and provide a provisional analysis of their origin. Subsequently, the large, axially located backarc volcanoes, Marsili and Vavilov, will be illustrated in the same manner.

3. - THE SUBMERGED AEOLIAN ARC

3.1. - NORTHEASTERN ARC VOLCANOES

Three volcanoes, Alcione and the twin cones of the Lametini seamounts (fig. 2), lie in the Calabrian slope delimited by the Palinuro volcanic complex to the north and Stromboli Island to the south. The volcanoes develop in the westerly deepening lower slope at a depth in the order of 2000 m. At this depth, the slope gradient decreases to form a relatively lower

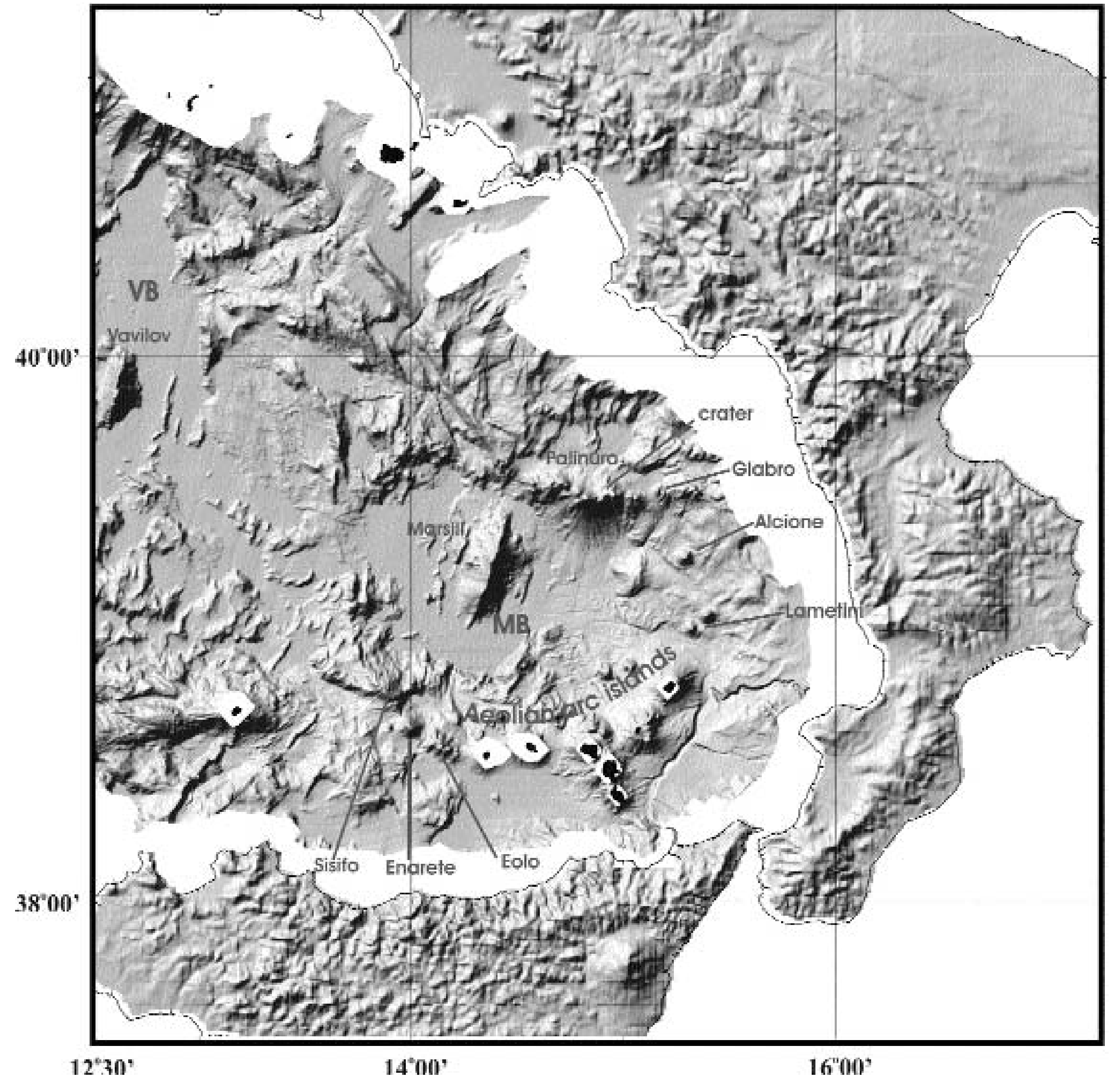

Fig. 1. - *Shaded relief bathymetry (illum. from NW) of the central-southern Tyrrhenian Sea with features discussed in the text. MB and VB, Marsili Basin and Vavilov Basin respectively.*

gradient bench (LAMETINI-ALCIONE flat, GAMBERI & MARANI, this volume) on which the volcanoes arise.

3.1.1 - *Alcione.*

Dredge hauls indicate a calc-alkaline basaltic composition for the seamount (BECCALUVA *et alii*, 1985). Measurement of the height of the volcano is dependant on the sloping bench on which it is situated. Summit heights vary from 900 m to 1200 m for the eastern summit and from 825 m to 1125 m for the western one determined on whether the heights are taken from the eastern base of the volcano or from the deeper western base of the volcano respectively (tab. 1). This ~1000 m high volcano is a textbook example of primary edifice gravitational instability. It's general conical shape is dissected by NNW-SSE trending, 100 m relief arcuate scarp (fig.3) that displaces downwards the western (seaward) half of the edifice. The top of the volcano is characterised by two summit areas, separated by the scarp: an eastern one, directly flanked by the scarp, elongated along the scarp trend and a western conical summit,

Tab. 1 - *Summary table of the dimensions of the submarine Aeolian arc volcanoes. h1 and h2 refer to volcano heights taken respectively from the upper slope and lower slope directions when the edifices bases are located on sloping seafloor; for the Palinuro crater these refer to maximum and minimum crater wall heights. d1 refers to water depths of volcano summits (in the case of Alcione, d2 refers to the water depth of the second summit). Volumes have been estimated by averaging summit heights when two summits are present. Note the comparatively large volumes of Eolo and Enarete.*

	Morphology	h_1 m.	h_2 m.	d_1 m.	d_2 m.	D_{iam} km.	A_{base} km^2	V km^3
Alcione	conical	1125/1200	825/900	850	925	6.3	33	11
Lametini N	conical	1300	900	900		6.0	24.5	10
Lametini S	conical	850	650	1450		4.2	14	3.5
PVC Hshoe	cratered	290	180	500		2.7		~0.58
Glabro W	split cone	670		830		4		2.85
Glabro E	irregular	450		870				~1.2
Eolo	flat summit	900		775		8 x 10	80	~40
Enarete	conical	1700		300		9.8	75	42

located 500 m from the scarp and 75 m deeper than the former.

The distinguishing morphological features of Alcione are to some extent similar to analogue models involving basement fault activation beneath a volcanic edifice (VIDAL & MERLE, 2000) or differential flank creep and spreading (WALTER & TROLL, 2003) although not all the morphological elements seen in the model runs are present on the volcano.

3.1.2 - *Local structure of Alcione region.*

A summary analysis of the basement structure around the volcano furnishes an indication to verify which, if any, of the above-mentioned modelled processes are active on Alcione. Surrounding seafloor morphology shows two steep, N-S trending, 400m high fault scarps located north and east of Alcione and a NW-SE scarp west of its base. The northern scarp intersects the northern flank of the volcano, the eastern one makes up the slope buttress to the eastern flank of the edifice and is sidestepped to the right by ~4 km. The scarp to the west delimits the flat area on which the volcano develops. If the scarps are the surface expression of a fault system, the volcano could be located in the relay ramp area linking the two N-S faults. E-W seismic profiles crossing the edifice show seismic basement dropping ~600 m, from 2400 m depth East of the volcano to 3000 m depth west of it and sediment fill increasing from ~400 m to ~700 m across the drop. The seismic signal beneath the volcano is obscured but it is reasonable to assume the existence of a fault system in this position. It is however significant to note that the analysis of seismic profiles in the Alcione region illustrate that faults do not affect the sedimentary cover, indicating that tectonic activity probably ceased in the past. Thus, the direct influence of an active fault on the volcano structure can be realistically ruled out. Moreover, analogue modelling results demonstrate that volcano deformation due to basement fault activation provides an accurate estimate of fault trend, in the case of Alcione this should be NNE-SSW and no structures with this trend are observed to directly affect the volcano. Flank creep due to differential spreading of the western portion of Alcione is, on the other hand a possible mechanism considering the E-W asymmetry of the volcano base, the basement drop beneath it and the thicker sediment pile to its west. Spreading or creep should be towards WSW, perpendicular to the edifice-cutting scarp with a deep-seated decollement plane probably located within the weaker sedimentary material.

3.1.3 - *Lametini seamounts*

The two conical edifices of the Lametini seamounts are located 20 km due south of Alcione on the same gently sloping bench area (fig. 4). They are aligned in a NE-SW direction 3 km apart. The NE volcano (LamN) is larger than the SW one (LamS). Dredge samples from LamN (BECCALUVA *et alii*, 1985) recovered basalts. Both volcanoes display E-W asymmetry due to the sloping bench, LamN having heights between 1300 m and 900 m and LamS between 850 m and 650 m measured along the western and eastern flanks respectively (tab. 1). Apart from its size, a distinctive characteristic of LamN, is a prominent slide scar on its western flank (fig. 5). It initiates as a 600 wide scar at the summit and broadens to 1500 m at the base of the edifice. Scarp walls are in the order of 100/150 metres high at the top, diminishing downwards. Interestingly, a feature with positive relief, within the lower part of the scar, from 1600 m depth to the base of the cone at 2100 m, possibly represents the proximal portion of the slide material still lying on the volcano flanks. There is no indication, however, of slide deposits on the adjacent seafloor, at the base of the volcano.

