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Generation and Disruption of Subducted Lithosphere in the Central-Western Mediterranean Region and Time-Space Distribution of Magmatic Activity Since the Late Miocene

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Abstract

The long migration of the Balearic Arc (Alpine-Apennine and Alpine-Maghrebian belts) in the Early-Middle Miocene caused the formation of a subducted lithospheric edifice in the western and central Mediterranean regions. Then, since the Late Miocene, this slab was almost completely disrupted, only maintaining a narrow and deformed remnant beneath the southernmost Tyrrhenian basin. This work describes a tentative reconstruction of the tectonic processes that caused the formation of major tears and breakoffs in the original slabs and the consequent disruption of the subducted lithosphere. In particular, it is suggested that this relatively fast process was produced by the collision between the Anatolian-Aegean system and the continental Adriatic domain, which triggered a number of extrusion processes. Possible connections between the proposed tectonic evolution and the spatio-temporal distribution and geochemical signatures of magmatic activity are then discussed. It is supposed that such activity has been mainly conditioned by the occurrence of transtensional tectonics in the wake of escaping orogenic wedges.

Keywords

Deep Tectonics, Slab Tears and Slab Breakoffs, Magmatism, Central-Western Mediterranean

1. Introduction

It is widely agreed that in the Middle Miocene, the shallow and deep tectonic settings in the central Mediterranean region were similar to the one shown in **Figure 1** (e.g., [1] [2] [3] [4]). The consumption of a large part of the remnant Tethys oceanic domain and the consequent formation of the subducted lithosphere was determined by the migration of the Balearic Arc (Alpine-Apennine and Alpine-Maghrebian belts), driven by the Nubia-Eurasia convergence (e.g., [5] [6] [7] [8]).

The formation of the most northern slab (lying north of the Selli fault) ceased around the upper Miocene, when the Balearic Arc collided with the continental Adriatic domain, whereas the development of the southern slab has prosecuted until the Present, due to the SE ward migration of the southern Apennines and Calabrian wedges (e.g., [6] [8]). This can explain the different dimensions of the above subducted lithospheric bodies.

At present, the distribution of deep earthquakes indicates that the only rigid remnant of the Middle Miocene subducted lithosphere is located beneath the Southernmost Tyrrhenian basin and Calabria (e.g., [9] [10] [11]). Furthermore, the shape of that lithospheric body (**Figure 2**) clearly reveals a strong deformation, characterized by verticalization, narrowing and distortion with respect to its presumed original shape.

In the study area subcrustal earthquakes are also observed beneath the northern Apennines [12] [13] [14] [15], but the depths of hypocentres are mostly shallower than 70 km and the magnitudes of shocks do not overcome magnitude 5.

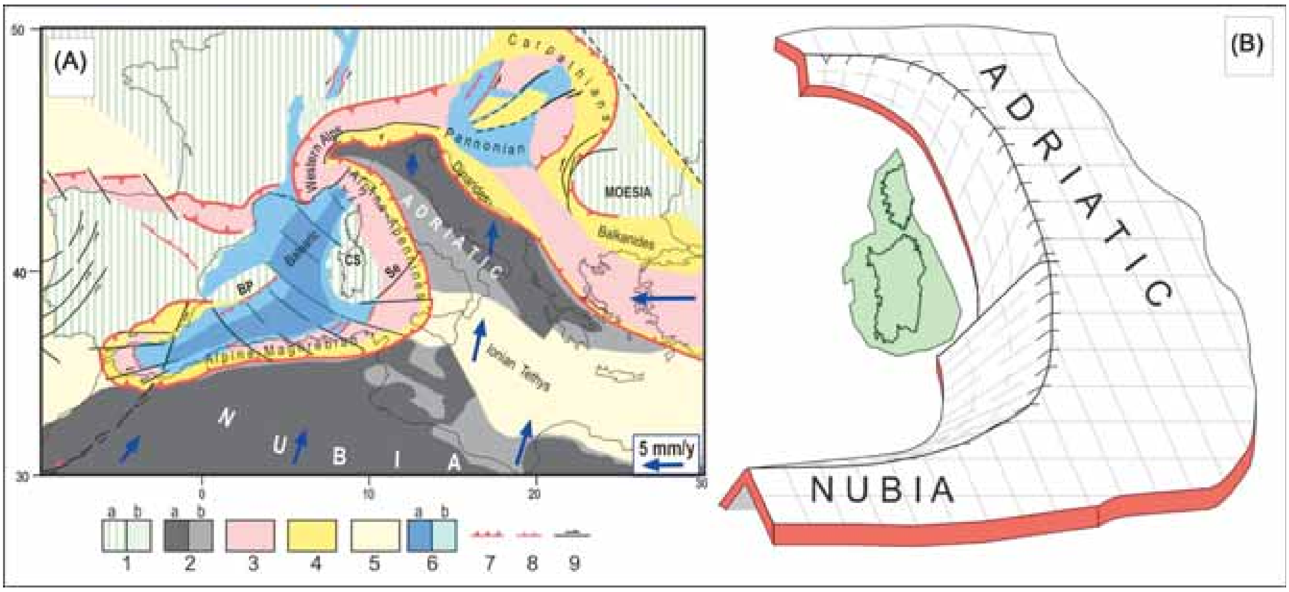


Figure 1. (A) Middle Miocene tectonic setting (after [6] [8]). 1) Continental (a) and thinned continental (b) Eurasian domains 2) Continental (a) and thinned continental (b) African/Adriatic domains 3) Old Alpine orogenic belt 4) Other orogenic belts 5) Old oceanic domains 6) Zones affected by intense (a) and moderate (b) crustal thinning 7) 8) 9) Compressional, extensional and strike-slip features. BP = Balearic Promontory, CS = Corsica-Sardinia block, Se = Selli fault. Present geographical contours (thin black lines) are reported for reference. Blue arrows indicate plate velocities with respect to a Eurasian reference frame (scale in the inset). (B) Perspective view of the subducted lithosperic edifice built up by the migration of the Alpine-Apennine and Alpine-Maghrebian belts.

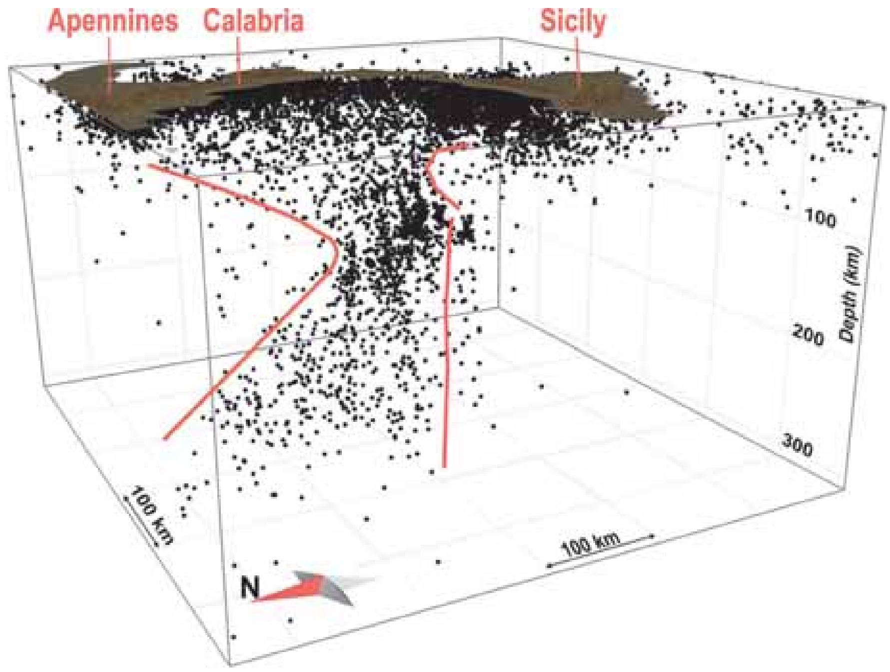
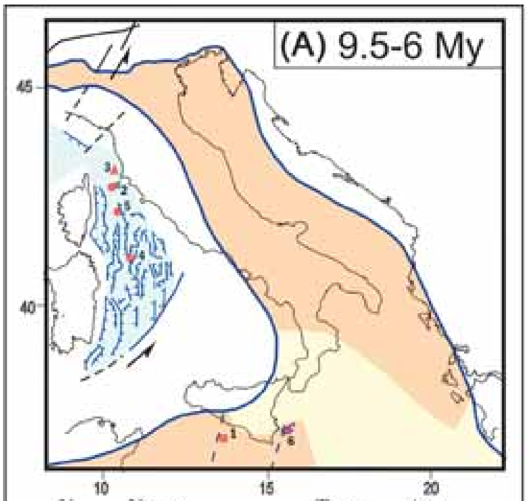


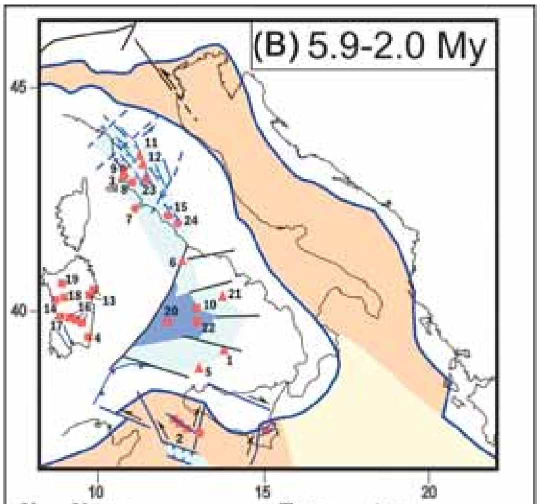
Figure 2. 3D view of earthquake hypocentres beneath the southern Tyrrhenian [11]. Slab boundaries are tentatively delineated by red lines.

