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Super-inflation of a spreading ridge through vertical accretion
Dilatazione di un centro di espansione attraverso accrezione verticale

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ABSTRACT - The 2 Myr-old Marsili basin is the youngest ocean crust floored portion of the Tyrrhenian back-arc basin. A large, ~1400 km^3, N-S elongated volcano is axially positioned in the basin, constituting the only significant relief on the otherwise 3500 m deep, flat lying basin floor.
In this paper, it is suggested that Marsili volcano represents the, super-inflated spreading ridge of the Marsili basin. The morphologically anomalous ridge is considered to result from the up-rise of deep buoyant asthenosphere across lateral tears that develop at the sides of the subducting Ionian lithosphere, making vertical accretion the dominant mechanism acting within a restricted spreading environment.
Onshore and offshore regional data, along with the spreading centre characteristics of the volcano are presented to support this interpretation.

KEY WORDS: Volcano morphology, subduction, lithosphere dynamics, seafloor spreading, Tyrrhenian Sea

RIASSUNTO - Il bacino del Marsili (2 Ma), rappresenta la porzione oceanizzata più recente del bacino di retro-arco del Mar Tirreno. L'omonimo, vulcano, esteso in direzione N-S, con un volume di ~1400 km^3 che occupa la parte assiale del bacino costituisce l'unico elemento topograficamente significativo della piana abissale, profonda 3500 m, del bacino.
In questo lavoro, il vulcano Marsili viene interpretato come un centro di espansione dilatato del bacino Marsili. L'estrema anomalia morfologica del centro di espansione risulta dalla risalita di livelli astenosferici profondi attraverso gli strappi laterali che si sviluppano ai lati della placca Ionica in subduzione. L'accrezione verticale rappresenta il meccanismo dominante nell'ambito di un ambiente di espansione termicamente e spazialmente ristretto.

PAROLE CHIAVE: morfologia vulcanica, subduzione, dinamica dalla litosfera, espansione oceanica, Mar Tirreno

1. - INTRODUCTION

The majority of mid-ocean ridges (MORs) have an established morfological makeup according to whether sea-foor spreading is fast or slow (MACDONALD *et alii,* 1991; MACDONALD *et alii*, 1992; SEMPÉRÉ *et alii*, 1995; SMITH *et alii*, 1995; MAGDE & SMITH, 1995). Their makeup is so distinctive that intermediate velocity spreading ridges have also been described and defined (HOOFT & DETRICK, 1995).

Morphologies of spreading ridges principally depend upon their thermal structure, which is controlled by the magma budget. Moreover, magma supply to the ridge can be taken as a proxy for spreading velocity. Thus, magma oversupply or undersupply relative to the expected for a given spreading rate will result in anomalous MOR morphologies. Well known examples include the Reykjanes Ridge that displays an anomalous slow spreading morphology (MURTON & PARSON, 1993) and the Australian-Antarctic Discordance that has an anomalous fast spreading morphology.

In the southern Tyrrhenian Sea, the recent-most ocean floored Marsili back-arc basin has largely all the geological and geophysical characteristics of oceanic backarc spreading basin (KASTENS *et alii*, 1988). However, it lacks the most evident feature in ocean basins, namely the typical morphology of a spreading centre where new crust is produced. Instead, the axial portion of the basin is occupied by the Marsili seamount, the largest volcano in the Tyrrhenian Sea, 3500 m high and strongly elongated in a NNE-SSW direction. Despite its bulk, the detailed morphology of

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Marsili volcano reveals remarkable similarity to the high order segmentation and volcanic landforms described in the axis and near-axis portions of mid-ocean spreading ridges.

In this paper it is proposed that Marsili volcano exemplifies a morphologically anomalous end-member spreading ridge generated by super-inflation following the model proposed by MARANI & TRUA, 2002. As a consequence, Marsili volcano is here considered the key to understanding the dynamics of spreading and backarc lithosphere formation in the young Marsili basin.

2. - MARSILI BASIN

Marsili basin is the recent-most of two oceanic sub-basins that form the Tyrrhenian Sea. The basin is <2 Myr old, the emplacement of basaltic ocean crust generated by ESE-directed extension (KASTENS *et alii*, 1990) taking place above the presently northwesterly-subducting Ionian oceanic slab (KASTENS *et alii*, 1988,1990; SARTORI, 1990; JOLIVET, 1991). Marsili basin is characterised by a Moho depth of 11 km, matched by thinning of the lithosphere to less than 30 km (SUHALDOC & PANZA, 1989; NICOLICH, 1989; SCARASCIA *et alii*, 1994) and by heat flow values that reach over 200 mWm^{-2} (DELLA VEDOVA *et alii*, 1984; MONGELLI *et alii*, 1992). Average basin basement depth is in the order of 4 km, giving a crustal thickness of ~7 km.

The subducting slab represents a remnant of the Mesozoic oceanic lithosphere that occupied the western and central Mediterranean. Since Early Miocene, most of the ocean domain had been consumed (BECCALUVA *et alii*, 1990), with the exception of the Ionian ocean, delimited to the southwest by its ancient margins, the Malta and Apulian escarpments (fig. 1)

In step with backarc basin expansion, subduction-related island arc volcanism developed in the currently active Aeolian island arc (SERRI 1997 and references therein), generating the present-day arc/backarc configuration of the Marsili basin region (fig. 2).

