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How and why the present tectonic setting in the Apennine belt has developed

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Abstract

The building of the Apennine belt slowed down or ceased around the Early Pleistocene. Since then, the belt has undergone strong uplift and considerable distortion. Such drastic change, from belt-normal to belt-parallel shortening, has been determined by the fact that the continental Adriatic domain (Adria) was almost completely surrounded by buoyant orogenic structures. In that context, the mobility of Adria underwent a considerable reduction, while uplift and deformation of its southern part was strongly emphasized as an effect of the convergence of the confining plates. Around the middle Pleistocene, the deformation pattern in the periAdriatic zones changed again, in response to the acceleration of Adria. In the Apennines, the outer (Adriatic) sector of the chain underwent belt parallel shortening, accommodated by uplift and outward escape of upper crustal wedges. The separation between the extruding wedges and the almost stable inner belt has generated a series of extensional /transtensional fault systems along the axial part of the Apennines, that now correspond to the main seismogenetic sources. The main tectonic reorganizations in the study area are supposed to have been controlled by the least-action principle.

The Apennine chain (Fig.1) built up during the Miocene and Pliocene as an effect of the subduction of the Adriatic domain beneath the migrating advancing Alpine belt (e.g. Patacca et al., 1990; Mantovani, 2005, Viti et al., 2006; Molli, 2008; Mantovani et al., 2009, 2014). Around the early Pleistocene, this orogenic process underwent slowdown/cessation and the edifice of thrust sheets began to be significantly uplifted and distorted, with the formation of several arcs and troughs (e.g., Patacca et al., 1990; Hyppolite et al., 1994; Galadini, 1999; Schiattarella et al., 2003; Costa, 2003; Catalano et al., 2004; Patacca and Scandone, 2001, 2007; Piccardi 1999, 2006; Caiazzo et al., 2006; Scisciani and Calamita, 2009; Macchiavelli et al., 2012; Mazzoli et al., 2015). This last tectonic phase was accompanied by major volcanic episodes in two zones of the inner (Tyrrhenian) Apennine belt, the Roman and Campanian provinces (Savelli, 2002; Peccerillo, 2005; Alagna et al., 2010).

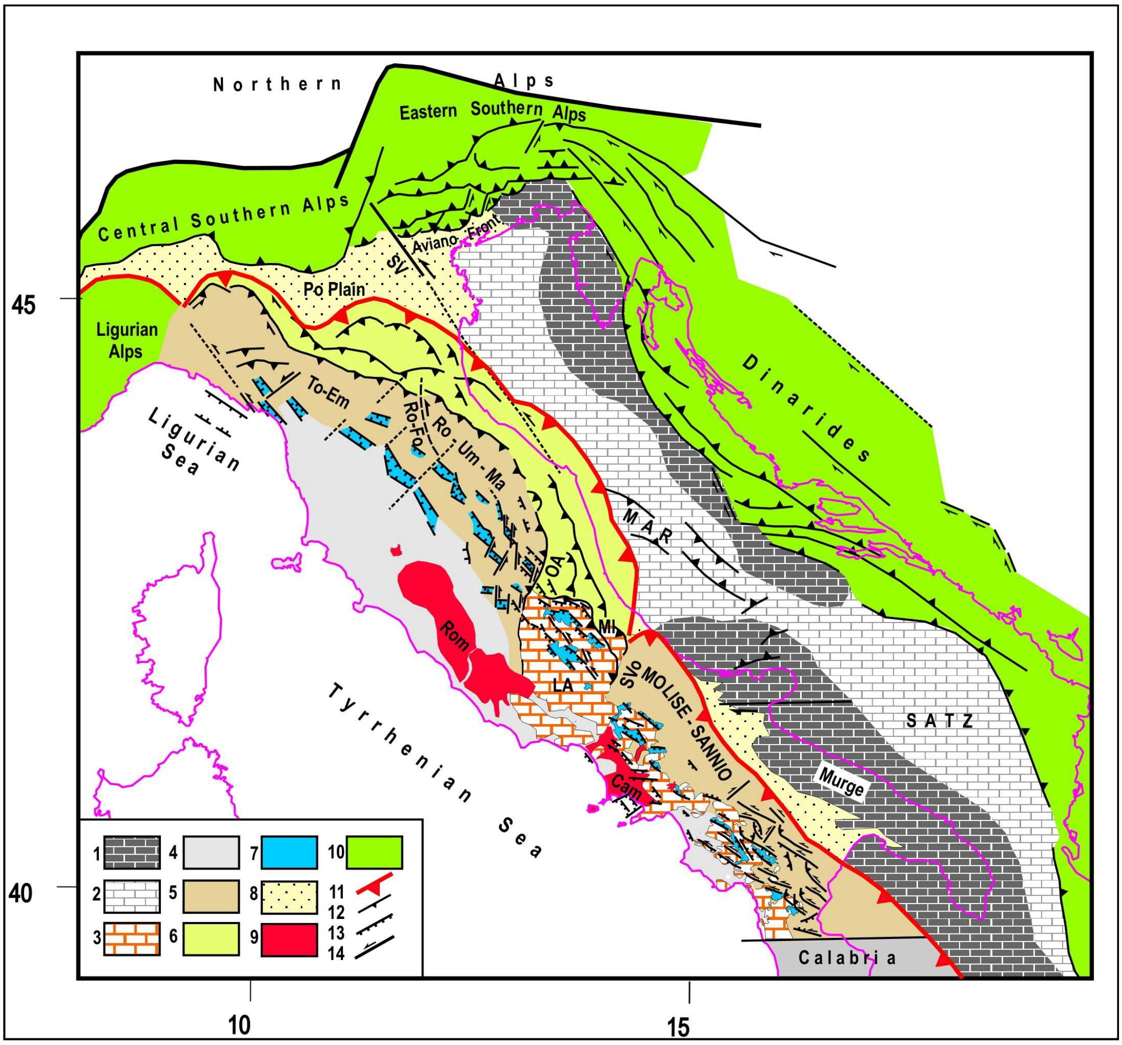

Fig.1 *Tectonic sketch of the Apennines and other periAdriatic belts. 1,2) Continental and thinned continental Adriatic domains 3) Apennine carbonate platforms 4,5,6) Inner, axial and outer sectors of the Apennine belt 7) Main Quaternary extensional troughs 8) Foredeep basins 9) Main Quaternary volcanism 10) Other periAdriatic belts 11) Outer fronts of the Apennine belt 12,13,14) Main compressional, extensional and transcurrent features. Cam=Campanian volcanism , LA=Lazio-Abruzzi platform, MAR=Mid Adriatic Ridge, Ml=Maiella massif, OA=Olevano-Antrodoco thrust front, Ro-Fo=Supposed fault system in the Romagna Apennines and Forli zones, Rom=Roman volcanism, Ro-Um-Ma=Romagna-Umbria-Marche Apennines, SATZ=Southern Adriatic thinned zone, SV=Schio-Vicenza fault system, SVo=Sangro Volturno thrust front, To-Em=Toscana-Emilia Apennines.*

Plate convergence can be accommodated by various kinds of shortening processes, such as subduction, crustal thickening, and lateral escape of buoyant crustal wedges at the expense of low buoyancy lithosphere. The distribution of such processes in time and space is controlled by the least-action principle, i.e., the need of minimizing the total work of horizontal, kinematically induced forces against any kind of resistance, such as buoyancy, friction, and viscous resistance of the mantle (e.g., Sleep et al., 1979; Molnar and Lyon-Caen, 1988; Closs, 1993; Masek and Duncan, 1998: Mantovani et al., 2000).