Exploiting the information achieved in previous studies about the evolution of crustal structures in the study area [6] [8] [16] [17], this work aims at identifying the tectonic processes that caused deformation, segmentation and then progressive disruption of the subducted lithosphere. To check the plausibility of the proposed evolutionary pattern, we report some considerations about its compatibility with the spatio-temporal distribution and geochemical signatures of magmas (**Figure 3**). A main distinction is adopted between two types of magmas, one, called anorogenic, related to mantle sources not modified by crustal recycling at subduction zones and one, orogenic, derived from mantle sources metasomatically enriched by subduction fluids carrying a sediment signature (e.g., [18] [19] [20] [21]). Some authors (e.g., [19] [22]) suggest that in the Italian-Tyrrhenian region it is possible to recognize another type of magma type, defined as transitional between arc type and Oceanic Island Basalt (OIB) type, that is associated with the formation of slab tears and breakoffs (e.g., [23] [24]). Such discontinuities may generate windows in the subducted lithosphere, through which asthenospheric material can uprise, triggering magmatic activity with different characteristics respect to typical subduction related products (e.g., [22] [25] [26] [27]).

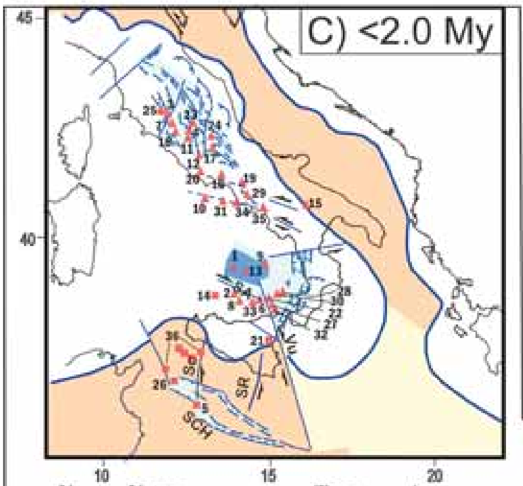
In our reconstruction, we rely on the hypothesis that the occurrence of volcanism is conditioned by the development of a transtensional strain regime in the crust. The connection between transtensional faulting and volcanism in the Roman and Campanian provinces has been pointed out by [28]. Other major examples of this connection have been recognized in the Andes belt by [29], who observed that subduction-related volcanic products were generated in the period



N.	Name	Type	Age
1	Nameless Bank	Anor	9.5
2	Mt.Capanne, Elba	Anat	8.5-6.2
3	Capraia	Or, T-R	7.6-4.6
4	Vercelli	Anat	7.5-6.5
5	Montecristo	Anat	7.1
6	Iblei	Anor	7-1.5



N.	Name	Type	Age
1	Glauco Smt.	Or	Pliocene
2	Tetide-Anfitrite-Galatea-Cimotoe Smts.	Anor	Pliocene-Quaternary
3	Campiglia	Anat	5.9-4.3
4	Capo Ferrato	Anor, S	5.3-4.9
5	Anchise Smt.	Or	5.2-3.6
6	Ponza	Or, Ty	5-1
7	Giglio	Anat	5.1
8	Gavorrano	Anat	4.9-4.3
9	San Vincenzo	Anat	4.7-4.4
10	ODP 655	Anor, Ty	4.6-4.0
11	Orciatico	Or, T-R	4.1
12	Montecatini	Or, T-R	4.1
13	Orosei-Dorgali	Anor, S	3.9-2.0
14	Montiferro	Anor, S	3.8-2.3
15	Tolfa	Anat	3.8-2.3
16	Central Sardinia	Anor, S	3.5-2.1
17	Monte Arci	Anor, S	3.2
18	Campeda-Planargia	Anor, S	3.2-2.0
19	Logudoro	Anor, S	3.2-0.1
20	Magnaghi	Anor	3.0-2.7
21	ODP 651	Or, Ty	3.0-2.6
22	Vavilov	Anor	Late Pliocene-0.1
23	Roccastrada	Anat	2.5-2.2
24	Cerite	Anat	2.4



N.	Name	Type	Age
1	ODP 650	Or, Ty	1.9-1.7
2	Sisifo	Or, Ae	1.3-0.9
3	Radicofani	Or, T-R	1.3
4	Cimini	Or, T-R	1.3-0.9
5	Linosa	Anor	1-0.5
6	Filicudi	Or, Ae	1-0.04
7	Torre Alfina	Or, T-R	0.9
8	Anarete and Eolo	Or, Ae	0.8-0.6
9	Palinuro	Or, Ty	0.8-0.3
10	Ventotene	Or, Ty	0.8-0.1
11	Vico	Or, T-R	0.8-0.04
12	Sabatini	Or, T-R	0.8-0.04
13	Marsili	Or, Ty	0.8-0
14	Ustica	Anor	0.75-1.13
15	Vulture	Or, Lu	0.7-0.1
16	Ernici	Or	0.7-0.08
17	Cupaello	Or, Um	0.6-0.5
18	Vulsini	Or, T-R	0.6-0.1

N.	Name	Type	Age
19	Roccamonfina	Or	0.6-0.1
20	Alban Hills	Or, T-R	0.6-0.04
21	Etna	Anor	<0.5
22	Salina	Or, Ae	0.4-0.01
23	San Venanzo	Or, Um	0.3
24	Polino	Or, Um	0.3
25	Amiata	Anat	0.3-0.1
26	Pantelleria	Anor	0.3-0.005
27	Lipari	Or, Ae	<0.25
28	Stromboli	Or, Ae	0.2-0
29	Phlegraean Fields (buried volcanism)	Or, Ca	<0.2 2
30	Panarea	Or, Ae	0.15-0.01
31	Ischia	Or, Ca	<0.15
32	Vulcano	Or, Ae	<0.12
33	Alicudi	Or, Ae	0.06-0.03
34	Procida-Vivara	Or, Ca	0.05-0.01
35	Somma-Vesuvio	Or, Ca	<0.03
36	Graham Bank, Foerstner	Anor	Late Pleistocene-Holocene

Figure 3. Late Neogene magmatic activity in the tyrrhenian-apennine region in three periods (A), (B), (C) [19] [21] [22] [34] [35] [36] [37]. Magma types: Anat = Crustal anatectic (circles); Or = Orogenic (triangles, Ae = Aeolian, Ca = Campanian, Lu = Lucanian, Ty = Tyrrhenian, T-R = Tuscan-Roman, Um = Umbrian); Anor = Anorogenic (squares, S = Sardinia). Numbers relate to the lists. SA = Sisifo-Alicudi fault system; SC = Sciacca fault, SR = Scicli-Ragusa fault, SCH = Sicily Channel fault system, Vu = Vulcano fault.

35 - 10 My, but their uprise through the crust was only allowed since the late Miocene, when a major strike-slip fault system developed. The priority importance of transtensional regimes in volcanic activity is also underlined by the fact that in major subduction zones (as the Aleutine-Alaska, Andes and Indonesia) volcanoes are associated with major strike-slip fault systems, while whole arc extension is not observed [30]. The above condition implies that the age of magmatism does not necessarily coincide with the emplacement of magmas in the underlying structure, which may have occurred much earlier (e.g., [21] [31] [32] [33]).

The main magmatic centers in the study area, divided in three evolutionary phases, are reported in **Figure 3**. During the first phase (upper-late Miocene), magmatism mainly occurred in the northern Tyrrhenian extensional zone and in the Hyblean domain. In the second phase (Pliocene), magmatic activity involved the northern Apennines, the central Tyrrhenian (Vavilov basin), the Sardinia block and the Sicily Channel. In the third and last phase, magmatism developed in the inner parts of the Romagna-Marche-Umbria wedge (Northern Apennines) and of the Molise-Sannio wedge (Southern Apennines), in the southern Tyrrhenian zone (Marsili basin), in the Aeolian arc lying north of Sicily and in the Sicily Channel.