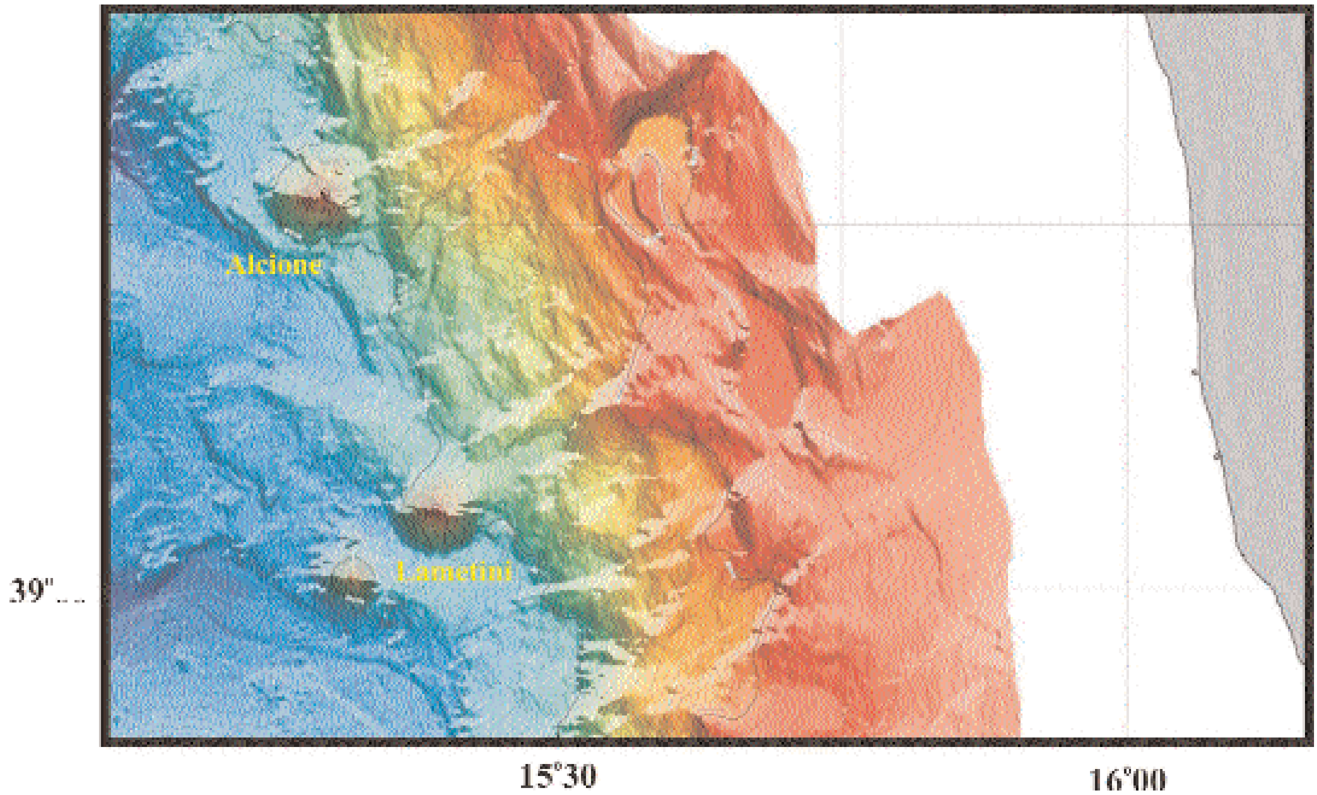

Fig. 2. - *Colour-coded relief bathymetry (illum from N) of the Calabrian slope and location of the submerged eastern Aeolian arc volcanoes. Note the position of Alcione and the Lametini volcanoes on the slope bench. Contour interval 50 m.*

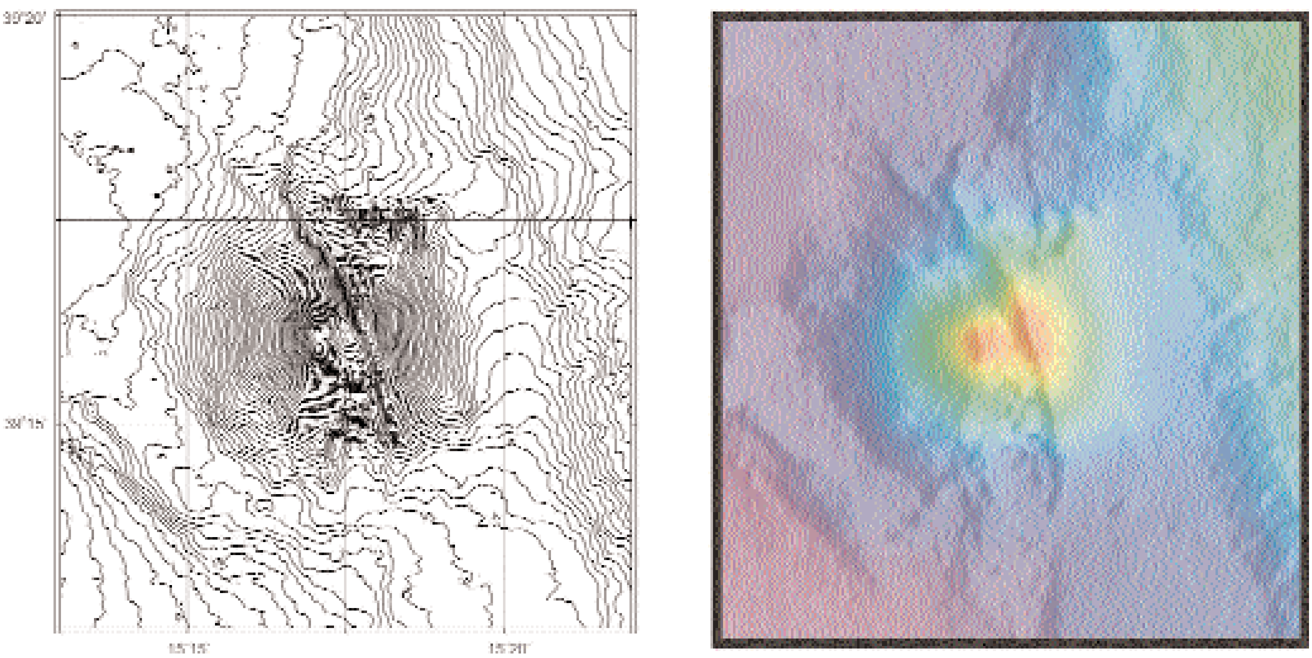

Fig. 3. - *Alcione volcano. Left: bathymetry, contour interval 25m; Right: colour-coded relief (illum from E). Note the scarp cutting across the edifice. Contour interval 25 m. For discussion refer to text.*

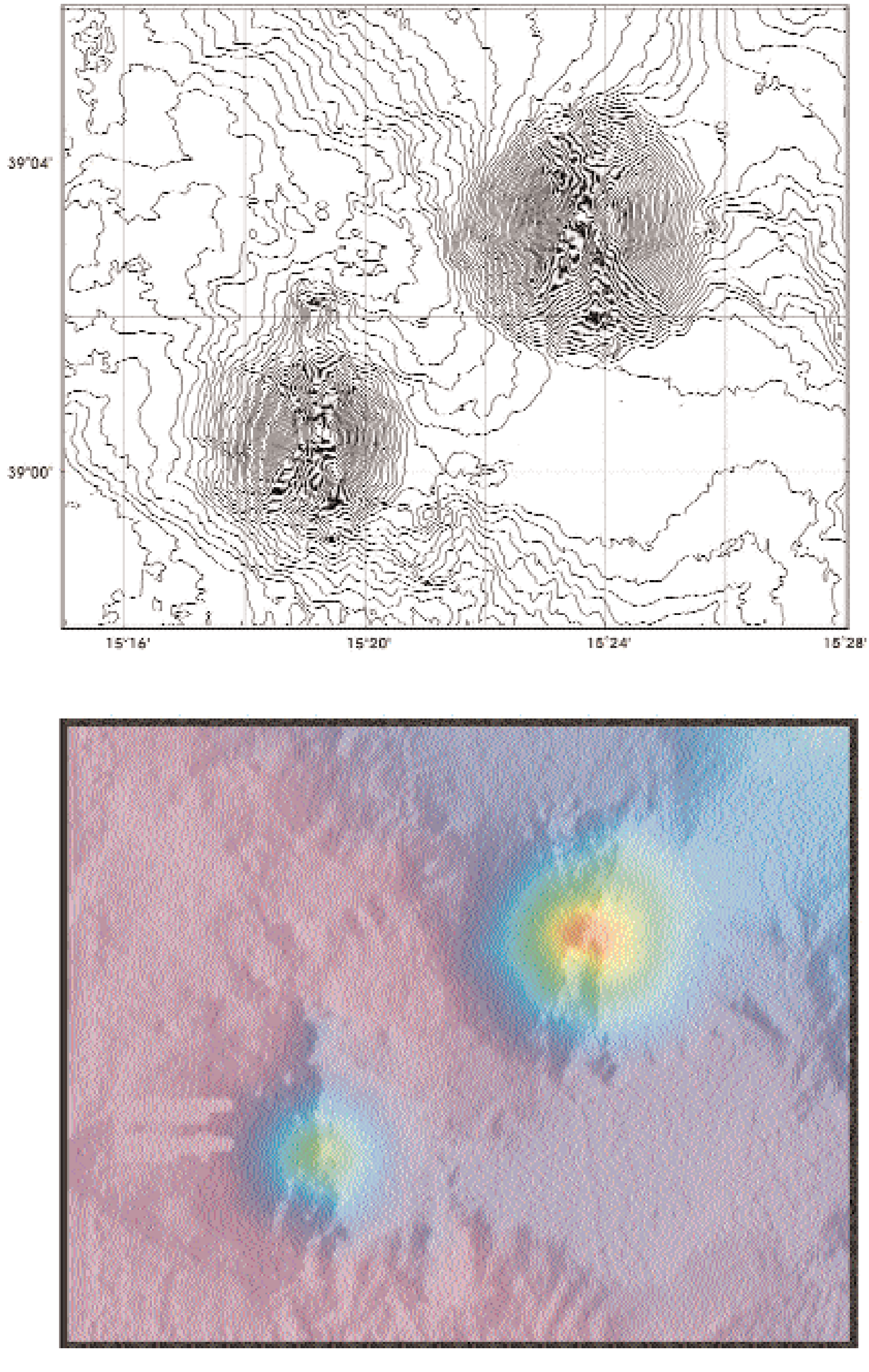

Fig. 4. - *Lametini Seamounts. . Top: bathymetry, contour interval 25m; Bottom: colour-coded relief (illum from E). Refer to figure 5 for details of the larger cone. See text for discussion.*

