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Geodynamics of the central-western Mediterranean region: plausible and non-plausible driving forces

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Abstract. The observed deformation pattern in the central-western Mediterranean area, in particular the development of the Northern, Central and Southern Tyrrhenian basins in three well distinct phases, can hardly be explained as an effect of the gravitational sinking of subducted lithosphere, an hypothesis often advanced in literature. A more plausible and coherent explanation of the spatio-temporal distribution of major tectonic events in the study area can instead be achieved by supposing that tectonic activity has mainly been driven by the convergence of Africa and Eurasia and the roughly westward displacement of the Anatolian-Aegean-Pelagonian belt. The development of Arc-Trench-Back Arc systems is interpreted as an effect of extrusion processes, that in some constricted contexts have represented the most convenient shortening process for accommodating plate convergence.

Keywords: Mediterranean, geodynamics, slab-pull, extrusion

1. Introduction

In the last 30-35 My the Mediterranean area has undergone a drastic change (Fig. 1), as suggested by several authors (e.g., Dercourt et al., 1986; Meulenkamp and Sissingh, 2003; Mantovani, 2005, Mantovani et al., 2006, 2009; Viti et al., 2009 and references therein). The pre-existing Alpine orogenic belt has undergone considerable distortions and long migrations of even several hundreds of Km. Some zones, mainly located in the internal side of the migrating arcs, have undergone crustal extension and consequent thinning, with the formation of large basins (Balearic, Tyrrhenian, Aegean and Pannonian). The oceanic and thinned continental zones which surrounded the African/Adriatic promontory have been almost completely consumed by subduction. Since extensional deformations are generally considered as scarcely compatible with the compressional context induced by plate convergence, some authors have tentatively advanced the hypothesis that other types of forces acted in the Mediterranean region. In particular, the most often cited interpretation suggests that the migration of arcs and the related back-arc extension have been driven by the gravitational sinking of subducted lithosphere, as originally proposed by Malinverno and Ryan (1986) and Royden (1993). In this work, we argue that the main implications of the above interpretation can hardly be reconciled with the observed features and that a more plausibile and coherent explanation of the evolutionary history can be achieved by supposing that Arc-Trench-Back Arc systems (ATBA) have developed in the framework of extrusion processes, driven by the convergence of the confining plates. With respect to previous attempts (e.g., Mantovani et al., 2009, 2014; Viti et al., 2009), this work reports new evidence and arguments about the compatibility of the interpretations here discussed with the observed deformations.

2. Balearic and Tyrrhenian basins interpreted as effects of the slab-pull genetic mechanism: main problems

Balearic basin

In the Oligocene, the western Alpine belt, tentatively reconstructed by the Al-Ka-Pe-Ca system, and the Corsica-Sardinia block (Fig.1a) detached from the European-Iberian foreland and underwent a fairly long eastward migration and strong bowing (Fig.2), while crustal extension occurred in the wake of the migrating arc, forming the Balearic basin (e.g., Maillard and Mauffret, 1999; Gaspar-Escribano et al., 2004; Gattacceca et al., 2007; Lustrino et al., 2009; Etheve et al., 2016)

Several authors (e.g., Royden and Burchfiel, 1989; Schmid et al., 1996, 2004; Stampfli et al., 1998; Finetti et al., 2005a; Handy et al., 2015) suggest that the western Alpine belt built up as an effect of the subduction of the Valais and Piemont-Ligurian oceanic domains and the European thinned continental margin, which generated a southward verging slab. In the Oligocene, such process underwent slowdown/cessation, when continental crust entered the trench zone. Then, along the Alpine sector lying aside the Iberian domain, another opposite verging (North to NW ward) subduction process started, involving the consumption of the Tethyan oceanic domain under the migrating Al-Ka-Pe-Ca belt (Gaspar-Escribano et al., 2004; Lustrino et al., 2009; Schettino and Turco, 2006; Handy et al., 2015; Etheve et al., 2016). This implies that when the ATBA system began to migrate, in the Oligocene, the northward dipping slab did not exist or was scarcely developed, being thus unable to induce a sufficient slab-pull force. To this regard, it should be considered that laboratory and numerical modelings suggest that a minimum slab length (150-300 km) is required in order to initiate back-arc extension driven by slab-pull (e.g., Hassani et al., 1997; Faccenna et al., 1999; Schellart, 2005).

Other authors instead, suggest that prior to the formation of the Liguro-Provencal basin (30-25 My) there was a well developed northward dipping slab at least 150 km long (Jolivet and Faccenna, 2000, Carminati et al., 2012; van Hinsbergen et al., 2014, Faccenna et al., 2014a) beneath the Alpine belt. However, no clear information is provided about the correspondence between the dimension and age of the present Alpine-Apennine belt and the orogenic material that the presumed subduction process would have accumulated in the trench zone.

The fact that during the formation of the Balearic basin the Northern Al-Ka-Pe-Ca arc underwent an evident sinistral NE-SW shift with respect to the Western Alps (Fig.2), leading to the formation of the Ligurian basin (e.g., Makris et al., 1999; Mosca et al., 2010), suggests that such arc was stressed by belt-parallel push. This kind of stress field is also suggested by the kinematics of the strike-slip faults and lateral escape of blocks in the Sardinia-Corsica microplate (e.g., Carmignani et al., 1994, 2004; Oggiano et al., 2009 and references therein). The Oligocene-Aquitanian age of this tectonic regime has been mainly constrained by the analysis of the infilling succession of transtensive basins. The above evidence is not compatible with the roughly eastward orientation of the trench suction force that would have been induced by a slab-pull mechanism.

Another major feature of the Balearic ATBA system that cannot easily be explained as an effect of slab-pull forces is the strong bowing that the Arc underwent during its migration (Fig. 2b). Numerical modelings of a slab-pull mechanism (e.g., Schellart et al., 2007) could justify a curvature of the migrating arc, but the resulting effect is much smaller than the one that really occurred in the western Mediterranean area (Mantovani et al., 2001a; 2002; Viti et al., 2009 and references therein**).** Moreover, the horizontal bowing predicted by modellings would need more than 16 My to develop (e.g., Schellart et al., 2007). Other laboratory experiments suggest instead a linear shape of the retreating subduction boundary, without significant arc bowing (Becker et al., 1999).

It is not demonstrated that the trench-suction force induced by gravitational sinking of a slab can break the upper plate. The results of some laboratory and numerical experiments (e.g., Shemenda, 1993; Hassani et al., 1997; Capitanio et al., 2010) indicate that slab-pull cannot produce significant deformation in the upper plate unless it was not previously weakened by other tectonic or magmatic processes. Even in this last case, the trench suction force would be unable to produce extension in the overriding plate until the slab has reached a length of about 150-300 km.

Northern Tyrrhenian basin (9-6 My)

From about 9 to 6 My, the sector of the Alpine-Apennine belt that lay aside the Corsica-Sardinia block (Fig. 3a) underwent roughly E-W crustal extension and consequent thinning (e.g., Mauffret et al., 1999; Sartori et al., 2001; Carmignani et al., 2004; Finetti et al., 2005a; Peccerillo, 2005; Sartori, 2005; Moeller et al., 2013; Cornamusini et al., 2014). This process formed the Northern Tyrrhenian basin (Fig.3b), a roughly triangular zone confined to the South by the Selli fault, which divided the extending Tyrrhenian area from an orogenic Alpine-Apennine body (Sartori et al., 2001, 2004).

Explaining the main features of such extensional event as an effect of slab-pull forces (e.g., Malinverno and Ryan, 1986; Royden, 1993) involves serious difficulties.

Most authors suggest that the stop of the northern Al-Ka-Pe-Ca Arc and the Corsica-Sardinia block occurred when the Adriatic continental domain entered the trench zone, around 15 My (Speranza et al., 2002; Finetti et al., 2005a; Gattacceca et al., 2007; Molli 2008, Malusà et al., 2016). In that context, any further development of slab roll-back would have encountered very strong resistance from buoyancy forces (e.g., Brancolini et al., 2019). In fact, in the subsequent period (from about 15 to 9 My) no possible effects of trench retreat (such as crustal extension) has developed in the zone overlying the slab (Faccenna et al., 2001, 2014a; Finetti et al., 2005a). Thus, the hypothesis that the subducted Adriatic margin has undergone gravitational sinking from about 9 to 6 My, forming the Northern Tyrrhenian basin, suggests some questions:

- Why slab-roll back did not occur for about 6 My and why it would have resumed at 9 My ?

- Why from 9 to 6 My gravitational sinking would have only affected the northern sector of a long slab lying beneath the whole Apennine belt ? in spite that the slab sector lying under the Central-Southern Apennines and Calabria was certainly more developed.

- Why was there no accretionary activity in the Northern Apennine belt during the formation of the Northern Tyrrhenian basin ? If crustal extension is supposed to be an effect of slab-pull forces, one could expect to observe as well the other major effect of that driving mechanism, i.e. the development of accretionary activity along the front of the migrating Arc, as indeed occurred in the previous period, during the formation of the Balearic basin.

- Why was the zone affected by crustal extension confined by the Selli fault, which is obliquely oriented with respect to the eastward orientation of slab roll-back (and of crustal extension) ?

- Why in the Messinian (6-5 My) gravitational sinking of the slab would have ceased beneath the Northern Apennines and started beneath the Southern Apennines ?

The attempts at interpreting the evolution of the Northern Tyrrhenian-Apennine system as an effect of slab-pull forces are encouraged by some tomographic studies (Lucente et al., 1999; Piromallo and Morelli, 2003; Spakman and Wortel, 2004) which suggest the presence of a well developed lithospheric body (hundreds of Km long) beneath that belt. However, these interpretations cannot easily be reconciled with the results of other tomographic investigations (Scafidi et al., 2009; Scafidi and Solarino, 2012) and CROP seismic soundings (e.g., Finetti et al., 2001, 2005a), which do not evidence any well developed lithospheric slab beneath the Apennine-Tyrrhenian system. The occurrence of some subcrustal earthquakes beneath the Northern Apennines cannot be used to confirm the results of tomography, since focal depths are mainly lower that 70 km (e.g., Chiarabba et al., 2005) and the magnitudes are very low (ISIDe Working Group, 2016). It is worth noting that the distribution of subcrustal earthquakes is compatible with the geometry of the crustal slivers suggested by CROP sections (Finetti et al., 2005a).

Some authors have tried to identify possible explanations for episodic effects of gravity on subducted lithosphere. For instance, Faccenna et al. (2001, 2014a) recognize the problem of episodic slab retreat, stating that it could be explained by the interaction of the subducted lithosphere with the 670 km-depth mantle discontinuity. The inability of the slab to penetrate across such discontinuity would cause a sudden decrease of the subduction rate and trench retreat. Only after the slab has folded over the mantle discontinuity, subduction and trench migration may resume again, leading to a new phase of back-arc extension (Faccenna et al., 2004, 2007). However, it must be considered that the above results have been obtained by experiments where the upper plate is not present at all, a quite irrealistic condition. Other experiments have shown that the presence of a sufficiently strong upper plate can prevent slab roll-back (see figure 11 by Capitanio et al., 2010 and Shemenda, 1993; Hassani et al., 1997).

Central Tyrrhenian basin (about 5-2 My)

In the late Miocene-Early Pliocene crustal extension ceased in the Northern Tyrrhenian and began to develop in the Alpine-Apennine sector located south of the Selli fault, generating oceanic crust in the central Tyrrhenian area (Magnaghi and Vavilov basins, Fig.4, e.g., Finetti and Del Ben, 1986, 2005a; Mascle and Rehault, 1990; Sartori, 1990, 2005; Sartori et al., 2004; Guillaume et al., 2010).

Such extension was accompanied by other coeval major tectonic events in the central Mediterranean region, as listed in the following.

- Thrusting and folding underwent a significant acceleration in the Apennine belt (e.g., Patacca et al., 1990; Coward et al., 1999; Catalano et al., 2004; Cerrina Feroni et al., 2004; Parotto and Praturlon, 2004; Patacca and Scandone, 2007; Ghielmi et al., 2013).
- In the Northern Apennines, the foredeep geometry underwent a major change during the Late Pliocene, passing from a continuous (cylindrical) to highly fragmented (non-cylindrical) pattern (Amadori et al., 2019).

- Seismic soundings (Finetti et al. 2001, Finetti et al., 2005b) indicate that since the latest Miocene the Adriatic lithosphere has undergone strong shortening, accommodated by major thrust faults cutting the entire crust and that significant shortening (several tens of Km) also affected the migrating arc.

- Since the late Messinian, a major transtensional fault system (Sicily Channel, Medina and Victor Hensen, Fig. 4) developed in the Pelagian and Ionian zones (e.g., Finetti and Del Ben, 1986, 2005b; Boccaletti et al., 1987; Cello, 1987; Reuther et al., 1993; Hieke et al., 2003, 2006 and references therein).

- During the Lower Pliocene, the western border of the thinned Hyblean domain (Sciacca fault) was activated as a dextral shear zone (Civile et al., 2018), while compressional deformation is recognized in the Maghrebian sector lying north of the Adventure block (Pepe et al., 2005) and an extensional regime formed the Pantelleria trough (Civile et al., 2014, 2018, Finetti and Del Ben, 2005b).

- The Malta and Linosa troughs started developing (Catalano et al., 1994; Furlani et al., 2013).

- The Sicilian Apennines underwent a southward bending, attributed to E-W shortening (e.g., Ghisetti et al., 2009), forming the Gela nappe.