3. - THE SPREADING RIDGE MORPHOLOGY OF MARSILI VOLCANO

The fine-scale make-up of Marsili seamount displays distinctive volcano-tectonic features closely analogous to those characterising the axial or near-axial zones of MORs, notwithstanding the highly anomalous seamount morphology on which these features develop. Moreover, the available chronology of rocks dredged from the summit and the magnetic anomaly patterns in the region of the volcano are shown to support and to be consistent with the observed morphological characters, suggesting that Marsili volcano represents a spreading ridge, the super-inflated locus of present-day crust accretion in the Marsili basin.

3.1. - BULK MORPHOLOGY OF THE VOLCANO

Marsili volcano rises 3500 metres from the basement level of Marsili basin to a minimum depth of 489 metres, and is elongated 50 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 (fig. 3), marks the summit zone that stretches 20 km along the main axis of the

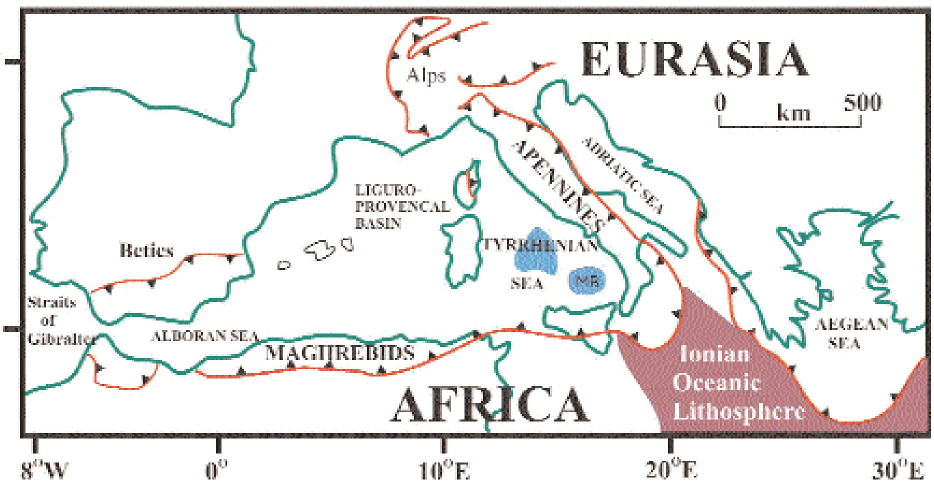

Fig. 1. - *Sketch map displaying remnant Mesozoic Ionian ocean crust in subduction beneath Calabria and the Agean. Surrounding Apennine and Alpine age belts are traced. MB, recent (2 Ma) ocean crust floored Marsili basin.*