2. Post Middle Miocene Tectonic Evolution and Magmatic Activity

The Middle Miocene configuration of the Alpine-Apennine belt in the framework of the Mediterranean tectonic setting (**Figure 1**) suggests that such orogenic Arc, stressed by the Nubia-Eurasia convergence, may have undergone S-N shortening, most probably accommodated by eastward oroclinal bending. This deformation triggered the detachment (at least partial) of the belt from the Corsica-Sardinia block, inducing an extensional regime in the interposed zone. This may explain the formation of the Corsica trough, as sketched in **Figure 4** [38] [39] [40] [41] [42] and the occurrence of volcanic activity along the eastern border of the Corsica-Sardinia block (Sisco, 14 My, Cornacya, 12 My, Cornaglia 10 My [43] [44]).

The reconstruction of the tectonic evolution of the western Mediterranean, based on the observed deformations [6] [7] [8] [45], suggests that volcanism with orogenic signature (Sisco and Cornacya, **Figure 4**) could relate to the uprise of previously generated magmas (**Figure 5**). This possibility is more likely for the magmatic activity in northernmost Corsica (Sisco, **Figure 4**).

On the basis of tomographic investigations, some authors (e.g., [46] [47] [48]) envisage a western-dipping slab under the northern Apennines and northern Tyrrhenian. However, this interpretation is not confirmed by the results of other kinds of studies. The analysis of seismic soundings in the northern Tyrrhenian-Apennine system [2] [49] suggests that the Adriatic margin underthrusted the northern Apennine belt, but the buried structure only reached depths of some tens of km, in agreement with the distribution of subcrustal earthquakes.

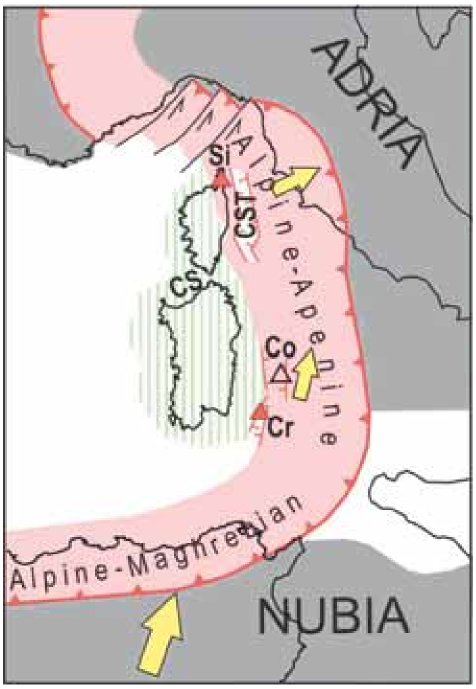


Figure 4. In the Middle-Late Miocene, the roughly SSW-NNE compression induced by the Nubia-Eurasia convergence caused oroclinal bending of the Alpine-Apennine belt, leading to its partial detachment from the Corsica-Sardinia block and to the consequent formation of the Corsica trough. Red triangles indicate the locations of magmatic centres with orogenic signature. The empty triangle indicates no clear information on the signature of volcanism (See the discussion of [43] [44]). Yellow arrows indicate the Nubia-Eurasia convergence and the consequent displacement of the stressed belt. CS = Corsica-Sardinia block, Co = Cornaglia seamount (10 My), Cr = Cornacya seamount (12.6 My), CST = Corsica trough. Si = Sisco (14 My).

Geological evidence in the northern Apennines, with particular reference to the lack of accretionary activity and the occurrence of subsidence, with the formation of several troughs [50]-[55], does not suggest the development of a significant subduction process during the opening of the northern Tyrrhenian basin. Moreover, one should take into account that the presumed consuming process along that trench would have involved the hardly subductable continental Adriatic lithosphere, *i.e.* the domain that forced the Balearic Arc (Corsica-Sardinia-Alpine-Apennine belts) to stop its eastward migration in the Middle Miocene [6] [7] [8]. Further ambiguity about this problem is given by the fact that more recent tomographic investigations in this zone (e.g., [56] [57]) do not indicate the presence of a well-developed slab under the northern Apennines.

The partial detachment of the Alpine-Apennine belt from the Corsica-Sardinia block and the escape of Eastern Alpine wedges towards the Carpathian zone favoured a major change in the kinematics of the northern Adriatic promontory, which allowed overcoming the highly resisted constrictional context created by the continental collision between the Adriatic promontory and Eurasia in the Alps (**Figure 1**). Such change was triggered by the decoupling of the main Adriatic domain from its northwestern edge (deeply stuck into the

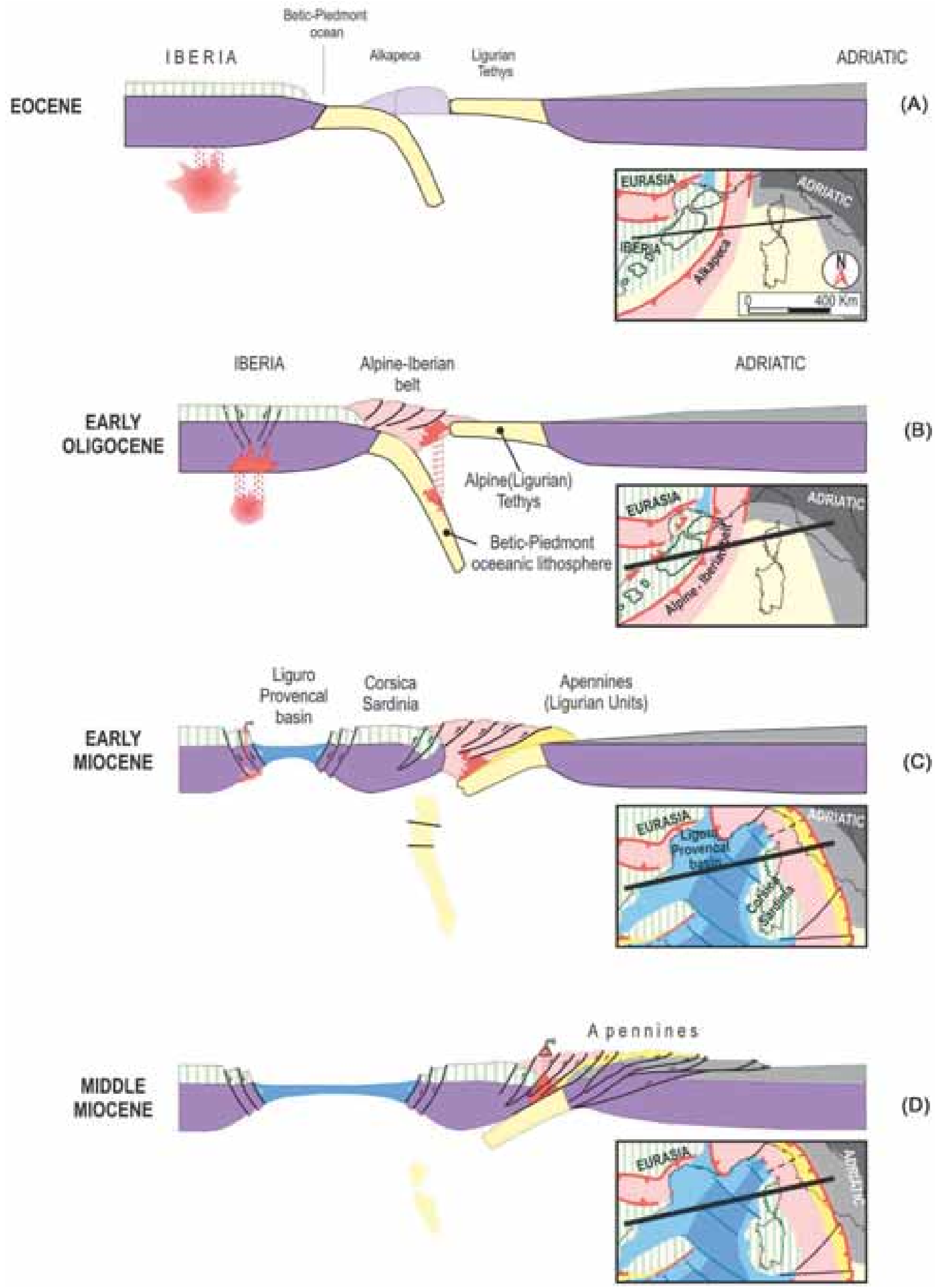


Figure 5. (A) Eocene. The Betic-Piedmont oceanic lithosphere subducts beneath the AlKaPeCa system (Alboran-Kabylides-Peloritani-Calabria, e.g. [45]). Subduction-related calc-alkaline magmas (generated by the slab dipping perpendicular to the section) accumulate in the lower crust of eastern Iberia. (B) Early Oligocene. The Betic-Piedmont oceanic lithosphere is completely consumed and the Alpine–Iberian accretionary belt (including AlKaPeCa) is formed. Crustal transtension starts developing in the Iberian domain, in the wake of the Northern Alpine-Iberian-Corsica-Sardinia arc, allowing the subduction-related calc-alkaline magmas generated in the previous phase to rise through the upper crust. This kind of magmas also accumulated above the slab dipping eastward beneath the AlKaPeCa structure. (C) Early Miocene. The opening of the Liguro-Provençal basin develops in the wake of the Northern Alpine-Iberian-Corsica-Sardinia arc, while the old eastward dipping slab is undergoing progressive disruption. The Ligurian Tethys oceanic domain is consumed. (D) Middle Miocene. The Liguro-Provençal basin is formed. The convergence between the Arc and the Adriatic is accommodated by consumption of the thinned continental Adriatic lithosphere. Accretionary activity along the outer front of the migrating Arc led to the formation of the Apennine belt. The triangle indicates the volcanic activity (Sisco in eastern Corsica) caused by magmas generated in the Oligocene by subduction of the Betic-Piedmont oceanic lithosphere (modified after [8]).