- Dextral transpressional deformation, associated with a system of NW-SE faults, is recognized in the Maghrebian belt lying north of the Hyblean-Adventure promontory (Fig. 4, e.g., Catalano et al., 1994, 1996; Sulli, 2000; Guarnieri, 2004; Finetti et al., 2005c).

- An old NW-SE discontinuity in the northern Adriatic foreland reactivated with a sinistral strike-slip regime (the Schio-Vicenza fault system, Fig. 4, e.g., Castellarin and Cantelli, 2000; Zampieri et al., 2003; Massironi et al., 2006; Pola et al., 2014).

- Since the late Miocene, NW-SE to N-S thrusting in the Southern Alps mostly affected the sector lying east of the Schio-Vicenza fault (e.g., Bressan et al., 1998; Galadini et al., 2005), while such activity almost ceased west of that discontinuity.

- In the Northern Dinarides several thrust faults reactivated as dextral strike-slip faults (Placer et al., 2010).

Any attempt at explaining the formation of the Central Tyrrhenian basin as an effect of slab-pull forces should provide plausible answers to some demanding questions:

- Why in the Pliocene would gravitational sinking have only affected the sector of the slab located beneath the Southern Apennines ? (although at that time the slab was well developed under the Calabrian Arc).
- Why would such sinking have only begun in the latest Miocene ? notwithstanding the slab under the Apennines was already well developed in the middle Miocene.
- Why would the effects of slab-pull forces beneath the southern Apennines have ceased in the late Pliocene-early Pleistocene ? i.e. when crustal stretching ended in the Central Tyrrhenian basin.

Other major problems for slab-pull supporters are discussed in the following:

The subsidence predicted by the slab-pull mechanism in the trench zone (Shemenda, 1993; Hassani et al., 1997; Buiter et al., 2001; Hampel and Pfiffner, 2006; Husson, 2006) is just opposite to the uplift that most of the Apennines belt and Calabrian Arc have undergone in the Pliocene and Quaternary (e.g., Westaway, 1993; Pizzi, 2003; Schiattarella et al., 2003; Rusciadelli, 2005, Ghielmi et al., 2013).

Belt-parallel shortening of the whole Apennine chain, evidenced by the formation of major and minor arcs and transversal thrust fronts, as the Olevano-Antrodoco and Sangro-Volturno (e.g., Pizzi and Galadini, 2009; Di Domenica et al., 2012; Ghielmi et al., 2013; Amadori et al., 2019), is not compatible with the trench suction forces implied by slab roll-back.

The Northern Adriatic foredeep does not show any evidence of tilting after the early Pliocene, suggesting that tectonic activity in the Apennine belt can hardly be imputed to slab-pull forces (Brancolini et al., 2019).

Since the activation of major fault systems in the Pelagian zone (Sicily Channel) and the northern Adriatic foreland (Schio-Vicenza) can hardly be explained as effects of slab-pull forces beneath the Southern Apennines, there remains the problem of identifying which other driving mechanisms were active in the central Mediterranean zone during the Pliocene. In this regard, Faccenna et al. (2004, 2007) suggest that transtensional deformation in the Sicily Channel could be related to the breaking that would have affected the most curved sector of the wide slab formed during the Balearic phase. Such deep break would have caused the Late Miocene alkaline volcanism in northern Tunisia and Sardinia and deformation in the Sicily Channel zone. However, slab breaking and related magmatism (e.g., Lustrino and Wilson, 2007) do not necessarily presuppose passive lithosphere sinking. Moreover, one must consider that tectonic activity in the Sicily Channel relates to transcurrent fault systems, with some sectors of pull-apart extension, which cannot simply be generated by uprising of magma.

Southernmost Tyrrhenian (Pleistocene)

In the early Pleistocene, crustal stretching ended in the Central Tyrrhenian and started developing in the southernmost Tyrrhenian area (Marsili basin, e.g., Finetti and Del Ben, 1986; Sartori, 1990; Savelli, 2002). This extension (Fig. 5) was accompanied by other major tectonic events in the surrounding regions:

- In the late Pliocene-Early Pleistocene thrusting underwent slowdown/cessation in the Southern Apennines (e.g., Cello and Mazzoli, 1999; Catalano et al., 2004; Patacca and Scandone, 2004, 2007).
- Tectonic activity considerably strengthened in the Calabria-Peloritani wedge, with development of major troughs, transversal discontinuities and relative block rotations, accompanied by fast uplift (e.g., Westaway, 1993; Van Dijk and Scheepers, 1995; Zecchin et al., 2004, 2010, 2011, 2015; Finetti, 2005a; Tansi et al., 2007; Del Ben et al., 2008; Spina et al., 2011; Roda-Boluda and Whittaker, 2017; Tripodi et al., 2018).

- Thrusting and folding increased along the external front of the Calabrian wedge, with the formation of the External Calabrian Arc complex (e.g., Patacca et al., 1990; Del Ben, 1993; Finetti, 2005a).

-Tectonic and volcanic activity increased at the Taormina and Palinuro fault systems (e.g., Finetti and Del Ben, 1986; Finetti et al., 1996; Ventura et al., 1999; Savelli, 2002; Peccerillo, 2005).

- Thrusting at the front of the Adventure block and extension in the Pantelleria graben slowed down with respect to the Pliocene (Pepe et al., 2005; Civile et al., 2010, 2018).

- The southern Adriatic plate underwent upward flexure, with the formation of the Apulian swell (e.g., Finetti and Del Ben, 1986; Tropeano et al., 2002; Santangelo et al., 2012).

- In the Early Pleistocene, the northern Adriatic foreland and the surrounding foredeeps were affected by intense subsidence (Ghielmi et al., 2013; Zecchin et al., 2017).

Explaining the formation of the southernmost Tyrrhenian basin and the coeval tectonic events cited above (Fig. 5) as an effect of slab-pull forces involves some major problems, as discussed in the following.

-The uplift that the Calabrian Arc underwent in the Pleistocene cannot be reconciled with the subsidence predicted by gravitational sinking of the underlying slab (Shemenda, 1993; Hassani et al., 1997: Buiter et al., 2001; Hampel and Pfiffner, 2006; Husson, 2006; Faccenna et al., 2014b).

- The strong deformation that the Calabria-Peloritani wedge has undergone since the late Pliocene, with the formation of several longitudinal troughs and transversal sphenocasms and the bowing and uplift of that arc, is compatible with belt-parallel compression, which can hardly be taken as an effect of slab roll-back.

- The upward flexure of the southern Adriatic domain (Apulian swell) cannot easily be explained as an effect of slab roll back.

- The very small width of the Marsili basin (about 50 Km, Fig.5) would imply the roll-back of a corresponding narrow slab. However, such slab shape would require the presence of major decoupling tear faults between the sinking lithosphere and the lateral (not sinking) sectors. When and why did such tears develop ?

Recent/present tectonic setting in the Apennine belt

Around the middle Pleistocene (Fig.6), the deformation pattern in the Apennines underwent an important change, recognized by most authors (e.g., Hippolyte et al., 1994; Galadini, 1999; Bartolini, 2003; Piccardi et al., 2006):

- Strike-slip tectonics has developed in the southernmost (Lucanian) sector of the Southern Apennines, with the formation of 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).
- In the northern sector of the Southern Apennines, from the Irpinia to Matese zones, a system of normal faults roughly trending NW-SE has developed in the axial part of the belt (e.g., Ascione et al., 2003, 2007; Brozzetti, 2011).
- In the Central Apennines, sinistral transtension is recognized in the system of NW-SE normal-oblique faults located in the axial belt (e.g. Galadini, 1999; Piccardi et al., 1999; Galadini and Messina, 2004; Elter et al., 2012).
- In the Northern Apennines, sinistral transtensional faulting in the axial belt (e.g., Cello et al., 1998, 2000; Boncio and Lavecchia, 2000; Tondi and Cello, 2003; Piccardi et al., 2006) and thrusting at the outer border (e.g., Boncio and Bracone, 2009; Scisciani and Calamita, 2009; Boccaletti et al., 2011) have occurred. The middle-upper Pleistocene evolution of this belt sector indicates a predominance of vertical motion, with uplift and widening of the Northern Apennine range (Ghielmi et al., 2013).
- Uplift has affected the axial and outer sectors of the whole Apennine belt (e.g., Argnani et al., 2003; Bartolini, 2003; Schiattarella et al., 2003, Ascione et al., 2008).

- Compressional features have developed in the inner part of Adria, such as the Middle Adriatic Ridge (Fig. 6, e.g., Scisciani and Calamita, 2009).
- Two major volcanic episodes (Roman and Campanian provinces, Fig.6) occurred in the western side of the Apennine belt (Peccerillo, 2005; Alagna et al., 2010). The emplacement of such volcanism has been related to transtensional faulting (Milia and Torrente, 2003; Acocella and Funiciello, 2006).
- Around the middle-late Pleistocene, the northern part of the Calabrian wedge reaches the continental Adriatic domain and a new major fault system (Sibari), almost parallel to the Adria border develops (Fig. 6, e.g., Guarnieri, 2006; Del Ben et al., 2008; Ferranti et al., 2014; Zecchin et al., 2015, Volpi et al., 2017).
- The Crati and Mesima longitudinal troughs and the Catanzaro and CapoVaticano transversal troughs/faults develope in the Calabrian Arc (e.g., Spina et al., 2011; Zecchin et al., 2015; Tripodi et al., 2018).
- The Vulcano-Syracuse fault system activates (e.g., Finetti and del Ben, 1986; Del Ben et al., 2008; Sulli et al., 2013).
- The Sciacca fault system becomes a sinistral shear zone and is affected by magmatic activity (e.g., Lodolo et al., 2012; Civile et al., 2018, Fedorik et al., 2018).

The present kinematic pattern in the Italian region is fairly well defined by the analyisis of geodetic data observed in more than 700 permanent GPS stations in the period running from January 1, 2001 to December 31, 2018. The horizontal velocity field derived by such data (Fig. 7) with respect to a fixed Eurasian frame (Euler pole at 54.23˚N, 98.83˚W, ω = 0.257˚/Myr, Altamimi et al., 2016) shows that the outer sector of the Apennine belt, including the buried thrusts and folds under the Po Plain, moves considerably faster (4-5 mm/y) and with a greater eastward component with respect to the inner belt (1-2 mm/y). In the Padanian zone that lies west of the Giudicarie fault system velocity values show a significant decrease and a different trend, with respect to the outer

Apennine belt. In southern Italy, the geodetic field confirms the long-term roughly NE ward motion trend of Calabria and the NNW ward motion trend of the Hyblean zone.

To interpret the drastic change of tectonic style that occurred in the Apennine belt around the middle Pleistocene as an effect of slab-pull forces, one should explain why the effect of such deep driving mechanism on shallow structures has considerably changed at that time. An attempt in this sense has been made by some authors (e.g., Faccenna et al., 2014b), who suggest that the Pleistocene deformation pattern in the Apennine belt has been controlled by changes of deep seated dynamic processes (mantle convection) connected with the development of windows in the western subducted margin of Adria located beneath the Central and Southern Apennines (e.g., Wortel and Spakman, 2000; Piromallo and Morelli, 2003; Faccenna et al., 2007)**.** However, this interpretation cannot easily be reconciled with some major features of the observed deformation pattern, as discussed in the following:

- Pleistocene uplift is recognized in the whole belt, from the Northern Apennines to Calabria, although this effect would only be expected in the belt sectors (Central and Southern Apennines) located above the supposed slab windows.
- The velocity field derived from GPS measurements in the Italian region (Fig. 8) indicates that the outer sector of the Apennine belt is moving faster (4-5 mm/y NEward) than the inner sector (1-2 mm/y N to NWward). This almost homogeneous kinematic pattern all along the whole belt can hardly be imputed to mantle upwelling above slab windows in the Central and Southern Apennines.
- The Hyblean wedge, confined by tectonic zones (Sicily channel, Syracuse fault and Maghrebian belt) is moving roughly North to NW ward, while the Calabrian wedge is moving roughly ENE ward (Fig. 8). Explaining such microplate kinematics as an effect of mantle upwelling in the Southern and Central Apennines appears to be a rather difficult task.

3. Proposed geodynamic interpretation

Main concepts

The observed deformation pattern in the Mediterranean region has been driven by the convergence of the Africa/Adriatic and Eurasia plates and by the roughly westward motion of the Anatolian-Aegean-Pelagonian belt, induced by the indentation of Arabia (e.g., Mantovani et al., 2006, 2009, 2014; Viti et al., 2009). The shortening of the interposed Mediterranean structures, constituted by orogenic belts, oceanic zones and the Adriatic continental and thinned continental domains, has been accommodated by a variety of tectonic processes, whose spatio-temporal distribution has been controlled by the well know least-action principle, aimed at minimizing the resistance of gravity, fault friction and mantle viscosity.