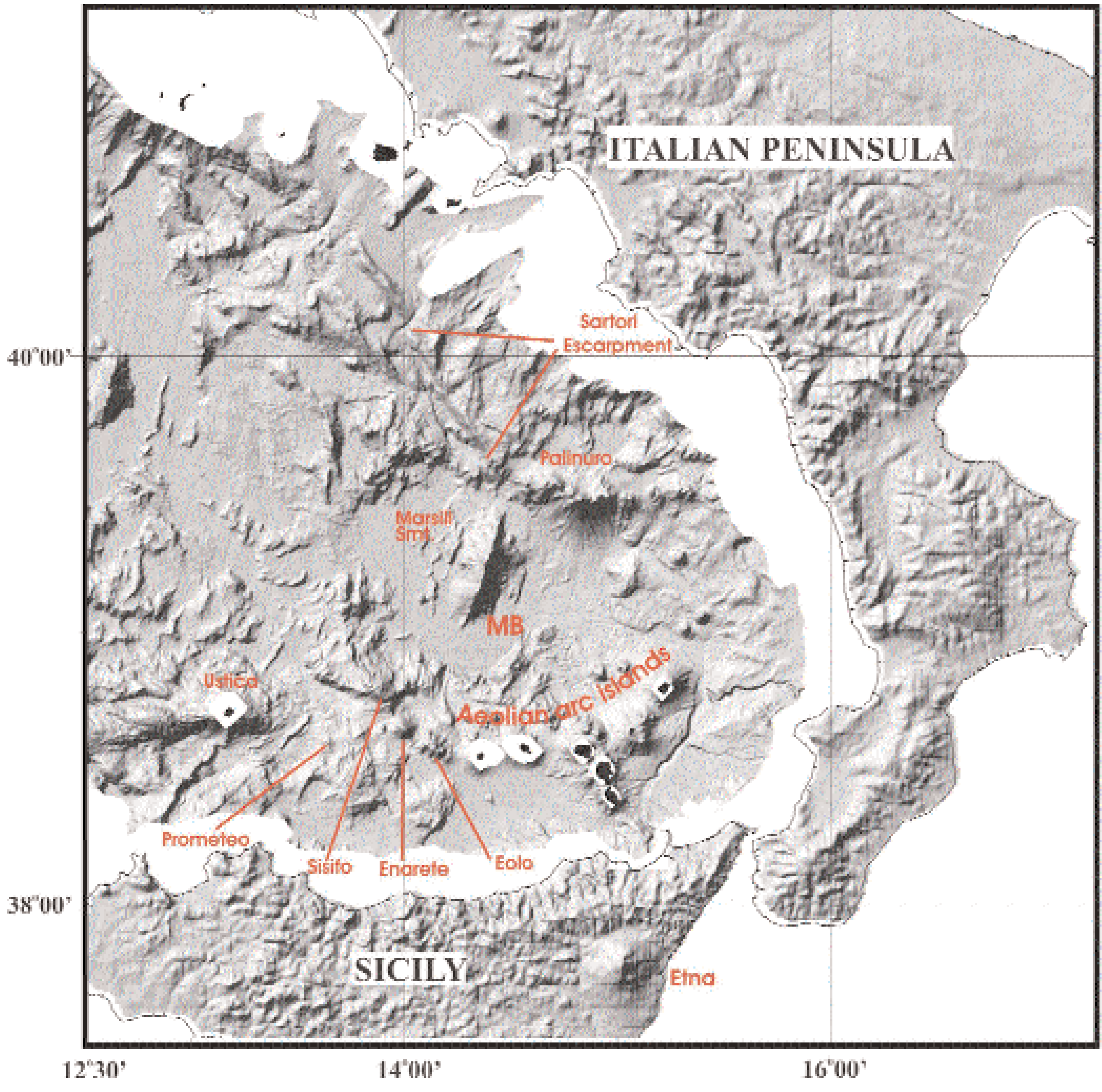

Fig. 2. - *Shaded relief bathymetry (illum from NW) of central and southern Tyrrhenian Sea with feature names discussed in the text. MB, Marsili basin.*

volcano. The summit zone is highlighted (fig. 3) by a region of high gradient relief (>20°) positioned between the axis perimeter and the main slopes (~10°). On the lower flanks of the volcano 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. 3).

3.2. – Segmentation

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 contiguous volcanic cones, elongated along-axis to build narrow, linear cone ridges (LCRs), 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.

3.3. - Flank seamounts

Numerous small seamounts grow on the flanks of Marsili volcano (fig. 3), being most developed on its northern tip. The cones have circular bases with