In this work, it is argued that the recent evolution of the study area has been mainly determined by tectonic reorganizations in the central Mediterranean area, controlled by the least-action principle after the consumption of thinned continental or oceanic domains that previously lay around the continental part of Adria.

With respect to previous attempts (Viti et al., 2006; Mantovani et al., 2009, 2014), the geodynamic interpretation here proposed aims at better explaining the structural and dynamic conditions that caused the major Pleistocene changes of tectonic setting in the Apennine belt.

Late Miocene: first least-action tectonic reorganization in the central Mediterranean area (decoupling of the Adria plate from Africa)

The tectonic setting in the central Mediterranean region changed considerably around the Late Miocene, as indicated by a large amount of evidence (Mantovani et al., 2009, 2014 and references therein). As argued in a number of papers (Mantovani et al., 2006, 2007, 2009, 2014; Viti et al., 2006, 2011), such reorganization took place in order to overcome the critical situation which occurred when the thinned domains (Ionian oceanic zones and thinned continental Adriatic margins, Fig. 2a) that previously separated the southernmost Adriatic continental domain (moving roughly NE to NNE ward as a part of Africa, e.g., Mantovani et al., 2007, 2015a) and the Northern Hellenides (pushed roughly westward by the Anatolian-Aegean system) was were mostly consumed (Fig. 2b). The consequent collision between the converging buoyant continental or orogenic domains caused a drastic increase of resistance against any further convergence at that boundary zone. In that new context, the convergence between the Anatolian-Aegean-Hellenic system and the Africa-Adriatic plate was allowed by a profound reorganization of the tectonic/kinematic context in the whole central Mediterranean region (Fig.2b), aimed at replacing highly resisted consuming processes at collisional boundaries between buoyant structures with alternative, less resisted, shortening processes, mainly involving the consumption of the remnant oceanic or thinned continental crustal domains which were still present on the western side of the continental Adriatic domain.

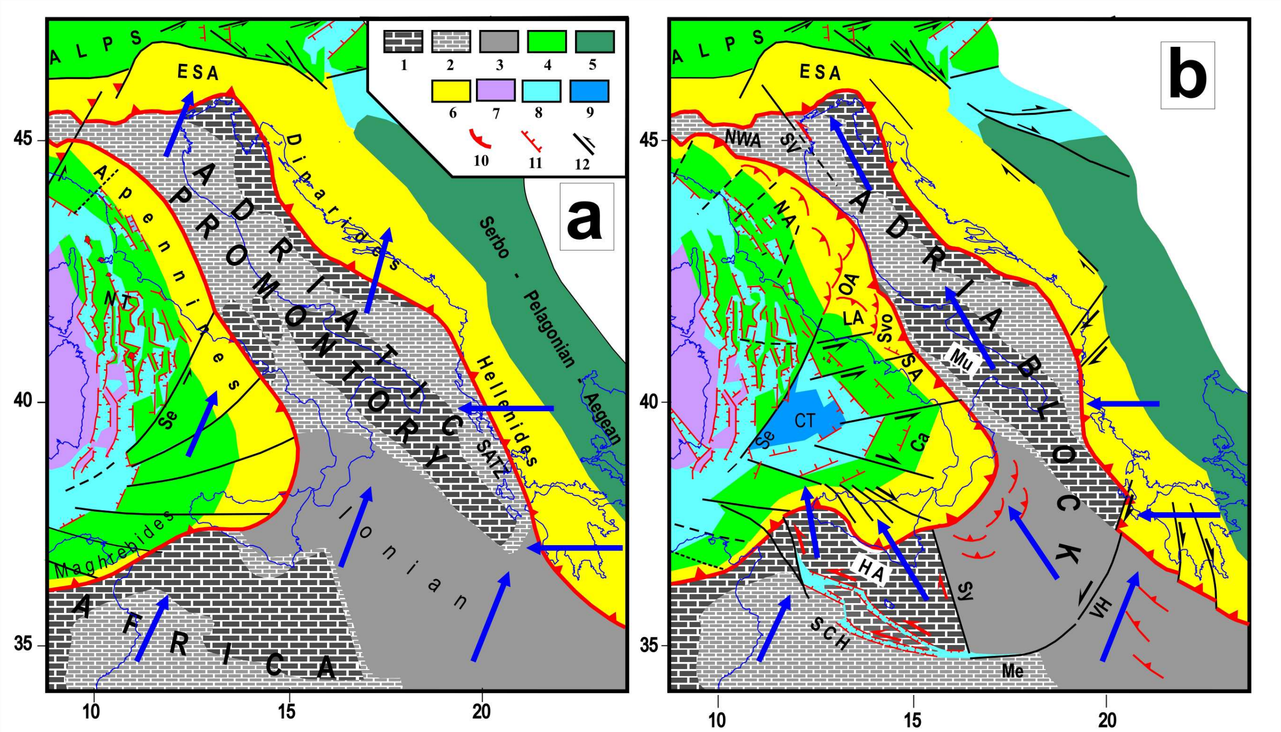

Fig. 2. (**a**) *Tentative reconstruction of the Upper Miocene configuration and kinematic pattern in the central Mediterranean area (Viti et al., 2006; Mantovani et al., 2009) 1,2) Africa-Adriatic continental and thinned*

continental domains 3) Ionian oceanic domain 4) Alpine and lower Miocene Apennine belt 5) Serbo-Pelagonian-Aegean-Anatolian metamorphic belt 6) Neogene accretionary belts 7) Corsica-Sardinia 8,9) Neogene extensional basins and oceanized zones 10,11,12) Major compressional, extensional and transcurrent tectonic features. ESA=Eastern Southern Alps, NT=Northern Tyrrhenian basin, Se=Selli fault system. SATZ=Southern Adriatic thinned zone. Blue arrows indicate the proposed kinematic pattern (velocities lower than 1 cm/y) with respect to Eurasia (Mantovani et al., 2007, 2015a; Viti et al., 2009, 2011). (**b**) *Pliocene configuration and kinematic pattern after the drastic tectonic reorganization that led to the decoupling of the Adria block from Africa (by the activation of the Victor Hensen-Medina-Sicily Channel fault systems) and from the Northwestern Adriatic protuberance (by the activation of the Schio-Vicenza fault system), see text. Ca=Calabria, CT=Central Tyrrhenian, HA= Hyblean-Adventure, LA=Lazio-Abruzzi carbonate platform, Me=Medina fault system, Mu=Murge, NA=Northern Apennines, NWA=Northwestern Adriatic protuberance, OA=Olevano Antrodoco thrust front, SA=Southern Apennines, SCH=Sicily Channel fault system, SV=Schio-Vicenza fault system, SVo=Sangro-Volturno thrust front, Sy=Syracuse fault system, VH=Victor-Hensen fault system.*