It is known that in a buoyancy-controlled context the most efficient way to gain space in a constricted area is the subduction of lithosphere and that such process is mainly favored when oceanic domains are involved (e.g., Cloos, 1993; Stern, 2004). However, one must take into account that the consumption of such domains cannot simply be determined by horizontal compression exerted by plate convergence. This consideration is mainly suggested by the fact that during the long collisional phase between the Africa-Adriatic plate and Eurasia, the Ionian oceanic domain did not undergo any subduction beneath the African and Adriatic continental domains. The fact that during such phase the push of Africa was very efficiently transmitted by the Ionian zone to the continental Adriatic domain is testified by the compressional deformations that took place along the northern boundary of that promontory (e.g., Castellarin and Cantelli, 2000; Ceriani and Schmid, 2004; Rosemberg and Kissling, 2013; Handy et al., 2015). The physical plausibility of the above evidence is confirmed by the computation of rheological profiles (e.g., Viti et al., 1997), which indicates that in long-term (geological) time intervals the horizontal compressional strength of the oceanic lithosphere is not lower than the one of a continental domain. That old and cold oceanic lithosphere can effectively transmit horizontal compression is also suggested by the persistence of continental collision at the Himalayan-Tibet boundary, without any new subduction zone in the central Indian Ocean (e.g. Stern, 2004; Copley et al., 2010). Another example is the Black Sea oceanic lithosphere, which has transmitted compression from northern Anatolia to central-southern Eurasia since Eocene (e.g., Hippolyte et al., 2018).

To understand why the consumption of oceanic domains has often occurred in the Mediterranean region since the Oligocene, it is necessary to take into account that the lateral escape of orogenic wedges may have created the conditions which can make that process feasible. When the margin of an oceanic domain is overthrust by extruding orogenic material, it undergoes downward flexure, due to isostasy. This deformation perturbs the previous equilibrium between horizontal forces, triggering the sink of the denser lithosphere, under the action of plate convergence (see e.g. the mechanism of subduction initiation given by Hall, 2018).

Laboratory experiments (Driehaus et al., 2013) show that the extrusion of a continental belt over an adjacent oceanic domain (driven by belt-parallel compression) may induce subduction when the density ratio between the oceanic and continental plates is larger than 1.4.

The above considerations can explain why the consumption of most Tethyan zones has often occurred since the Oligocene, when most extrusion processes have developed in the study area (e.g., Mantovani et al., 2006, 2009, 2014; Viti et al., 2009).

Another type of tectonic reorganization that may allow the activation of more convenient shortening processes in a constricted context, involves a change of plate mosaic, through the activation of major decoupling faults. In the new plate configuration, the kinematic pattern of buoyant blocks (microplates and orogenic wedges) is reorganized in order to address most intense stresses towards the less buoyant domains. Two major examples of this kind of tectonic reorganization have occurred in the middle Miocene and late Miocene in the central Mediterranean area, as discussed in the next sections.

Laboratory (e.g., Ratschbacher et al., 1991; Davy et al., 1995; Faccenna et al., 1996; Driehaus et al., 2013; Boutelier et al., 2018) and numerical (e.g., Mantovani et al., 2000, 2001b, 2007b) experiments suggest that in constricted buoyant structures the lateral escape of wedges (arcs) is the most convenient shortening process and that in the internal side of an extruding/migrating arc crustal extension may develop. Extension occurs when the divergence between the migrating arc and the stable foreland is faster than the shortening induced by plate convergence.

Balearic basin

The development of the Balearic ATBA system (Fig.2) was triggered by the collision between the northern margin of the African continent and the southernmost edge of the Al-Ka-Pe-Ca belt (the Atlas compressional phase, e.g. Benaouali-Mebarek et al., 2006; Tesòn and Teixell, 2008; Frizon de Lamotte et al., 2009). After the remarkable increase of resistance induced by that collision, the prosecution of the Africa-Eurasia convergence was allowed by a peculiar shortening process, given by the eastward bowing/extrusion of the Al-Ka-Pe-Ca-Corsica-Sardinia arc, at the expense of the adjacent Tethyan domain (Fig. 2). Crustal extension developed in the wake of the migrating arc, leading to the formation of the Balearic and Algerian basins, while thrustings developed in the trench zones (Apennines and Maghrebides). A detailed description of the proposed geodynamic interpretation and of how it can account for the observed deformation pattern in the Western Mediterranean region is given by Viti et al. (2009).

Northern Tyrrhenian basin (9-6 My)

The conditions that led to the formation of the Northern Tyrrhenian basin were created by the reactivation of a major old discontinuity in the Northwestern part of the Adriatic promontory (the Giudicarie fault system, Fig. 9a,b). This decoupling allowed to overcome the critical situation that had gradually developed along the collision zone between the Adriatic promontory and the European plate. In the Oligocene-Lower Miocene, such collision caused the accumulation of a huge amount of light crustal material in the trench zone (e.g., Schmid et al., 2004; Finetti, 2005b). Thus, the resistance of gravity against any further underthrusting was getting higher and higher.

The possibility of mitigating such critical situation was offered to the Adriatic promontory by the development, in the early-middle Miocene of a weak lateral boundary zone, constituted by the Carpatho-Pannonian ATBA system (e.g., Royden et al. 1983; Tari and Pamic, 1998; Horvath et al, 2015, Rèka et al., 2018; Mantovani et al., 2006, 2009). The presence of that tectonized structure allowed the eastward extrusion of buoyant crustal wedges from the Eastern Alps (a process also revealed by the formation of the Tauern window in the wake of the extruding wedges, Fig.4b, e.g., Ratschbacher et al., 1991; Robl and Stuwe, 2005; Wolfler et al., 2011), which favoured the NNEward displacement of the Adriatic domain (Peresson and Decker, 1997; Frisch et al., 2000). However, this displacement could only occur after the decoupling of the main Adriatic domain from its northwestern protuberance, which at that time was deeply stacked beneath the Western Alps. Such decoupling was allowed by the reactivation, around the Tortonian (Martin et al. 1998; Castellarin and Cantelli, 2000; Viola et al., 2001; Fellin et al., 2002), of an old discontinuity in the northern Adriatic foreland, the Giudicarie fault system (Fig. 9b), where sinistral transpressional activity is recognized until the early Messinian (e.g., Favaro et al., 2017). The NNE ward displacement, with clockwise rotation, of the northern Adriatic domain that followed such decoupling allowed that promontory to release the internal elastic deformation that such indenter had accumulated during its oblique collision with the European domain.

The sinistral motion between the decoupled Adriatic domain and its northwestern Padanian protuberance (by then closely connected with the Western Alps) is testified by the fact that since then thrusting activity in the Alps mostly occurred in the sector lying east of the Giudicarie fault (e.g., Frisch et al., 2000, Viola et al., 2001; Zampieri et al., 2003; Castellarin et al., 2004).

The consequent divergence between the mobile Adriatic domain and the Corsica-Sardinia block (stable since the middle Miocene, Gattacceca et al., 2007 and references therein) caused crustal extension in the interposed zone, constituted by a sector of the Alpine-Apennine orogenic belt lying north of the Selli fault, leading to the formation of the Northern Tyrrhenian basin (Fig.9b). This hypothesis can explain why crustal extension affected the zone comprised between the Adriatic promontory and the Corsica-Sardinia block, why such activity started around the middle Tortonian (about 9 My), just after the reactivation of the Giudicarie fault system, and why the extended area was confined to the South by the Selli fault.

Central Tyrrhenian basin and other major coeval tectonic events

Since the late Miocene, tectonic activity in the Mediterranean region was significantly influenced by the westward displacement of the Anatolian-Aegean-Pelagonian belt (Fig.1). In the previous evolution, this last kinematic boundary condition did not have significant effects in the Central Mediterranean area, because the convergence between the Africa-Adriatic plate and the above belt was mainly accommodated by the consumption of the interposed thinned domain (the Ionian zone in figure 9a, e.g., Robertson and Shallo, 2000). The resistance against this convergence considerably increased in the upper Miocene, when more buoyant domains reached that consuming boundary (Mercier et al., 1987; Sorel et al., 1992). This critical situation, with progressive slowdown of accretionary activity, lasted up to the late Miocene-early Pliocene, when a drastic change of plate mosaic and kinematic pattern allowed other less resisted shortening processes to occur. This reorganization started by decoupling a large portion of the Adriatic promontory (Adria plate in figure 9c) from Africa, through the activation of a long fracture, the Sicily Channel-Medina-Victor Hensen transtensional fault system. Prior to this tectonic phase, the Hyblean-Adventure promontory was part of the undeformed African foreland (Pelagian zone, e.g. Finetti and Del Ben, 1986, 2005b; Hieke et al., 2003, 2006; Lentini et al., 2006; Fedorik et al., 2018). The new motion trend of Adria required another major decouplig (at least partial) in the northern Adriatic zone, which was achieved by the reactivation of an old weak zone, the Schio-Vicenza sinistral fault system (Fig. 9c). After that decoupling, the northern Adria domain moved roughly NNW ward, as indicated by a change in the orientation of the compressional axis from SW-NE to SSE-NNW in the eastern Southern Alps (e.g., Castellarin and Cantelli, 2000) and by the reactivation of many thrust zones as right lateral strike-slip faults in the Northern Dinarides (Placer et al., 2010). The decoupling of the Adria plate from Africa and the new kinematics of that plate (Fig. 9c) avoided an highly resisted collision with the Anatolian-Aegean-Pelagonian belt.

The E-W convergence between southern Adria and the northern African promontory (the present Algeria-Tunisia zone) required the roughly Northward expulsion of an African fragment (the Adventure block), guided by the Egadi and Sciacca fault systems (Fig. 9c,d), and the E-W shortening of the Hyblean domain. The extrusion of the Adventure block in the early Pliocene may explain the thrusting recognized at the outer front of that wedge (in the Maghrebian belt, Pepe et al., 2005), the formation of the Pantelleria trough at the inner side of the same block (Civile et al., 2010, 2018) and the dextral shear recognized in the Sciacca fault system (Civile et al., 2018). The E-W shortening of the Hyblean domain, constituted by thick and thin zones (Fig. 9c,d), was accommodated by the southward bending of the Sicilian Apennines, with the consequent formation of the Gela nappe (at the expense of the thinned Hyblean domain), and by fracturation and redistribution of small ridge fragments in the Sicily channel zone (see i.e. Finetti and Del Ben, 1986). The occurrence of local extension between diverging fragments caused the formation of the Malta and Linosa troughs, as tentatively reconstructed in figure 10.

The roughly northward displacement of Pelagian blocks is also suggested by the fact that the sector of the Alpine (Kabylo-Calabrides)-Maghrebian belt which lies in front of them (e.g., Ben Avraham et al., 1990; Lentini et al., 1994; Sulli, 2000; Gueguen et al., 2002) shows a northward shift with respect to the lateral North African and Calabrian sectors (see fig. 10 of Mantovani et al., 2007b and references therein).

The complex evolution of the Sicily channel tectonic zone may have favored the ambiguity that still surrounds the shear sense in that transcurrent fault system (e.g., Grasso and Pedley, 1985; Boccaletti et al., 1987; Cello, 1987; Reuther et al., 1993; Kim et al., 2003; Finetti and Del Ben, 1986, 2005b; Catalano et al., 2009). Since the break of the thick continental African domain is a major tectonic event in the evolution of the central Mediterranean region, any hypothesis advanced about the nature (dextral or sinistral strike slip or pure passive rifting) and the genetic mechanism of that discontinuity should also provide a geodynamic justification for the coeval deformations observed in the surrounding zones. For instance, one should consider that a dextral movement at the Sicily Channel fault system would imply a SE ward motion of the Hyblean domain with respect to Africa. However, the deformation predicted by such kinematics in the surrounding zones (shortening in the Ionian zone facing the Hyblean block and extension in the zone lying between the Hyblean promontory and Sardinia) are not compatible with the observed features. No evidence of shortening is recognized in the Ionian area, especially at the Syracuse escarpment, as shown by CROP seismic sections (e.g., Finetti and Del Ben, 2005c) and a considerable shortening, instead of the expected extension, is evidenced by the CROP section crossing the Sardinia and Sicily Channels (Finetti et al., 2005c). We would like to remark that the geodynamic framework we propose as responsible for the formation of the Sicily Channel tectonic zone may provide plausible explanations for the major coeval late Miocene-Pliocene tectonic events in the central Mediterranean region (as discussed in the text), whereas this result cannot be achieved with the very general alternative interpretations so far proposed.

We suppose that the occurrence of crustal extension in the Sicily Channel tectonic zone may be an effect of pull-apart troughs at step-overs of the main transcurrent faults (as suggested by Reuther et al., 1993). This hypothesis is compatible with the occurrence of volcanic activity. In fact, the most plausible genetic mechanism of magma uprise through the crust is generally considered the one involved by pull-apart troughs (e.g., Tamburelli et al., 2000; Gudmundsson, 2001; Acocella and Funiciello, 2006). The normal faults generated by a pure extensional regime (in diverging plate boundaries, for instance) are stressed by a very high compression, which does not allow uprising of magmas.

The northward displacement of the Adventure block played an important role in the formation of the Central and Southern Tyrrhenian basins and in the subsequent evolution of the Apennine belt, since the indentation of that continental fragment onto the Alpine-Apenninic orogenic material which lay south of the Selli fault caused the lateral escape of wedges, at the expense of the Ionian Tethys and the thinned margin of the Adriatic domain (Fig. 9c,d). This process may explain why since the late Miocene intense accretionary activity occurred in the Apennine belt, in front of the extruding wedges (Viti et al., 2006 and references therein), and crustal extension developed in the wake of those wedges, with the formation of the central Tyrrhenian basin. The relatively high velocity (up to 5-8 cm/y) of the consequent trench retreat recognized at the related consuming boundary, during the Pliocene (Patacca and Scandone, 1989; Finetti et al., 2005b; Guillaume et al., 2010), might be due to the contemporaneous actions of two opposite kinematic boundary conditions, i.e. the roughly NW ward motion of southern Adria and the roughly ESE ward migration of the Alpine-Apennines wedges (Fig.9c,d).

