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Generation of Back-Arc Basins as Side Effect of Shortening Processes: Examples from the Central Mediterranean

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Abstract

The evolution of the Mediterranean area since the Oligocene-Lower Miocene has been driven by the convergence of the surrounding plates. This implies that the observed deformation pattern in that region must be the most convenient shortening pattern, *i.e.* the one controlled by the minimum action principle. To understand why the fulfilment of such condition has required a complex spatio-temporal distribution of major tectonic events, such as uplift, lateral displacement and bending of orogenic belts, consumption of large lithospheric domains and formation of back arc basins, it may be very useful to take into account a basic tectonic concept, which helps to identify the process that can minimize the resistance of tectonic forces. Such concept starts from the fact that the most convenient consumption process is the one that involves low buoyancy oceanic lithosphere (Tethyan domains). However, such process is highly favoured where the oceanic lithosphere is stressed by vertical forces, a situation that develops when orogenic wedges are forced to over thrust and load the oceanic domain to be consumed. This interpretation can provide plausible and coherent explanations for the complex pattern of the observed deformations. In this view, the generation of back arc basins is taken as a side effect of an extrusion process, as suggested by numerical and mechanical experiments.

Keywords

Central Mediterranean, Extrusion Tectonics, Back-Arc Basins

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1. Introduction

The structural/tectonic setting of the Central Mediterranean region (**Figure 1**) has undergone a drastic change since about the middle Miocene, mainly due to the formation of three basins (Northern, Central and Southern Tyrrhenian) with distinct locations and timings, strong deformation, migration and fragmentation of the previously formed peri-Adriatic orogenic belts (Alps, Apennines, Hellenides and Maghrebides), new accretionary activity at those belts, formation of a major discontinuity crossing the Ionian oceanic domain (Medina-Victor Hensen fault system) and the Hyblean-Pelagian African zone (Sicily Channel), stop of old subduction processes and activation or acceleration of new consuming boundaries, etc.

The fact that the opening of relatively large basins has occurred in a zone stressed by the convergence of the confining plates has led some authors to suppose that such tectonic event can hardly be explained without invoking the contribution of additional driving forces, such as the ones induced by gravitational sinking of subducted lithosphere [1]-[3]. As an alternative, in a number of papers [4]-[11] it has been suggested that back arc basins may develop as side effects of shortening processes, for instance in the wake of extruding orogenic wedges. It is argued that this hypothesis may plausibly and coherently account for the main features [times of starting and ending, location, dimensions, tectonic style, etc.] of the major tectonic events that developed in the Mediterranean area since the middle Miocene. In this work, we integrate the evidence and above all the arguments reported in the above papers, in order to provide better and firmer support to the proposed geodynamic interpretation, concerning the central Mediterranean region and the Tyrrhenian-Apennine system in particular.

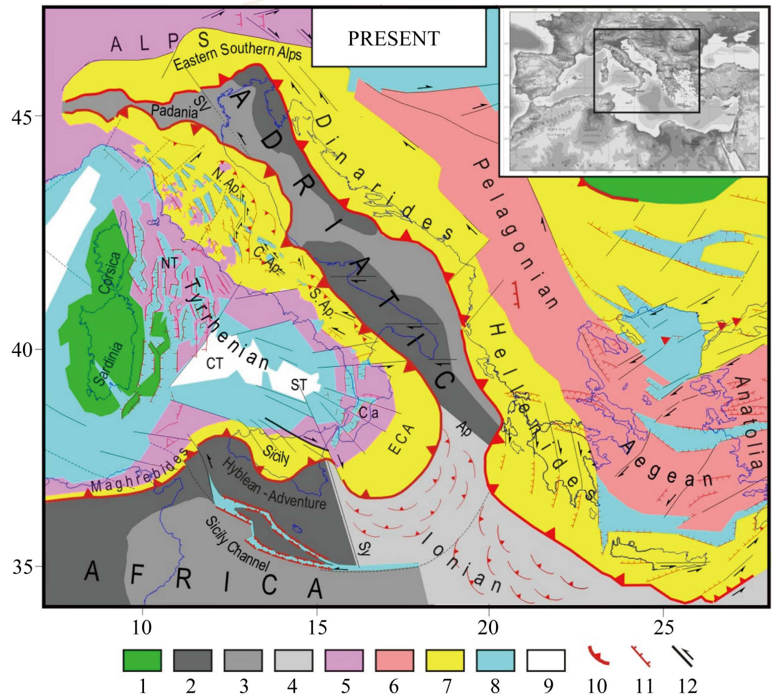

Figure 1. Present tectonic setting in the central Mediterranean region. 1) European continental domain; 2,3) Africa-Adriatic continental and thinned continental domains; 4) Neotethys Ionian oceanic domain; 5) Alpine and lower Miocene Apennine belts; 6) Pelagonian-Aegean-Anatolian metamorphic massifs; 7) Neogene accretionary belts; 8,9) Neogene extensional basins and oceanized zones 10,11,12) Major compressional, extensional and transcurrent tectonic features. Ap = Apulian escarpment, C.Ap. = Central Apennines, Ca = Calabria wedge, CT = Central Tyrrhenian basin, ECA = External Calabrian Arc, N.Ap = Northern Apennines, NT = Northern Tyrrhenian basin, S.Ap. = Southern Apennines, ST = Southern Tyrrhenian basin, SV = Schio-Vicenza fault system, Sy = Syracuse escarpment. The inset shows the location of the study area within the Mediterranean region.

The next section aims at making clear a key aspect of the proposed evolutionary reconstruction that has not been properly focused in previous papers, that is the fact that the starting of a subduction process involving old oceanic lithosphere has to be favoured by extrusion of high buoyancy orogenic wedges.