A major role in such tectonic reorganization was played by the decoupling of a large part of the African promontory (comprising the Adriatic domain, the northern Ionian oceanic zone and the Hyblean-Adventure block) from the main Africa plate (Fig. 2b), through the activation of the Victor-Hensen, Medina and Sicily Channel fault systems (Finetti and Del Ben, 2005a; Hieke et al., 2003, 2006), and from the northwestern Adriatic protuberance, through the activation of the Schio-Vicenza fault system (e.g., Massironi et al., 2006; Pola et al., 2014). Such major decouplings allowed the new independent plate (Adria hereafter) to move compatibly with the roughly westward motion of the Anatolian-Aegean-Hellenic system (Mantovani et al., 2009, 2014; Viti et al., 2011). The Hyblean-Adventure block decoupled from Adria by dextral movement at the Syracuse fault system and underwent a roughly Northward extrusion.

The new kinematics of these structures, and in particular the roughly northward indentation of the extruding Hyblean-Adventure block, induced a strong compressional regime in the Alpine-Apennine orogenic body which lay south of the Selli fault system, causing lateral escape of wedges (mainly the Southern Apennines and Calabria), at the expense of Ionian oceanic domain and thinned continental Adriatic domain (Fig. 2b). In the wake of those migrating wedges, crustal stretching developed, causing the opening of the Central Tyrrhenian basin (Mantovani et al., 2009, 2014; Viti et al., 2009, 2011).

The above tectonic pattern lasted until the late Pliocene-Early Pleistocene, when the building of the Apennine belt ceased (e.g., Patacca et al., 1990; Cello and Mazzoli, 1999; Tavarnelli and Prosser, 2003; Catalano et al., 2004), as discussed in the next section.

Early Pleistocene: second tectonic reorganization (internal deformation, with uparching and dextral torsion, of the Adria plate

When the migrating Southern Apennine wedge reached the western margin of the continental Adriatic domain, around the Early Pleistocene, the resistance against any further development of that consuming process increased considerably. We suppose that such critical situation required a new reorganization of the central Mediterranean tectonic setting, in order to activate alternative less resisted shortening processes, able to accommodate the convergence of the confining plates (Africa, Eurasia and Anatolian-Aegean system). In particular, we suppose that the above compressional context was mainly absorbed by uparching/uplift and internal deformation of the southern Adriatic platform and by the other tectonic events described in the following:

- After the end of subduction in suture of the Southern Apennine consuming boundary, the roughly NNE ward push of Africa and the westward push of the Anatolian-Aegean system (through the Hellenides belt) induced a strong roughly E-W compression, accompanied by dextral torsion, in the southern part of Adria. This dynamics caused internal deformation of the plate, respectively given by the acceleration of upward flexure, up to form the present structural dome in the Murge zone, generally recognized as Apulian Swell (e.g., Finetti and Del Ben, 1986; Argnani et al., 1993; Tropeano et al., 2002; Santangelo et al., 2012) and by the formation of an oblique anticlinal feature (Mid Adriatic Ridge, Fig. 3, e.g., Scisciani and Calamita, 2009). Since the compressional regime that affected the southern Adriatic domain in the Early Pleistocene was almost completely accommodated by the internal deformation (uparching and dextral torsion), one may suppose that during such phase the mobility of Adria was relatively low (Fig.3). This hypothesis is compatible with the deformation pattern of the periAdriatic zones during that phase (e.g., Mercier et al., 1987; Moulin et al., 2016).

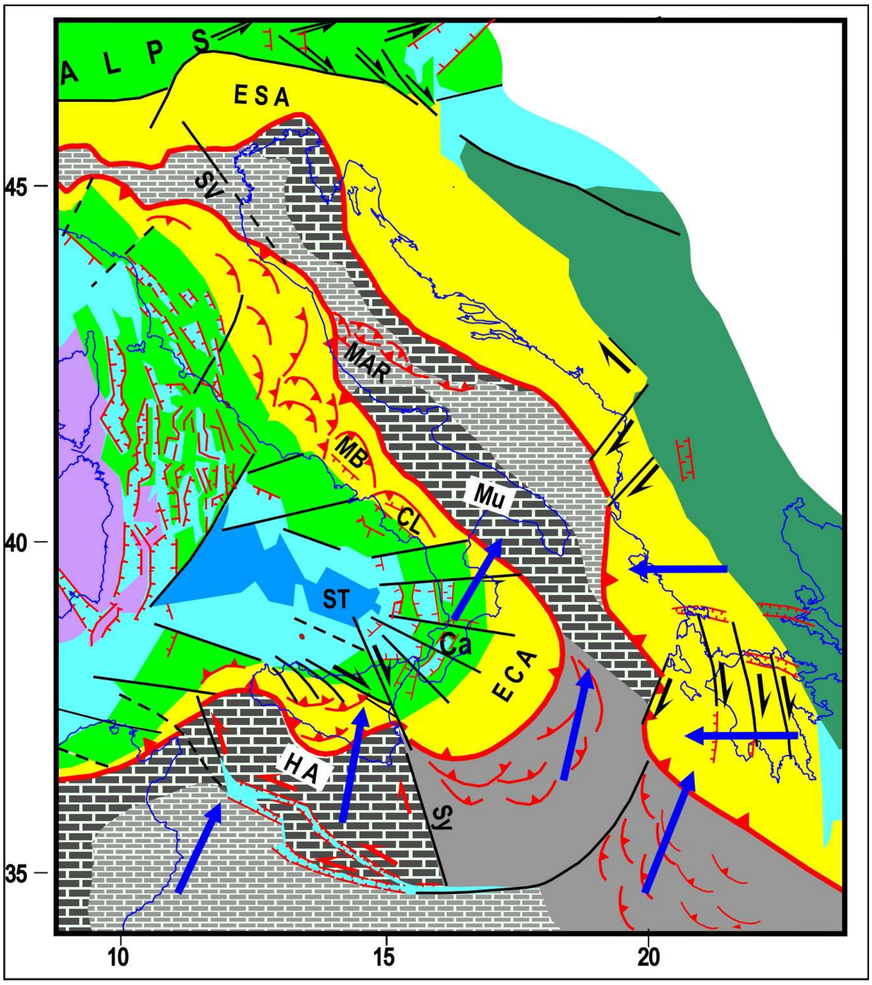

Fig. 3. *Early Pleistocene configuration, CL = Campania-Lucania arc, ECA=External Calabrian Arc, MAR=Mid Adriatic ridge, MB = Matese-Benevento arc, ST=Southern Tyrrhenian basin. Symbols, colours and other abbreviations as in figure 2.*

- The outer thrust front of the Southern Apennine wedge stopped, while the most rigid shallowest layer of that wedge, the carbonate platform units, underwent uplift and horizontal bowing. This led to the formation of two major arcs, the Campania-Lucania and the Matese-Benevento (Fig.3), as indicated by the thrusts which are recognized in the pelagic/terrigenous units (Molise-Sannio wedge) that lay along the outer fronts of those arcs (e.g., Corrado et al., 1997; Menardi Noguera and Rea, 2000; Patacca and Scandone, 2001; Piedilato and Prosser, 2005). The overthrusting of the above units onto the Adriatic foreland is indicated by the development of duplex structures (e.g., Cello et al., 1989; Menardi Noguera and Rea, 2000; Fantoni and Franciosi, 2010). The SE-NW orientation of shortening in the Apennines is consistent with the fact that the westward push of the Anatolian–Aegean system, transmitted by the Hellenides, and the NE ward push of Africa, transmitted by the Calabrian and Hyblean-Adventure wedges, imply a resulting driving force mainly parallel to the Apennine trend (Fig. 3).

- The deformation and lateral escape of the Calabrian wedge, at the expense of the Ionian oceanic domain, significantly accelerated, as suggested by the fact that this belt sector underwent horizontal bowing, fast uplift (1 mm/y) and a general strengthening of tectonic activity, with the formation of several troughs and sphenocasms (Fig.3, e.g., Van Dijk and Schepeers, 1995; Monaco and Tortorici, 2000; Zecchin et al., 2012; Vitale and Ciarcia, 2013). Significant accretionary activity developed along the outer front of the migrating wedge, forming the External Calabrian Arc (e.g., Rossi and Sartori, 1981; Finetti and Del Ben, 1986; Volpi et al., 2017). Coeval crustal stretching occurred in the wake of the same wedge (e.g., Mantovani et al., 2009), generating the southernmost Tyrrhenian, the Marsili basin (Fig.3, e.g., Sartori, 2005; Finetti and Del Ben, 2005b).

Middle Pleistocene: Third tectonic reorganization (the Adria plate accelerates, reactivating tectonic activity in the surrounding belts)

We suppose that around the Middle Pleistocene the sum of resistances against the shortening processes that developed in the Early Pleistocene (described in the previous section) reached a critically high value, making thus necessary a new reorganization of the kinematic/tectonic setting in the central Mediterranean area. The deformation pattern that developed since then suggests that such tectonic reorganization mainly involved the mobilization of Adria, with the kinematics indicated in figure 4. This solution was most probably favored by the release of the gravitational energy that the southern part of Adria had accumulated during the previous phase of strong uplift and by the fact that such escape allowed Adria to move towards less constricted zones. The above hypothesis is compatible with the tectonic activity that developed since the Middle Pleistocene along the periAdriatic belts, as described in the followings.

Eastern (Northern Hellenides and Dinarides) and Northern (Southern Alps) Adria boundaries

- Accretionary activity reactivated in the Northern Hellenides and Southern Dinarides around the Middle Pleistocene (e.g., Mercier et al., 1987; Sorel et al., 1992). This deformation is still going on, as suggested by studies of seismic sources in the Dinarides, which indicate WSW-ENE to E-W thrusts and NNW-SSE dextral strike-slip faults (e.g., Markusic and Herak, 1999; Finetti and Del Ben, 2005b; Ilic and Neubauer, 2005; Herak et al., 2005).

- In the northernmost Dinarides belt, it is recognized that in several NW-SE fault systems thrusting activity has been accompanied by dextral motion in the most recent evolution (e.g., Poljak et al., 2000; Burrato et al., 2008; Kastelic et al., 2008; Slejko et al., 2011; Moulin et al., 2016), which is compatible with a dextral transcurrent motion of the Adriatic plate with respect to the Carpathian-Pannonian zones.

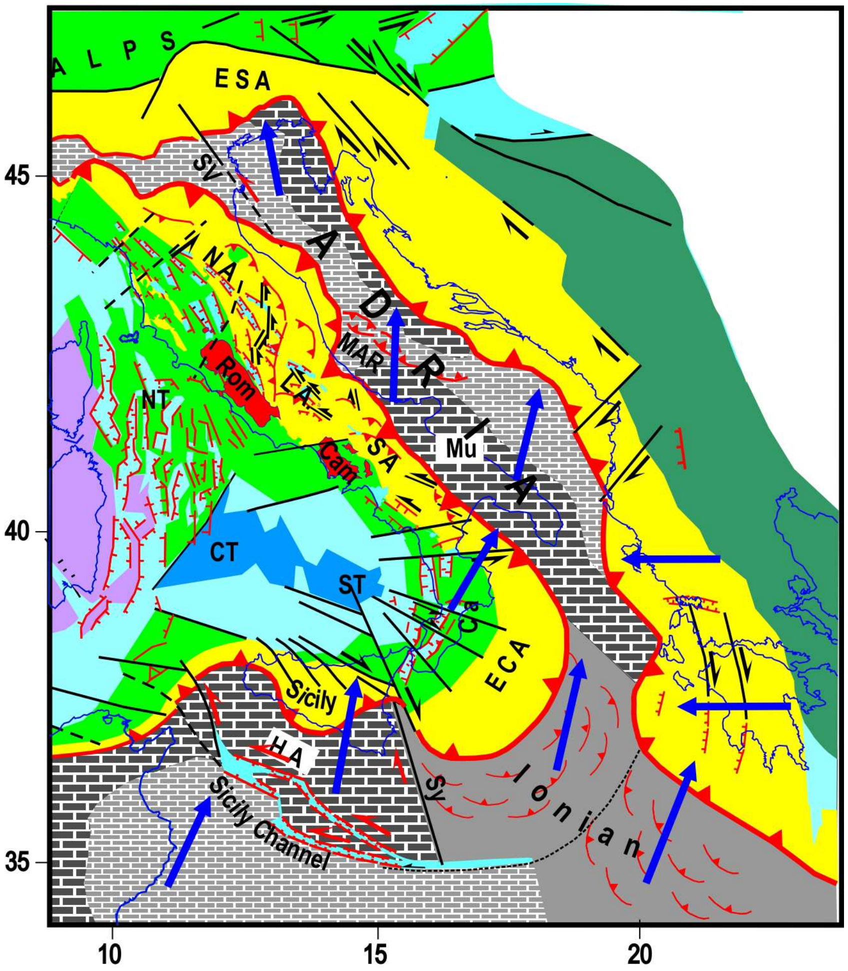

Fig.4. *Post middle Pleistocene tectonic setting in the central Mediterranean region. Symbols, colours and abbreviations as in figures 1, 2 and 3.*

- An acceleration of thrusting and strike-slip deformation is recognized in the northern front of Adria (Southern Alps, Veneto and Friuli plains, e.g., Benedetti et al., 2000; Galadini et al., 2005). In particular, this activity has involved the Aviano compressional front (Fig. 1), constituted by a series of WSW-ENE thrust structures connected by sinistral strike slip faults (e.g., Del Ben et al., 1991), which indicate a roughly perpendicular motion of the Adriatic plate in the Southern Alps.

- Evidence of Middle Pleistocene to Present sinistral transcurrent activity in several segments of the Schio-Vicenza line has been recognized (e.g., Zampieri et al., 2003). Such activity may be connected with the roughly northward motion of the main Adria plate with respect to its more stable western protuberance Padanian sector. The SE-ward prosecution of the above fault would run under the thick sedimentary cover of the Po Plain and Adriatic Sea (Pola et al., 2014). However, it is worth noting that significant seismic activity occurs along the offshore zone running from Ancona to Rimini and that the focal mechanisms of recent earthquakes in the Ancona zone (the 1972 and 2013 sequences) are compatible with a sinistral strike-slip regime (e.g., Boncio and Bracone, 2009; Mazzoli et al., 2015).

Western Adria boundary (Apennines)

The effects of Adria's acceleration in the Apennine belt have been quite peculiar and different with respect to the ones that developed in the eastern and northern Adria boundaries. Such difference is mainly due to the fact that the motion of Adria has been mostly parallel to the Apennine belt. This kinematics of Adria has determined a sort of dragging and longitudinal push on the Apennines, which has induced belt-parallel shortening in the outer sector of that chain, i.e. the one that is more connected with the underlying Adriatic slab. Another important aspect of the above dynamic mechanism is the fact that the part of Adria that stressed the Apennine belt was the Apulian swell, i.e. the uplifted part of the Adriatic platform. Thus, the most intense push has acted on the uppermost crustal layers of the Apennines. Since many sectors of the belt are characterized by the presence of Triassic evaporites at the basis of the sedimentary cover (e.g., Bosellini, 2004; Ciarapica and Passeri, 2005; Hude and Jackson, 2008; De Paola et al., 2008, 2009), the above dynamic context has caused the decoupling of upper crustal wedges from the underlying crust. Such dynamic and structural context has caused uplift and outward escape of the Molise-Sannio and Romagna-Marche-Umbria wedges, at the expense of the underthrusting Adriatic margin (Fig.5) This interpretation can plausibly account for the deformation pattern evidenced by a large amount of evidence, synthesized in the followings.

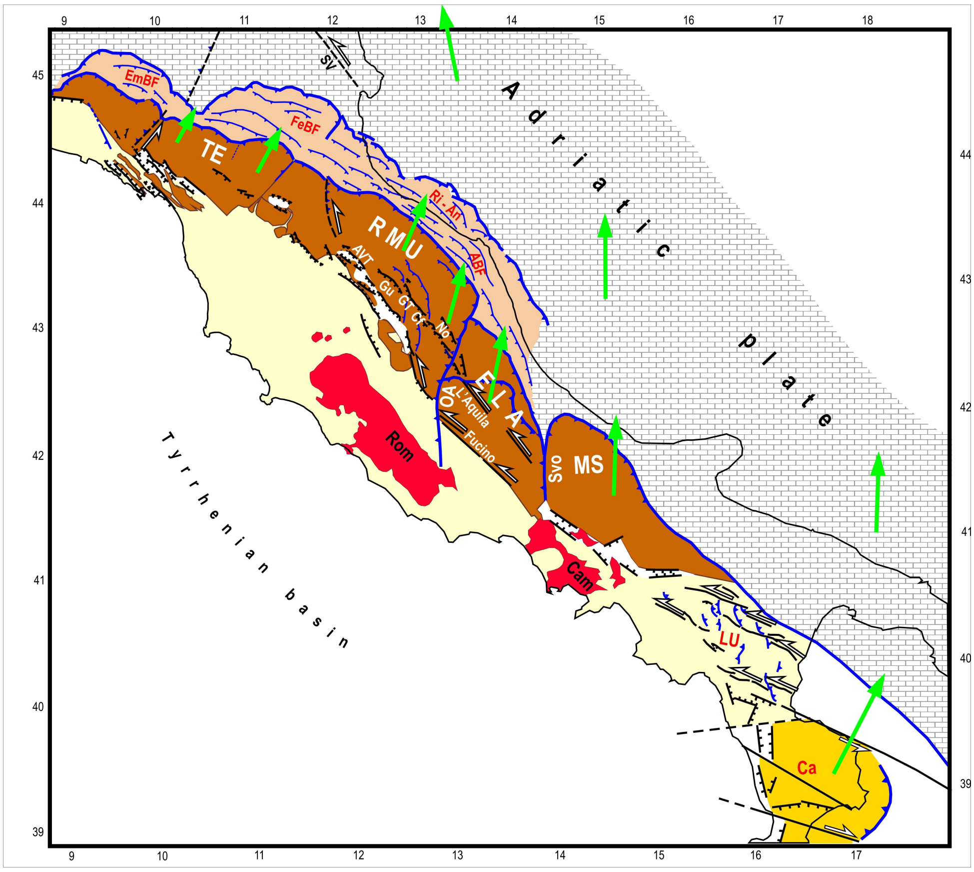

Fig.5. *Main upper crustal wedges in the outer most mobile sector of the Apennines (dark brown): MS=Molise-Sannio, ELA=Eastern-Lazio-Abruzzi, Lu=Lucania Apennines; RMU=Romagna-Marche-Umbria and TE=Toscana-Emilia. The buried external folds in the Northern Apennines (EmBF= Emilia, FeBF=Ferrara, ABF=Adriatic), are light brown. AVT=Alta Valtiberina, Ca=Calabria, Cf=Colfiorito, GT=Gualdo Tadino, No=Norcia, Ri-An=Rimini-Ancona zone*, *Other symbols and abbreviations as in figure 1. Green arrows indicate the presumed kinematic pattern.*

- The southernmost sector of the Apennine belt (Lucanian Apennines) has been dissected by a system of NW-SE sinistral strike-slip faults, accompanied by compressional and tensional features at restraining and releasing stepovers respectively (e.g., Cello et al., 2003; Catalano et al., 2004, Maschio et al., 2005; Ferranti et al., 2009, 2014). Some of these last features now correspond to main seismic sources (e.g., Maggi et al., 2009). The sinistral shear indicated by the above features may be an effect of the left lateral motion of Adria with respect to the Calabrian wedge and southernmost Apennines (Fig.5).

- A system of normal faults, roughly trending NW-SE, has developed in the internal side of the Molise-Sannio wedge (e.g., Cucci et al., 1996; Ascione et al., 2003, 2007; Brozzetti, 2011) These extensional features, corresponding to main seismic sources in the Irpinia and Matese-Benevento zones (e.g., Valensise and Pantosti, 2001), may be due to fact that the Molise-Sannio wedge, being carried by Adria, has undergone an oblique separation from the inner less mobile belt (Fig.5). The results of seismic surveys (Improta et al., 2003) and the depth distribution of earthquake hypocentres in the above zones (e.g., Di Bucci et al., 2006; Fracassi and Valensise, 2007; De Matteo et al., 2018) suggest that the Molise-Sannio migrating wedge encompasses the strongly deformed cover of the allochthonous pelagic and terrigenous units, the underlying embricated Apulian carbonate platform and perhaps the top of the Adriatic Paleozoic basement.

- In the Upper Pleistocene, abundant volcanic activity has occurred in the Campania province (e.g., Peccerillo, 2005; Alagna et al., 2010). The location and timing of the above magmatic activity may suggest that such episode was produced by the extensional features (mainly pull-apart troughs) generated by the oblique divergence between the Molise-Sannio wedge and the innermost belt (e.g., Tamburelli et al., 2000). The location of such activity is related to where the subduction-related magmas had been previously generated and accumulated by the melting of the uppermost Adriatic slab, while the timing of magma erupting is related to when pathways through the crust have opened, in response to the transtensional regime cited above.

- Strong uplift (~1mm/yr since 0.7 My, Pizzi, 2003; Ascione et al., 2008) has affected the Maiella zone, at the boundary between the Southern and Central Apennines. Such deformation could be an effect of a transpressional regime, as proposed for the Monte Alpi zone located in the southern (Lucanian) Apennines (Brankman and Aydin, 2004). Indeed, Elter et al. (2012) consider the Maiella zone as a pop-up structure which formed at a restraining bend of a sinistral strike-slip fault system. The fact that the Maiella and Monte Alpi, both parts of the embricated Apulian carbonate platform, are constituted by exhumed rocks and correspond to the most uplifted structures of the whole Apennine belt (e.g., Ghisetti and Vezzani, 1999) might imply similar genetic mechanisms.

- In the Central Apennines (Lazio-Abruzzi platform), the development of NW-SE sinistral and conjugate dextral normal-oblique faults and block rotations about vertical axes (e.g., Piccardi et al., 1999; Galadini, 1999) indicates that since the Middle Pleistocene sinistral shear has affected the axial part of the Lazio-Abruzzi platform (e.g., Galadini e and Messina, 2004; Elter et al., 2012). This strain regime may be due to the fact that the belt-parallel push of the Molise Sannio wedge was mainly applied to the eastern sector of the LA platform, causing greater shortening of that sector with respect to the inner one. This deformation may be connected with the formation of the Gran Sasso Arc and of the L'Aquila and Fucino transtensional fault systems along the inner boundary of that arc (Pizzi and Galadini, 2009; Elter et al., 2012; Blumetti et al., 2013).

- Fast uplift has affected the outer sector of the northern Apennines since the Middle Pleistocene, as documented by numerous geomorphological indicators (e.g., Argnani et al., 1997; Bartolini, 2003). The foothills of the Umbria-Marche units in the Northern Apennines, located between the axial belt and the Adriatic coast, have undergone a considerable uplift (e.g., Coltorti and Pieruccini, 1997; Calamita et al., 1999; Cerina Feroni et al., 2001; Centamore and Nisio, 2003; Boccaletti et al., 2010).

- Compressional features of Upper Pleistocene age are recognized along the outer front of the RMU wedge with particular reference to the Rimini zone (e.g., Boncio and Bracone, 2009). The interpretation of seismic surveys along the Marche coastal region suggests a main shortening axis perpendicular to the thrust fronts (Lavecchia et al., 2007; Vannoli et al., 2004; Boncio and Bracone, 2009; Visini et al., 2010; Elter et al., 2012; Artoni, 2013). Evidence of Upper Pleistocene thrusting are also observed along the outer Padanian front of the Tuscany-Emilia wedge (e.g., Argnani et al., 2003; Ghielmi et al., 2010). Earthquake focal mechanisms indicate that the above compressional regime is still active at the outer front of the RMU and TE wedges. (e.g., Boncio and Bracone ., 2009; Lavecchia et al., 2012; Mazzoli et al., 2015).
- The results of seismic surveys (Finetti et al., 2001, 2005) and borehole data (Corrado et al., 1998; Patacca et al., 2008) indicate that the Northern Apennine crustal material, which has been involved in the outward migration, mainly correspond to the sedimentary cover (Triassic evaporites and overlying Mesozoic and Cenozoic units). The decoupling of these wedges from the deeper crust and from the more internal Tuscany units is most probably taken up by sliding along low angle normal faults bordering the troughs recognized in that zone, for instance the Val Tiberina trough in the seismic section CROP-03 (GS-1, GS-2 and GS-3 faults, Finetti et al., 2001, 2005; Mantovani et al., 2015c). The outward escape of the RMU wedge, testified by the deformations cited above, has been driven by the belt-parallel push of the ELA wedge. However, major evidence suggests that the sector of LA which has indented the Northern Apennines has become narrower and narrower over time (Viti et al., 2015). At present, the main transtensional fault systems at the inner boundary of the ELA wedge are the L'Aquila and Fucino ones (Fig. 5). The seismic activity that occurred in the last centuries (Rovida et al., 2016) suggests that the activation of the L'Aquila fault system is more frequent than the one of the Fucino fault system. When the seismic decoupling develops at the L'Aquila fault, the RMU sector that is stressed by the ELA acceleration is the most external one (Mantovani et al., 2015c), i.e. the one bordered by the fault system that runs from L'Aquila to Norcia, Colfiorito, Gualdo Tadino, Gubbio, up to the AltaValtiberina trough (Fig. 5**).** These belt-parallel faults bound a series of depressions connected by a network of N-S sinistral strike-slip faults (e.g., Cello et al., 1997; Tondi, 2000; Elter et al., 2012). This last very young fault system (Late Pleistocene, e.g., Boncio and Lavecchia, 2000; Calamita et al., 2000; Decandia et al., 2002; Brozzetti et al., 2009; Pizzi e Galadini, 2009; Chicco et al., 2017) cuts transpressional structures which were built up during the previous compressional phase, with particular regard to the SW-NE Olevano-Antrodoco thrust front.