Western Alps), allowed by the reactivation of an old weakness zone (Giudicarie) as a sinistral shear fault system [58] [59] [60] [61]. Once decoupled, the northern Adriatic domain underwent a roughly NNE ward displacement and clockwise rotation (**Figure 6**), so releasing the internal deformation (upward flexure and counterclockwise torsion) accumulated during the long oblique collision with the Eurasian continental domain.

The Giudicarie decoupling was followed within a short time interval by the development of the northern Tyrrhenian basin. The analysis of the deformation pattern in the whole central Mediterranean region suggests a close connection between the above tectonic processes [6] [8] [61]. The divergence between the Adriatic domain and the fixed Corsica-Sardinia block induced extension in the interposed zone, leading to the formation of the northern Tyrrhenian basin. One may expect that during this phase the western buried margin of Adria (dragged NNE ward) underwent subsidence and stretching, since the deepest tip of that slab was most probably fixed under the Corsica-Sardinia block (**Figure 7(B)**). This deformation of the slab is suggested by mechanical considerations and by the subsidence and E-W extension that affected the overlying Apennine-Alpine belt, with the formation of the Northern Tyrrhenian basin and the occurrence of subsidence and extension in the inner Apennine belt (**Figure 7(B)**). The northern Tyrrhenian extensional zone was confined to south by the Selli fault (most probably corresponding to a major discontinuity of the underlying slab, (**Figure 6**), which decoupled the subsiding Adria buried margin from the slab which lay beneath the Central-Southern Apennines-Calabria orogenic belt. The proposed genetic mechanism of the northern Tyrrhenian basin can plausibly account for the onset time of this event (triggered by the Giudicarie decoupling event in the Tortonian), for the almost triangular shape of the basin (developed between the fixed Corsica-Sardinia block and the rotating Adria continental domain) and for the location of its southern boundary (the Selli fault system).

The Northern Tyrrhenian extensional phase can explain the age (8.5 - 6 My) and location of the anatectic magmatism that developed in the Northern Tyrrhenian (**Figure 3(A)**). The orogenic signature of magmas in Capraia (7.6 - 4.6 My) may be related to a previous subduction process, as discussed earlier (**Figure 5(B)**). The lowering of the Adriatic buried margin with respect to the Adria domain lying west of the Giudicarie fault system generated a vertical offset in that fault (**Figure 7(B)**, [6]), now buried under the thick sedimentary cover of the Po Valley [61].

As suggested in previous papers [5] [6] [8] [16] [17], the tectonic setting in the central Mediterranean area underwent a drastic change around the late Miocene-Early Pliocene, due to the collision between the Adriatic continental domain and the Aegean sector of the Tethyan belt, after the complete consumption of the interposed thinned domains (**Figure 8(A)**). The strong increase of resistance against any further shortening in the Adria-Aegea collision zone (crustal thickening and uplift) and the consequent need of activating a less resisted

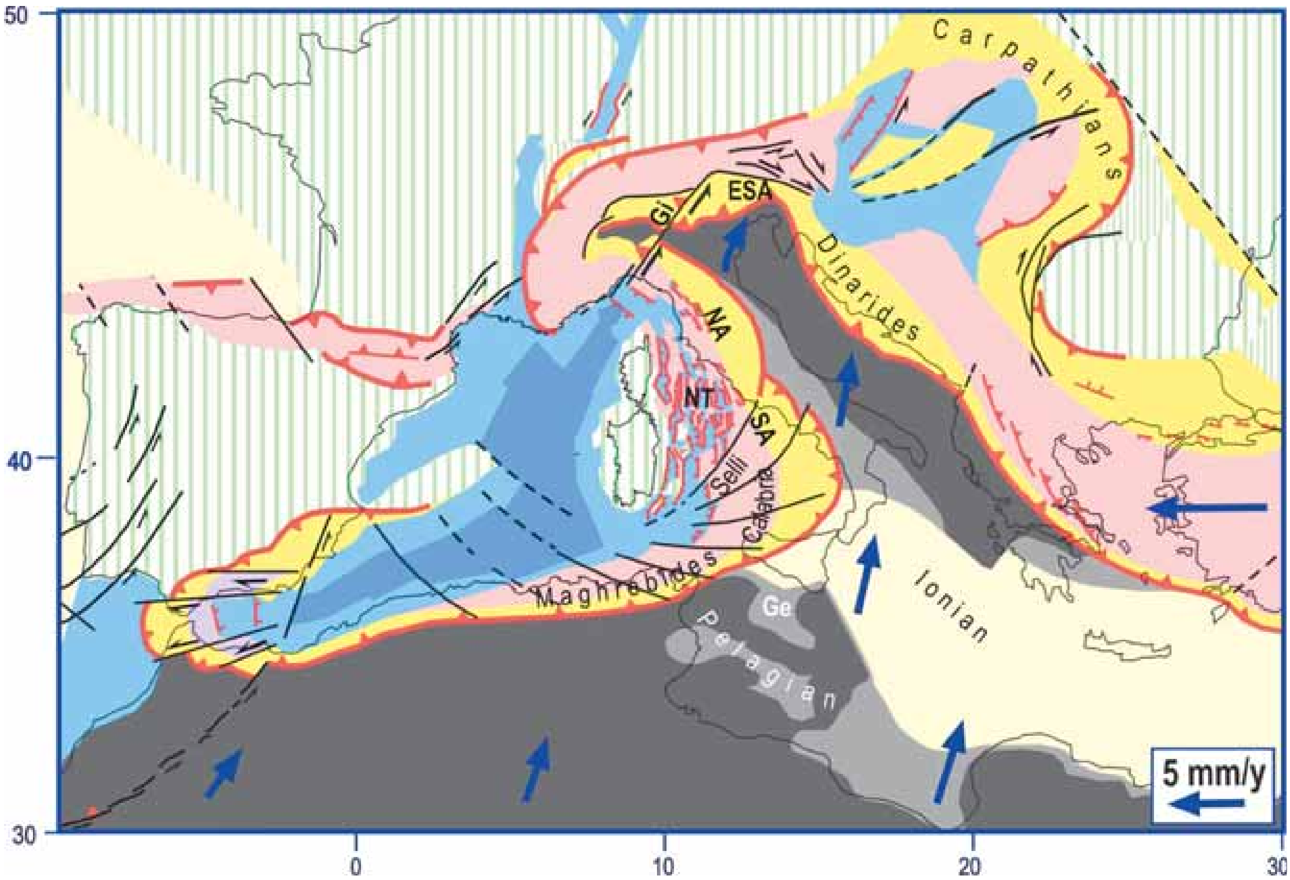


Figure 6. Late Miocene-Early Pliocene tectonic setting. The activation of the Giudicarie fault system allowed the main Adria domain to decouple from its northwestern edge and to move NNE ward. This determined the stretching and subsidence of the buried Adriatic margin, with the consequent formation of the northern Tyrrhenian basin in the overlying crust (**Figure 7**). ESA = Eastern Southern Alps, Ge = Gela thinned domain, Gi = Giudicarie fault system, NA = Northern Apennines, NT = North Tyrrhenian basin, SA = Southern Apennines.

shortening pattern caused a drastic reorganization of the tectonic setting in the central Mediterranean region, aimed at consuming the thinned domains that in the Early Pliocene were still present in that zone. The main tectonic event which favoured such final objective was the decoupling of the Adria plate from Nubia, by the activation of the Victor Hensen and Sicily Channel fault systems, and its clockwise rotation accompanied by a minor NNW ward motion (**Figure 8(A)**). The consequent convergence between the southern part of Adria, moving roughly westward, and Nubia, moving NNE ward [7] [8] [17] [62], produced a complex of shortening processes in the Pelagian and northern Nubian zones [6] [7] [8]. A major effect of this compressional context was the northward extrusion of the Adventure wedge and the consequent displacement of the facing Alpine-Maghrebian belt. On its turn, this displacement induced a strong S-N compressional regime in the Alpine-Apennine orogenic structure which lay south of the Selli fault, causing the lateral eastward escape of wedges (southern Apennines and Calabria), at the expense of the thinned continental Adriatic margin (and possibly of the remnant Tethys domains, **Figure 8(A)**). This