2. Spatio-Temporal Distribution of Tectonic Events Controlled by the Minimum-Action Concept

To accommodate the convergence of the confining Africa and Eurasia plates since the Miocene, the Mediterranean region had to undergo considerable shortening. Because the structural/tectonic configuration of the Mediterranean area before the formation of the Balearic and Tyrrhenian back arc basins encompassed relatively large old oceanic domains (Mesozoic Alpine and Ionian Tethys, e.g., [12] [10] and references therein), one could expect that the consumption of those lithospheric domains, being characterized by the lowest buoyancy with respect to others [13], was the main objective of plate convergence.

However, major evidence in the study area suggests that the subduction of oceanic lithosphere driven by horizontal tectonic forces is not always the most convenient shortening process in a constricted environment. For instance, it must be considered that the Ionian oceanic lithosphere which lay in between the African foreland and the continental Adriatic promontory did not undergo any consumption during the long phase (Upper Oligocene-Miocene) that involved the indentation of that promontory against Europe (**Figure 2**). A similar behaviour of an oceanic domain can also be recognized in the central Indian Ocean Basin, where intraplate shortening started about 8 My ago [14]. Such deformation, recognized by bathymetry patterns and seismic activity, has been accommodated by folding of Cretaceous lithosphere over a broad belt, without involving any subduction [14]. Indeed, the combined effect of small crustal thickness and low surface heat flux may lead to considerable compressional strength for old oceanic lithosphere, which makes difficult the generation of a subduction fault in absence of pre-existing weakness [15]. So, the above evidence would suggest that deforming continental Asia at the Himalaya-Tibet collision boundary was easier than starting a new subduction zone within the Indian plate [16].

With regards to the Mediterranean area, however, one must also consider that in the Miocene and Pliocene

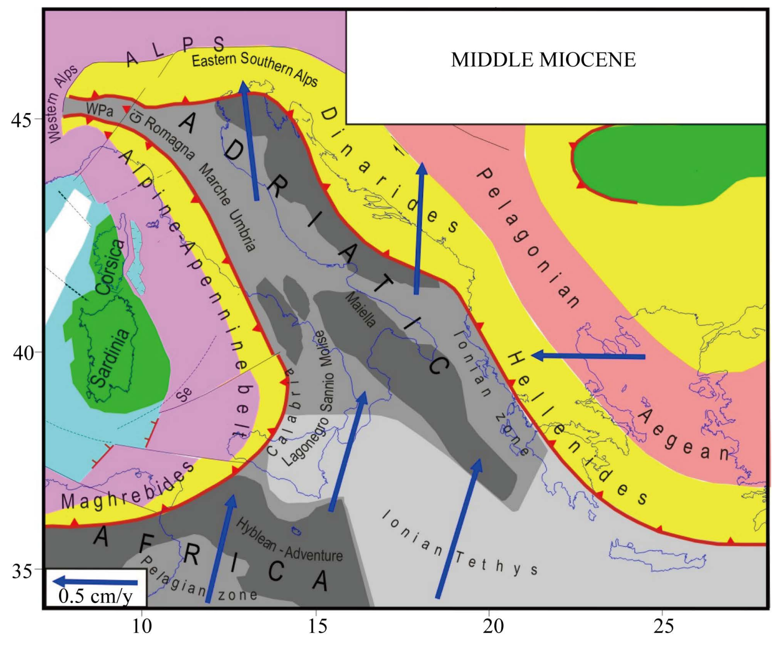

Figure 2. Tentative reconstruction of the middle Miocene structural-tectonic configuration in the central Mediterranean region (see text). Gi = Giudicarie fault system, Se = Selli fault system, WPa = Western Padania. Abbreviations, symbols and colours as in **Figure 1**. Blue arrows (scale in the inset) show a tentative reconstruction of plate motions with respect to Eurasia (From [8], modified).

(**Figures 2-4**) the Alpine Tethys lithosphere was completely consumed and a large part of the Ionian Tethys has completely disappeared in subduction zones, as indicated by several major pieces of evidence, such as the distribution of ophiolite remnants, the pattern of subduction-related magmatic products and imaging of subducted slabs [17]-[19].

Thus, one should explain why in certain contexts oceanic lithosphere represents the weakest point of the system, while in other contexts the same kind of domain can efficiently transmit very strong compressional regimes without undergoing any consumption. This question has received considerable attention in literature, but none of the various answers proposed so far are now widely accepted [16].

In this work, we propose an interpretation that hinges on the following concepts. When stressed by horizontal forces, generally induced by plate convergence, the oceanic lithosphere opposes a strong resistance to subduction. For the Mediterranean region, the above hypothesis is supported by the computation of rheological profiles [20], which indicates that the Ionian oceanic lithosphere (about 70 km thick) is characterized by relatively large compressional strength in both the brittle and plastic regimes. Thus, the subduction of this lithosphere can hardly represent the most convenient shortening process in the Africa-Eurasia convergence zone. This consideration is compatible with the fact that in the Miocene the Ionian Tethys oceanic zone very efficiently transmitted the push of Africa to the Adriatic promontory without undergoing any subduction, as indicated, in particular, by the main features of the Syracuse and Apulian passive margin escarpments [21].