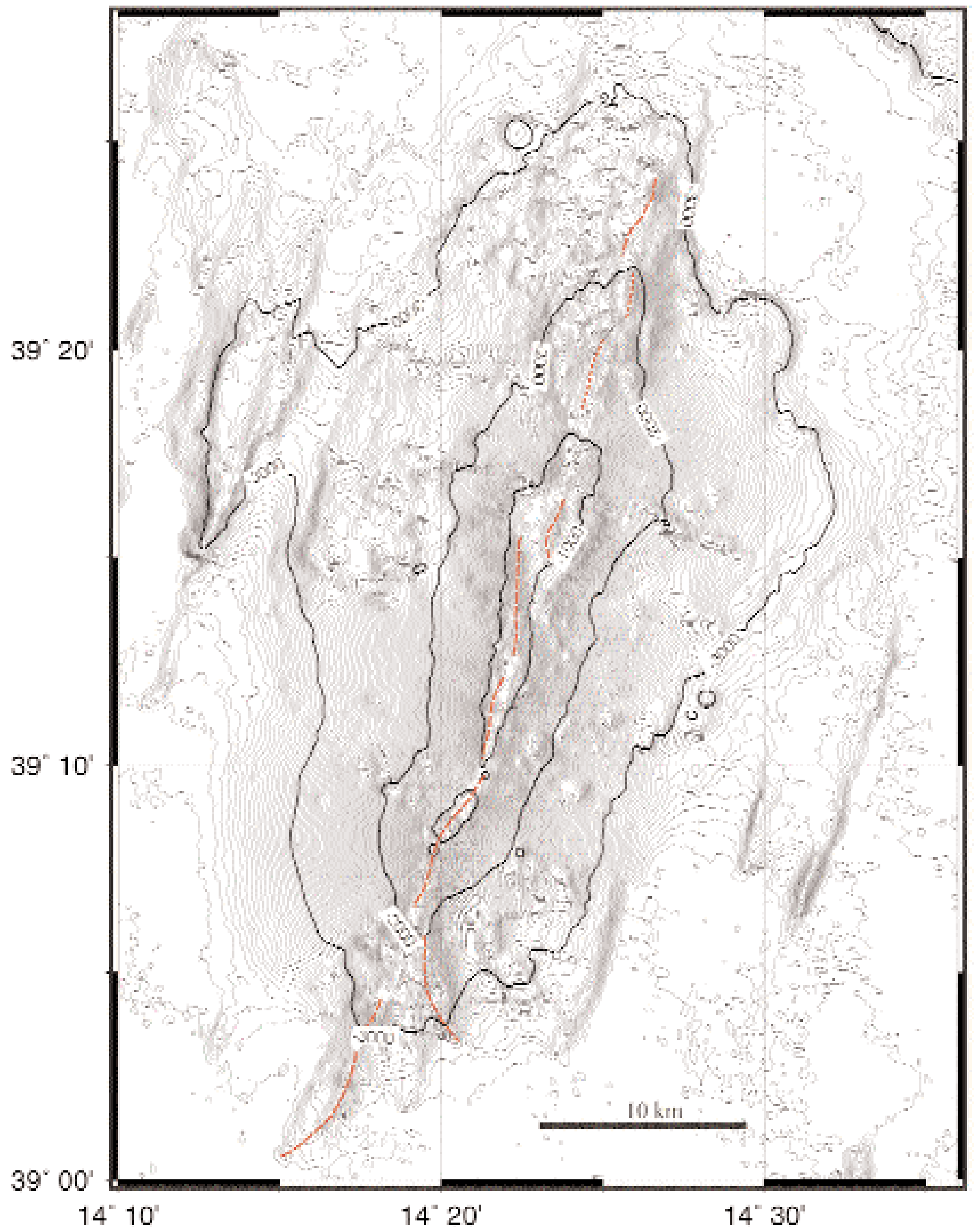

Fig. 3. - *Bathymetry of Marsili volcano (contour interval 25m). In red are traced the linear features that characterise the axial portion of the volcano. Segmentation is given by linear ridges in the northern tip, LCRs along the summit region and circular cone alignments in the southern tip.*

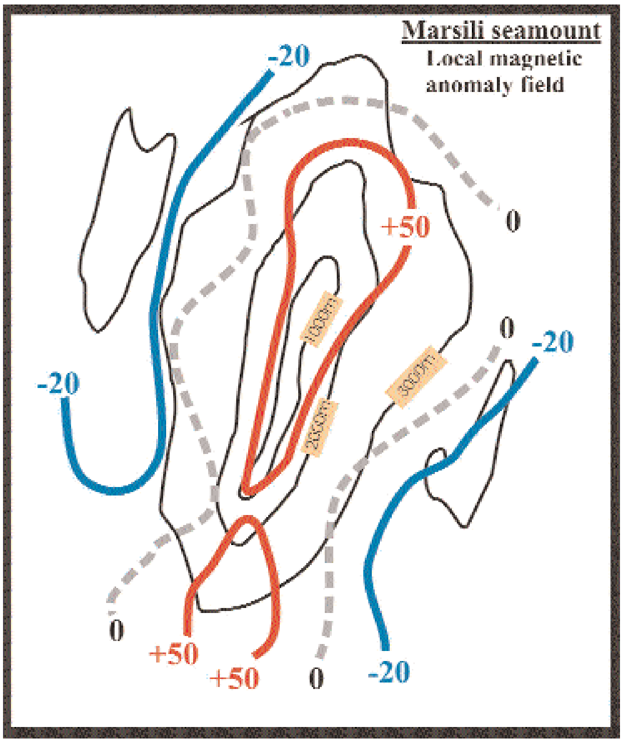

Fig. 4. - *Sketch map of the local magnetic anomaly field centered on Marsili volcano (outlined in black), modified from* FAGGIONI *et alii, 1995. See text for discussion.*

diameters up to 1500 metres and heights up to 300 metres; several are characterised by very low gradient, flat tops (see MARANI & GAMBERI, this volume).

3.4. - BASIN FLOOR FAULTS

Two NNE-SSW-directed (N16°) fault sets, parallel to the general trend of the summit axis, develop symmetrically (fig. 3) in the basin-floor region bounding the south-eastern and north-western flanks of the volcano, forming horst and graben pairs at the sides of Marsili volcano.

3.5. - CHRONOLOGY AND MAGNETIC DATA

Chronological data provide only a partial reconstruction of the volcanic activity of this region: biostratigraphic and magnetostratigraphic constraints indicate that inception of spreading in the western Marsili basin took place between 1.87-1.67 Ma (KASTENS *et alii,* 1988), whereas lavas from the summit of Marsili volcano yield K/Ar ages of 0.1-0.2 Ma (SELLI *et alii*, 1977).

However, this sparse chronological data, in conjunction with the available magnetic anomaly data in the region (FAGGIONI *et alii*, 1995), renders comparative dating possible. Positive anomalies characterise the bulk of Marsili volcano (fig. 4), with highest values distributed along the axis. Locally distinct negative anomalies are positioned on, or in the vicinity of, the basin floor fault zones. The regional anomaly field of the Marsili basin (fig. 5) displays the general spreading setting of the basin.

On the basis of the local and regional magnetic anomaly fields, the 0.1-0.2 Ma summit lavas correlate the positive magnetic anomaly of the volcano to the present-day normal polarity geomagnetic chron C1 (Brunhes, 0.78-0 Ma) (FAGGIONI *et alii*, 1995). The bordering, inversely magnetised basin-floor is attributed to the post Olduvai, late Matuyama chron (1.67-0.78 Ma) (SAVELLI & SCHRIEDER, 1991; FAGGIONI *et alii*, 1995); a time-span which is consistent with the 1.87-1.67 Ma age (positively magnetised Olduvai chron) for inception of spreading in the western Marsili basin based on ODP hole 650 (KASTENS *et alii,* 1988).