The transtensional fault systems, associated with pull-apart troughs, that have been generated by the oblique relative motion between the extruding RMU wedge and the inner Apennine belt may have favoured the uprise of magmas in the Roman volcanic province (Fig.5, Argnani and Savelli, 1999; Tamburelli et al., 2000 and references therein; Brogi et al., 2010), analogously to what occurred in the wake of the Molise Sannio extruding wedge in the Southern Apennines.

The hypothesis that the Apennine belt has been stressed by belt-parallel compression can account for the fact that such chain contemporaneously experienced extensional deformation in the axial zone and general uplift and thrusting in its outer sector. A similar geodynamic driving mechanism has been also suggested by other authors (e.g., Elter et al., 2012). Moreover, the concept of belt- parallel shortening has been successfully adopted in order to explain the seismotectonic setting of other important orogens in the world, as the Cascade Range in the northwestern Pacific American border (Wells et al., 1998; Wells and Simpson, 2001; Fay and Humpreis, 2008). Finally, very recent analogue modelling discusses the physical and structural parameters which may control the belt-parallel shortening mechanism (Boutelier et al., 2018).

The kinematic pattern that is delineated by the analysis of GPS data in the Italian area (e.g., Cenni et al., 2012; Mantovani et al., 2015a) is compatible with the hypothesis that the outer part of the Apennine belt moves faster and with a larger eastward component with respect to the inner belt.

In a number of papers, we argued that the short-term effects of the Apennine tectonic pattern described in this note are compatible with the spatio-temporal distribution of major earthquakes in the last centuries (Mantovani et al., 2010, 2015b, 2017; Viti et al., 2012, 2013).

Discussion

Other attempts at explaining the Pleistocene change of tectonic pattern in the Apennine belt suggest that such event was influenced by fragmentation of Adria (e.g., D'Agostino et al., 2008). However, such hypothesis can hardly be reconciled with the fact that no clear decoupling zone can be recognized in the almost aseismic Adriatic foreland (see for instance the discussion given by Mantovani et al., 2015). It is difficult to believe that the relative motion between fragments of a thick continental plate can occur without generating significant seismicity, magmatism and well recognized deformations (e.g., Babbucci et al., 2004; Argnani, 2006; Nocquet, 2012; Le Breton et al., 2017). The ambiguity which surrounds the possible Adria decoupling zones is underlined by the considerable spreading of the proposed decoupling discontinuities, concerning location, trend and strain regime (e.g., Mantovani et al., 2015a and references therein). Furthermore, the presumed plate fragmentation is hardly compatible with the poor deformability of the Adriatic lithosphere, which appears to be one of the coldest and most rigid in the whole Mediterranean and Western Europe, as highlighted by seismological and rheological investigations (e.g., Debayle et al. 2005; Cloetingh et al., 2006). From this point of view, our model of belt-parallel compression is more acceptable as it implies the decoupling of the sedimentary cover from underlying basement, without involving the Adriatic deep crust and lithospheric mantle.

A possible fragmentation of Adria has also been taken into account by Moulin and Benedetti (2018) to tentatively explain the fact that in the Eastern Alps the present (18-15 ka) shortening rate (1.5 mm/yr) has been lower (and more northward oriented) than the average one estimated for the last 14 Ma (3mm/yr). In our opinion, the kinematics of Adria can hardly be constrained by only considering the deformation pattern in a limited boundary zone and in a very short time interval. To obtain a reliable reconstruction of the kinematic history of such plate, one should take into account the major tectonic events that occurred in the periAdriatic zones, as the ones cited in this and previous works. In particular, one could wonder why Moulin and Benedetti (2018) have not taken into account the Messinian reactivation of a major fracture in the northern Adriatic domain (Schio-Vicenza fault system), which, along with other major coeval tectonic events in the periAdriatic zones (Viti et al., 2006; Mantovani et al., 2009), may provide important information on the kinematics of Adria. It may be noted that our reconstruction (involving a roughly NNW ward post Messinian motion of Adria) is compatible with the shortening trend recognized by Moulin and Benedetti (2018) in the Eastern Alps. The fact that the present shortening rate in the above zone is lower than the previous average rate is compatible with the slowdown that the Adria plate is supposed to have undergone in the Pleistocene (Viti et al., 2006; Mantovani et al., 2009). As concerns the motion of Nubia, it might be useful taking into account the considerations given by Mantovani et al. (2007, 2015a) and Viti et al. (2009), which points out the possible uncertainties on the Nubia-Eurasia relative motion proposed by global kinematic models (e.g., Calais et al., 2003). The main problem of these models is reconciling the considerable difference between the supposed motion trend of Nubia (roughly NNWward) and the present motion trend of Adria (roughly NE ward, clearly indicated by geodetic data, e.g., Serpelloni et al., 2013, Mantovani et al., 2015a) with the lack of any significant decoupling zone between Nubia and Adria.

An Adria kinematic pattern significantly different from the one here delineated has been proposed by other authors (e.g., Le Breton et al., 2017), who suggest that in the last 20 My the above plate has undergone a CCW rotation of 5±3° and a NW ward translation of about 113 km. This hypothesis is based on estimates of shortening in the Alps and Dinarides and extension in the Sicily Channel. However, assuming pure extension (an d plate divergence) in the Sicily Channel is not compatible with the available evidence (e.g., Cello et al., 1987; Reuther et al., 1993; Finetti and del Ben., 2005), which rather indicates a system of transcurrent faults (Figs. 3 and 4). The limited zones of tectonic extension in the Sicily Channel correspond to pull-apart troughs developed at step-overs of strike-slip faults. Furthermore, one should take into account that the Sicily Channel fault system has developed since the Late Miocene.

Other authors (Faccenna et al., 2014) argue that the Pleistocene deformation pattern in the Apennine belt has been influenced by changes of deep-seated dynamic processes (mantle convection pattern), linked to the development of windows in the western subducted margin of Adria. This hypothesis is based on estimates of residual topographies in the Apennine belt, which indicate positive values in the central Apennines and negative values in the northern Apennines and Calabria. The positive values in the central Apennines are tentatively imputed to upwelling induced by mantle convection in a sector of the Adriatic subducted lithosphere where a slab window is supposed to have developed since the early Pleistocene. However, since the detachment of that slab is also recognized beneath the southern Apennines (e.g., Faure Walker et al., 2012) one would expect that an analogous effect has developed in such belt sector, which however is not considered in the analysis of Faccenna et al. (2014). Most probably, this is due to the fact that the topography and uplift rate in the southern Apennines are quite different from the ones observed in the central Apennines. One could also note that the subsidence predicted by Faccenna et al. (2014) in Calabria is not compatible with geological data, which clearly indicate that Calabria has undergone a fast uplift in the last Ma, with rates comparable to the ones in the Apennines (Cucci, 2004; Zecchin et al., 2004; Antonioli et al., 2004; Ferranti et al., 2009)., The presence and possible shape of the presumed subducted lithospheric bodies are surrounded by uncertainty since such features are recognized by various tomographic images not always similar. The only clear evidence of a well developed rigid subducted lithosphere is given by the occurrence of deep earthquakes (with a complex distribution of hypocenters in a narrow zone) beneath the central-southern Tyrrhenian basin. Beneath the northern Apennines, subcrustal earthquakes are mainly shallower than 70 km and characterized by low magnitudes.