During this phase, belt-parallel compression also stressed the central-northern Apennines, causing the formation of arcs, with in-sequence thrusting at external fronts (e.g., Calamita et al., 1994; Costa, 2003, Ghielmi et al., 2013; Brancolini et al., 2019), out-of-sequence thrust reactivations (e.g., Boccaletti et al., 1999) and extensional to transtensional tectonics in the internal side of the arcs, accompanied by regional uplift (e.g., Martini and Sagri, 1993; Bossio et al., 1998). The formation of arcs is also suggested by the fact that during this phase the geometry of foredeeps in the Northern Apennines changed from continuous, cylindrical, to highly fragmented, non cylindrical (e.g., Amadori et al., 2019). The hypothesis that in the Pliocene the belt underwent a compressional regime is also suggested by the shortening evidenced by CROP seismic sections (e.g., Finetti et al., 2005a).

The geodynamic interpretation here proposed may explain why the coeval occurrence of compression in the outer belt and extension in the inner side of the northern Apennines has developed since the late Miocene (e.g., Elter et al., 1975; Bossio et al., 1993). The fact that the above deformation pattern was accompanied by anatectic magmatism (e.g., Peccerillo, 2003) could be explained by considering that the most physically plausible genetic mechanism of the crustal pathways that allow magmas to uprise through the upper crust is the transtensional regime that is expected to occur at the inner side of extruding wedges (e.g., Tamburelli et al., 2000; Gudmundsson, 2001; Acocella and Funiciello, 2006).

The fact that lateral escape of wedges may have contemporaneously involved belt-parallel shortening and perpendicular extension in the northern Apennines could explain why both types of strain styles are recognized in that zone (e.g., Bonini et al., 2014; Brogi et al., 2013; Liotta et al., 2015). Anyway, the geodynamics here proposed provides that extensional deformation in the above Apennine sector is the dominant deformation, as indicated by most structural and morphological evidence (e.g., Brogi et al., 2013).

During the Late Miocene-Pleistocene interval, a complex system of elongated foredeeps developed in the eastern sector of the Po Plain and in the northern Adriatic area and severe tectonic activity affected the northern Apennines and the Padanian area (Ghielmi et al., 2013).

The peculiar fact that the Apennine belt has contemporaneously undergone thrusting, uplift and transtensional deformations is compatible with the strain pattern expected from belt-parallel compression, as suggested by the results of numerical experiments (Viti et al., 2004; Mantovani et al., 2007b), which show that the deformation pattern observed in the Tyrrhenian-Apennines system since the latest Miocene can be reproduced as an effect of the kinematic boundary conditions shown in Fig. 9c,d.

Southern Tyrrhenian basin (Early Pleistocene)

When the extruding Southern Apennine wedge reached the continental Adriatic domain, the resistance against such consuming process underwent a significant increase, which led to the progressive stop of that wedge, revealed by the end of thrusting at its outer front and of crustal stretching in the Central Tyrrhenian basin, at the inner side of the wedge.

After that trench suture, the convergence of the confining plates was mainly accommodated by the fast lateral escape of the Calabria-Peloritani (CP) wedge, i.e. the only sector of the belt that was still facing an oceanic domain (the Ionian Tethys, Fig. 9d).

The acceleration of the CP wedge is mainly testified by the strengthening of accretionary activity along its outer front, which built up the External Calabrian Arc, and by the occurrence of crustal stretching in the wake of that wedge, which has generated the Marsili basin. In this regard, it can be noted that the width of this basin is comparable with the internal (Tyrrhenian) side of the CP wedge (Fig.9d). The lateral guides of the above extrusion process were constituted by the Taormina and Palinuro transcurrent fault systems, as suggested by acceleration of tectonic and volcanic activity along those faults.

Nicolosi et al. (2006) suggest that the spreading of the Marsili basin has mainly developed from 2.1 to 1.6 Ma (with a very high rate, 19 cm/y) and that since 0.78 Ma spreading has undergone a considerable slow down. The initial high spreading rate could be due to the fact that such wedge had to extrude through a very narrow corridor between lateral continental domains (Africa and Adria). The subsequent slowdown of the CP wedge could be due to the collision of northern Calabria with the continental Adria domain (e.g., Del Ben et al., 2008, Zecchin et al., 2004, 2011, 2015; Mantovani et al., 2019 and references therein).

The strong belt-parallel compressional regime that stressed the CP wedge during its extrusion can explain the fast uplift, the horizontal bowing and the strong fragmentation of that structure, with the formation of transpressional fault systems, troughs and sphenocasms (e.g. Ghisetti and Vezzani, 1981; Van Dijk and Schepeers, 1995; Monaco and Tortorici, 2000; Tansi et al., 2007; Del Ben et al., 2008; Zecchin et al., 2004, 2010, 2011, 2015; Roda-Boluda and Whittaker, 2017 and references therein).

The fast uplift of the CP wedge has been alternatively explained as an effect of isostatic rebound in response to breakings of the underlying Ionian slab (e.g., Westaway, 1993; Wortel and Spackman, 2000) or as due to the decoupling of the Calabrian arc from the underlying slab by convective removal of the deep root (e.g., Gvirtzman and Nur, 2001). However, these interpretations cannot easily account for the reconstruction of the Apennine-Maghrebian slab geometry based on several studies (e.g., Massari and Prosser, 2013 and references therein), which suggests that since about 10 My two large slab windows have developed beneath that belt, one in the sector running from Tunisia to eastern Sicily and the other beneath the central and southern Apennines. If this reconstruction is reliable, one can hardly understand why the most intense uplift expected from isostatic rebound has affected the Calabrian Arc.

Since the suture of the Southern Apennines consuming boundary, in the Late Pliocene-Early Pleistocene, the strong compressional regime induced by the surrounding plates in the southern Adria domain, being not anymore absorbed by the consumption of thinned domains, was accommodated by upward flexure, which accelerated the formation of the Apulian swell. The uplift of southern Adria could have induced an opposite vertical effect in the northern edge of that plate, which might explain the subsidence that affected such zone in the Early Pleistocene (Ghielmi et al., 2013; Zecchin et al., 2017; Brancolini et al., 2019).

Recent present tectonic setting in the Apennine belt (Middle-Late Pleistocene)

Since the middle Pleistocene, the gravitational energy accumulated by the southern Adria domain in the previous Early Pleistocene phase favored the northward displacement of that plate (Fig. 9e), as suggested by the resumption of thrusting and strike-slip tectonics in the eastern (Dinarides) and northern (Eastern Alps) boundaries of Adria (Viti et al., 2006 and references therein). A more complex effect of Adria’s acceleration has developed along its western boundary, the Apennine belt. Since the external (eastern) sector of that chain was more closely connected with the underlying Adriatic domain, it underwent a more efficent drag from Adria, with respect to the inner belt (which was overlying a much deeper Adriatic lithosphere). This drag has resulted in a greater mobility, stronger deformation and uplift of the outer belt, which has progressively separated from the inner belt, forming the series of troughs located in the axial chain. This mechanism may explain why since the middle Pleistocene the compressional tectonic style in the Apennines was replaced by a dominant left lateral transcurrent regime (Viti et al., 2006 and references therein). The compressional features previously developed in the two main Pliocenic extruding wedges, the Molise-Sannio (MS) and the Romagna-Marche-Umbria (RMU), were cut by a series of longitudinal trastensional fault sytems, as the Irpinia-Benevento-Matese (e.g., Pantosti and Valensise, 1990; Cinque et al., 2000; Ascione et al., 2007) in the MS wedge and the Norcia-Colfiorito-Val Tiberina (Calamita et al., 2002; Pizzi and Galadini, 2009) in the RMU wedge, connected by longitudinal transtensional fault systems (Aquila and Fucino) in the Lazio-Abruzzi platform (Fig. 10, Viti et al., 2006 and references therein). This dynamics also induced belt-parallel shortening in the outer belt, accommodated by the formation of arcs (e.g., Maiella, Gran Sasso, Laga Mt.) and a generalized uplift (e.g., Pizzi and Galadini, 2009; Elter et al., 2012; Blumetti et al., 2013).

In the northernmost belt (Romagna-Emilia Apennines), shortening has been accommodated by the formation of various arcs, also involving the buried folds beneath the Po valley, and progressive outward migration of thrust fronts (Cerrina Feroni et al., 2001; Costa, 2003; Vannoli et al., 2004, 2015; Boccaletti et al., 2011; Ghielmi et al., 2013; Chicco et al., 2019).

The relative motion between the southernmost sector of the mobile outer belt (MS wedge) and Calabria has been accommodated by a system of transcurrent faults in the Lucanian Apennines (Fig. 11, Viti et al., 2006 and references therein).

The recent/present kinematic pattern of the Apennine belt inferred from Pleistocene deformation pattern, involving a faster motion of the outer Apennine belt with respect to the inner belt (Fig.11), fairly well agrees with the velocity field derived by geodetic observations (Fig. 7).

It can be noted as well that the motion trend of Adria indicated by several GPS velocity vectors in the Apulia zone and in the Venetian plain (Fig.7) is compatible with the NNEward Africa-Eurasia convergence trend suggested by Mantovani et al. (2007a), which can explain the absence of major decoupling zones inside the Adriatic domain. If conversely, one adopts the roughly NNW ward convergence trend provided by global kinematic models (e.g., Calais et al., 2003) it becomes necessary to identify major tectonic discontinuities able to decouple the Adria plate from Africa. However, the very different solutions so far suggested by the numerous attempts in this sense (see

Babbucci et al., 2004 and references therein) clearly indicate the scarce significance of the available evidence about possible decoupling zones inside the Adria plate.

The lower GPS velocities of the northern Adriatic zone (2-3 mm/y) with respect to the southern Adriatic domain (5-6 mm/y) could be connected with a non rigid behaviour of the Adria plate, due to the non uniform time distribution of decoupling earthquakes along the circum Adriatic boundaries (Mantovani et al., 2015a). In this regard, one could suppose that the Pleistocene compressional deformations recognized in the inner part of Adria (such as the Middle Adriatic Ridge, Fig. 6, e.g., Scisciani and Calamita, 2009) may have developed during such transitory phases, characterized by an accelerated motion of southern Adria and a low mobility of the northern Adria (Mantovani et al., 2016).

The belt-parallel compression and the sinistral shear that affected the Apennine belt during the last evolutionary phase may have emphasized transtensional stresses in the inner side of the two main Pliocenic wedges, the Molise-Sannio and the Romagna-Marche Umbria (Fig.11), favouring the uprise of magmas in the Roman and Campanian magmatic provinces (e.g., Argnani and Savelli, 1999; Tamburelli et al., 2000; Peccerillo, 2005; Finetti, 2006; Tibaldi et al., 2010). This could provide a possible explanation for the two major features, i.e. the location and timing, of the most intense Quaternary volcanic episodes that has developed in the Apennine belt during this evolutionary phase.

Around the middle Pleistocene, a major reorganization of the tectonic setting has been caused by the collision of southern Calabria with the continental Adriatic domain (Fig. 9e). Such obstacle was overcome by the activation of the Sibari fault system (e.g., Volpi et al., 2017) which has allowed the Calabrian wedge to gain a new extrusion trend, more parallel to the Adriatic border (Fig. 9e). This change also had major effects in the interaction zone with the Hyblean domain, favoring the activation of the Vulcano-Syracuse fault system, which has become the main decoupling zone between the Calabrian wedge and the Hyblean block, that were moving in almost opposite directions. After the activation of such decoupling, the Hyblean block may have accelerated its northward motion, as suggested by the fact that the border with the Ventura block (Sciacca fault) has become a sinistral shear zone (Civile et al., 2018). The fact that magmatic activity in the Sciacca fault system has mainly developed in the Pleistocene could suggest that the inversion of the strike slip sense at that fault may have favoured the development of pull-apart mechanisms. The hypothesis that the Syracuse fault is an active decoupling zone is supported by the occurrence of great damages in the eastern side of Sicily (e.g., 1169 and 1683, Rovida et al., 2016).

The reliability of the evolution here proposed may also be supported by the fact that major features of the spatio-temporal distribution of main earthquakes in the periAdriatic regions are compatible with the short-term implications of the present tectonic setting, as discussed in a number of papers (Mantovani et al., 2010, 2012, 2015b, 2016, Viti et al., 2006, 2012, 2013, 2015a,b, 2016).

4. Conclusions

Discussions about Mediterranean geodynamics mainly concern the driving mechanism of the ATBA systems. To overcome the apparent difficulty raised by the occurrence of crustal extension in zones of plate convergence, some authors suggest that such tectonic process may be produced by deep seated forces, mainly induced by gravitational sinking of subducted lithosphere. However, the implications of that genetic mechanism can hardly be reconciled with the observed deformation pattern. In particular, the development of the northern, central and southern Tyrrhenian basins in three well distict phases, would require a discontinuos, very peculiar and scarcely plausible action of gravity on the Adriatic subducted margin. This and other major problems discussed in the text suggest that slab-pull forces can hardly be invoked to explain the surface deformation pattern.