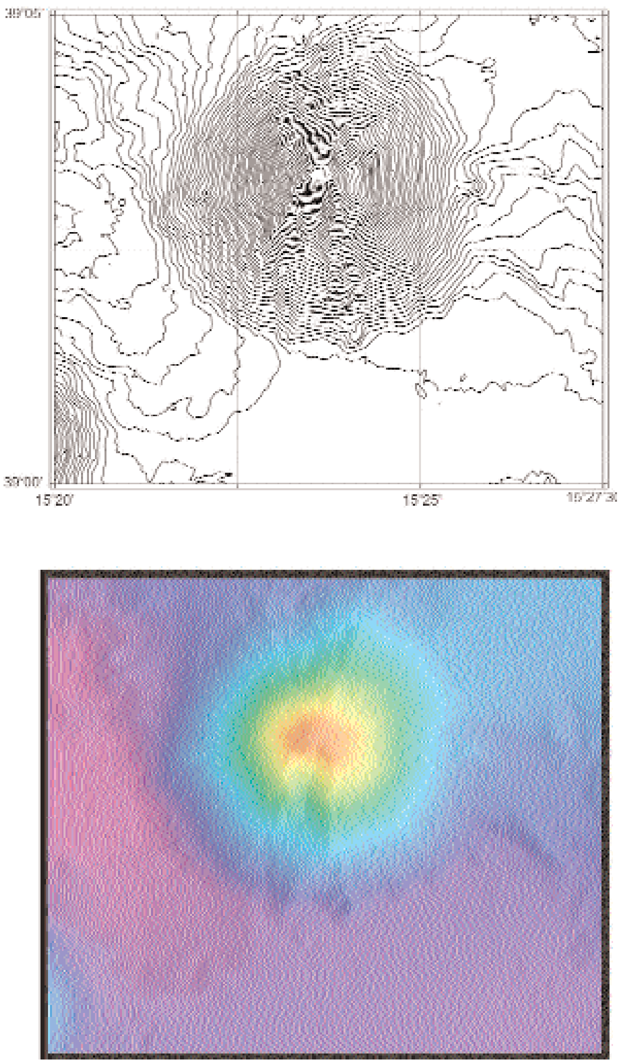

Fig. 5. - *Largest Lametini cone (LamN in text). Top: bathymetry, contour interval 25m; Bottom: colour-coded relief (illum from E). Note the large scar affecting the southern flank of the cone and the positive relief at its base, possibly representing the proximal portion of the failed material.*

3.1.4 - *Local structure of the Lametini region*

Although scarce, seismic data in the Lametini region indicate variations in basement depth, which could be related to the location and alignment of the two volcanoes. Basement depth, in fact, is 2800 m north of the cones, dropping to 3250 m south of them. Available data however preclude any accurate estimate of the direction of the structure affecting the basement.

As to the slide scar on LamN, the feature is most probably related to a mass-wasting event along a shallow-seated detachment plane, evidence of gravitational instability due to the sloping (~15°) flanks of the volcano and not associated to any form of deep-seated source.

3.2. - Palinuro

Palinuro is made up of basalts and basaltic andesites and has been dated to 0.35 Ma (Beccaluva *et alii*, 1985). The composite Palinuro volcanic complex (PVC) stretchs E-W for 75 km. It stands between the lower slope at 2000 m water depth to its north and the deep Marsili basin (3400 m depth) to its south. The PVC delimits the north-western extent of Aeolian arc volcanism. At least eight single volcanic edifices can be recognised along the PVC (fig. 6), their bases coalescing to form a near continuous volcanic ridge. Shallow water depths characterise the central portion of the PVC, with two volcanoes between 14°45' and 14°50' reaching 175 m and 70 m depths. They display flat tops, mostly due to emersion during glacial times.

To the west of the two shallower volcanoes, clusters of small cones surround a depressed area (14°40'-14°45') bordered by an arcuate northwestern ridge and smooth slope. This morphology could be related to a caldera-forming gravitational collapse event of a pre-existing volcanic edifice, followed by the creation of resurgent domes; the linear scarp bordered by the smooth slope could be the sole remainder of the original volcano flank.

To the east, adjacent to the central area (14°50'-15°00'), a series of smaller cones develop, mostly exhibiting horseshoe morphology and cratered summits. Further east, the PVC is affected by tectonic structures that are very prominent in the morphology of the last volcano, Glabro (centred on 15°10'), isolated from the PVC by a narrow moat.

Rather than describing the Palinuro complex as a whole, the features of two of its components have been chosen as examples to illustrate the differences in genesis and post-edifice construction diversity.

3.2.1 - *Cratered volcano (14o53'-14o55')*

The volcano is a small cone characterised by an asymmetric crater located at a minimum water depth of 500 m (fig. 7). Based on the difference in slope of its eastern flank and the flat seafloor to the west, the base of the cone lies at ~800 m water depth. Crater walls have a maximum height of 290 m, diminishing to 180 m at its western rim. The floor of the crater is at 130 m above the base of the volcano. No data are available about the rock composition. Assumptions may be made for the generation of this feature that range from explosive activity (wholly possible at this depth, Head & Wilson, 2003) or lava drain-back and/or lava lake formation.

3.2.2 - *Glabro*

This easternmost volcano from the PVC is treated for fairly obvious reasons given its outstanding morphology (fig. 8). No samples are available for

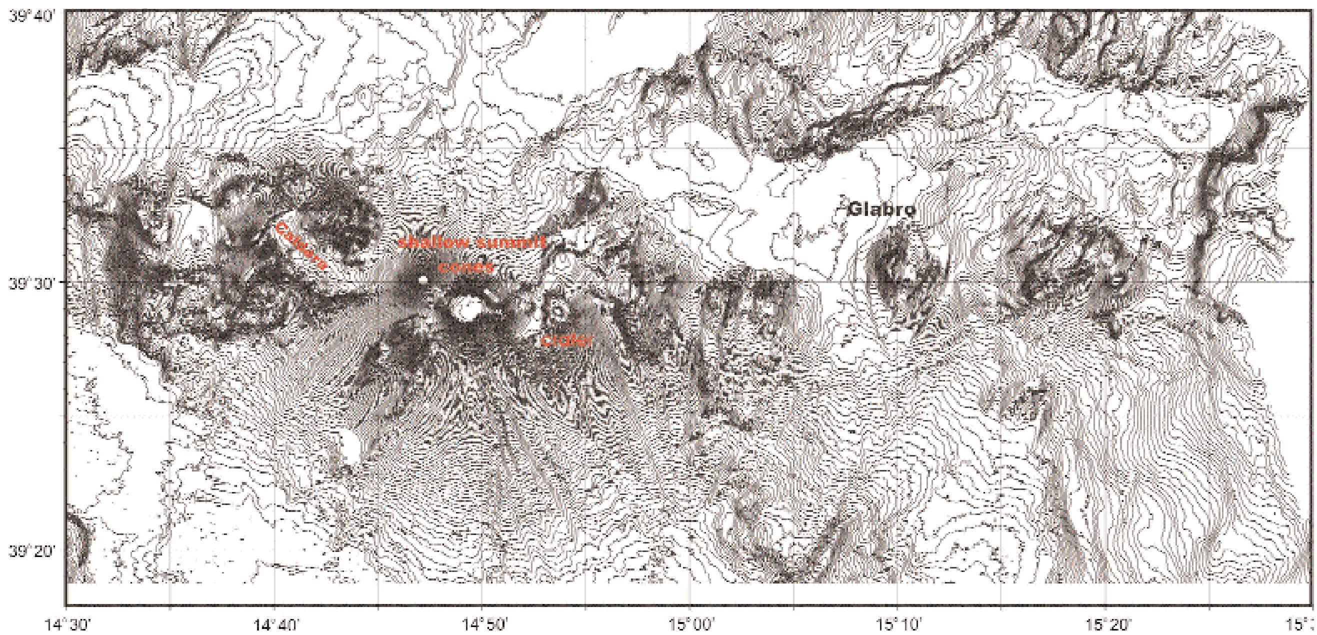

Fig. 6. - *25m interval bathymetry of the Palinuro Volcanic Complex (PVC), with main features described in text labeled. See text for discussion of details of the crater and Glabro volcanoes.*