We argue that the consumption of oceanic lithosphere may encounter much less resistance when one margin of such domain is overthrusted by an orogenic wedge, sideway expulsed from a constricted environment. Since the buoyancy of an old oceanic lithosphere is generally very low, as its average density may exceed that of the underlying asthenosphere [13], any additional load may lead the overthrusted lithospheric margin to sink into the mantle. The feasibility of this phenomenon has been investigated by analytical and numerical modelling [16]. Once started, the above process tends to become easier and easier, since the downward flexure of the oceanic margin favours the trench-ward sliding of the escaping wedge, which, on its turn, favours the subsidence of the oceanic lithosphere, and so on. This argument implies that within a compressional regime the lateral expulsion of relatively light orogenic material, at the expense of an adjacent dense oceanic domain, may represent the most

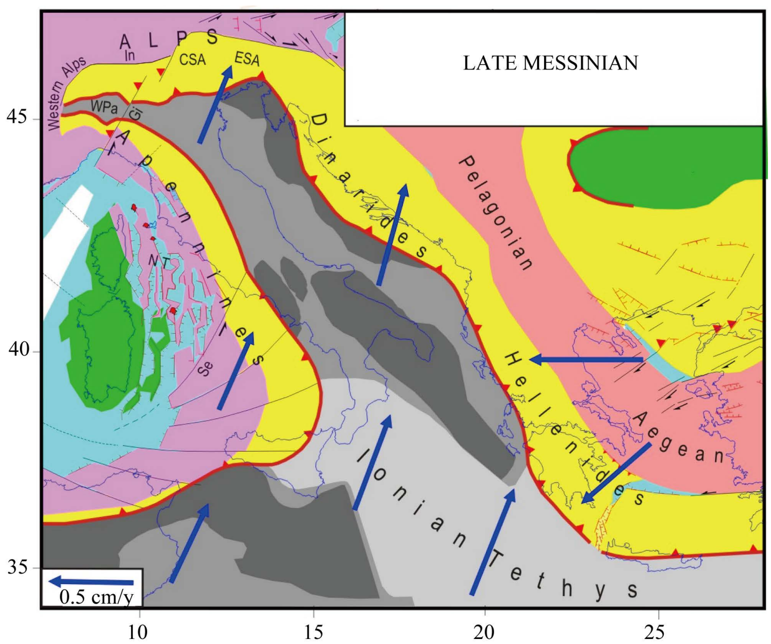

Figure 3. Late Messinian configuration, after the opening of the Northern Tyrrhenian basin, driven by the divergence between the Adriatic promontory and the almost fixed Corsica-Sardinia block [see text]. Red spots indicate magmatic products [19]. CSA = Central Southern Alps, ESA = Eastern Southern Alps, In = Insubric Lineament. Abbreviations, symbols and colours as in **Figure 1** and **Figure 2** (From [8], modified).

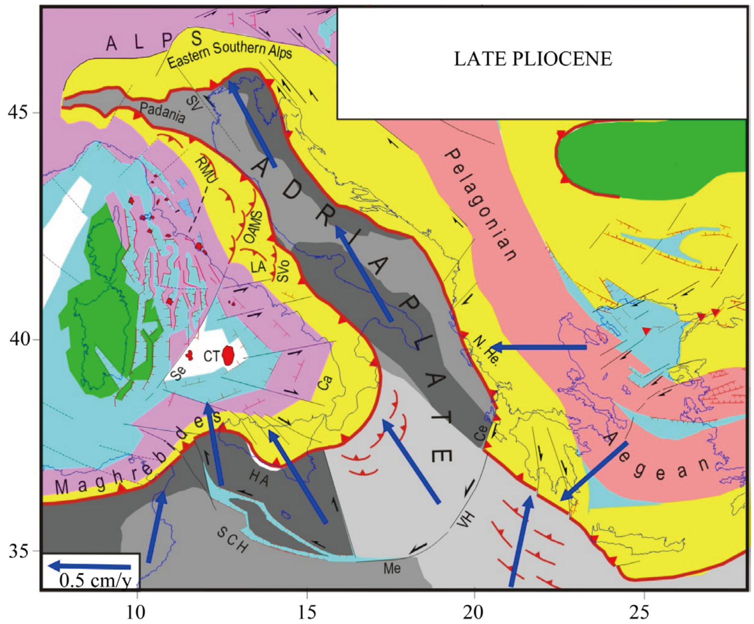

Figure 4. Late Pliocene configuration, after a drastic reorganization of the tectonic setting, triggered by the collision between the Anatolian-Aegean-Pelagonian system and the Adriatic promontory. To accommodate the new dynamic context, the Adriatic promontory decoupled from Africa, by the Victor Hensen-Medina-Sicily Channel fault system, and by its Padanian sector, by the Schio-Vicenza fault system. The indentation of the Hyblean-Adventure block (HA) into the Alpine-Apennine belt caused the lateral escape of wedges, at the expense of the remnant Tethyan oceanic domain. The extensional deformation that developed in the wake of such extruding wedges generated the central Tyrrhenian basin (Magnaghi-Vavilov). Ca = Calabria, Ce = Cephalonia fault system, LA = Latium-Abruzzi carbonate platform, Me = Medina fault system, N.He. = Northern Hellenides, OAMS = Olevano-Antrodoco-Monti Sibillini thrust front, RMU = Romagna-Marche-Umbria units, SCH = Sicily Channel fault system, SVo = Sangro-Volturno thrust front, VH = Victor Hensen fault system. Abbreviations, symbols and colours as in **Figures 1-3** (From [8], modified).

convenient shortening mechanism. In this regard, laboratory and numerical experiments [22] [23] show that the above mechanism is particularly favoured when the shallow, brittle orogenic wedges are mechanical decoupled from the underlying plastic/viscous lower crust and mantle lithosphere. In the next section, we discuss on how the above mechanism may have conditioned the spatio-temporal distribution of major tectonic events since the middle Miocene.

3. Evolution of the Central Mediterranean Region [from the Middle Miocene to the Middle Pleistocene]

The structural/tectonic setting that presumably characterized the Central Mediterranean region in the middle Miocene, before the formation of the Northern Tyrrhenian basin, is shown in **Figure 2**. The evidence and arguments that support this reconstruction are discussed in several works [6]-[8] [11] [24]-[29]. The configuration of the Alpine-Apennine belt, including the Corsica-Sardinia continental fragment, was reached after a long migration and accretion (from the Oligocene to middle Miocene) that led to the formation of the Western Mediterranean trench-arc-back arc system [10] [24] [27] [30]-[33]. The roughly eastward displacement of the above belt, developed first at the expense of the Alpine Tethys domain and then of the thinned Adriatic margin, considerably slowed down, up to cease around the middle Miocene, [31]. At this stage (**Figure 2**), a relatively large oceanic zone (Ionian Tethys) was still present between the Adriatic and African continental domains.