So far, many laboratory and numerical experiments, both 2D and 3D, have investigated the dynamics of slab-pull. However, the parameters adopted in various experiments vary over wide ranges, making it difficult to compare among results provided by different works. For instance, one may consider the density difference between the slab and surrounding mantle ($\Delta\rho$), which crucially affects the magnitude of the slab-pull force. Capitanio et al. (2010) use the values $\Delta\rho = 30$, 60 and 90 kg m^{-3} for their numerical experiments. Schellart and Moresi (2013) instead adopt the value $\Delta\rho = 80$ kg m^{-3}. Meyer and Schellart (2013) consider the significantly larger value $\Delta\rho = 103$ kg m^{-3}, which obviously provides a larger slab-pull force. Furthermore, some attempts disregard basic features of the subduction systems, in particular the role of the upper/overriding plate (e.g., Funiciello et al., 2003a,b, 2004, 2006; Schellart, 2010; Schellart et al., 2011). On the other hand, the upper plate may effectively resist slab retreat and back-arc extension (Shemenda, 1993; Hassani et al., 1997; Capitanio et al., 2010). Thus, the conclusions drawn by the above works cannot be considered as definitive ones, because they depend on questionable experimental settings or on still poorly constrained subduction parameters.

Furthermore, one should consider that the geodynamic interpretations based on the slab-pull genetic mechanism, advanced to explain the development of ATBA systems, can hardly account for the occurrence of other coeval major tectonic events in the central Mediterranean area, such as the activation of important fractures in the African foreland (the Sicily Channel-Medina-Victor Hensen fault system) and in the northern Adriatic region (the Giudicarie and the Schio-Vicenza fault systems), along with some peculiar variations of tectonic style in the periAdriatic belts.

In this and previous papers (Mantovani et al., 2006, 2009, 2019; Viti et al., 2006, 2009) it is suggested that the observed deformation pattern in the central-western Mediterranean has been driven the convergence of the confining plates (Africa, Eurasia and Anatolian-Aegean-Pelagonian system). The migration of arcs and the consequent occurrence of crustal extension in their wake can plausibly be explained as effects of extrusion processes, that develop where orogenic belts lying aside oceanic domains are stressed by plate convergence (Fig. 8). Some considerations about why the proposed geodynamic interpretation may better explain the evolution of the study area are given in the following.

- It takes into account a very large set of tectonic features, more complete than the ones considered in other attempts.

- All deformations considered are tentatively explained as effects of a unique driving mechanism (the convergence of the confining plates). In particular, it is taken into account the influence of an important kinematic boundary condition, the westward motion of the Anatolian-Aegean-Pelagonian belt, that has been often neglected by other attempts.

- It is based on clear tectonic concepts, related to the well known least-action principle, which allows finding plausible explanations for coeval tectonic events, even if located very far from each other. For instance, this scheme may allow to understand which was the possible connection between the activation of the Sicily Channel-Medina-Victor Hensen fault system in the Pelagian/Ionian zone and the reactivation of the Schio-Vicenza fault in the northern Adriatic domain.

- The present tectonic setting resulting from the proposed evolutionary reconstruction allows identifying plausible explanations for major features of the spatio-temporal distribution of major earthquakes in the last centuries.

In literature, many works concerning the Mediterranean region start by citing the various geodynamic interpretations so far proposed for this area, underlying the considerable ambiguity that still surrounds this problem. This uncertainty involves many negative implications, even concerning important social problems, as for instance the mitigation of seismic hazard. In fact, it is well known that a reliable attempt at recognizing the zones most prone to next strong shocks can only be made if one can rely on a deep knowledge of the ongoing tectonic processes. Exploiting this knowledge and the seismic history of the zone considered, one could try to recognize the perturbation of the strain/stress fields that may be caused by major earthquakes and how this effect may influence the subsequent spatio-temporal distribution of seismicity (Mantovani et al., 2015b, 2016, 2017; Viti et al., 2015a, 2016). However, since the reliability of the above results is heavily conditioned by the reliability of the adopted tectonic model, it is crucially important to exploit the information now available on the past deformations in order to recognize which driving mechanisms are actually stressing the Italian region. Thus, the Scientific Community should make all efforts to overcome the presumed ambiguity about this problem. This work aims at providing a contribution in this direction, by analyzing the plausibility of the geodynamic interpretations so far proposed, first focusing attention on the models most often cited in literature.

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Figure captions

Fig. 1. Comparison between the presumed Oligocene (A) and Present (B) tectonic settings in the Mediterranean area. Al-Ka-Pe-Ca=tentative assemblage of the Alboran, Kabylides, Peloritani and Calabrian fragments of the Alpine belt. 1, 2) Continental and thinned continental Eurasian domains 3, 4) Continental and thinned continental African and Adriatic domains 5) Old oceanic domains 6) Alpine belt 7) Other orogenic belts 8,9) Tectonically thinned and oceanized zones 10) Outer fronts

of belts 11, 12, 13) Compressional, extensional and transcurrent features. BP, CS=Balearic Promontory and Corsica-Sardinia fragments of the Iberian foreland. VH=Victor-Hensen fault. Blue arrows indicate the kinematics of the Africa/Adriatic domain and the Anatolian-Aegean-Pelagonian belt with respect to Eurasia (Mantovani et al., 2007a; Viti et al., 2009, 2011).

Fig. 2. A) Late Oligocene-Early Miocene. The outward migration of the Norhern Al-Ka-Pe-Ca Arc (NA) and the Corsica-Sardinia block (CS), at the expense of the Tethyan domain, builds up the Apennine accretionary belt, while crustal extension occurs in the wake of the Arc, forming the Balearic basin (BB). A more limited rotation is undergone by the Southern Al-Ka-Pe-Ca arc (SA) and the Balearic Promontory (BP), generating the relatively small Valencia trough (VT). The relative motion between NA and SA is accommodated by the North Balearic fault (NBF). **B**) **Middle Miocene.** The NA stops rotating after its collision with the continental Adriatic domain, causing the end of crustal extension in the Balearic basin, while the SA continues its migration at the expense of the Tethyan domain, until reaching the continental African domain. Back-Arc extension develops in the wake of SA, generating the Eastern Algerian basin (EAB). (From Viti et al., 2009, modified). Colours and symbols as in figure 1.

Fig. 3. Formation of the Northern Tyrrhenian basin (NTB), from the middle-upper Miocene (**A**) to the late Miocene (**B**). ESA=Eastern Southern Alps, Gi= Giudicarie fault system, NAp=Northern Apennines, SAp=Southern Apennines, TW=Tauern window, WPa= Western Padanian protuberance. Colours and symbols as in figure 1.

Fig. 4. A) Late Miocene-Early Pliocene (about 5 My). Crustal stretching occurs in the Alpine-Apennine sector lying south of the Selli fault (SF), generating the Central Tyrrhenian basin (CT). See text for the description of the other major coeval tectonic events. AB=Adventure block, Eg=Egadi fault, HB=Hyblean domain, Me=Medina fault, Pd=Padanian, Pl=Pantelleria trough,

Sci=Sciacca- fault, SV=Schio-Vicenza fault, VH=Victor-Hensen fault. **B) Late Pliocene** (2 My). Ge=Gela nappe, Li=Linosa trough, Ma=Malta trough Ta=Taormina fault. Colours, symbols and other abbreviations as in figures 1 and 3**.**

Fig. 5. Formation of the Southernmost Tyrrhenian basin (ST) in the early Pleistocene. AS=Apulian Swell, CP=Calabria-Peloritani wedge, ECA=External Calabrian Arc, Pa=Palinuro fault, SAp=Southern Apennines wedge. Colours, symbols and other abbreviations as in figures 1, 3 and 4.

Fig. 6. Present tectonic setting. 1) Africa-Adriatic continental domains, 2) Quaternary magmatism, Ca=Catanzaro trough, Cam=Campanian magmatic province, Cr=Crati trough, CV=Capo Vaticano fault, LuAp=Lucanian Apennines, MAR= Middle Adriatic Ridge, Me=Mesima trough, NAp, CAp, and SAp=Northern, Central and Southern Apennines, Rom=Roman magmatic province, Si=Sibari fault, Sy=Syracuse fault, Vu=Vulcano fault. Other colours, symbols and abbreviations as in figures 1-5.

Fig. 7. Horizontal velocity field (vectors) with respect to a fixed Eurasian frame in the ITRF2014 reference frame (Altamimi et al., 2016), obtained by GPS measurements. Scale in the bottom. Colours of GPS sites indicate velocities, in agreement with the chromatic scale given on the left. See Cenni et al. (2012, 2013) for details about the network and data analysis.

Fig. 8. Sketch of the tectonic process that is supposed to generate a Arc-Trench-Back Arc system. **A)** An orogenic belt, flanked by an oceanic domain, is longitudinally stressed by a continental indenter. **B**) The stressed belt undergoes uplift and bowing, through the lateral escape of crustal wedges, at the expense (subduction) of the adjacent oceanic domain. **C**) The separation of the migrating Arc from the stable plate induces crustal extension in the interposed zone (Back Arc

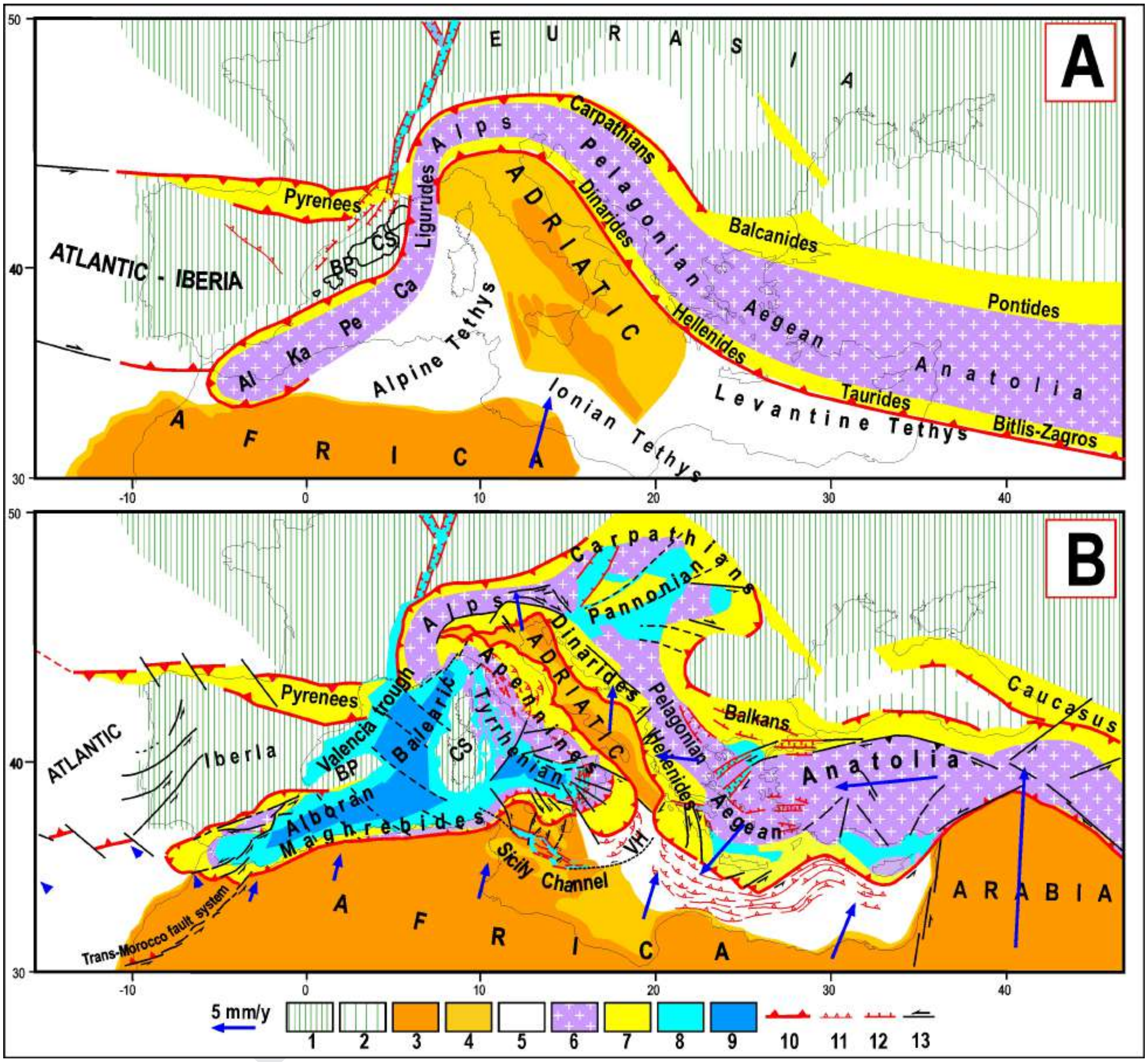
basin). See Driehaus et al. (2013) and Boutelier et al. (2018) for laboratory modeling of the above process.