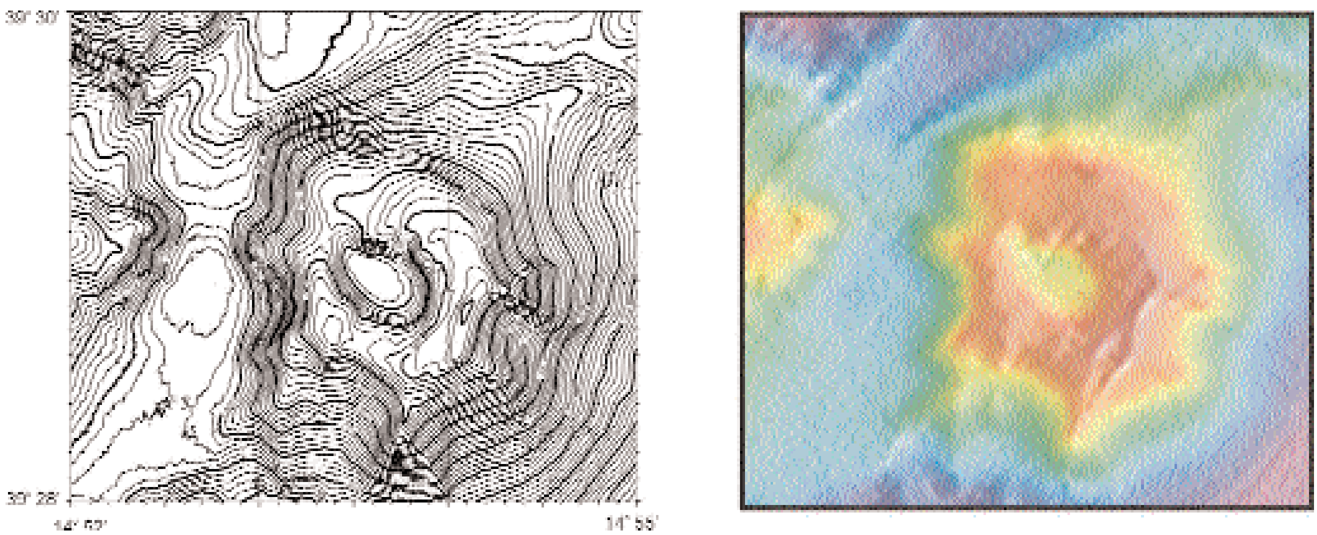

Fig. 7. - *Details of the cratered volcano on the PVC. Left: 10m contour interval bathymetry of the cone, Right: colour coded relief and contours. Note that the crater wall heights are asymmetric, nearing breach conditions to NW. This morphology is common for other cratered cones as well.*

Glabro. The volcano is dissected by a series of arcuate fault scarps into two separate parts characterised by N-S elongated, linear summit zones. Very steep internal scarps delimit the western (830 m water depth) and eastern (870 m water depth) summit portions of Glabro, separated by a 1.8km wide saddle lying at a water depth of 1100m. The western portion of Glabro is larger, higher (tab.1) and has a shape very similar to a smooth-flanked elongated cone split vertically into half. The flanks of the smaller, eastern portion are morphologically irregular, and its resulting shape is more complex. Surrounding perimeter faults also characterise the adjacent seafloor of Glabro. All perimeter fault scarps are west dipping, two intersecting the seafloor to the west of the edifice and one to the east.

The faults that have dissected Glabro, both the internal and perimeter features, have two distinctive properties. Firstly, all scarps are arcuate but with trends that fall into the N-S quadrant, elements with cross-cutting attributes are in fact lacking. Secondly, all the faults affect solely the area contiguous to the

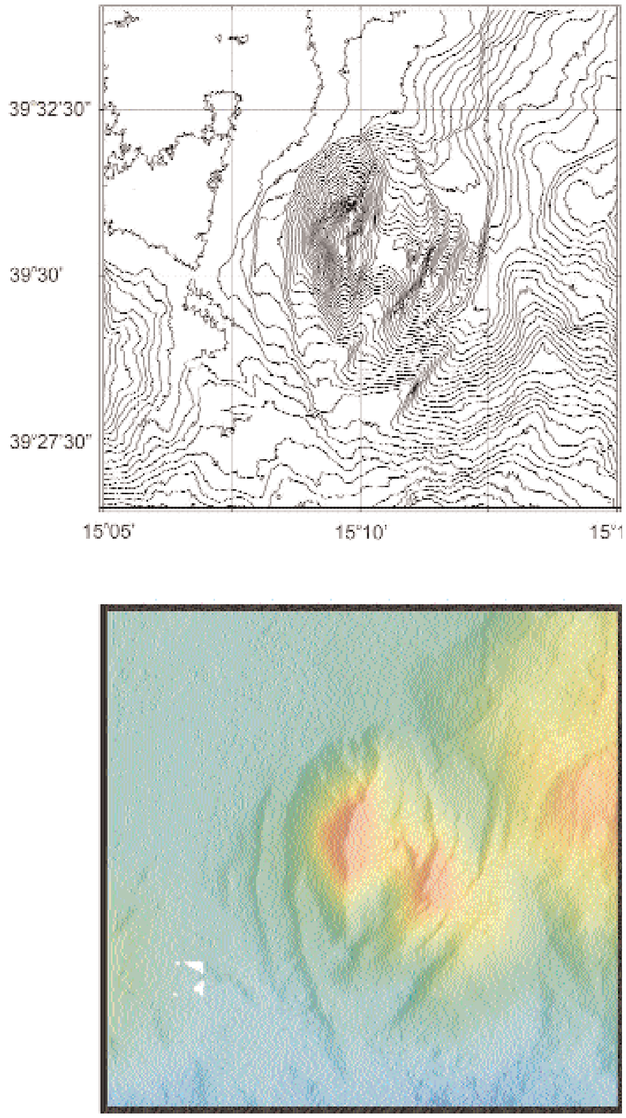

Fig 8. - *Glabro Volcano. Top: bathymetry, contour interval 25m; Bottom: colour-coded relief (illum from E). Glabro is made up of two summit areas bounded by striking internal and perimeter scarps. Note the diminishing throw of perimeter scarps away from the volcano. See text for discussion.*

volcano, conspicuously diminishing in height until terminating at the immediate external perimeter of the edifice. These elements lead to the conclusion that the observed volcano-tectonics is intimately linked to, and the surface expression of the destabilising processes that have affected Glabro.

3.2.3 - *Local Structure of the Glabro region*

Seismic reflection lines available in the vicinity of Glabro once again show that the volcanic structure is positioned on a ~800 m high basement step. In fact, to the northwest of the structure, the basement at a depth of around 2200 m is overlain by the 600 m thick sedimentary fill of an intraslope basin, ahile to the East and South of Glabro, the basement is at a depth of only 1200 to 1400 m. The basement data seem to fit with the structural elements described so far, in that the distribution of the volcano portions and directions of the faults point to an E-W or NE-SW trend of destabilisation. With regard to the processes at the origin of destabilisation, a first possibility is a thorough dissection of the volcano by normal faulting. A problem with this assumption is that since the faults are linked only to the volcano, some other process must have been at work to focus the faulting. A more credible process is directional gravitational spreading towards the E-NE. In effect, some of the elements characterising Glabro seem to have development close to the morphological characteristics of volcanic spreading described by the analogue modelling results of MERLE & BORGIA, 1996 and the numerical modelling of VAN WYK DE VRIES & MATELA, 1998. In the spreading case, the western scarps could be the surface expression of compression due to a slide surface underlying the entire edifice, probably initiating at the inward facing eastern fault. Movement along the decollement surface would cause destabilisation and dissection of the volcano summit, originating the two steep inward- facing collapse scars delimiting the two summit areas, developing as the flanks of a central leaf graben.

3.3. - WESTERN ARC VOLCANOES

Located on the seaward portion of the Cefalù basin, and west of the Island of Alicudi, the submerged portion of the western Aeolian arc is aligned in a NW direction and consists of Eolo and Enarete seamounts and the volcanic range comprising Sisifo seamount. Eolo, Enarete and the Islands of Filicudi and Alicudi are positioned at the northern margin of the Cefalu basin (fig. 9), flanking the 1500 m deep, flat-lying seafloor of the basin and bounded by a 500 m to 1000 m seawards-facing scarp to the north.

3.3.1 - *Eolo*

Eolo is located 20km due west of Alicudi Island. The volcano is generally characterised by irregular flanks, and a wide, 3 km by 2 km, relatively flat summit area, ~800 m deep, elongated in a NW-SE direction (figs. 10, 11). The flat summit is roughly square shaped and bounded by linear highs (75 to 125 m high) on 3 sides except to the SW (fig. 11). In this latter side, the southwestern portion of the summit area terminates at a 300 m deep scarp surrounded by 3 small cones (350 m, 250 m and 175 m high) which thus form a closed depression.

Dredge hauls from Eolo have included basalts, dacites and rhyolites, dated between 0.85-0.77 Ma (BECCALUVA *et alii*, 1985). The more silica-rich rocks characterise the small cones that surround the southwestern depression, suggesting a second episode