Such an arrangement of the anomaly field implies that the bulk structure of Marsili volcano is <0.78 Ma-old and that the off axis, basin floor is older (> 0.78 Ma), indicative of incremental development parallel to the axial elongation of the edifice.

3.6. - SPREADING DIRECTION

The likely direction of the least compressional stress in the Marsili basin region is perpendicular to the basin-floor faults at the time of their formation, and consequently denotes the spreading direction at that time as well. The resulting trend (N106°) is in accordance with the Pleistocene to present-day extensional stress directions (~N100°) that characterise the surrounding land areas (TORTORICI *et alii*, 1993; MAZZUOLI *et alii*, 1995).

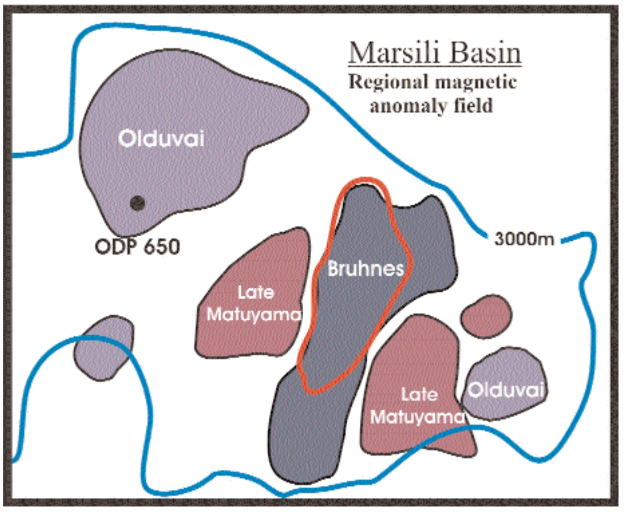

Fig. 5. - *Sketch map of the regional magnetic anomaly field in the Marsili basin (Marsili volcano outlined in red), modified from* FAGGIONI *et alii, 1995, showing interpreted geomagnetic age chrons. For further discussion see text.*

3.7. - Driving force of magma injection

Furthermore, analysis of the discordant directions between segmentation, ridge trend and spreading direction allows the determination of the ratio between the magmatic pressure difference (ΔP) and the regional tectonic stress (ΔS) (Abelson & Agnon, 1997). This results to be 0.33-0.23 for Marsili volcano, a value indicating the dominance of regional stress over magmatic pressure. The fast-spreading East Pacific Rise has a similar ratio, related to the high tensional stress induced by the slab pull forces of subduction at the Pacific active margins. The subduction setting of Marsili ridge is consistent with these observations. Although constructional from a volcanic point of view due to a high melt supply, the low (ΔP)/(ΔS) ratio of the Marsili ridge suggests that the driving forces of melt injection are primarily of tectonic origin.

3.8 - Enhanced magma supply rate

An estimate of the added magma flux to the ridge region to produce super-inflation can be made by conservatively considering the 7 km oceanic crust thickness of the basin. The estimated rates of magma supply to produce the -4000 m basement level along the 50 km length of Marsili ridge are 10.5/14 km^3kyr^{-1} at 3/4 $cmyr^{-1}$ full spreading rates respectively. The supplementary accreted volume of crust due to the above-basement construction of Marsili ridge over the last 0.7 Ma is roughly 1500 km^3, giving an added rate of magma supply of ~2.1 km^3kyr^{-1}, involving an increment due to super-inflation of 15-20% respect to the magma flux due to spreading alone.

4. - THE CASE FOR SUPER-INFLATION

In the previous section we have shown that MOR-like 3rd and 4th order (Macdonald, 1998) constructional and tectonic morphologies characterise the Marsili region. Further support for the spreading ridge nature of Marsili volcano derives from the axis-parallel incremental growth, demonstrated by the magnetic anomaly pattern of the region. Moreover, these features develop on and around the 3000 m high Marsili volcano, rendering necessary a 15-20% increase in the rate of magma supply, focused to the site of the volcano.

We propose that a strong increase of melt production, and resultant robust volcanism, within a relatively young (<2Myr) and immature slow spreading backarc environment are the basic components that concurrently are necessary to generate a super-inflated ridge such as Marsili volcano. This model paradoxically involves a thermally restricted young spreading setting simultaneously affected by a strong thermal pulse of increased magmatism.

4.1. - Thermal limitation –focused crust accretion

The young and immature nature of the backarc basin involves an abrupt transition between the oceanic lithosphere and the surrounding, thicker, continental one (fig. 6).

Bordering, cooler continental lithosphere thermally constricts ridge lengthening or propagation through lateral conductive cooling of the newly accreted Marsili crust, in time gradually restricting spreading ridge volcanism to the finite length-scale of Marsili volcano. As a consequence, accretion of new crust principally occurs through eruptive processes along the length of the resulting spatially restricted or "locked" super-inflated ridge. Horizontal plate separation due to the slow-spreading regime of Marsili basin may be effectively obscured, being outpaced by the increased magma supply to the surface resulting in vertical accretion to produce the super-inflated ridge.