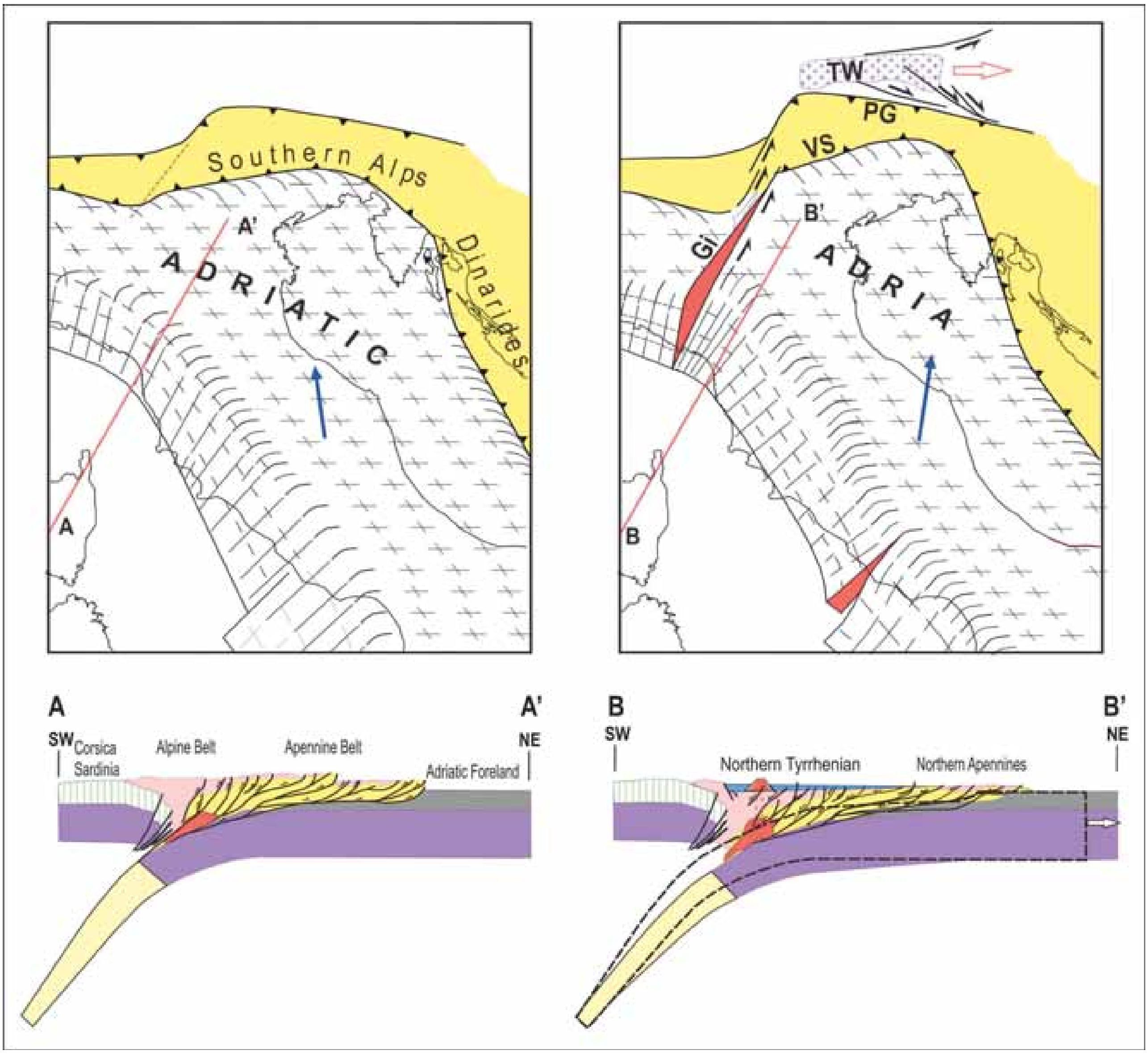


Figure 7. (A) Middle Miocene configuration. (B) Late Miocene: the reactivation of the Giudicarie fault allows the main Adria plate to move roughly NNE ward with respect to its northwestern edge. Since the deepest tip of the slab is fixed under the Corsica-Sardinia block, the NNE pull of Adria causes a stretching and consequent subsidence of the slab. The most intense subsidence occurred in the sector close to Corsica, leading to the formation of the northern Tyrrhenian basin, while more moderate extension and subsidence affected the eastern Apennine belt. The dashed line in the section BB' indicates the shape of the slab before stretching (modified after [61]). Gi = Giudicarie fault system, PG = Pusteria-Gail line, TW = Tauern window, VS = Valsugana Front.

consuming process caused further accretionary activity along the outer front of the southern Apennines and Calabrian wedges, while crustal stretching occurred in the wake of such escaping wedges, forming the Central Tyrrhenian basin (Vavilov). The retreat of the underlying slab caused its separation from the slab sector which lay beneath the northern Apennines (**Figure 8**), with the possible formation of a window in the subducted lithosphere underlying the central Apennines.

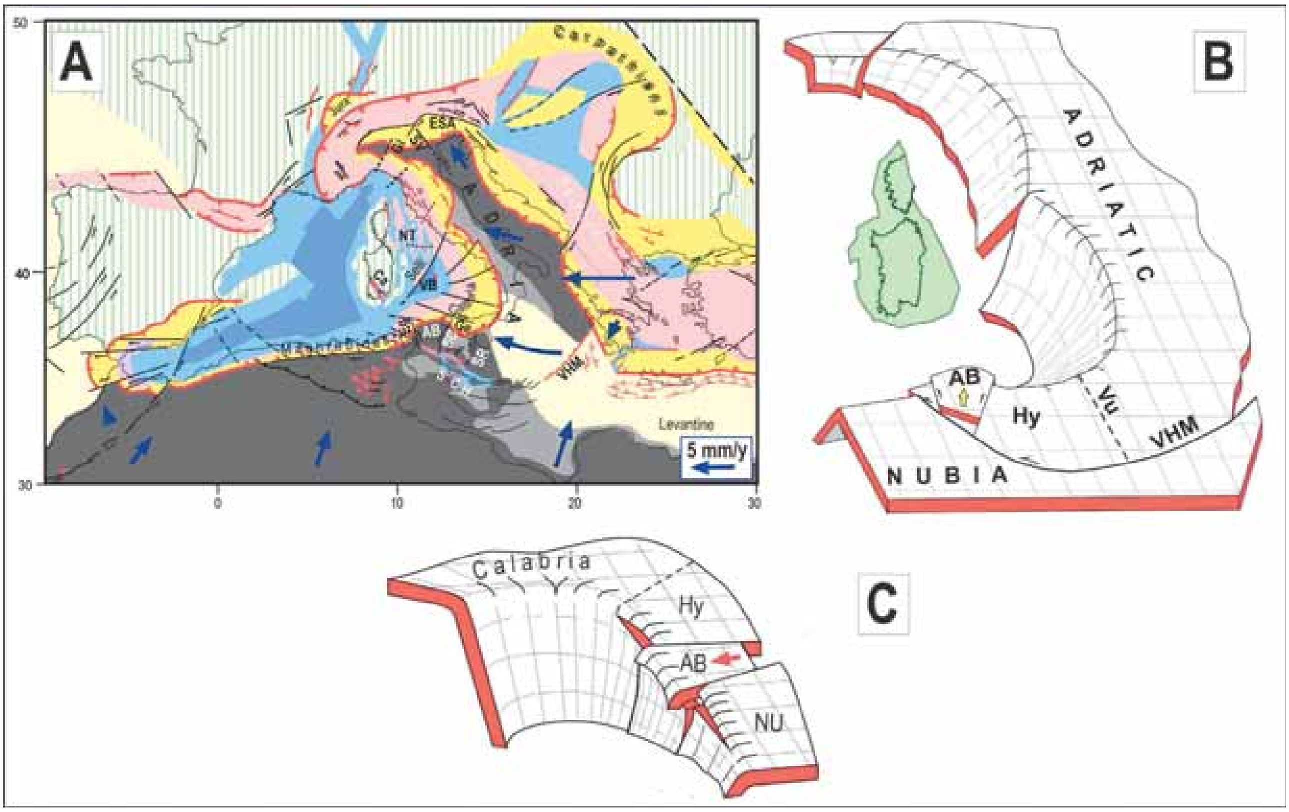


Figure 8. (A) Middle Pliocene tectonic setting AB = Adventure block, Ca = Campidano graben, ESA = Eastern Southern Alps, Gi = Giudicarie fault system, NT = North Tyrrhenian basin, SC = Sciacca fault, SCH = Sicily Channel fault system, SR = Scicli-Ragusa fault, SV = Schio Vicenza fault, VB = Vavilov basin, VHM = Victor Hensen-Medina fault system. (B) Perspective view of the subducted lithosphere. (C) Perspective view of the African slab (seen from NorthWest) which was deformed by the indentation of the Adventure escaping wedge. Hy = Hyblean block, NU = Nubia. Colours, symbols and other abbreviations as in **Figure 1** and **Figure 6**.