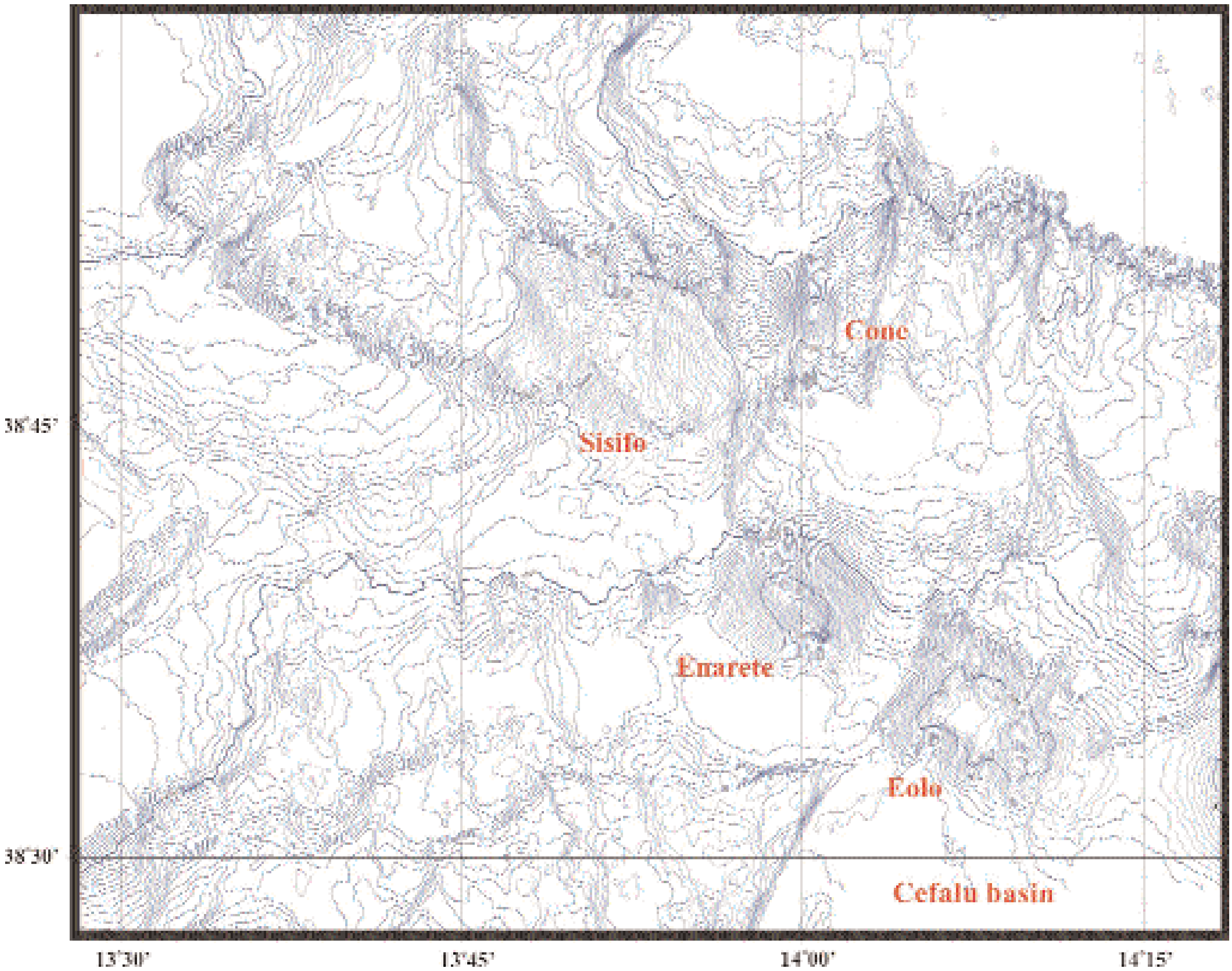

Fig. 9. - *Bathymetry (interval 50 m) of the western submerged Aeolian arc. Features discussed in text are labeled.*

of volcanism and cone emplacement following gravitational collapse of this flank of Eolo. The wide irregular base area of Eolo does not seem proportional to its present morphology. A conjecture could interpret the flat lying summit surrounded by delimiting highs as a filled caldera, implying the destruction of a previously larger edifice.

3.3.2 - *Enarete*

Enarete lies 10 km to the NW of Eolo. This volcano, from which basalt rocks, dated 0.78-0.67 Ma, were dredged (BECCALUVA *et alii*, 1985), has the morphology of a near perfect cone, slightly elongated with NW-SE trend (figs. 9, 10). It is asymmetric in height, ranging between 1700 m and 1450 m, given that its northern flank terminates at greater depth. About 3 km west from the base of Enarete, a small, 500 m high cone rises from the flat seafloor (fig. 10).

NW of Enarete lies the complex and irregular morphology of Sisifo seamount (fig. 9) which lies upon a WNW-ESE directed, 40 km long ridge. Made up of basalts and trachytes, dated 1.3-0.9 Ma, this edifice holds the oldest age data so far available for the Aeolian Arc. Younger volcanism, however, has been active in the region as shown by the morphological expression of a regular 1000 m high, conical volcano (fig. 9) located north of Enarete, at the southeastern margin of the Sisifo ridge.

3.3.3 - *Local Structure of the Eolo/Enarete/Sisifo region*

Both Eolo and Enarete are positioned above the seaward-facing border fault of the northern part of the Cefalù basin. The southern border of the Sisifo ridge, however, having the same trend as the Cefalù border fault, is characterised by a 500 m morphologically evident landward-facing scarp.

A significant volumetric difference emerges when comparing the western submarine volcanoes with the

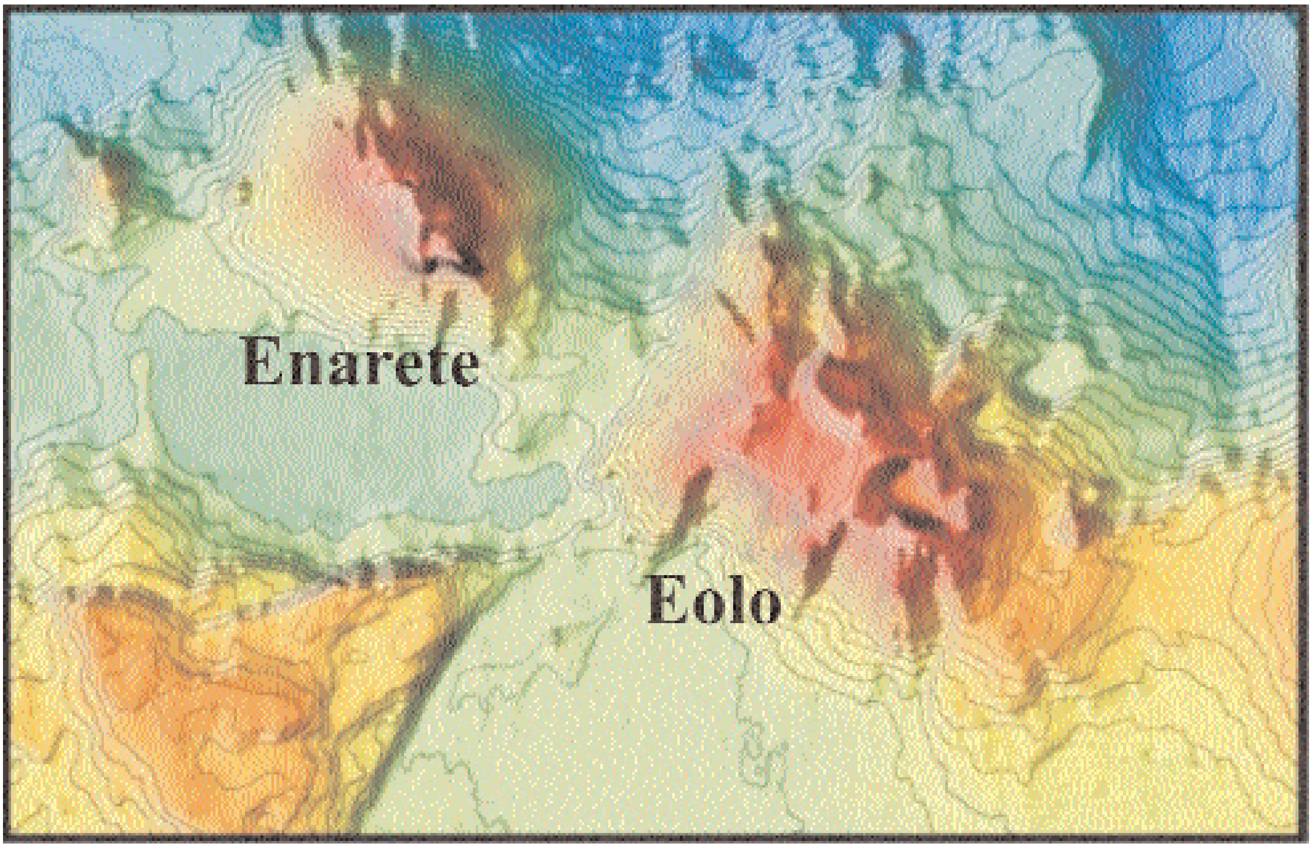

Fig. 10. - *Colour coded relief map of Eolo and Enarete volcanoes. Flat seafloor to southwest of the volcanoes is the Cefalù basin. For details of Eolo see figure 10.*

ones to the east. Enarete alone has a volume (tab. 1) that is close to double of the volumes of Alcione and the Lametini seamounts summed together. This is reflected in a comparison of the basal areas as well (tab.1), with both Eolo and Enarete having base areas close to the ones characterising the emerged volcanoes of Alicudi and Filicudi. In spite of the lack of age data for the eastern arc volcanoes, a simple difference in timing of formation cannot be ruled out, older volcanoes being larger, since an eastwards younging trend is evident, at least in the Recent. On the other hand, if one considers Palinuro as part of the northeastern arc, volume distribution could be more comparable.

4. - BACKARC VOLCANOES

4.1. - MARSILI

Marsili volcano rises 3000 metres from the Marsili basin seafloor to a minimum depth of 489 metres. It is elongated ~ 60 km NNE-SSW with mean width of 16 km. A narrow, 1 km wide linear region of lower gradient, approximately bounded by the 1000 metre isobath, marks the summit zone that stretches 20 km along the main axis of the volcano. On the lower flanks of the volcano, particularly to the NW and SE, numerous seamounts develop while the adjacent basin areas to the west and to the east of the Marsili edifice are characterised by large fault scarps (fig. 12).

The volcano summit axis zone and tip regions are characterised by the development of linear structures arranged in segments generated mainly by the alignment of narrow, linear cone ridges, or by the linear arrangement of several circular-based cones (MARANI & TRUA, 2002). Segment locations show that the central portion of the volcano is the main site of stress release and ensuing volcanic activity. These features, along with other morphological characteristics of the volcano and adjacent regional geology, led MARANI & TRUA, 2002 to interpret Marsili volcano as a super-inflated spreading ridge, constructed due to robust volcanism during the last 0.7Ma. In this paper we will deal with the small-scale volcanic features that occur on the NW flanks of the main volcano, in comparison and in contrast to the volcanoes of the volcanic arc.