Fig. 9. Proposed evolutionary reconstruction. **A) Middle-Upper Miocene (15-9 My).** Blue arrows indicate the the proposed kinematic pattern (Mantovani et al., 2007a, 2009, 2015a; Viti et al., 2009, 2011) **B) Upper Miocene (9-6 My**). After the reactivation of the Giudicarie fault system, the northern Adriatic promontory undergoes a NE ward motion and clockwise rotation, releasing its previous internal deformation. The divergence between that promontory and the stable Corsica-Sardinia block induces crustal extension in the interposed Alpine-Apennine belt, with the formation of the Northern Tyrrhenian basin. **C) Pliocene (5-2 My).** A large part of the Adriatic promontory decouples from Africa, by the activation of major discontinuities in the Pelagian and Ionian zones, the Sicily Channel-Medina (Me)-Victor Hensen (VH) fault systems and from its Padanian sector (Pd), by the reactivation of an old fracture in the northern Adriatic domain (the Schio-Vicenza fault system=SV). The E-W compression induced by the convergence between the southernmost Adria block and the northern African foreland (Tunisia) causes the roughly NW ward extrusion of a continental fragment, the Adventure block (AB), guided by the Egadi (Eg) and the Sciacca (Sci) fault systems. The northward indentation of such block causes eastward escape of wedges from the Alpine-Apennine belt lying south of the Selli fault, at the expense of the Tethyan domain and the thinned Adriatic western margin. Thrusting develops in front of the extruding wedges (Southern Apennines). Crustal stretching takes place in the wake of such wedges, forming the central Tyrrhenian basin (CT). **D) Early Pleistocene.** After the stop of the Southern Apennines wedge against the continental Adriatic domain, the convergence of the confining plates is accommodated by the outward extrusion of the CP wedge, at the expense of the Ionian domain, and the upward flexure of the southern Adriatic platform, forming the Apulian Swell (AS). Thrusting at the outer front of the Calabrian wedge forms the External Calabrian Arc (ECA), while extension at the inner side forms the Southern Tyrrhenian basin (ST). The Calabrian wedge undergoes strong uplift,

bowing and fragmentation. **E) Middle-Upper Pleistocene.** The potential gravitational energy accumulated by the southern Adriatic favors the northward displacement of that plate, which induces a longitudinal compression in the outer sector of the Apennine belt. Such regime is accommodated by the outward extrusion of wedges, which separate from the inner belt. After the contact with the Adriatic continental domain, the extrusion of the Calabrian wedge is guided by new lateral guides, the Sibari (Si) and Vulcano-Syracuse (Vu-Sy) faults. Colours, symbols and other abbreviations as in figures 1-6.

Fig. 10. Tentative reconstruction of the E-W shortening processes in the Hyblean-Adventure domain that determined the formation of troughs in the Sicily Channel. **A)** Late Miocene. Configuration of the Hyblean-Adventure domain just after the activation of the Victor-Hensen-Medina-Sicily Channel discontinuity, when the shortening of that zone, induced by the E-W convergence between the decoupled Adria plate and the Tunisian protuberance (Fig.9c) started to develop. Present geographical contours are reported for reference. **B)** Present tectonic setting (modified after Finetti and Del Ben, 1986). The Adventure block, decoupled from the Hybelan domain by the Sciacca fault system, has undergone a roughly NNWward escape, forming the Pantelleria trough. Contemporaneously, the heterogeneous Hyblean domain has undergone E-W shortening, at the expense of its thinned central part. In the northern side, the Maghrebian belt has been forced to bend southward, forming the Gela nappe. In the southern side, the original NW-SE plateau, in the Sicily channel zone, has undergone a considerable fragmentation, in order to accommodate E-W shortening. Local crustal extensions, induced by the divergence between fragments, have formed the Malta and Linosa grabens and other minor troughs. Toothed lines indicate the fronts of belts. Geological-geophysical data from Finetti and Del Ben, 1986, 2005b; BenAvraham et al., 1990; Lentini et al., 1994). Lit, Mat, Plt =Linosa, Malta and Pantelleria troughs Em, Gi, Li, Ma, Se, Ur =Empedocle, Girgenti, Linosa, Malta, Selinunte, Urialo plateau fragments.

Fig. 11. Outer mobile sector of the Apennine belt (green), stressed by the Adria plate**.** Ben=Benevento, Ca=Calabria, Ir=Irpinia, LA=Lazio-Abruzzi wedge, Lu=Lucania Apennines, Ma= Matese, MS=Molise-Sannio, No-Cf=Norcia-Colfiorito fault system, OA=Olevano-Antrodoco thrust front, RMU=Romagna-Marche-Umbria wedge, SVo= Sangro-Volturno thrust front, TE=Toscana-Emilia wedge. The buried external folds in the Northern Apennines are light green. Red arrows indicate the kinematic pattern, compatible with the Pleistocene deformation pattern and geodetic data (Fig. 7). Other symbols and abbreviations as in figures 1-6.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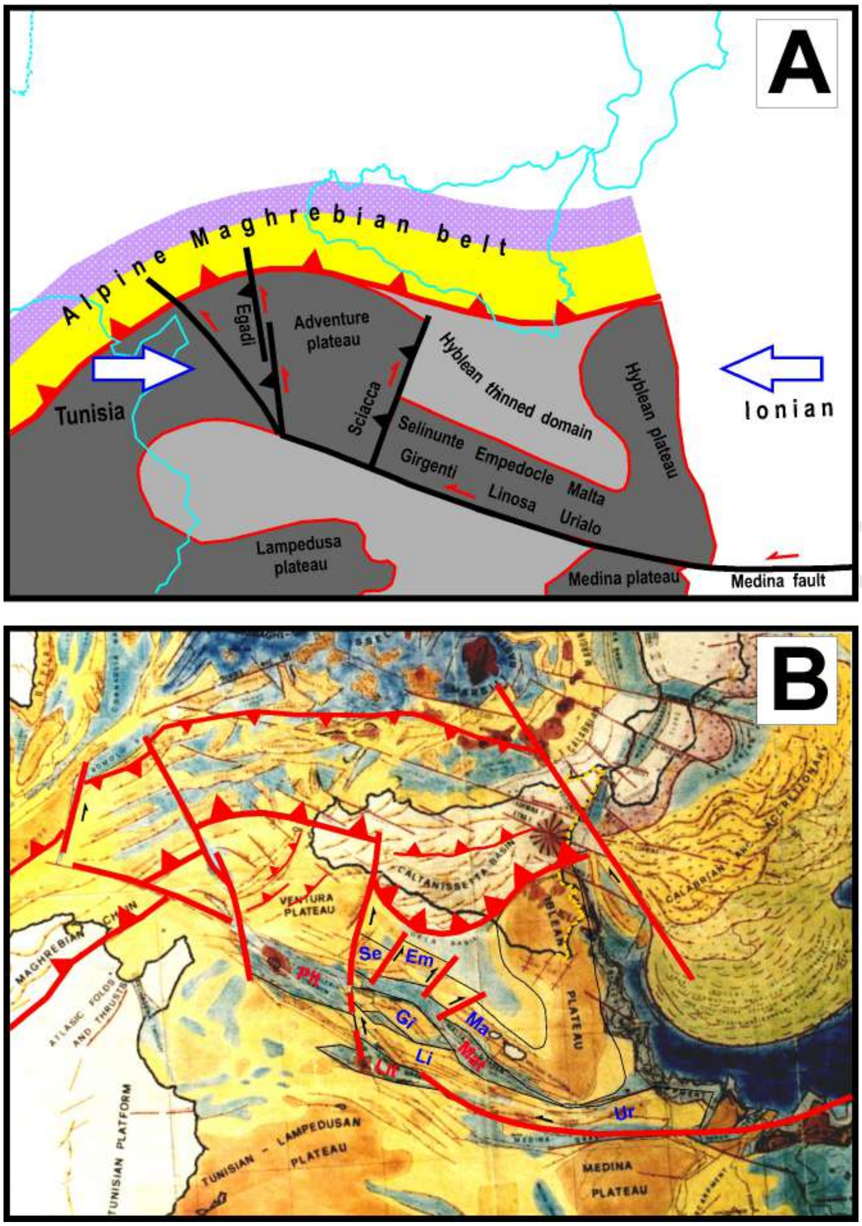
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Adventure plateau
Sciacca
Hyblean thinned domain
Hyblean plateau
Ionian
Tunisia
Selinunte
Empedocle
Girgenti
Malta
Linosa
Urialo
Lampedusa plateau
Medina plateau
Medina fault
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VENTURA PLATEAU
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ATLASIC FOLDS AND THRUSTS
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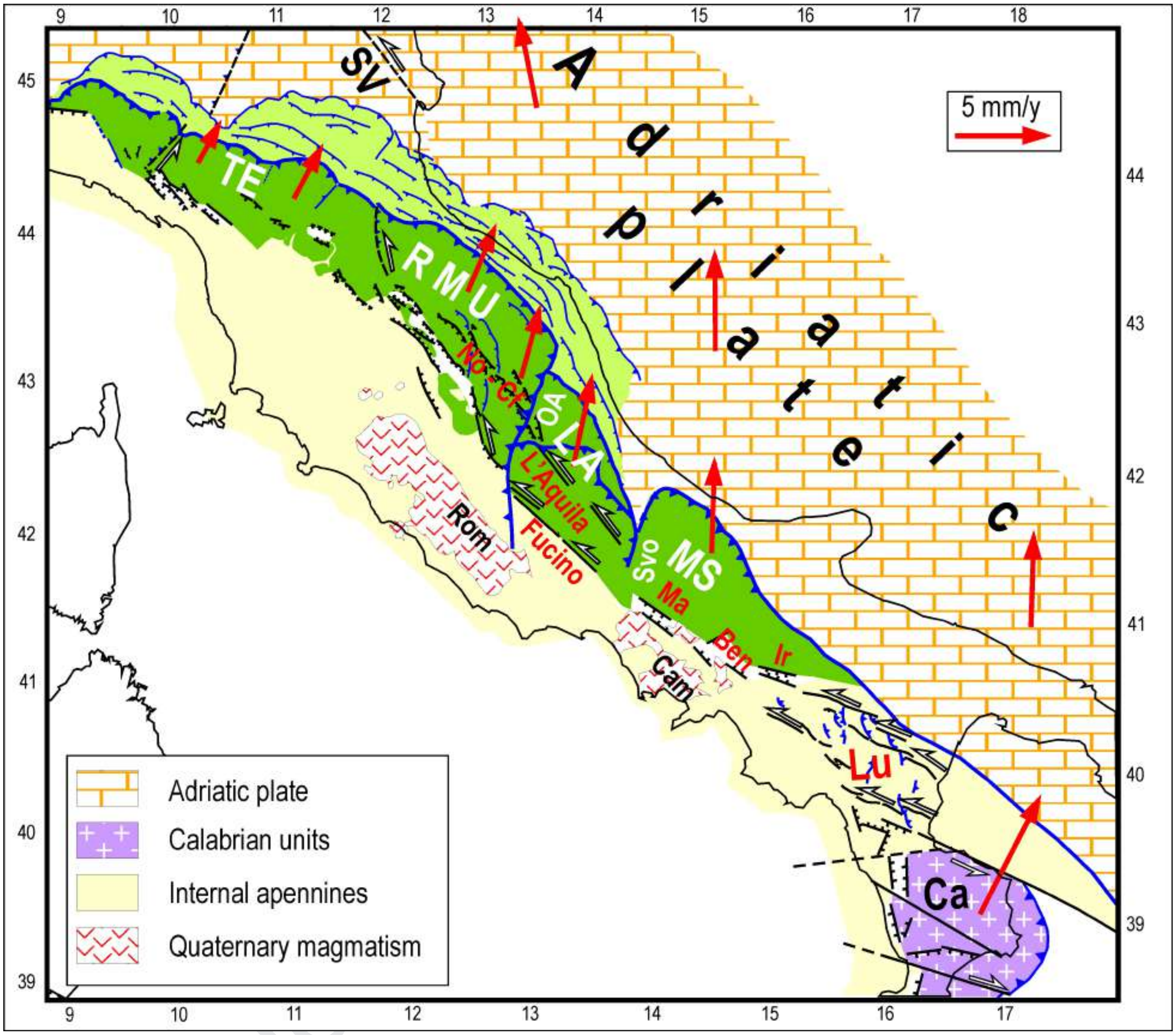
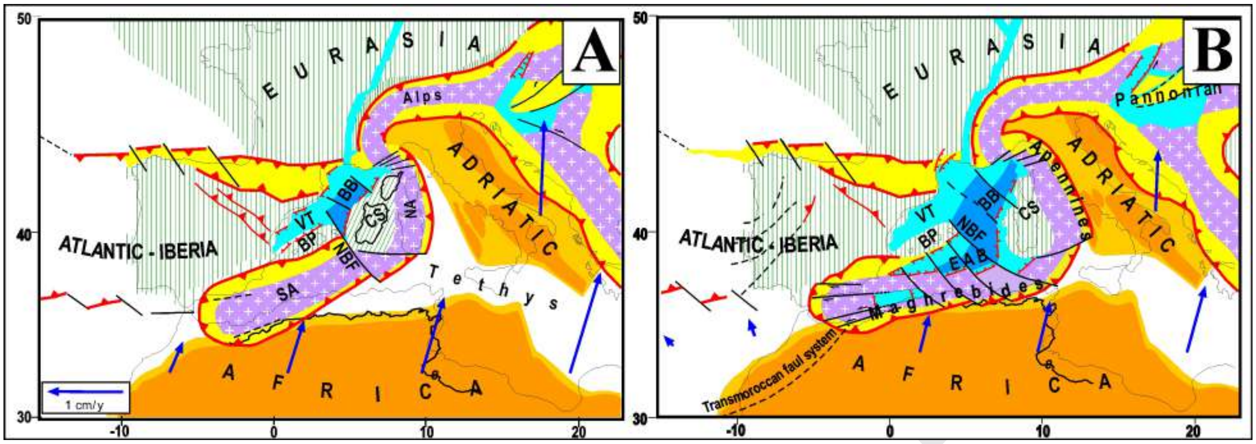
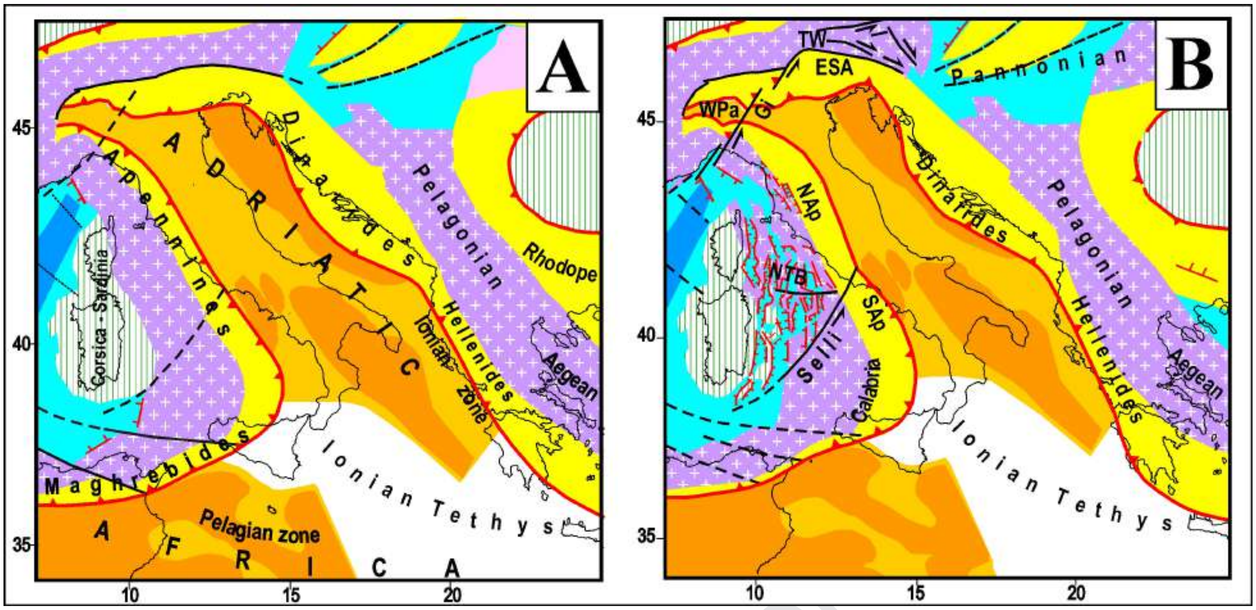
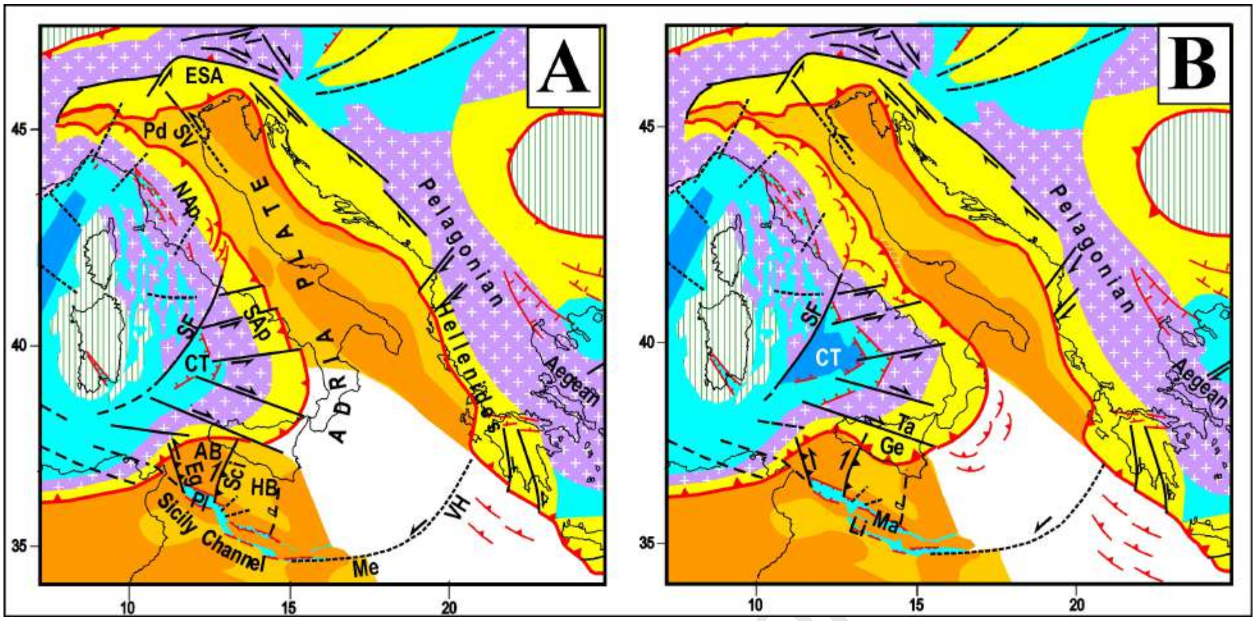
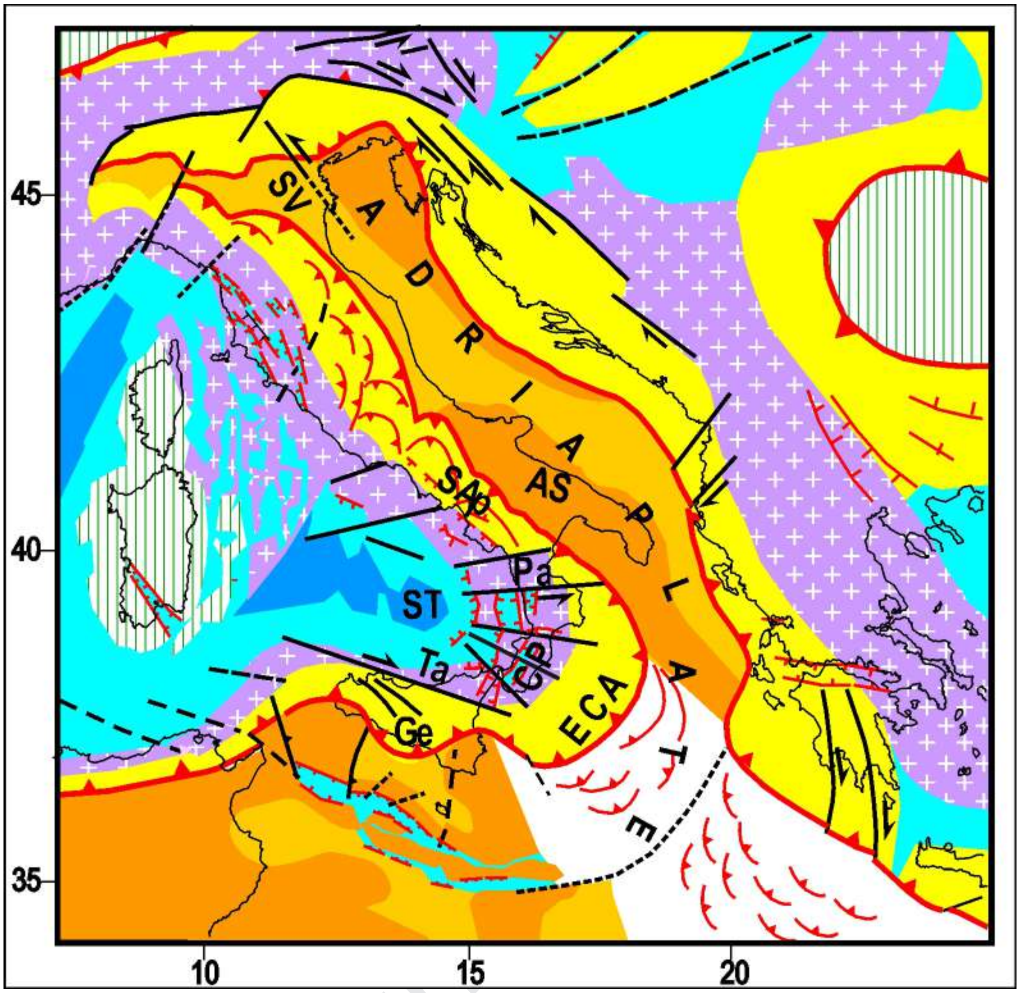
TUNISIAN - LAMPEDUSAN PLATEAU
MEDINA PLATEAU