4.2. - Thermal resurgence – augmented magma flux

Recently, Gvirtzman & Nur, (1999) linked shallow lateral asthenospheric mantle flow, due to slab tears of the Ionian slab, to the formation of Etna volcano in Sicily and to decoupling of the upper plate in Calabria, resulting in the strong uplift observed there since 0.7 Ma ago.

In developing the Gvirtzman & Nur (1999) model further, by taking into account the back-arc region, it results that the development of the tear faults in the Ionian slab occurred at the time (~0.7 Ma-ago) that we propose the Marsili spreading centre became thermally constricted and functioned as a super-inflated ridge. We relate the increase in melt production in the backarc region to lateral asthenospheric flow induced by the development of the tear faults within the subducting Ionian slab at the time of ridge formation.

At the deep mantle level of the Marsili basin, low pressure produced at the free, torn, boundaries of the moving slab generates lateral flow of asthenospheric mantle along the deep-seated portions of the slab tears, permitting the injection of buoyant high-temperature material upwards (fig. 7). At the time of detachment, when the slab was torn, triggering fast slab sinking and retreat, the concurrent up-welling of deeper, hot asthenosphere would have thermal perturbed the mantle wedge, inducing partial melting to feed the Marsili ridge region. Geophysical confirmation of the presence of "hot" mantle material restricted to beneath the Marsili basin is provided by the attenuation of mantle-earthquake derived S and Sn shear waves (Mele *et alii*, 1997; Mele, 1998), coherent with the high heat flow present over the Marsili basin.

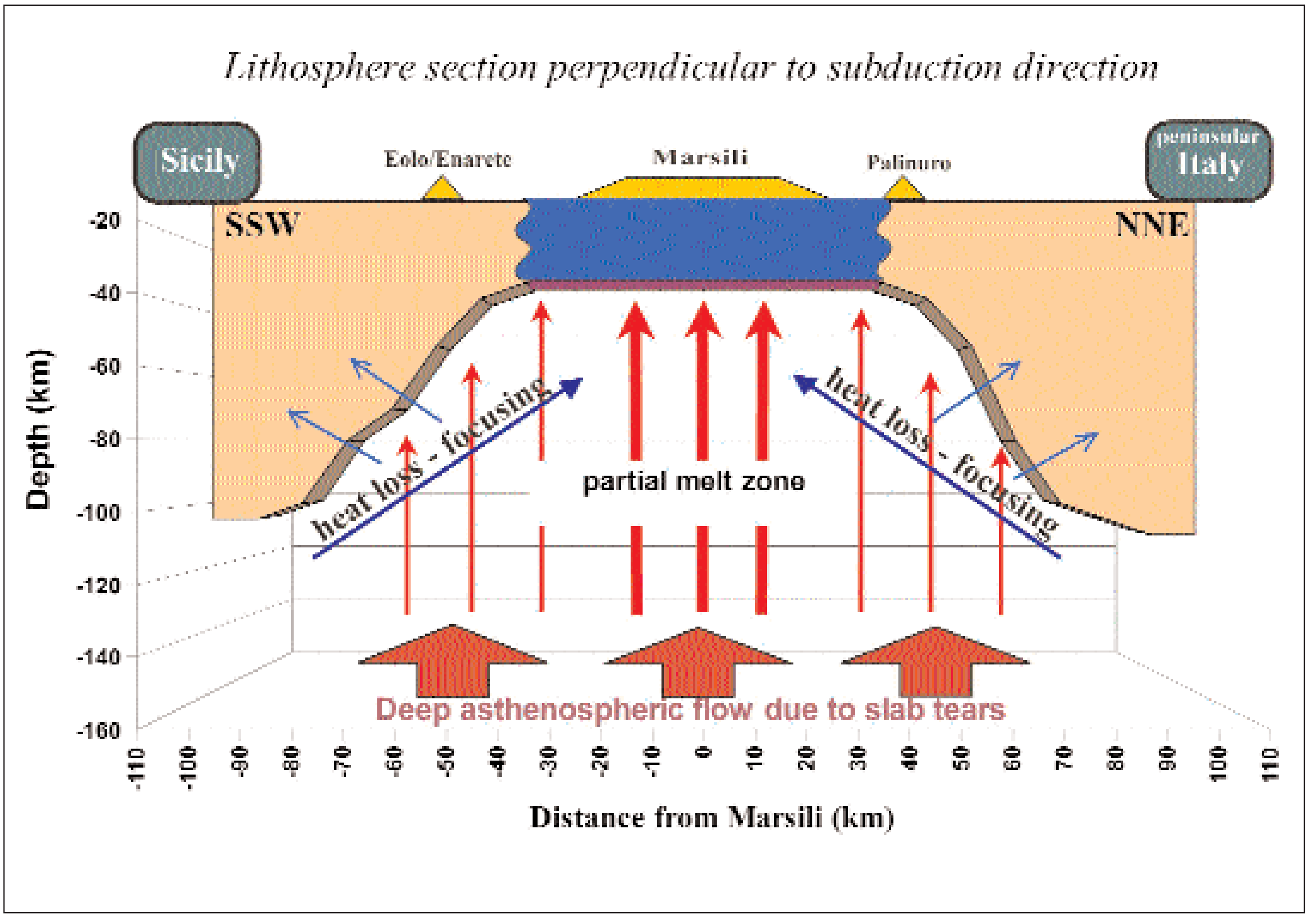

Fig. 6. - *Sketch of lithosphere section perpendicular to the subduction direction showing approximate lithosphere thickness adjacent to the Marsili basin causing focusing of magma supply due to conductive thermal cooling.*