Formation of the Tyrrhenian Basins

After a long accretionary phase, the Alpine-Apennine belt which lay east of the Corsica-Sardinia block began to undergo roughly E-W crustal extension and consequent subsidence around the middle Tortonian [34]-[38]. This extensional phase lasted up to the late Messinian, determining the formation of the present Northern Tyrrhenian basin (**Figure 3**).

We argue that a geodynamic context which can plausibly and coherently account for the major features of that tectonic event, such as starting and ending times, location and configuration of the stretched zone, trend of crustal extension, spatio-temporal distribution of magmatism, etc., may be identified by taking into account the large scale tectonic setting and boundary conditions that preceded the opening of the Northern Tyrrhenian basin. First of all, it must be pointed out that in the middle Miocene (**Figure 2**) buoyancy forces were opposing very strong resistance to any further crustal shortening in the Adriatic-Eurasia collisional zone (Alps), due to the presence of a large amount of light upper crustal material accumulated during the long phase of plate convergence [39]. Thus, one may suppose that within such critical situation the Adriatic promontory was prone to exploit any favourable variation of boundary conditions to develop a new minimum-action tectonic configuration, through the activation of alternative, less resisted, shortening processes [6] [27] [40]. It has been suggested [6]-[8] that favourable condition progressively developed at the northeastern side of the Adriatic promontory, in the Carpatho-Pannonian region, due to the strong deformation (also involving crustal extension) that such zone was undergoing [41].

The presence of that weak zone favoured the eastward expulsion of wedges from the strongly constricted eastern Alpine belt (**Figure 3**, [42]-[44]), allowing a roughly NE ward displacement to the Adriatic promontory. Since this plate motion would have hardly been compatible with the fact that the northwestern (Padanian) protuberance of such promontory was almost irremovable, being deeply stuck into the European foreland beneath the Western Alps, a major decoupling zone (the Giudicarie fault system [45] [46]) developed in the central Padanian zone around the Tortonian (**Figure 3**, **Figure 4**). The surface trace of that fault system crosses the central Southern Alps from the Insubric Lineament to the Po Plain. The configuration of the Giudicarie discontinuity, along with other major evidence, suggests that after the above decoupling, the part of the Adriatic promontory lying east of the Giudicarie moved roughly NE to NNE-ward [44]. This new kinematics is compatible with the fact that in the successive evolution accretionary activity at the northern Adriatic boundary mostly continued east of the Giudicarie tectonic belt, in the eastern Southern Alps [46].

Considering that the location of the Corsica-Sardinia microplate has not changed significantly since the middle Miocene [47], one can expect that during the above phase crustal extension occur at the divergent boundary between that almost fixed microplate and the Adriatic promontory, moving N/NNE ward. This effect really took place in the sector of the Alpine-Apennine belt that was comprised between the Adriatic promontory and the Corsica-Sardinia block (**Figure 3**). The Tyrrhenian area which was affected by extensional deformation during the above phase is confined to the north by the Giudicarie fault system and to the south by the Selli Line, just in the zone where the major effects of the supposed plate divergence are expected. The available evidence indicates that during the above evolutionary phase the Selli discontinuity was a well-defined boundary between the northern Tyrrhenian zone, experiencing extension, and the southern sector of the Alpine-Apennine belt, which was still characterized by an orogenic morphology [34] [48] [49].

Geological and magmatological evidence suggests that crustal thinning in the Northern Tyrrhenian mainly started around the middle Tortonian and mostly lasted until the late Messinian [19] [25] [34] [36] [50]. Both these major constraints are consistent with the interpretation here proposed. The starting of extension corresponds to the reactivation of the Giudicarie fault system. The end of extension in the Northern Tyrrhenian around the late Messinian is coeval with the occurrence of several major tectonic events in the central Mediterranean region, which can coherently be interpreted as the effects of a drastic change of the tectonic setting in that area. Such change was preceded by a progressive increase of the resistance that the underthrusting of the eastern Adriatic margin (Ionian zone in **Figure 2** [51]) was encountering beneath the northern Hellenides. In the latest Miocene-earliest Pliocene, the above process reached a critical stage, which triggered a major transition to a new minimum-action tectonic setting. The first effect was the suture of such consuming boundary [52] [53], which implies no further relative motion between the Aegean system and the Adriatic.

After this event, the westward motion of the Anatolian-Aegean-Pelagonian metamorphic-orogenic system became incompatible with the roughly NNE ward motion of the continental Adriatic promontory. The way by which the above system came out from that critical situation was found, as expected, at the expenses of a large part of the remnant oceanic lithosphere that lay west of the Adriatic promontory. Since the consumption of that domain could only be achieved by activating sideway expulsion of high buoyancy orogenic wedges, as argued earlier, the new minimum-action tectonic configuration was reached by a complex pattern of tectonic events (**Figure 4**). Initially, the old Adriatic promontory (hereafter Adria plate) decoupled from the surrounding structures in order to make possible its independent motion (**Figure 4**). During the Messinian the decoupling of Adria from Africa was allowed by the activation, around the Messinian, of major sinistral transcurrent discontinuities in the central Ionian area (Medina and Victor Hensen, **Figure 4**) and in the Pelagian zone (Sicily Channel [54]-[58]). The decoupling of Adria from the Padanian protuberance of the previous African promontory was allowed by the reactivation, as a sinistral strike-slip fault system, of an old discontinuity in the northern Adriatic domain [the Schio-Vicenza fault system [45] [46] [59]). This hypothesis is supported by the fact that after that decoupling thrusting activity in the Alps mostly continued east of the Schio-Vicenza fault (**Figure 4**), with a NW-SE to N-S shortening trend [60]-[62].