4.1.1 - *North-western Flank seamounts*

Numerous small seamounts grow on the flanks of Marsili volcano, being most developed on its northern tip. The cones have circular bases with diameters up to 1500 metres and heights up to 300 metres (fig. 13).

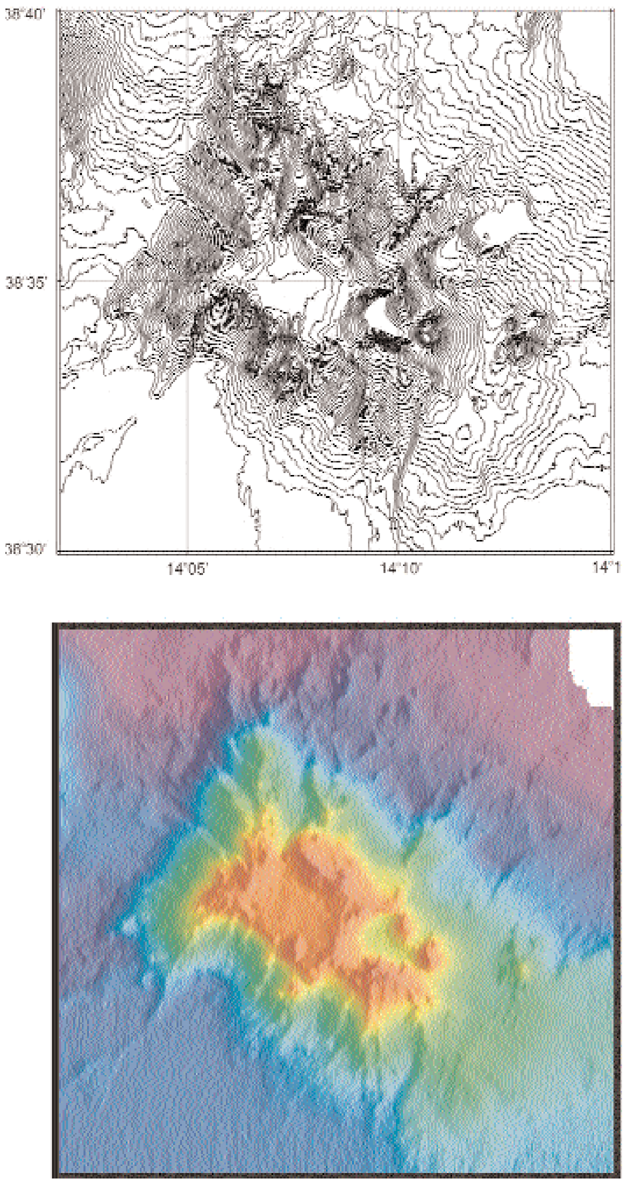

Fig. 11. - *Eolo volcano. Top- bathymetry, contour interval 25m; Bottom - colour-coded relief (illum from E). Note the broad, flat lying summit zone and the wide irregular base of the edifice. For discussion see text.*

Several are characterised by very low gradient, flat tops and a few display summit craters. In addition, a number of volcanic constructs form flat topped, semi-circular terraces, formed by up-slope buttressing on the inclined flanks of Marsili volcano. Similar features have been reported from the submarine Puna Ridge offshore Hawaii (ZHU *et alii*, 2002). Essentially, terraces can be considered a morphological variant of typical submarine flat topped volcanoes that are constructed on sloping terrain, forming flat steps with semicircular, steep down-slope flanks. On the contrary, cones are volcanic constructs characterised by a circular base, that add significant (~50 m) vertical relief to the slope and identified bathymetrically by enclosing contours. The morphology of cones nevertheless display asymmetry, with higher relief in the down-slope direction. Slope gradient, taking lava production and eruptive products constant, could thus be the discriminating parameter between the formation of the two morphologies. Cones would develop in lower gradient sectors while terraces would characterise higher gradient portions of the Marsili volcano. Examples of the former include the cone 1 (fig. 13) that develops in the distal slope area adjacent to the flat-lying Marsili basin floor (summit depth 3050 m). The cone has a flat top (base diameter ~1750 m; summit diameter ~1250 m), which culminates in a dome like feature. Morphologically, the cone is asymmetric, displaying a height of 240 m in the down slope direction and a relief of only ~60 m towards the saddle separating it from the sloping Marsili flanks. About 3 km south of cone 1, a series of terraces, characterised by typical semi circular steeply sloping flanks bounding flat seafloor (fig. 13), develop from 2800 metres depth. Dimensions are variable, widths of the flat summits averaging ~600 m and flanks ~100-150 m high. The pre-existing volcano flank slope profile, estimated from terrace morphologies is in the range of 10-12°, sharply contrasting with terrace flanks which reach 30° slopes.

A final, particular volcano morphology is displayed by three cones trending NW-SE at ~2400 m depth southeast of cone 1 (fig. 13). The three cones are a striking example of the evolution of cratered edifices. The most southern cone is characterised by horseshoe morphology, open to the southeast, with entirely enclosing, variable height crater walls. Crater depth is ~100 m, taken from the highest standing portion of the wall, the diameter is in the order of 1 km. The middle cone also displays horseshoe morphology with similar crater depth and diameter but is fully breached northeastwards, towards the northernmost cone. This latter, in reality consists of only the 150 m high western flank of what could have been a structure similar to the previous ones, the lacking portion of the original edifice located to the east. Thus, by following the morphology of the three cones northwards, one can trace the possible fate of these singular edifices. At the moment, it is difficult to make assumptions to explain the origin and characteristics of these volcanoes. If the increasing asymmetry is due to failures of the crater walls, it is difficult to explain the different trends, mostly away from the steeper slopes of Marsili. On the contrary, an eruptive origin to explain the features would be in line with random near-breach or breach directions but leaves open the question of why this process should affect only these volcanoes. A third possibility is that the volcanoes have been affected by extreme lava drawback due to intersection of younger magma conduits basically feeding new constructs in adjacent regions.

4.2. - VAVILOV

Vavilov volcano has a length of ~30 km, elongated in a N-S direction with a maximum width of ~14 km. It rises 2800 m from the flat Vavilov basin floor 3600 m

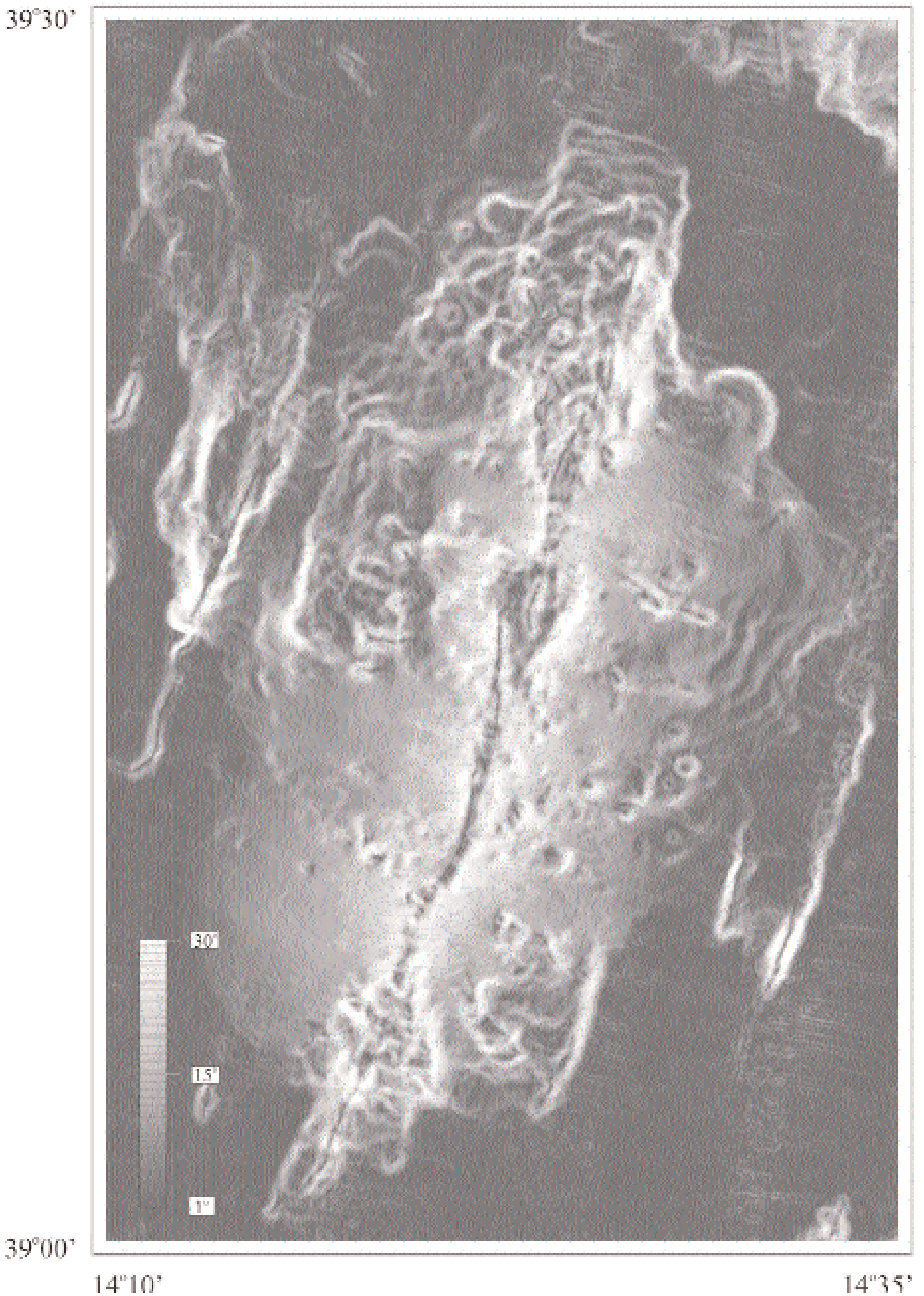

Fig. 12. - *Grey shaded gradient map of Marsili volcano. Steeper slopes are white, flat lying areas are black. Note development of numerous cones on the NW flank of the volcano.*