5. - REGIONAL GEOLOGICAL EVIDENCE FOR SLAB TEARING

At the time of formation of the axial part of Marsili volcano (about 0.7 Ma), the central-southern Apennines, formerly undergoing NE-SW shortening, begin to show belt-parallel extension and uplift (PATACCA *et alii*, 1990; HIPPOLYTE *et alii*, 1994; DOGLIONI *et alii,* 1994; GALADINI 1999) which is still observable at present (MONTONE *et alii*, 1997; MARIUCCI *et alii*, 1999). Contemporaneously, strong uplift is also registered in Calabria and north-eastern Sicily (WESTAWAY, 1993; ROBERTSON & GRASSO, 1995; LENTINI *et alii*, 1995; BUTLER *et alii*, 1995).

Tomographic investigations (LUCENTE *et alii*, 1999; CIMINI, 1999) of the Tyrrhenian subduction zone reveal that the ~100 km thick, continuous high velocity mantle anomaly of the slab dips ~70° north-westwards beneath the Marsili basin, to 500 km depth. Shear wave propagation (MELE, 1998) and seismicity (GIARDINI & VELONÀ, 1991; SELVAGGI & CHIARABBA, 1995) demonstrate that the narrow (<200 km) and long (~570 km) Ionian subducting slab is laterally restricted to the terrains of the Calabrian arc and north-eastern Sicily.

The tear faulting event can account for the Early/Middle Pleistocene structural variations, triggering the contemporaneous uplift and extension occurring not only in Calabria, but also in the southern Apennines and Sicily as well. The uplift in the Southern Apennines and Sicily is taken to be the effect of their rebound in response to the release of the lateral stresses that existed prior to tearing.

6. - OFFSHORE VOLCANISM AND TECTONICS RELATED TO SLAB TEARING

The slab tears, detectable by the abrupt NW-SE deep seismicity cutoffs along the south-western margin of peninsular Italy and offshore north-eastern Sicily (FREPOLI *et alii*, 1996), are shown to be capable of transmitting their effects to the overlying crustal regions. The region which we interpret to be above the southern slab tear, is characterised by a roughly NW-SE trending belt composed of the Etna and Ustica Island edifices (fig. 2), both with Ocean Island Basalt (OIB)-type activity showing a slight mantle source contamination from subduction related fluids (BECCALUVA *et alii*, 1982). Along the same alignment,

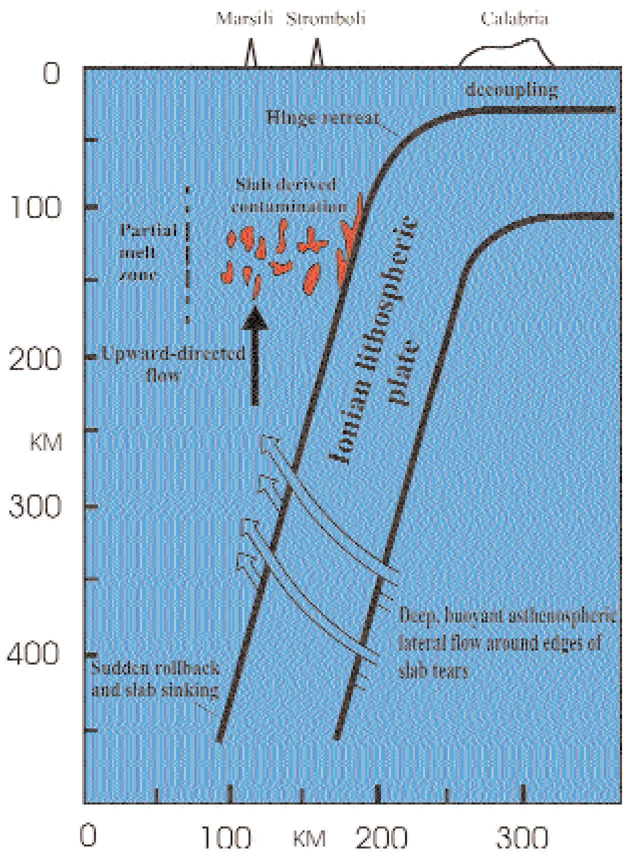

Fig. 7. - *Cartoon representation of the Ionian lithospheric plate with locations of Marsili ridge, Aeolian arc, and Calabria indicated for reference. An abrupt increase of rollback due to the full development of lateral tears in the Ionian slab, between early and middle Pleistocene, generates lateral flow of deep asthenosphere around slab edges, provoking thermal rejuvenation in the previously slab-contaminated partial melting. Kinematics of slab rollback and decoupling are adapted from* GVRITZMAN & NUR (1999a). *See text for discussion.*