In the Pliocene, the northward push of the Maghrebian belt, transmitted by the Alpine-Apennine orogenic body lying south of the Selli line, induced S-N compression in the northern Apennine wedge, causing or enhancing its outward oroclinal bending. The sinistral transtensional regime that developed in the inner side of that arc (e.g., [63]) may have favoured the uprise of anatectic magmas in the western side of Tuscany (**Figure 3(B)**). The orogenic signature of magmas in Orciatico and Montecatini (4.1 My), in analogy with the previous activity in Capraia (7.6 - 4.6 My), may derive from the uprise of magmas emplaced during a previous subduction process (**Figure 5(B)**).

The Northward displacement of the Maghrebian belt, pushed by the Adventure block, also stressed the Corsica-Sardinia block, as suggested by the formation of the Campidano graben in the Pliocene [64] [65] [66]. This event can hardly be attributed to other driving forces, given the lack of interaction of the Corsica-Sardinia block with any other structure since the middle Miocene [6] [8]. The S-N compression that the above block underwent during that phase may have induced the E-W extension that allowed orogenic magmatic products to reach the surface (5.3 - 0.1 My, **Figure 3(B)**).

The high spreading rates (4 - 5 cm/y) recognized in the Vavilov basin [67] [68] during the Pliocene can be due to the fact that the compressional regime that caused the lateral escape of the Southern Apennines-Calabrian wedge was strengthened by the clockwise rotation of the Adria plate. This additional driving force may have accelerated the extrusion rate of the Apennines wedges and consequently the extensional rate in the back-arc Vavilov basin.

During the Pliocene, crustal stretching in the Central Tyrrhenian basin (Vavilov) generated anorogenic volcanism (Na-alkaline, transitional and thoelitic), as the ODP 655 (4.6 - 4.0), Magnaghi (3.0 - 2.6 My) and Vavilov (Late Pliocene-0.1 My), along with orogenic magmas (calcalkaline and shoshonitic), as the Anchise (5.2 - 3.6 My), Ponza (5 - 1 My), and ODP 651 (3.0 - 2.6 My). Orogenic products may relate to the uprise of contamined magmas generated in a previous subduction process (**Figure 8**). The fact that the magmatic activity in the Hyblean plateau (7 - 1.5 My) is coeval with the post late Miocene rotation of the Adria plate, may suggest that such activity was related to the generation of pull-apart troughs along major shear faults (such as the Scicli-Ragusa, **Figure 3**) that developed in this plateau in response to the strong E-W compression induced by Adria's rotation.

During the Pliocene, major deformation of subducted lithosphere may also be expected in the slab underlying the Alpine-Maghrebian belt, due to the northward extrusion of the Adventure block [6] [8]. The mechanism that may have caused the deformation and progressive disruption of the slab is tentatively sketched in the sections of **Figure 9**. This kind of process may occur when the foreland continental domain of the upper plate involved in a subduction zone is forced to move against its buried margin. At first, this mechanism is most probably accommodated by upward flexure of the trench zone and verticalization of the uppermost slab. Then, such deformation can generate tears or thinning in the most stressed slab sectors (necking), leading to its progressive disruption. This may explain why no evidence of subducted lithosphere is now recognized under the Alpine-Maghrebian belt.

A major deformation in the Tyrrhenian slab most probably developed since the late Pliocene, after the suture of the southern Apennines consuming boundary (**Figure 10**). Since that suture, the compressional regime in this zone (due to the convergence of the confining blocks: Nubia, Adria and Adventure block) was mainly accommodated by the lateral escape of the Calabrian wedge, at the expense of the Ionian oceanic domain. To retreat under the migrating Calabrian wedge the underlying slab had to decouple from the fixed southern Apennines slab by the formation of major tears and breakoffs. After this fragmentation/necking, the slab may have undergone a progressive disruption, which may explain why no deep earthquakes occur beneath the southern Apennines (**Figure 2**). The formation of tears in the above phase could have allowed the uprise of asthenospheric material under the southern Apennines.

The conditions that have allowed such magmas to reach the surface in relatively large zones (**Figure 3(C)**) were created by the deformation that the

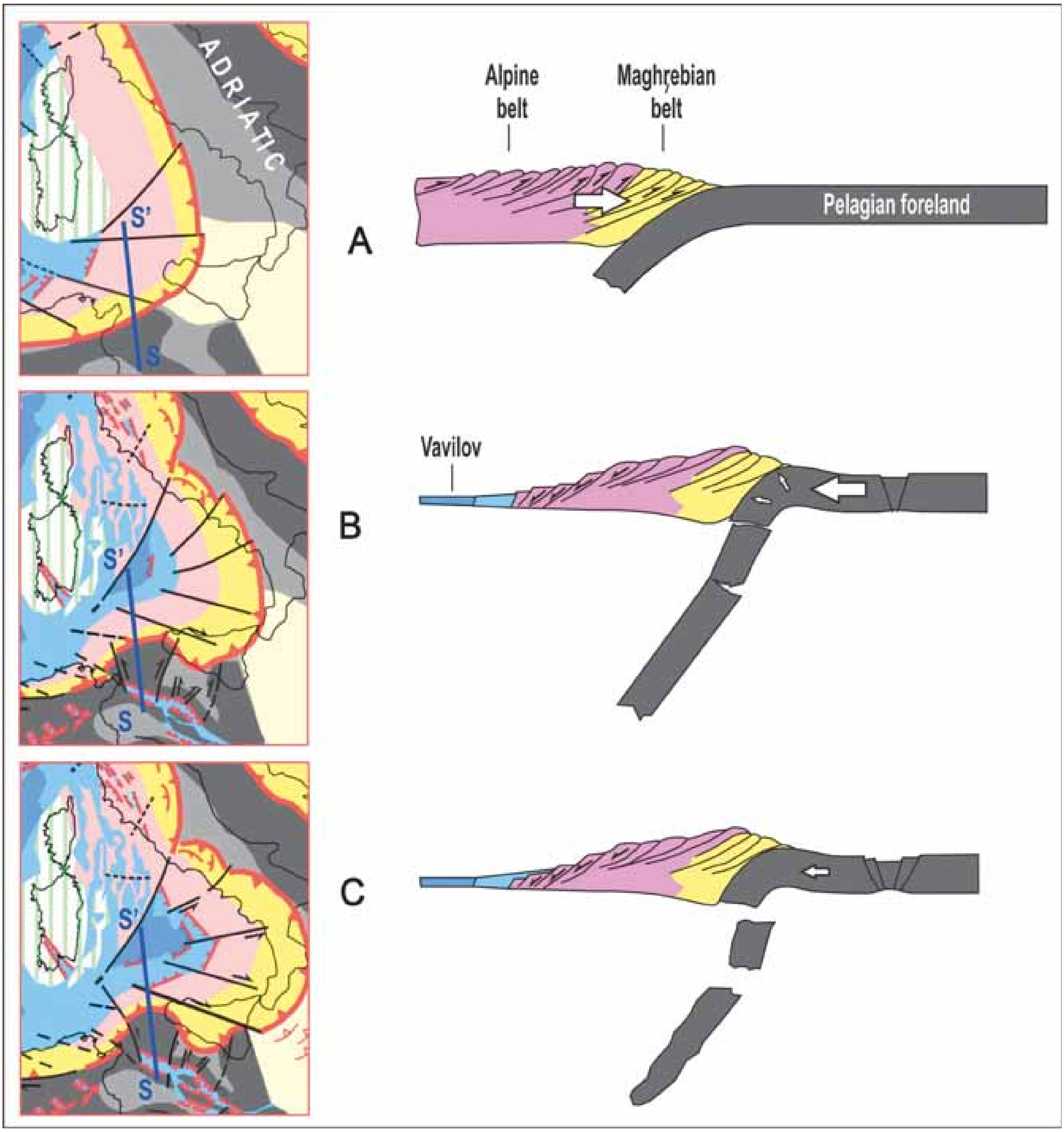


Figure 9. Tentative reconstruction of the tectonic evolution of the slab underlying the Alpine-Maghrebian belt along the trace of the section SS'. (A) Middle Miocene, configuration after the stop of the Corsica-Sardinia block. (B) Middle Pliocene. The northward extrusion of the Adventure block causes the displacement of the Alpine-Maghrebian belt and the eastward extrusion of the Alpine-Apennines wedges. The underlying slab undergoes verticalization and bending. (C) Early Pleistocene. The fragmentation of the slab triggers the progressive destruction of the subducted lithosphere. Colours and symbols as in **Figure 1**.