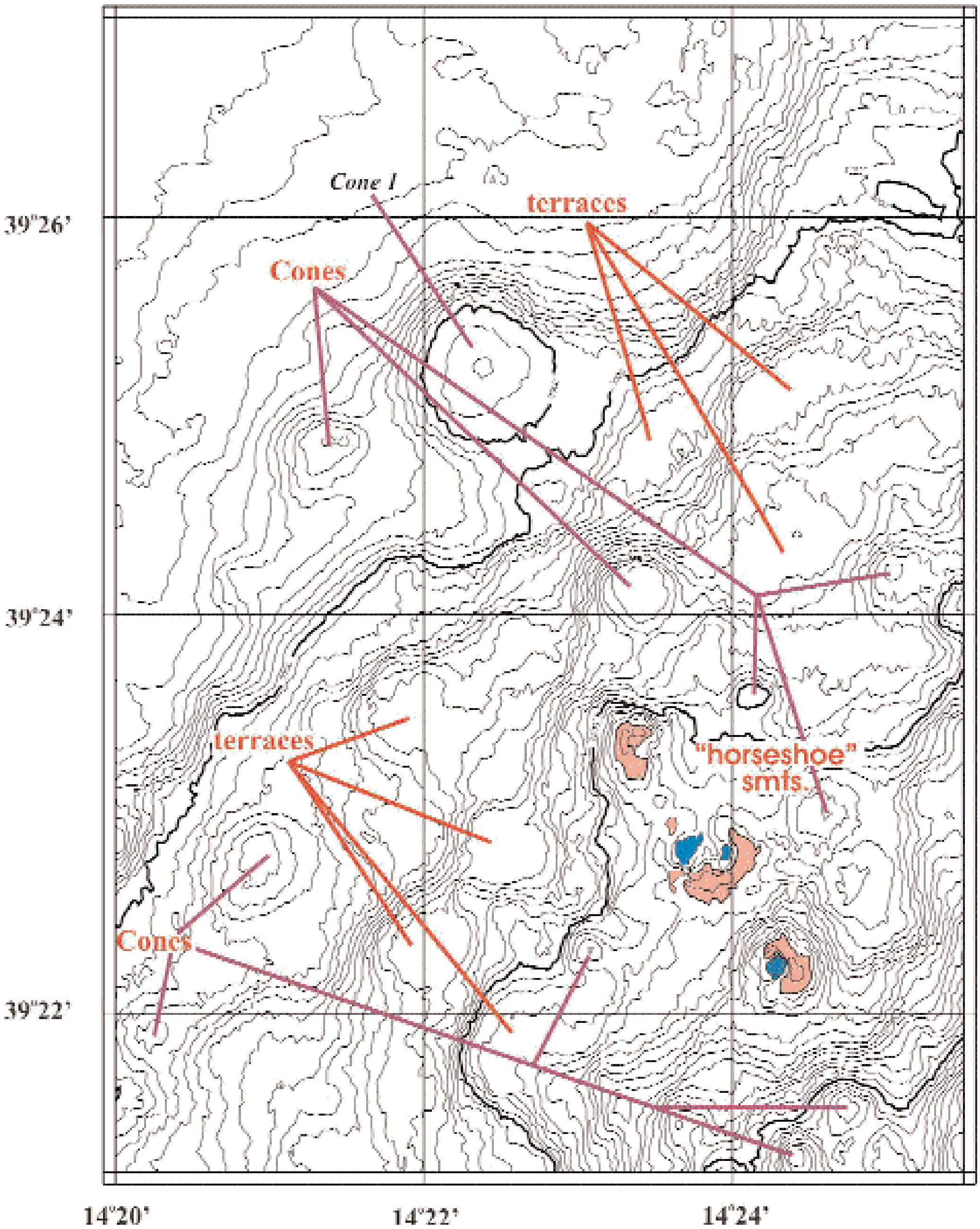

Fig. 13. - *25m interval bathymetry of the northwestern flank of Marisli volcano. Features discussed in detail in the text are labeled. Note that both cones and terraces develop on the flanks.*

deep to minimum water depth of 800m. Vavilov is a mature volcano, its formation occurring at the time of oceanisation of the Vavilov backarc basin at about 3Ma (KASTENS *et alii*, 1988). The summit area, however, seems to have been subsequently active (ROBIN *et alii*, 1987) at 0.4 to 0.1Ma.

The overall morphology of Vavilov volcano is dominated by the strong asymmetry between its eastern and western flanks (figs.14, 15). While the eastern flank, dipping on average 15°, displays irregular "volcanic" topography due to small cones, restricted terraces and ridges, a large portion of the western flank is steeply dipping (from >30° above 2800 m depth to 20° along the lower flanks) and is remarkably smooth, displaying a complete lack of small scale topography. Considering the arcuate scar that bounds the high gradient western flank, it is likely that this portion of the volcano has been affected either by one or more flank collapses or by faulting that has resulted in the removal of a large volume of the pre-existing edifice.

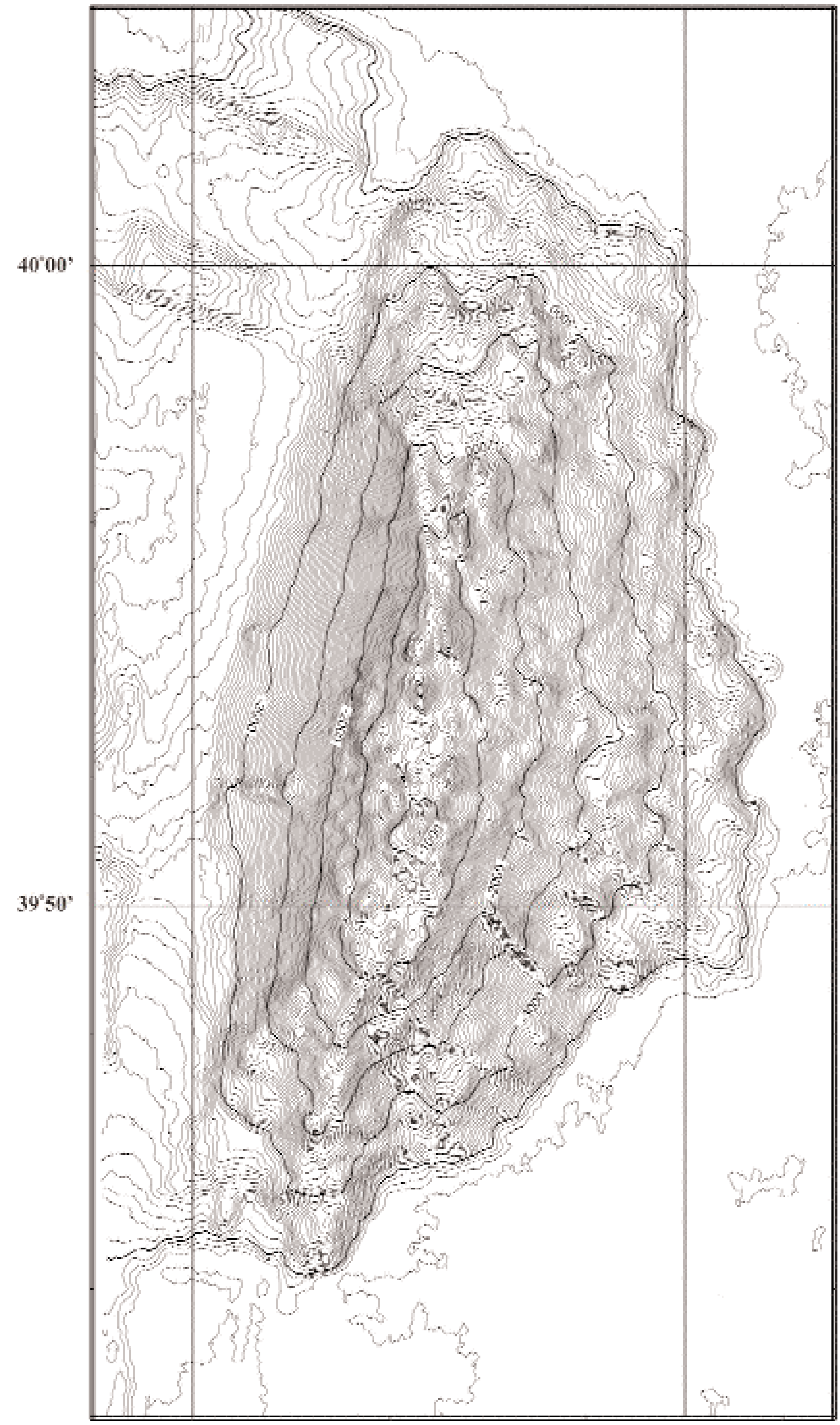

Fig. 14. - *Vavilov volcano. Bathymetry, contour interval 50m. The asymmetry of the volcano is evident as well as the range of features occurring on the volcano flanks, including terraces and small conical volcanoes.*