The roughly E-W shortening required by the convergence between the new Adria plate and the African sector lying south of Sardinia was accommodated by the roughly North to NNW ward escape of the Hyblean-Adventure (HA) block. The extrusion of this wedge, associated with clockwise rotation, was favoured by two lateral guides, constituted by the Syracuse [63] and Sicily Channel fault systems (**Figure 4**). The non-linear geometry of the second fault system caused the formation of pull apart extensional troughs in the Sicily Channel. The North to NNW ward expulsion of the HA block is testified by the shape of the Maghrebian-Alpine belt lying along the outer front of such wedge [7] [8].

On its turn, the roughly northward indentation of the HA block caused eastward extrusion of wedges from the Alpine-Apennine orogenic body which lay east of Sardinia, as tentatively reconstructed in **Figure 4**. The lateral escape of the resulting Alpine-Apennine wedges developed at the expense of the Ionian Tethys lithosphere that in the middle-upper Miocene lay between the Hyblean and continental Adriatic domains (**Figure 3**).

This interpretation may plausibly and coherently account for the tectonic events that developed in this region since the latest Miocene. The acceleration of accretionary activity in the Southern Apennines and Calabrian Arc [17] [18] [29] [64]-[66] is compatible with the deformation expected along the outer front of the extruding wedges. The coeval E-W extension and magmatism in the central Tyrrhenian, the Magnaghi and Vavilov basins [19] [34] [38] [49] [48] may have developed in the wake of the same migrating wedges. The thickening and uplift that the migrating Alpine-Apennine wedges underwent during the opening of the Tyrrhenian basin [33] [66] may thus be explained as an effect of the belt-parallel compressional regime that drove that extrusion process (**Figure 4**).

The evidence provided by CROP seismic sections across the Adriatic-Apennines system [25] [66]-[68] indicates that since the latest Miocene the Adriatic lithosphere has undergone strong shortening, accommodated by major thrust faults cutting the entire crust and that from the late Messinian to the late Pliocene, several shallow thrust zones of the Northern Apennines were reactivated (see the discussion given by [8]). It is worth considering that the timing and entity of that shortening is fairly compatible with the proposed interpretation (**Figure 4**).

During this phase, the Central and Northern Apennines underwent belt parallel shortening, accommodated by the formation of arcs, with in-sequence thrusting at outer fronts [69]-[71], and out-of-sequence thrust re-activaction [67]. The opening of large marine and continental basins on the western margin of the Northern Apennines [72] may be explained as an effect of the extensional regime that developed in the wake of the extruding wedges, mainly concerning the Romagna-Marche-Umbria structure [73].

In the Central Apennines, belt-parallel compression caused the formation of arcs, mainly in the eastern Latium-Abruzzi carbonate platform [74] [75]. The results of numerical experiments [7] [73], show that the major features of the deformation pattern recognized in the study area can be reproduced as an effect of the proposed kinematic boundary conditions (**Figure 4**).

The tectonic setting that developed during this evolutionary phase, with particular regard to crustal stretching in the Magnaghi-Vavilov basins and accretionary activity in the adjacent Apennine sector, mostly stopped around the late Pliocene [49]. A discussion about the conditions which determined that tectonic change and the starting of other events is given in the following.

In the upper Pliocene, as thicker and thicker lithosphere was entering the consuming boundary facing the Southern Apennines, the resistance of buoyancy forces was getting stronger and stronger. When finally such resistance reached a critical value, the tectonic context underwent a drastic change that involved the stop of old processes and the activation of new less resisted shortening mechanisms. This may explain why in the late Pliocene accretionary activity in the Southern Apennines underwent a drastic slowdown up to cease [29] [64] [76] [77]. Since at that time the only sector of the belt which was still facing oceanic lithosphere was the Calabrian arc (**Figure 4**), one may expect (in the minimum-action view) that the lateral escape of that buoyant orogenic wedge at the expense of the adjacent low buoyancy Ionian lithosphere was the most viable tectonic process.

This prediction matches geological observations reflecting that period (**Figure 5**), as testified by the distribution of major tectonic activity in and around the Calabrian Arc:

- At the outer front of the Calabrian wedge, accretionary activity underwent a considerable acceleration, building up the External Calabrian Arc orogenic complex [17] [18] [54] [69].
- Crustal stretching, accompanied by remarkable volcanic activity, has led to the formation of the southern Tyrrhenian (Marsili) basin, from the latest Pliocene to early Pleistocene [19] [34] [36] [54]. It is worth noting that the width of this basin is comparable with the inner (Tyrrhenian) side of the extruding wedge (**Figure 5**).
- Tectonic and volcanic activity accelerated at the Vulcano and Palinuro fault systems [19] [54] [78], that acted as transcurrent lateral guides for the extruding Calabrian wedge.
- During this phase, the Calabrian wedge, being stressed by belt-parallel compression, underwent major deformations, such as thickening and consequent uplift [79] [80], activation of transversal discontinuities, relative rotations of blocks and generation of belt-parallel troughs [17] [54] [81] [82].

In the lower Pleistocene, after the suture of the Southern Apennines consuming boundary, the Adria plate, being almost completely surrounded by high buoyancy orogenic belts [62], was characterized by a reduced mobility. During this phase the convergence of the confining plates was presumably accommodated by internal deformation of Adria, as for instance up-arching, as suggested by geological data and geophysical modelling [83] [84].