Apennine belt underwent in response to the northward motion of the Adriatic plate (**Figure 11**, [6] [7] [16] [69]). The belt-parallel shortening induced by such tectonic mechanism mainly stressed the eastern side of the belt (being more closely connected with the underlying Adriatic margin) while the western belt

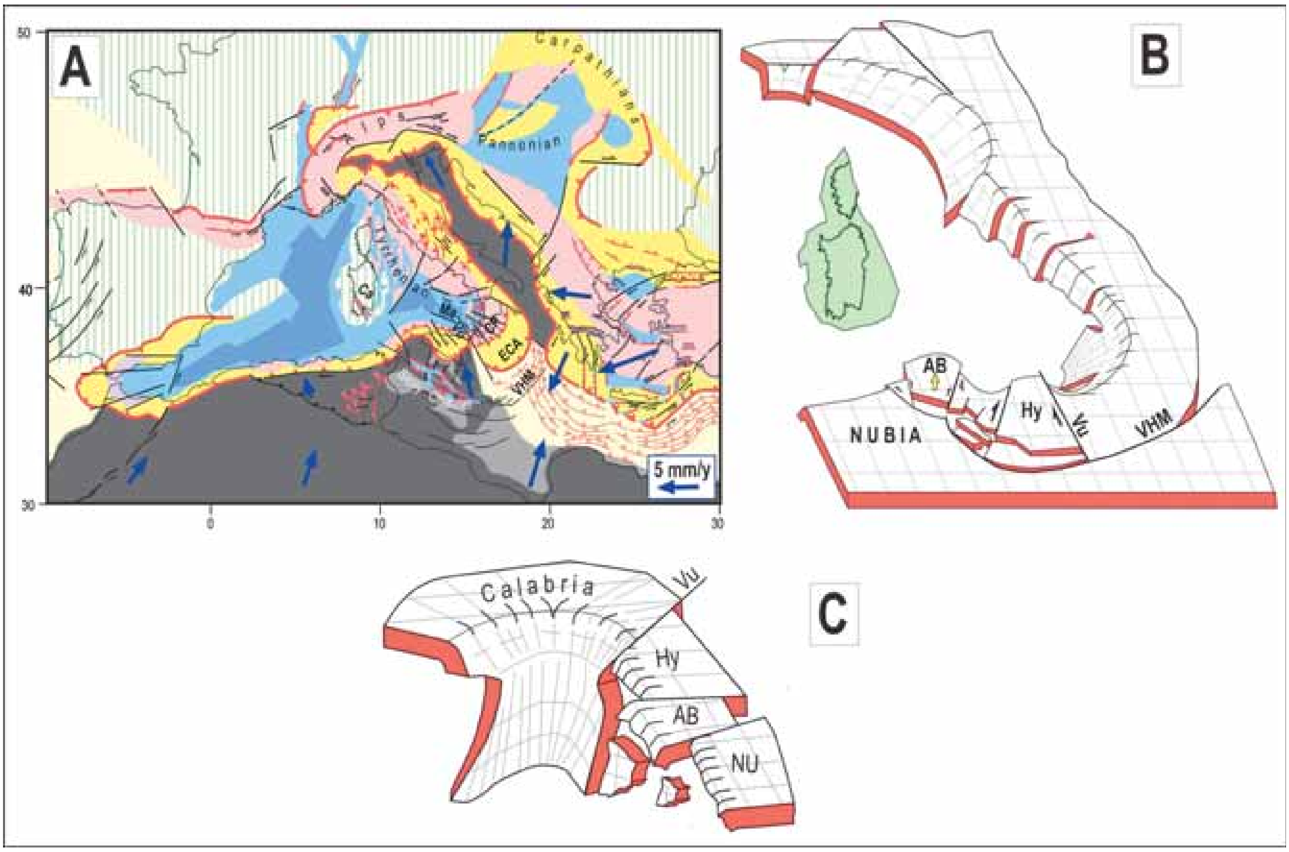


Figure 10. (A) Pleistocene tectonic setting, after the suture of the Southern Apennines trench zone. CP = Calabria-Peloritani wedge, ECA = External Calabrian Arc, Ma = Marsili basin, Vu = Vulcano fault (B) Perspective view of the subducted lithosphere. (C) Perspective view of the African slab (seen from NorthWest), deformed by the indentation of the Adventure and Hyblean escaping wedges. Colours, symbols and other abbreviations as in **Figure 1** and **Figure 8**.

side, being less connected with the (deeper) underlying Adriatic margin, was poorly involved in this process. The above tectonic mechanism resulted in a faster motion of the eastern side of the belt with respect to the western side. Such kinematic pattern in the Apennines is still going on, as indicated by geodetic data (e.g., [70] [71]). The relative motion between the inner and outer Apennine bands generated a sinistral transtensional regime in the axial part of the chain. This regime was particularly intense in the inner side of the two main extruding wedges of the eastern belt, the Molise-Sannio and Romagna-Marche-Umbria (**Figure 11**), creating a favourable condition for the uprise of the magmas emplaced in previous tectonic processes [31]. In this regard, it can be noted that the large Roman and Campanian magmatic provinces are just located along the internal boundaries of the two extruding wedges (**Figure 11**).

The extensional/transtensional regime that developed in the wake of the Calabrian wedge, forming the Marsili basin, may be responsible for the occurrence of volcanic activity in the southernmost Tyrrhenian zone during the Quaternary. Crustal stretching most probably generated anorogenic volcanism, while the orogenic signature of the Aeolian volcanic Arc may be related to the deformation and breaking of the underlying slab (**Figure 10**).

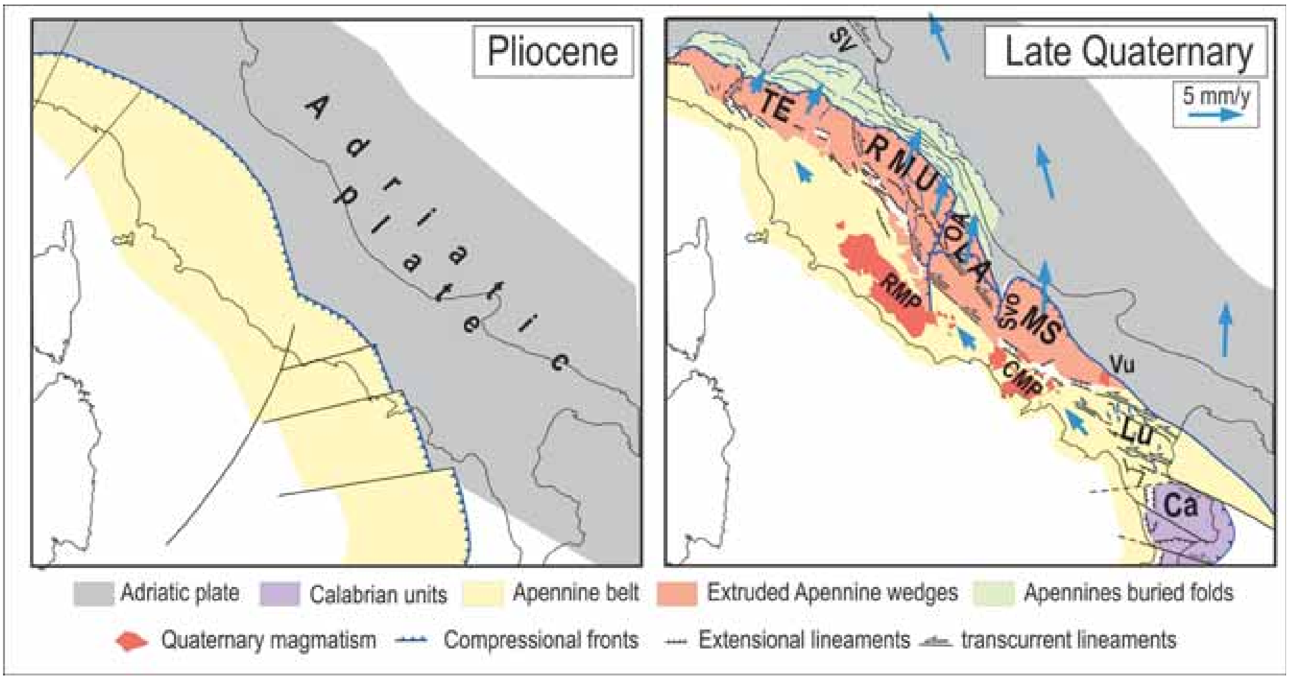


Figure 11. Pliocene: Configuration of the Apennine belt. Late Quaternary: Stressed by the Adriatic plate, moving roughly northward, the eastern part of the Apennine belt (dark brown) underwent belt parallel shortening, mainly accommodated by the formation of arcs, transversal thrusts and by intense uplift. Ca = Calabria, CMP, RMP = Campanian and Roman magmatic provinces, LA = Lazio-Abruzzi wedge, Lu = Lucania Apennines, MS = Molise-Sannio wedge, OA = Olevano-Antrodoco thrust front, RMU = Romagna-Marche-Umbria wedge, SV = Schio-Vicenza fault, SVo = Sangro-Volturno thrust front, TE = Toscana-Emilia wedge, Vu = Vulture. Blue arrows indicate the kinematic pattern, compatible with Pleistocene deformations and geodetic data [70] [71].