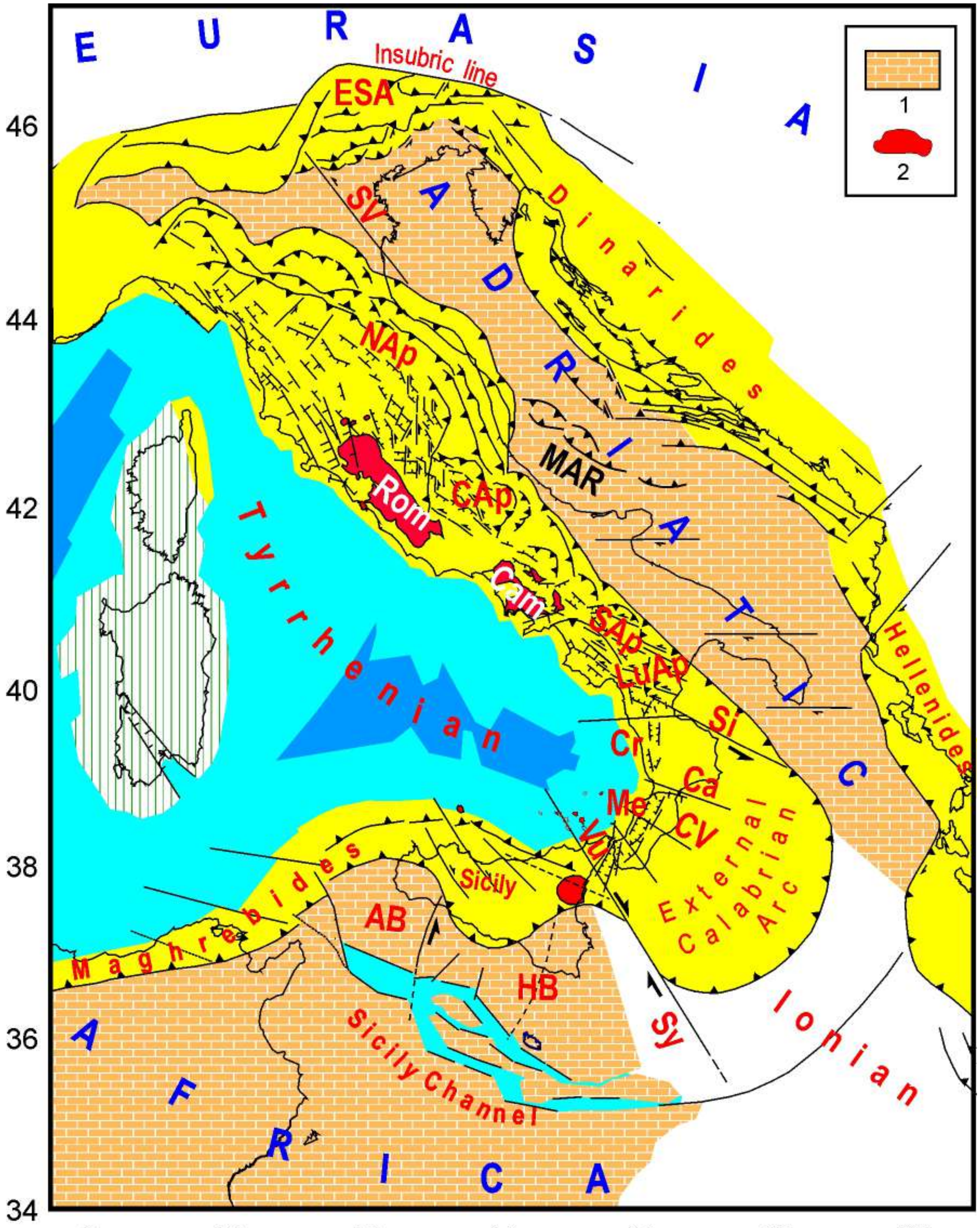

9
10
11
12
13
14
15
16
17
18
45
44
43
42
41
40
39
Adriatic
5 mm/y
SV
TE
RMU
No-Cf
OA
LA
L'Aquila
Fucino
Rom
Svo
MS
Ma
Ben
Ir
Cam
Lu
Ca
Adriatic plate
Calabrian units
Internal apennines
Quaternary magmatism