Effects of the belt-parallel compression that determined the sideway expulsion of the Calabrian wedge, may also be recognized in the Southern Apennines, where the most rigid sector of the belt, *i.e.* the carbonate platform units, underwent significant bending, leading to the formation of two major arcs, the Campania-Lucania and Matese-Benevento (**Figure 5**). This is suggested by the development of thrusting at the outer front of such features [77] [85], extensional tectonics in the inner area [86] [87] and uplift of the extruding belt [9] [79] [88].

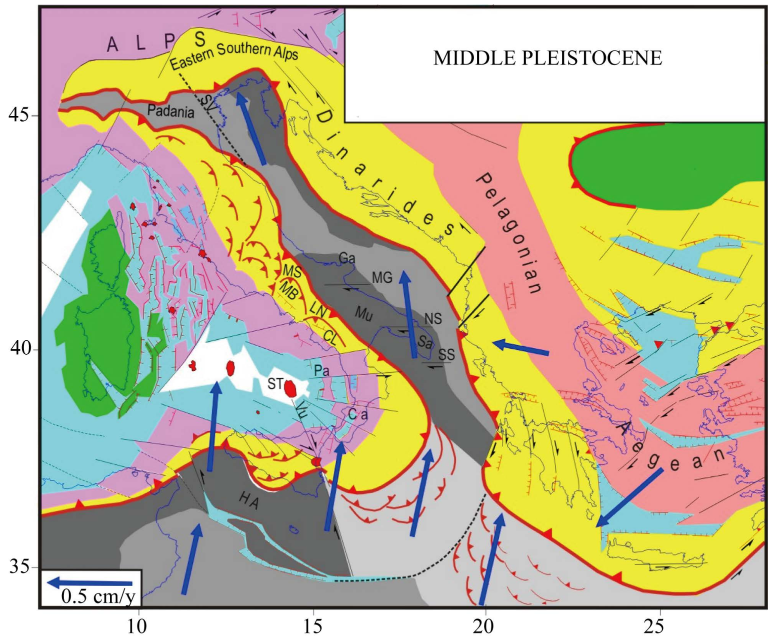

Figure 5. Middle Pleistocene configuration, after the formation of the southern Tyrrhenian basin [Marsili], developed in the wake of the outward extruding Calabrian wedge (see text). CL = Campania-Lucania arc, Ga = Gargano, LN = Lagonegro units, MB = Matese-Benevento arc, MG = Mattinata-Gondola fault system; MS = Molise-Sannio units, Mu = Murge, NS = North Salento fault, Pa = Palinuro fault, Sa = Salento, SS = South Salento fault, Vu = Vulcano fault system. Abbreviations, symbols and colours as in **Figures 1-4** (From [8], modified).

4. Development of the Present Tectonic Setting: Drastic Change of Deformation Style in the Apennine Belt since the Middle Pleistocene

Geological data at the Northern Hellenides indicate that around the middle Pleistocene, accretion reactivated, after a phase of inactivity. This implies the reappraisal of underthrusting at that sector of the Adria boundary [52] [53]. Such evidence suggests that since then the Adria plate has recovered some mobility. This hypothesis finds considerable support in the fact that tectonic activity strengthened at most peri-Adriatic zones [29] [64] [76] [77] [89]. To explain the above drastic change of the tectonic setting, we suggest that since the middle Pleistocene, the underthrusting of the Adriatic domain (even if involving thinned continental lithosphere) beneath the southern Dinarides and eastern Southern Alps could have again become the most efficient shortening process, with respect to the lower-middle Pleistocene, when the convergence of the confining plates was mostly accommodated by internal deformation (buckling and up-arching) of the Adriatic lithosphere.

In the southern Dinarides, a reappraisal of accretionary activity since the middle Pleistocene is clearly indicated by geological data [52] [53] [89]. In the northern Dinarides, tectonic activity observed at the Slovenian NW-SE dextral fault system [61] [90] [91] suggests an acceleration of the transcurrent motion of the Adriatic plate with respect to the Carpatho-Pannonian system. Similar activity, connected with WSW-ENE to E-W thrusts and NNW-SSE dextral strike-slip faults, is also recognised in the central Dinarides [90] [92] [93].

Evidence about an acceleration of thrusting since the late Pleistocene may also be recognized at the northern front of Adria in the eastern Southern Alps (**Figure 6**), with particular reference to the Aviano compressional