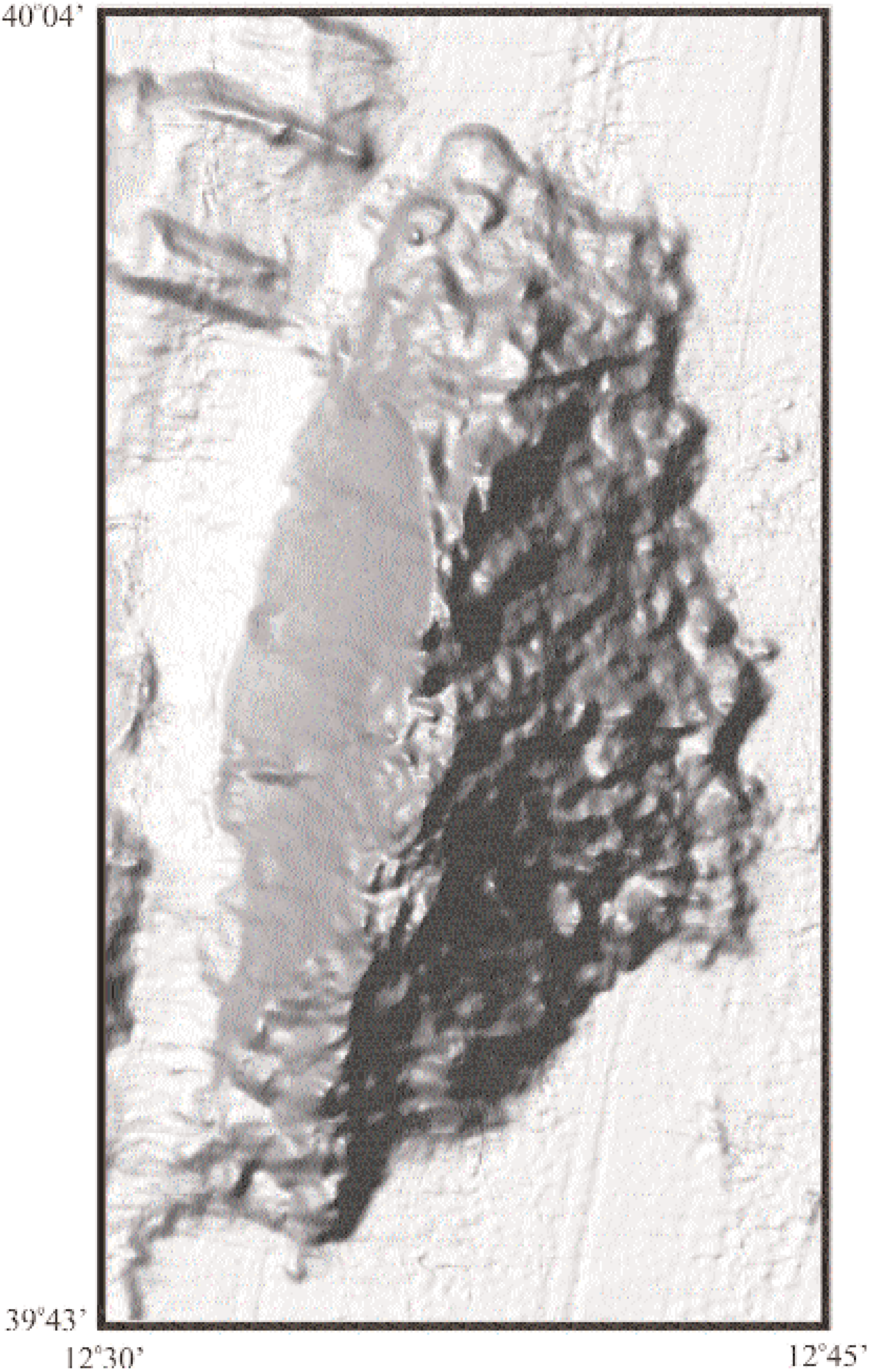

Fig. 15. - *Shaded relief bathymetry (illum. from E) of Vavilov volcano showing the marked morphological asymmetry of the edifice, both in terms of gradient variation and smaller-scale topography. For discussion see text.*

The summit of the volcano is composed of a relatively low gradient area occupied by two large 250 m high, circular cones and a number of smaller edifices. In general the morphology of the flanks of the Vavilov seamount has a more subdued character in comparison with the Marsili edifice most probably due to sediment blanketing. Both the southern and northern flanks of the volcano are traversed by 100-150 m high ridges, some characterised by the development of small cones, that originate at the summit tips and continue to the base of the volcano. Particularly on the northern flank, interruption of the ridges by steep transverse scarps gives rise to terrace-like morphologies. Apart from the summit cones, Vavilov volcano is the site of a number of circular based cones that, however, are located for the major part, on the lower slope portions, between 2500 m and 3500 m depth.

An interesting feature related to the bulk of the volcano is that the eastern base is consistently at least 100 m (in the central part ~300 m) deeper than the western one. Since the base level of the basin flanking the Vavilov seamount is for all practices the same, the shallower depth of the basin adjacent to the western flank could be due to the accumulation of the material derived from the assumed collapse. The lack of rugged topography on the basin floor could be related to sediment blanketing, thus indirectly indicating a timing of the event.

5. - DISCUSSION AND CONCLUSION

Although based exclusively on morphological grounds, the brief and non-exhaustive descriptions given above illustrate the diversity of the submarine volcanism of the Tyrrhenian basin. All volcanoes of the Aeolian arc are conical except for Eolo seamount that has a wide, flat summit area. Rough volume estimates show that the western submarine arc sector is the site of major production, with Enarete having near double the volume of the northeastern edifices summed together. The different edifices demonstrate that more or less long lived stationary magma vents are at the origin of the volcanoes. The vents are essentially isolated, as shown by the variations of geochemical signatures of the products between adjacent volcanoes, and may tap portions of a heterogenous mantle beneath the arc, most probably affected by different degrees of contamination from the subducted slab. A probable exception is the Palinuro volcanic complex. Although complicated by a range of volcanic morphologies, its linearity given by the uninterrupted merging of its vents could be indicative of the stability of magma supply along a major crustal discontinuity. Moreover, its trend and location, together with it being the limit of arc volcanism in this sector, are distinctive characters that differentiate Palinuro from the other submerged Aeolian volcanoes, and make it more similar to the two major backarc seamounts.

Backarc volcanoes of the Tyrrhenian are characteristically large reaching relatively shallow water depths (500-800 m) with bases at ~3500 m water depth. Both Marsili and Vavilov display satellite cones and terraces on their flanks, and relatively lower gradient summits characterised by a series of cones. The younger Marsili exhibits a range of flank seamount morphologies from flat top volcanoes, deeply cratered cones, elongated cone ridges and well developed terraces. The differentiating parameters of these various morphologies is still unclear but merit further study. Vavilov displays a more subdued topography probably due to sediment draping, but nevertheless shows the development of similar features described for Marsili.

A variety of instability processes have affected several of the described volcanoes. In the arc sectors, these processes are linked to the ubiquitous basement faults that underlie the volcanoes. In particular, since the analysis of seismic lines seems to rule out present-day activity of these faults, it is the basement step that provokes instability, with the volcano straddling a shallow, stable basement on one side and a sequence of weaker sedimentary layers on the other. This framework could favour gravitational spreading, which causes the most outstanding morphological transformation in the arc. It may be incipient in the case of Alcione and in a mature stage in the case of Glabro. If these two examples represent the end members of the spreading case, it follows that this process takes place by slow movement along the sliding surface, demonstrated by the development of the two cone summits on Alcione and the integrity, albeit disjointed, of the Glabro edifice. On the contrary to deep-seated spreading, the northern Lametini seamount displays a relatively large flank slide scar, most probably related to the failure along a slide surface limited to the edifice and due to the high gradient of the flanks. This type of instability evolves within a much more restricted time frame than that of gravitational spreading. Vavilov volcano is the most representative candidate for this style of gravitational instability, in this case leading to large-scale catastrophic sector collapse. The asymmetrical morphology of Vavilov, in fact, may be the result of a landslide scar that occupies almost its entire western sector. Although no estimate can be made regarding the possibility of multiple events forming the scar, the sector failure would have been to all effects instantaneous.

In addition to morphological adaptation to the general case of gravitational stress, a series of volcanoes display modification due to particular eruptive styles that result in cratered volcanoes. Examples include those described on Palinuro and Marsili volcanoes. The observed cratered volcanoes commonly exhibit asymmetrical crater wall heights, thus having a horseshoe shape in plan view. Some are entirely breached, having no positive relief bounding the crater in one sector. All are relatively small, 150-250 m high with a basal diameter of ~1 km and crater depths of 100 m on average. Less common than conical or flat top volcanoes, cratered cones however have particular morphologies that suggest two opposing models for their origin. A first case considers the interior dynamics of magma flux, in which reduction of supply results in magma withdrawal from the vent, the formation of the crater depression and ensuing instability and failure of part of the crater walls. Reduction in magma flux could be a general phenomenon or be induced by intersection of a later conduit leading to the development of parasite volcanism in the vicinity of the cratered edifice.

A conjecture may be made for the case of Marsili volcano, in which the cratered cones may have fed or be linked to the generation of the surrounding lava terraces. The second case involves the explosive expulsion of lava and the formation of a pyroclastic cone around an explosive vent. In the Palinuro case, the ~500 m water depth poses no limit to submarine explosive activity. However, the Marsili cratered cones lie at ~2400 m water depth. Although explosive volcanism has been shown to be possible at these depths, a necessary requirement for submarine pyroclastic eruptions is that the feeding magma possesses a high volatile content allowing gas exsolution and lava disruption and/or gas pressure build-up in the reservoir. Thus, in both the Palinuro and Marsili cases, the cratered cones would have been necessarily fed by a unique magma, with different characteristics than the one at the origin of the regular or flat top cones and terraces that occupy their immediate vicinity.

A significant case involves Eolo seamount. The volcano is 900 m high, its broad, 3 km-wide flat lying summit reaching depths of 800 m, and is characterised by a large, irregular base area. Perimeter scarps partly enclose the summit area seemingly representing relics of a former edifice suggesting perhaps the formation of a caldera structure due to the explosive destruction of the previous high-standing volcano.

Recalling the particular nature of swath bathymetry as a remote sensing tool for the exploration of the seabed, together with the advantages and disadvantages specific of such a method, it is however noteworthy that the morphology alone of many of the landforms described provides clues to their origin and evolution. This is especially true in the marine realm in which the direct observation of actively forming volcanic constructs is precluded.

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