samples recovered from the recently discovered Prometeo submarine lava field (MARANI *et alii,* 1999; TRUA *et alii*, 2003), located SE of Ustica Island reveal geochemical characteristics closely resembling those of the hawaiites and mugearites of Ustica island (TRUA *et alii*, 2002; 2003). It is thus suggested that the Prometeo lava field is derived from an intraplate asthenosphere mantle source located at or along the southern boundary of the Ionian slab, as earlier proposed by BECCALUVA *et alii* (1982) for Ustica and Etna volcanoes. This NW-SE trending OIB-type volcanism offers strong evidence supporting the existence of up-welling asthenospheric flow (TRUA *et alii,* 2003) at a location which is aligned with the deep seismicity cut-off tracing the southern tear of the subducting slab, consistent with the model of enhanced melting beneath the super-inflated Marsili ridge. Based on bathymetry data, the offshore NW-SE trending Eolo-Enarete-Sisifo (EES) volcanic alignment (fig. 2), that effectively delimits OIB-type and subduction-affected magmatism, may represent the surface trace of the deep slab tear. The persistence of the EES trend onshore in Sicily, through the Taormina/Tindari-Letojanni tectonic lines (GHISETTI, 1979a; 1979b) which link the Tyrrhenian offshore with the Malta Escarpment, the ancient boundary of the Ionian ocean-floored basin, confirms the structural importance of the composite EES lineament in relation to the Ionian plate (MARANI & TRUA, 2002). In fact, the right-lateral characters of the onshore tectonic lines are in accordance with the expected dextral shearing expected to occur at the southern slab tear.

The deep seismicity cut-off along the northern boundary of the Ionian slab occurs along the central and northern parts of the 1 km scarp of the Sartori Escarpment (SE) system (CURZI *et alii*, 2003) (fig. 2). The left-lateral movement of the SE (MUSACCHIO *et alii*, 1999) is compatible with the shearing sense expected to affect the northern slab tear. These elements point out that perhaps at this boundary of the slab the surface response to tearing is expressed tectonically. Southwards, the NW-SE-trending SE terminates against the E-W structure of Palinuro volcano (fig. 2) essentially outlining the northern limit of the Aeolian arc activity in the region, and thus exerting some form of control on the deep volcanic processes affecting the eastern portion of the volcanic arc.

7. - CONCLUSIONS

The centrally located Marsili volcano is the outstanding feature within the slow-spreading, 2 Ma-year old, Marsili basin. It displays constructional and tectonic features similar to those that characterise MOR spreading centres. Magnetic anomalies in the region show that the bulk of the Marsili volcano developed in the last 0.7 Ma and that incremental growth parallel to the axial elongation of the edifice took place.

It is proposed that Marsili volcano represents a morphologically anomalous, end-member, super-inflated spreading ridge. Increased melt production, and resultant robust volcanism, within the relatively immature (<2Myr) slow spreading Marsili backarc basin is the basic mechanism necessary to generate super-inflation.

Thermal constriction of crust production, due to cool continental lithosphere surrounding the young oceanic basin, restricted spreading-ridge lengthening or propagation to the finite length-scale of Marsili volcano. Emplacement of new crust would thus principally take place through eruptive processes along the length of the spatially restricted "locked" ridge. Slow spreading plate separation at the ridge is outpaced by magma production, resulting in vertical accretion generating the growth of a super-inflated ridge.

Enhanced melt generation in the area of Marsili volcano is provoked by lateral tear faulting of the Ionian slab that occurred in Early/Middle Pleistocene. Sideways flow of asthenosphere developing along the deeper edges of the slab tears causes the injection of

buoyant high-temperature asthenosphere upwards, inducing increased melting in the backarc regions.
Geophysical evidence for the slab tears is furnished by lateral southern and northern cut-offs of the seismicity that traces the subducting slab. Regionally, it is proposed that the Early/Middle Pleistocene extension and uplift of the onshore areas surrounding the Ionian slab, in Calabria, the southern Apennines and north-eastern Sicily, are caused by events of decoupling and rebound, the direct effects of the tearing event.

Surface volcanism and tectonics demonstrate that the effects of the development of slab tears is transmitted to the overlying crust. OIB-type volcanism, trending NW-SE, from the Island of Ustica to Etna volcano by way of the Prometeo submarine lava field offers strong support for the existence of up-welling asthenospheric flow at the southern tear of the subducting slab. Bathymetrically, the surface evidence of the southern tear is suggested to be the submarine alignment of the Eolo and Enarete volcanoes and the Sisifo ridge.
The northern edge of the Ionian slab is marked structurally by an extensive NW-SE-trending sinistral strike-slip fault system that runs along the eastern Tyrrhenian submarine slope. To the south, the fault system ends abruptly at the western edge of the structurally controlled E-W Palinuro volcano alignment, which marks the northernmost limit of Aeolian arc volcanic activity.

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