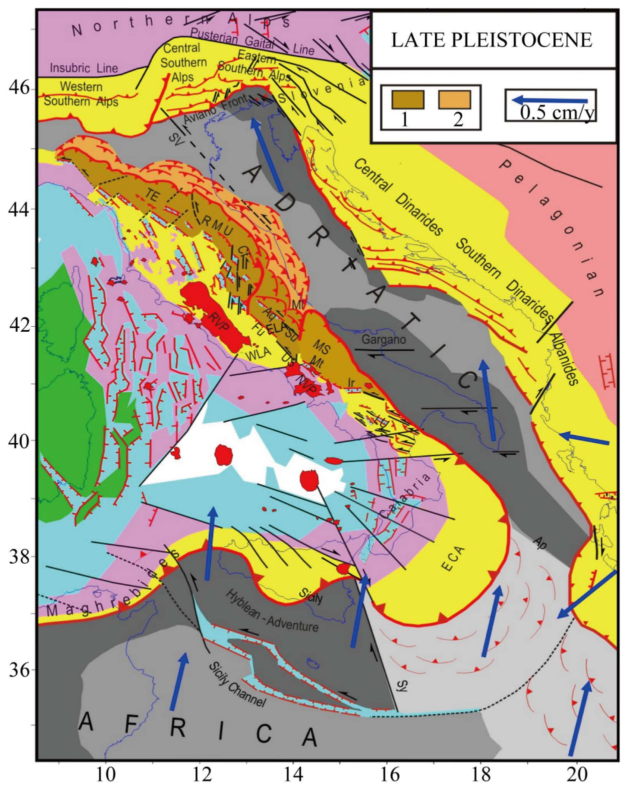

Figure 6. Late Pleistocene to Present configuration, focused on the Apennine belt, where most tectonic features are identified. The outer mobile sector of the Apennine belt and its buried margin are indicated by dark (1) and light brown (2) respectively. Information on the proposed kinematics is given by [11] and [28]. Aq = L'Aquila basin; Cf = Colfiorito basin; ELA = eastern part of the Latium-Abruzzi platform; Fu = Fucino basin; Ir = Irpinia; LU = Lucanian Apennines; Ml = Maiella; MS = Molise-Sannio wedge; Mt = Matese; NVP = Neapolitan volcanic province; RMU = Romagna-Marche-Umbria wedge, RVP = Roman volcanic province; Su = Sulmona basin; TE = Toscana-Emilia wedge; US = Upper Sangro basin, WLA = western part of the Latium-Abruzzi platform. Abbreviations, symbols and colours as in previous figures.

front, which presumably marks the present northern active border of the Adria plate [60]. Geological and geomorphological analysis, related to terrace formation and river drainage modification, due to uplift of anticlines and thrust hanging walls and often connected with historical large earthquakes [60] [61] [94], suggests post-middle Pleistocene activity at the above compressional features.

The western border of the most mobile Adria plate could tentatively be located along the NW-SE sinistral Schio-Vicenza fault system (**Figure 5**). This feature likely represents a deep structural boundary, as suggested by the striking lateral variation in gravity anomalies and crustal thickness recognised across it [95]. Evidence of post middle Pleistocene activity in several segments of the Schio-Vicenza line has been described by [59].

It has been suggested that the acceleration of Adria has produced important changes of tectonic activity in the Apennine belt [6] [8] [9] [11] [28]. In particular, such acceleration may have induced belt-parallel shortening in the outer sector of the Apennines, which has been accommodated by a roughly NE-ward extrusion of some shallow crustal wedges (*i.e.*, Molise-Sannio, eastern sector of the Latium-Abruzzi platform, Romagna-Marche Umbria and Toscana-Emilia). In the southernmost (Lucanian) sector of the Southern Apennines, previous thrust zones have been dissected (since the late Pleistocene) by a system of NW-SE sinistral strike-slip faults, accompanied by compressional and tensional features at restraining and releasing step-overs respectively [64] [86] [96]. These processes may identify the activation of a sinistral strike-slip fault system which has accommodated the relative motion between the Molise-Sannio wedge, extruding roughly NE ward, and the Calabrian wedge, extruding roughly eastward (**Figure 6**).

In the Southern Apennines, from the Irpinia to the Matese zones, a system of normal faults roughly trending NW-SE has developed in the axial part of the belt [97] [98]. This may be interpreted as an effect of the divergence between the Molise-Sannio wedge [extruding outward] with respect to the inner almost fixed part of the belt. The boundary zone (Maiella structure and Sangro-Volturno lineament) between the Southern and Central Apennines has undergone a significant acceleration of uplift since the middle Pleistocene [99] [100]. Moreover, some very recent morphotectonic structures, such as the Holocene extruded wedges recognized in the eastern limb of the Maiella anticline [101], indicate that transpressional deformation is still going on in that zone. The above deformation pattern is compatible with the proposed belt-parallel compression in the Apennine chain.

In the Central Apennines, previously affected by a NE-SW lengthening, sinistral shear has become more evident since the middle Pleistocene (**Figure 6**). This is suggested by neotectonic deformation, mainly NW-SE sinistral and conjugate dextral normal-oblique faults, and block rotations about vertical axes [102]-[104] and by the focal mechanism of the large earthquake (1915, M = 7) that occurred in the Fucino basin [105]. The formation of this transtensional fault system is consistent with the fact that the northward push of the Molise-Sannio units has only applied to the eastern part of the Latium-Abruzzi (LA) carbonate platform (**Figure 6**), inducing a sinistral shear stress inside that platform. The same interpretation may also explain why the basins located in the central part of the LA platform, such as the Upper Sangro, Fucino, Sulmona and L'Aquila, have undergone further development, whereas the more western troughs became inactive [106].

In the Northern Apennines, belt parallel compression may account for the occurrence of sinistral transtensional faulting in the axial belt [107]-[109], thrusting at the outer border [67] [110] [111], acceleration of uplift in the central and outer parts of the Northern Apennines [112]-[114].

In a number of works [115]-[119] it is argued that the implications of the tectonic setting described above are also compatible with the spatio-temporal distribution of major earthquakes in the Apennine belt and the peri-Adriatic zones. Moreover, the compatibility of the proposed tectonic mechanism with the kinematic pattern of northern and central Italy, obtained from analysis of space geodesy (GPS) measurements, is pointed out by [120] [121].

Also, it is worth noting that the location of the late Pleistocene Neapolitan, Roman and Umbrian Pleistocene volcanic complexes [19] corresponds fairly well to the inner boundaries of the Molise-Sannio and Romagna-Marche-Umbria extruding wedges, respectively (**Figure 6**). We advance the hypothesis that the transtensional regime developed in the wake of such extruding wedges mainly controlled the occurrence of the above volcanism. In this regards, several authors have found, both in Italy and elsewhere, close relationships between transtensional tectonics and volcanic activity [78] [122]-[126].

5. Results and Discussion

The evolution of the central Mediterranean region since late Miocene has been characterized by some drastic changes of tectonic setting. In line with the minimum-action concept, one may expect that each of such changes has marked the transition from a highly resisted deformation pattern to a new, less resisted tectonic configuration. So, to recognize how this concept may have conditioned the distribution of tectonic events it is most important understanding which shortening processes may oppose lowest resistance against plate convergence.

Since the resistance that acts in tectonic processes is mainly related to buoyancy forces, one might expect that the shortening required by plate convergence would be best accommodated by the sinking of oceanic lithosphere, which is characterized by the lowest buoyancy. However, major evidence suggests that the subduction of this kind of lithosphere at convergent boundaries can hardly start when it is only driven by horizontal forces induced by plate convergence. We argue that such consuming process can only develop when it is adequately triggered by the vertical forces at a margin of the involved oceanic domain. In particular, such dynamic context may develop as an effect of the sideway expulsion of orogenic wedges from constricted belts, in that the extruding material overthrusts the adjacent oceanic lithosphere, which starts subsiding under that additional load. On its turn, the lowering of the oceanic domain facilitates the outward escape of the orogenic wedges. The fact that in the middle Miocene the Mediterranean region was characterized by the presence of relatively large oceanic remnants and old orogenic belts has strongly favoured the occurrence of the above process.

The first major change of tectonic setting occurred in the upper Miocene (Tortonian), triggered by the activation of the Giudicarie fault system, which allowed the Adriatic promontory to modify its kinematics, as discussed in the text. This change, involving a divergence between the Adriatic and the almost fixed Corsica-Sardinia block, caused crustal stretching and magmatism in the northern Tyrrhenian zone.

The second major change of tectonic setting took place in the latest Miocene (Messinian), when the converging continental Adriatic domain and the Anatolian-Aegean-Pelagonian system came into a close contact. When the higher and higher resistance that was developing at that continental collision zone reached a critical value, a new minimum-action tectonic configuration was achieved, through a profound reorganization of the tectonic setting in the central Mediterranean region. The main effect was the decoupling of the Adriatic promontory from Africa, by the activation of a major discontinuity in the Ionian area (Victor Hensen fault system) and the Pelagian zone (Sicily channel), and from its Padanian protuberance, by the Schio-Vicenza fault system. After such decouplings, the resulting Adria plate underwent a clockwise rotation with respect to Eurasia. This motion was mainly accommodated by the consumption of a large part of the Ionian Tethys, which was achieved through a complex reorganization of microplate kinematics in that area. In response to strong E-W compression that was induced by the Adria plate, the Hyblean-Adventure block underwent a roughly northward sideway expulsion, that, on its turn, caused the roughly eastward escape of wedges from the Alpine-Apennine orogenic body which lay south of the Selli discontinuity. The occurrence of crustal stretching in the central Tyrrhenian basin and related magmatism is explained as an effect of the extensional regime that developed in the wake of the Alpine-Apennine escaping wedges. The strong uplift, distortion [mainly horizontal bowing] and disruption that the extruding belt sectors have undergone during this phase may be explained as an effect of the belt parallel compression that drove such processes.

Around the late Pliocene, the only sector of the Alpine-Apennine belt which still faced oceanic lithosphere (Ionian Tethys) was the Calabrian Arc. In line with the minimum-action condition, the main effect of that context was an acceleration of the outward extrusion of the Calabrian wedge. In the wake of that wedge, crustal stretching and magmatism occurred in the southernmost Tyrrhenian basin.

The last change of deformation pattern, mainly involving the Apennine belt, occurred around the middle Pleistocene, when tectonic activity resumed at most eastern and northern peri-Adriatic boundaries (Hellenides, Dinarides and eastern Southern Alps), testifying an acceleration of Adria. This motion has induced belt-parallel compression in the outer sector of the Apennines belt, which has undergone a roughly NE ward lateral escape, at the expense of the adjacent Adriatic domain. The oblique separation of the extruding wedges (Molise-Sannio, eastern Latium-Abruzzi platform, Romagna-Umbria-Marche and Toscana-Emilia) from the inner (almost fixed) part of the belt has generated extensional and transtensional features in the axial part of the belt, which now represent the main sources of major earthquakes. Moreover, the Neapolitan, Roman and Umbrian volcanism may be interpreted as an effect of the transtensional tectonics that affected the inner margin of the above extruding wedges.

The interpretation proposed here can plausibly and coherently account for the major features of all tectonic and magmatic events (with regards to location, timing, dimensions, tectonic style, etc.) that are recognized in the post middle Miocene evolution of the study area. Moreover, similar tectonic mechanisms may provide a plausible interpretation for the Neogene evolution of the western and eastern Mediterranean regions [6] [10] [11] and of the tectonic contexts that led to the formation of other trench-arc-back arc systems in the world [4].

6. Conclusions

The observed post Middle Miocene deformation pattern in the Mediterranean region can plausibly be explained as an effect of the convergence of the confining plates, Africa Eurasia and Anatolian-Aegean-Pelagonian system, without invoking the contribution of other driving forces, such as the ones induced by the sinking of subducted lithosphere (slab-pull) or by active rifting. In particular, it is argued that the generation of back arc basins, as the central and southern Tyrrhenian, was a side effect of extrusion processes. The plausibility of this interpretation is supported by numerical and mechanical experiments.

We argue that the lateral escape of orogenic wedges in constricted contexts has played a basic role in the evolution of the study area, since this kind of process has made possible the consumption of large remnants of the Tethys ocean, which could have hardly developed if such structures were simply stressed by horizontal compression due to plate convergence. This concept can account for the drastic changes of tectonic setting that occurred in the study area around the upper Miocene, when the northern Tyrrhenian began to develop, around the late Messinian, when the central Tyrrhenian started opening, and around the late Pliocene, when the southern Tyrrhenian began to be generated.

The present tectonic setting in the Italian region has developed since the middle Pleistocene, when the outermost sector of the Apennine belt, under belt parallel compression exerted by the Adriatic plate, has started undergoing major uplift and outward extrusion, at the expense of the Adriatic domain. This effect has caused the separation of such Apennine sector from the inner part of the belt, with the formation of a series of troughs in the axial part of the belt. The short term implications of this tectonic setting may plausibly account for the spatio-temporal distribution of major earthquakes in the peri-Adriatic zones since 1400 AD [127].

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