More in general, we think that the approach adopted by Faccenna et al. (2014) does not take into account that topography and uplifting rate of an orogenic belt can be determined not only by isostasy and deep tectonic forces (mostly vertical). One must also consider the deformations that a belt can undergo when is stressed by horizontal compression, due to the convergence of the confining plates. Such dynamics can cause crustal thickening and uplift when the belt is laterally confined by buoyant domain, or alternatively may produce lateral escape, with spreading of orogenic material (and consequent crustal thinning), when the constricted belt is flanked by less buoyant domains, like an oceanic zone. Lateral (even very long) migrations of orogenic belts (Alpine and Apennine) is largely recognized in the Mediterranean region.

Our hypothesis that the Pleistocene deformation pattern of the Apennine belt was conditioned by belt-parallel compression is compatible with major features in that chain (Fig.1), as the presence of transversal thrust fronts (Olevano-Antrodoco and Sangro-Volturno, e.g., Mazzoli et al., 2005; Ascione et al., 2008), the development of major and minor arcs (e.g., Menardi Noguera and Rea, 2000; Costa, 2003; Satolli and Calamita, 2008; Scisciani and Calamita, 2009), the generation of troughs in the inner sides of arcs (Viti et al. 2006, Mantovani et al., 2009; Sani et al., 2009). To this regard, it is worth noting that the belt sector where topography is highest is comprised between the two thrust fronts cited above. Furthermore, the proposed tectonic context may account for major aspects of Quaternary volcanic activity in the belt, i.e. the location and time of the two main episodes (Roman and Campanian provinces, Fig. 5, Tamburelli et al., 2000; Peccerillo, 2005). Lateral escape of orogenic material (as effect of belt parallel compression) has mainly involved the Molise-Sannio wedge in the southern Apennines and the Romagna-Marche-Umbria wedge in the northern Apennines, which has consequently undergone spreading of orogenic material and crustal thinning. The central Apennines (Latium-Abruzzi platform) have instead undergone a very limited lateral escape, for the reasons explained by Viti et al. (2006) and Mantovani et al. (2009), and thus in such zone the horizontal shortening has been accommodated by more intense crustal thickening, as clearly indicated by enhanced topography and other morphological features.

More in general, we think that alternative geodynamic interpretations, as the ones cited in this discussion, do not pay sufficient attention to the spatio-temporal distribution of major tectonic events in the periAdriatic regions and often neglect major features, well documented in literature. In particular, we wonder why none of the alternative geodynamic solutions so far proposed provide possible explanations for the development of a major long discontinuity in the Ionian and Hyblean zones (i.e. in the African plate) in the late Miocene and for the fact that such major tectonic event has been accompanied by other important coeval events, as the end of accretionary activity at the collision zone between the southern Adriatic plate and the Aegean system, the reactivation of a major discontinuity (Schio-Vicenza fault zone) in the northern Adriatic foreland, the strengthening of orogenic activity in the Apennine belt, after a phase of reduced activity, the starting of crustal stretching in the central Tyrrhenian basin (Mantovani et al., 2009 and references therein).

Conclusions

In a zone stressed by plate convergence, as the Mediterranean region, tectonic activity and the kinematics of the interposed structures is mainly controlled by the activation of the shortening processes which allow to minimize the resistance of gravity. This result is mainly accomplished by consuming the less buoyant domains by subduction. The reconstruction of this last process, by studying the time development of accretionary activity in consuming boundaries, is the main information we have on the relative motions between the most buoyant elements, as continental domains and orogenic belts. The main drastic changes of tectonic pattern in the periAdriatic zones, with particular regard to the Apennine belt, are interpreted as effects of the strong increases of resistance that occurred at consuming boundaries where highly buoyant, continental structures came into direct contact, after the consumption of the interposed thinned continental or oceanic domains.

This kind of situation has occurred in the Late Miocene, in the Early Pleistocene and in the Middle-Upper Pleistocene. The most important corner point in the evolution of the Apennine belt was the stop of accretionary activity and the starting of a completely different tectonic pattern, mainly characterized by development of arcs, uplift and extensional/transtensional deformation in the axial part of the belt. This drastic change of tectonic style occurred in the early Pleistocene, when the continental part of Adria was almost completely surrounded by highly buoyant orogenic belts, once sutured after the suture of the Southern Apennines consuming boundary. Since then, the convergence of the confining plates (Africa, Eurasia and Anatolian-Aegean system) was accommodated by a strong deformation of the southern Adria domain zone (with uparching and dextral torsion). During that phase the outward escape of the Calabria wedge accelerated and the Southern Apennines underwent belt-parallel shortening, with the formation of the Campania-Lucania and Matese-Benevento arcs, while the mobility of the Adria plate underwent a considerable reduction.

Then, around the Middle Pleistocene, the tectonic pattern in the Apennine belt and in the other periAdriatic regions has undergone underwent a new important change, due to the acceleration of Adria. This mobilization, favored by the release of the gravitational energy that the southern Adria had accumulated during its Lower Pleistocene uplift, caused a reactivation of thrusting in the eastern (Dinarides) and northern (Southern Alps) Adria boundaries. In the Apennines, the acceleration of Adria emphasized belt-parallel shortening, which was accommodated by uplift and outward extrusion of upper crustal wedges (Molise-Sannio, Lazio-Abruzzi, Romagna-Marche-Umbria and Toscana-Emilia) in the outer part of the belt. The main effects of such tectonic mechanism are listed below:

In the southernmost sector of the belt (Lucanian Apennines), strike-slip tectonics has developed with the formation of a system of NW-SE sinistral strike-slip (locally trans-pressional or trans-tensional) faults.

In the Southern Apennines, from the Irpinia to Matese zones, a long and complex system of normal faults roughly trending NW-SE has developed in the axial part of the belt

In the Central Apennines, sinistral trans-tension characterized the system of NW-SE trending faults located in the axial belt In the Northern Apennines, sinistral trans-tensional faulting in the axial belt developed whereas thrusting affected the outer domain

Strong uplift has affected the axial and outer parts of the whole Apennine belt

Massive volcanic activity has occurred west of the Southern Apennine transtensional belt, generating the Campanian volcanism. Meanwhile, intense and widespread volcanism occurred along the inner (Tyrrhenian) side of the Northern Apennines, building up the Roman volcanic province

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