In this regard, [72] suggest that the dextral strike-slip Sisifo-Alicudi shear zone (**Figure 3**, also reported by [73] [74]) and the related volcanic edifices, may represent the shallow expression of the deep seated lithospheric tear discontinuity separating the Sicily and Calabria slab sectors. The same authors point out that the migration trend of volcanic activity in the western Aeolian arc changed from SE-ward (in the late Pliocene-early Pleistocene) to SSE-ward (in the middle-late Pleistocene). It can be worth noting that this variation and the stop of volcanic activity in the western Aeolian Arc is compatible with the change of extruding direction of the Calabrian wedge (e.g., [8]). This change was triggered by the activation of the dextral Vulcano fault which favoured the decoupling between the Calabrian wedge (moving SSE ward) and the Hyblean block (moving NNW ward). The end of volcanic activity at the western Aeolian Arc may be explained as an effect of the compressional regime [74] [75] that was induced in this zone by the motion of the Hyblean block. This last regime is compatible with the focal mechanisms of earthquakes occurred along the Sisifo-Alicudi fault zone [72].

3. Discussion

Many hypotheses have been advanced about the tectonic processes that can cause the destruction of subducted lithosphere, mostly based on the concept that such process is triggered by the formation of slab tears and slab breakoffs (e.g., [25] [76]). For the central Mediterranean region this kind of interpretation is suggested by [22], which suppose that the generation of slab tears is mainly due to different rates of slab retreat at trench zones. However, the approach used by these authors to recognize the main deep discontinuities is mainly based on the interpretation of tomographic data, which may be affected by significant uncertainties, as discussed in the following:

- The present structural setting resulting from the analysis of this kind of data might be different from the ones that may have caused the formation of the presumed slab discontinuities millions of years ago. The unique clear evidence on the presence of rigid lithospheric structures at depth is provided by deep earthquakes, which only occur under the southernmost Tyrrhenian. The tectonic role played by the deep structures that are characterized by positive velocity anomalies but are seismically silent is not clear.
- Any hypothesis about the activation of a major discontinuity in a given evolutionary phase should provide plausible explanations of the possible genetic tectonic processes. However, we think that such result may hardly be obtained starting from the assumption that trench-arc-back arc systems are mainly driven by gravitational sinking of slabs [77] [78], given that the implications of such view cannot easily be reconciled with major features of the observed deformation pattern [6] [8] [16] [17].
- It has been suggested that the lack of a subducted lithosphere below the central and southern Apennines is due to the end of subduction at those trenches [22] [79]. However, this hypothesis is not compatible with the evidence that accretionary activity in those consuming boundaries lasted at least up to the late Pliocene [68] [80] [81] [82] and with the fact that the disruption of a slab in a zone of continental collision requires more than 10 My, as indicated by numerical modeling [25] [76] [83].
- The central sector of the Apennines belt is the one where tomographic data indicate the presence of the most prominent slab window [22]. A significant deep discontinuity in the same zone is also suggested by the tectonic evolution of the Tyrrhenian-Apennine system. In the view proposed by [22], the presence of such slab window would imply the occurrence of intense magmatism in the Central Apennines, where, conversely, such activity is very scarce with respect to the Northern and Southern Apennines.

4. Conclusions

The distribution of intermediate and deep earthquakes reveals that at present rigid subducted lithosphere in the Central Mediterranean region only exists in the southernmost Tyrrhenian area. Since geological evidence clearly indicates that in the Upper-Late Miocene there was a wide subducted lithospheric edifice under the Alpine-Apennine and Alpine-Maghrebian belts (**Figure 1**), it would be very useful recognizing which tectonic mechanisms may have caused such relatively fast disruption of that lithospheric structure.

In this work, we suggest that the geodynamic/tectonic framework that caused the above processes was triggered in the late Miocene by the collision of the Anatolian-Aegean system with the Adriatic promontory and by the consequent decoupling of the Adria plate from Nubia. Once decoupled, that plate underwent a clockwise rotation determining a series of extrusion processes that caused strong deformation of the subducted lithosphere in the study area, with the formation of slab tears and slab breakoffs. The northward escape of the Adventure block in the Pelagian zone caused the deformation of the subducted lithosphere lying beneath the Alpine-Maghrebian belt, with the formation of slab tears and then the progressive destruction of that deep structure.

The eastward escape of wedges from the Alpine-Apennine belt (induced by the northward escape of the Adventure block) produced slab tears and slab breakoffs in the subducted lithosphere lying under the central and southern Apennines. The deep discontinuity under the central Apennines mainly developed in the Late Miocene-Early Pliocene, when the slab beneath the southern Apennines was forced to retreat, separating from the slab lying under the northern Apennines.

In the Pliocene (6 - 2 My), the SE ward escape of the Southern Apennines and Calabrian wedges caused the formation of a well-developed slab that was then ruptured by the effects of various tectonic processes: the clockwise rotation of the Adria plate, the suture of the southern Apennines consuming boundary and the consequent SE ward extrusion of the Calabrian wedge. In the slab lying under the southern Apennines major tears developed around the Late Pliocene-Early Pleistocene, when that slab sector (no longer retreating) decoupled from the slab sector which started retreating under the extruding Calabrian Arc.

Since the early Pleistocene, the SE ward migration of the Calabrian wedge further developed the underlying slab, which is still present under the Southernmost Tyrrhenian zone (**Figure 10**).

The formation of major discontinuities may have created gaps in the subducted lithosphere, allowing the underlying asthenospheric material to upwell (e.g., [22]). However, the uprise of such magmas through the upper crust only occurred when the overlying zones experienced transtensional strain regimes. The proposed tectonic evolution may provide plausible explanations for the spatio-temporal distribution of magmatic activity, which is divided in three phases (**Figure 3**).

In the first phase (9.5 - 6 My), magmatism mainly occurred in the northern Tyrrhenian region (**Figure 3(A)**). The location of this activity fairly well corresponds to the area that was affected by extensional and transtensional tectonics during the formation of the northern Tyrrhenian basin. The presence of some orogenic magmas in a zone where no active subduction process was taking place [6] [8] [16] strongly supports the hypothesis that such products were emplaced under the crust in a previous subduction process (Middle Miocene, **Figure 5**).

The second magmatic phase (5.9 - 2.0 My) involved the Sardinia block, the inner side of northern Apennines, the central Tyrrhenian basin (Vavilov) and the Hyblean plateau (**Figure 3**). The first two zones were affected by the transtensional regime induced by the sinistral motion of the Alpine-Apennine belt (pushed by the Alpine-Maghrebian belt) with respect to the Corsica-Sardinia block (**Figure 4**) and by the interaction of Corsica-Sardinia with the northward moving Adventure wedge (**Figure 6**). The anorogenic magmatic activity in the Vavilov zone may be connected with the extensional-transtensional regime which formed that basin (**Figure 8**). The period of magmatic activity in the Hyblean plateau (7 - 1.5 My), being coeval with the rotation of the Adria plate, might be related to the generation of pull-apart troughs along major shear faults (such as the Scicli-Ragusa, **Figure 3**) that developed in that plateau as effects of the strong E-W compression induced by the Nubia-Adria convergence. One could note that during this magmatic phase no activity occurred in the Central Apennines, notwithstanding the formation of major tears in the underlying slab. This may confirm the hypothesis that volcanic activity can only develop where a transtensional strain regime affects the upper crust.

The third magmatic phase (<2.0 My) involved the western side of the Northern and Southern Apennines (Roman and Campanian magmatic provinces), the southernmost Tyrrhenian basin (Marsili), the Aeolian arc, the Hyblean plateau (Etna) and the Sicily Channel (**Figure 3**). The abundant magmatism that occurred in the Roman and Campanian provinces provides a further significant example of the close connection between magmatism and transtensional tectonics. This is suggested by the fact that the above magmatic provinces well correspond to the inner extensional sides of the Romagna-Marche-Umbria and Molise-Sannio extruding wedges (**Figure 11**). In particular, it is worth noting that no or scarce magmatism occurred in the inner side of the Central Apennines, which is the sector of the belt that did not experience outward extrusion ([6] [8] [16] [69] and references therein). The orogenic activity in the Marsili basin (**Figure 3**) may be connected with the development of the slab underlying the migrating Calabrian wedge.

In the Aeolian arc magmatism could be related to the formation of tears and breakoffs in the underlying slab, generated by the deformation pattern described in **Figure 10**. In particular, the connection between slab tears and magmatism may explain why Lipari and Vulcano are located along the Vulcano major strike-slip fault (**Figure 3**). The anorogenic magmas of Mt. Etna, interpreted as a striking example of asthenospheric upwelling along a slab tear with a typical Ocean Island Basalts signature (e.g., [18] [19] [22]), may result from the intersection of major faults that developed in the continental Hyblean plateau as effects of the strong E-W compressional regime induced by the clockwise rotation of the Adria plate. The magmatism in the Pantelleria trough may be related to the extensional/transtensional regime that formed that trough, in the wake of the extruding Adventure block. Other magmatic centers in the Sicily Channel may be associated with transtensional features developed along the lateral guides of the Adventure block or to the faults that led to the formation of the Linosa and Malta troughs [6] [8].

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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