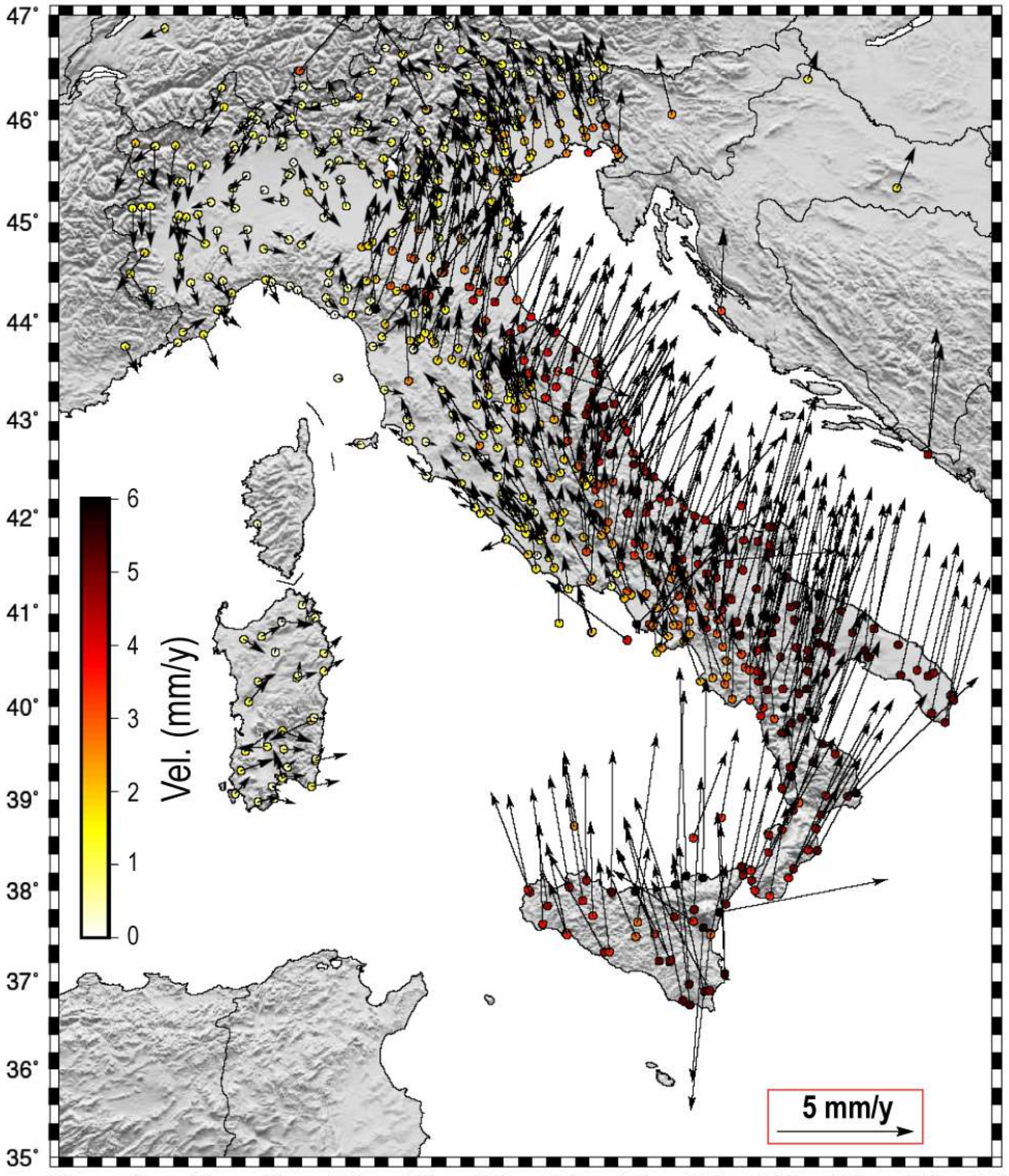

A
EURASIA
Alps
ADRIATIC
ATLANTIC - IBERIA
VT
BP
BBI
CS
NA
NBF
SA
Tethys
AFRICA
1 cm/y
50
40
30
-10
0
10
20
B
EURASIA
Pannonian
Apennines
ADRIATIC
ATLANTIC - IBERIA
VT
BP
BB
CS
NBF
EAB
Maghrebides
Transmoroccan faul system
AFRICA
50
40
30
-10
0
10
20

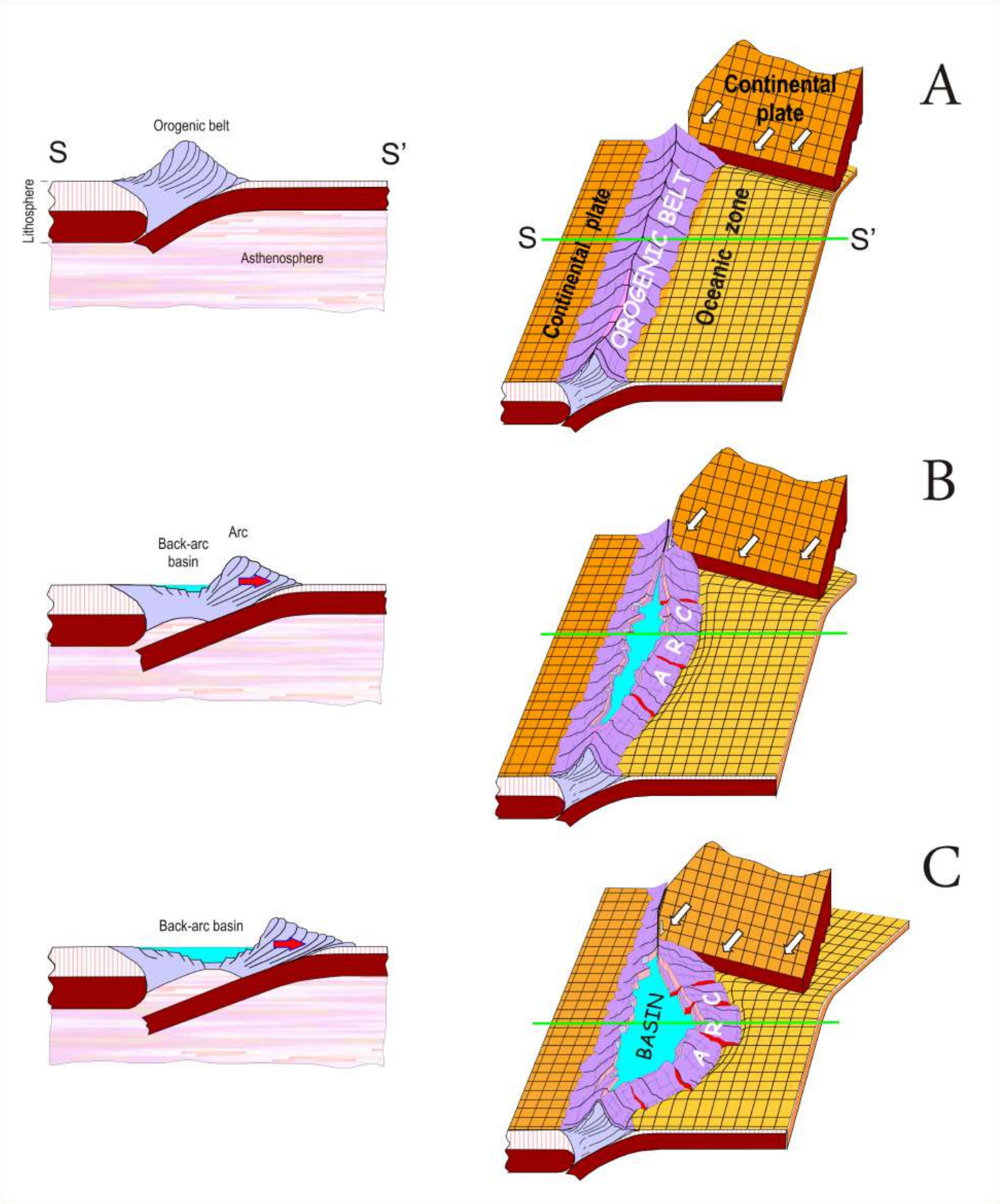

A
ADRIATIC
Apennines
Dinarides
Pelagonian
Rhodope
Corsica - Sardinia
Ionian zone
Hellenides
Aegean
Maghrebides
AFRICA
Pelagian zone
Ionian Tethys
45
40
35
10
15
20
B
TW
ESA
Pannonian
WPa
Gi
NAp
NTB
SAp
Selli
Calabria
Dinarides
Pelagonian
Hellenides
Aegean
Ionian Tethys
45
40
35
10
15
20

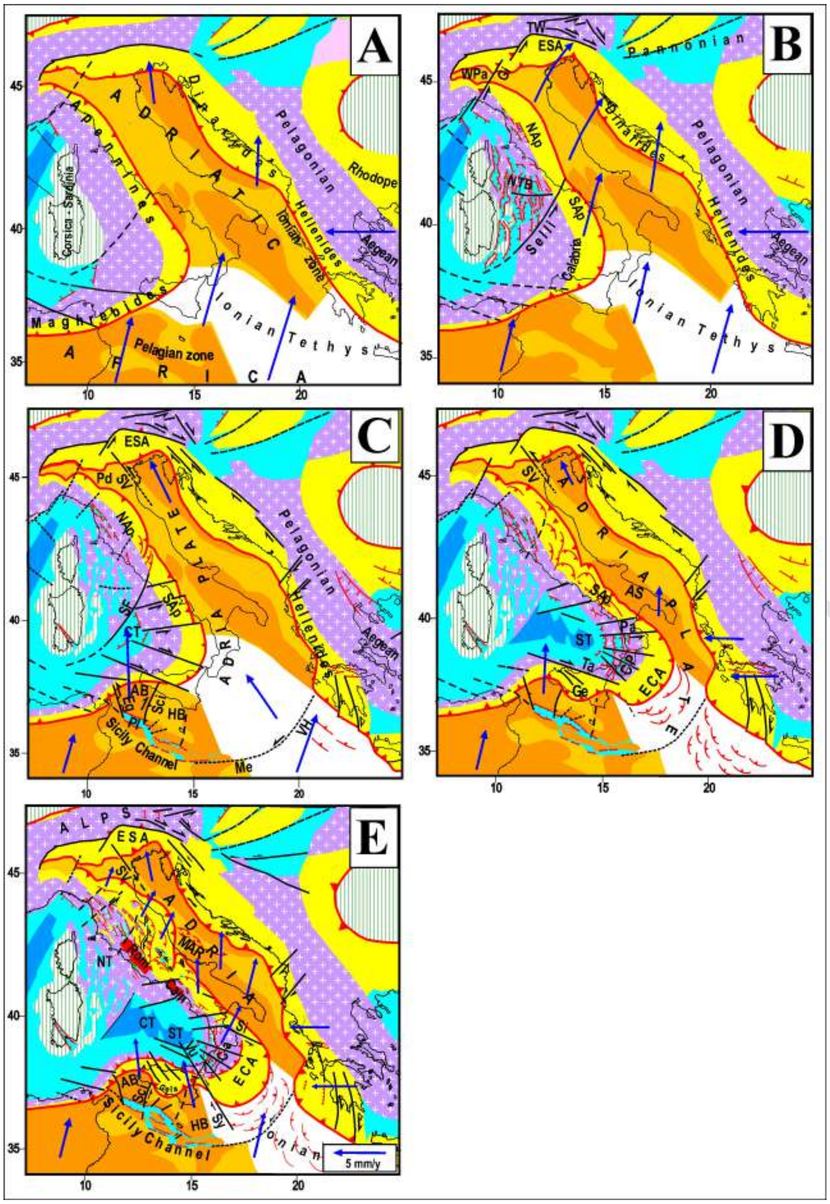

A
ESA
Pd
SV
NAp
SAp
SF
CT
P L A T E
A D R I A
Pelagonian
Hellenides
Aegean
AB
Eg
Sci
HB
Pl
Sicily Channel
Me
VH
B
SF
CT
Pelagonian
Aegean
Ta
Ge
Ma
Li
45
40
35
10
15
20


45
40
35
10
15
20
SV
A D R I A P L A T E
AS
SAp
Pa
ST
Ta
CP
ECA
Ge


E U R A S I A
Insubric line
ESA
SV
A D R I A T I C
Dinarides
NAp
MAR
Rom
CAp
Cam
SAp
LuAp
Si
Cr
Ca
Me
CV
Vu
Hellenides
T y r r h e n i a n
M a g h r e b i d e s
Sicily
AB
HB
External Calabrian Arc
Sy
I o n i a n
Sicily Channel
A F R I C A
1
2
46
44
42
40
38
36
34
8
10
12
14
16
18
20


47°
46°
45°
44°
43°
42°
41°
40°
39°
38°
37°
36°
35°
6°
7°
8°
9°
10°
11°
12°
13°
14°
15°
16°
17°
18°
19°
Vel. (mm/y)
0
1
2
3
4
5
6
5 mm/y


A
Orogenic belt
S
S'
Lithosphere
Asthenosphere
Continental plate
Continental plate
OROGENIC BELT
Oceanic zone
S
S'
B
Back-arc basin
Arc
ARC
C
Back-arc basin
BASIN
ARC


A
A D R I A T I C
Apennines
Dinarides
Pelagonian
Rhodope
Corsica - Sardinia
Ionian zone
Hellenides
Aegean
Maghrebides
Ionian Tethys
A F R I C A
Pelagian zone
B
TW
ESA
Pannonian
WPa
Gl
NAp
Dinarides
Pelagonian
NTB
SAp
Selli
Calabria
Hellenides
Aegean
Ionian Tethys
C
ESA
Pd
SV
NAp
P L A T E
A D R I A
Pelagonian
SF
SAp
CT
Hellenides
Aegean
AB
Eg
Sci
HB
Pl
Sicily Channel
Me
VH
D
SV
A D R I A
P L A T E
SAp
AS
Pa
ST
Ta
CP
Ge
ECA
E
A L P S
E S A
SV
A D R I A
MAR
NT
Roma
Cam
CT
ST
Vu
Ca
SI
ECA
AB
Scl
Gela
HB
SS
Sicily Channel
Ionian
5 mm/y
45
40
35
10
15
20

The observed deformation pattern in the study area is not compatible with slab pull forces, whereas it can be coherently and plausibly interpreted as an effect of plate convergence

Crustal extension can develop in the framework of extrusion processes

The subduction of oceanic lithosphere at convergent boundaries may require the triggering favoured by an extrusion process

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: