

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

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Geodynamics of the central-western Mediterranean region: Plausible and nonplausible driving forces

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	Journal Pre-proof
1	Geodynamics of the central-western Mediterranean region:
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16	Abstract. The observed deformation pattern in the central-western Mediterranean area, in particular
17	the development of the Northern, Central and Southern Tyrrhenian basins in three well distinct
18	phases, can hardly be explained as an effect of the gravitational sinking of subducted lithosphere, an
19	hypothesis often advanced in literature. A more plausible and coherent explanation of the spatio-
20	temporal distribution of major tectonic events in the study area can instead be achieved by
21	supposing that tectonic activity has mainly been driven by the convergence of Africa and Eurasia
22	and the roughly westward displacement of the Anatolian-Aegean-Pelagonian belt. The development
23	of Arc-Trench-Back Arc systems is interpreted as an effect of extrusion processes, that in some
24	constricted contexts have represented the most convenient shortening process for accommodating
25	plate convergence.
26	

## 27 Keywords: Mediterranean, geodynamics, slab-pull, extrusion

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## 30 1. Introduction

31

In the last 30-35 My the Mediterranean area has undergone a drastic change (Fig. 1), as 32 suggested by several authors (e.g., Dercourt et al., 1986; Meulenkamp and Sissingh, 2003; 33 Mantovani, 2005, Mantovani et al., 2006, 2009; Viti et al., 2009 and references therein). The pre-34 existing Alpine orogenic belt has undergone considerable distortions and long migrations of even 35 several hundreds of Km. Some zones, mainly located in the internal side of the migrating arcs, have 36 undergone crustal extension and consequent thinning, with the formation of large basins (Balearic, 37 Tyrrhenian, Aegean and Pannonian). The oceanic and thinned continental zones which surrounded 38 39 the African/Adriatic promontory have been almost completely consumed by subduction. Since extensional deformations are generally considered as scarcely compatible with the compressional 40 41 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 42 interpretation suggests that the migration of arcs and the related back-arc extension have been 43 driven by the gravitational sinking of subducted lithosphere, as originally proposed by Malinverno 44 and Ryan (1986) and Royden (1993). In this work, we argue that the main implications of the above 45 interpretation can hardly be reconciled with the observed features and that a more plausibile and 46 coherent explanation of the evolutionary history can be achieved by supposing that Arc-Trench-47 Back Arc systems (ATBA) have developed in the framework of extrusion processes, driven by the 48 convergence of the confining plates. With respect to previous attempts (e.g., Mantovani et al., 2009, 49 50 2014; Viti et al., 2009), this work reports new evidence and arguments about the compatibility of the interpretations here discussed with the observed deformations. 51

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# 53 2. Balearic and Tyrrhenian basins interpreted as effects of the slab-pull genetic mechanism: 54 main problems

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## 56 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)

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Several authors (e.g., Royden and Burchfiel, 1989; Schmid et al., 1996, 2004; Stampfli et al., 64 65 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 66 67 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 68 the Alpine sector lying aside the Iberian domain, another opposite verging (North to NW ward) 69 subduction process started, involving the consumption of the Tethyan oceanic domain under the 70 migrating Al-Ka-Pe-Ca belt (Gaspar-Escribano et al., 2004; Lustrino et al., 2009; Schettino and 71 Turco, 2006; Handy et al., 2015; Etheve et al., 2016). This implies that when the ATBA system 72 began to migrate, in the Oligocene, the northward dipping slab did not exist or was scarcely 73 developed, being thus unable to induce a sufficient slab-pull force. To this regard, it should be 74 considered that laboratory and numerical modelings suggest that a minimum slab length (150-300 75 km) is required in order to initiate back-arc extension driven by slab-pull (e.g., Hassani et al., 1997; 76 Faccenna et al., 1999; Schellart, 2005). 77

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 84 underwent an evident sinistral NE-SW shift with respect to the Western Alps (Fig.2), leading to the 85 formation of the Ligurian basin (e.g., Makris et al., 1999; Mosca et al., 2010), suggests that such arc 86 was stressed by belt-parallel push. This kind of stress field is also suggested by the kinematics of 87 the strike-slip faults and lateral escape of blocks in the Sardinia-Corsica microplate (e.g., 88 Carmignani et al., 1994, 2004; Oggiano et al., 2009 and references therein). The Oligocene-89 90 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 91 92 orientation of the trench suction force that would have been induced by a slab-pull mechanism.

93 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). 94 Numerical modelings of a slab-pull mechanism (e.g., Schellart et al., 2007) could justify a curvature 95 of the migrating arc, but the resulting effect is much smaller than the one that really occurred in the 96 western Mediterranean area (Mantovani et al., 2001a; 2002; Viti et al., 2009 and references therein). 97 Moreover, the horizontal bowing predicted by modellings would need more than 16 My to develop 98 (e.g., Schellart et al., 2007). Other laboratory experiments suggest instead a linear shape of the 99 retreating subduction boundary, without significant arc bowing (Becker et al., 1999). 100

101 It is not demonstrated that the trench-suction force induced by gravitational sinking of a slab 102 can break the upper plate. The results of some laboratory and numerical experiments (e.g., 103 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.

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108 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).

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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 119 block occurred when the Adriatic continental domain entered the trench zone, around 15 My 120 (Speranza et al., 2002; Finetti et al., 2005a; Gattacceca et al., 2007; Molli 2008, Malusà et al., 121 2016). In that context, any further development of slab roll-back would have encountered very 122 strong resistance from buoyancy forces (e.g., Brancolini et al., 2019). In fact, in the subsequent 123 period (from about 15 to 9 My) no possible effects of trench retreat (such as crustal extension) has 124 developed in the zone overlying the slab (Faccenna et al., 2001, 2014a; Finetti et al., 2005a). Thus, 125 the hypothesis that the subducted Adriatic margin has undergone gravitational sinking from about 9 126 to 6 My, forming the Northern Tyrrhenian basin, suggests some questions: 127

- 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 CentralSouthern 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 ?

141 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; 142 143 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 144 interpretations cannot easily be reconciled with the results of other tomographic investigations 145 (Scafidi et al., 2009; Scafidi and Solarino, 2012) and CROP seismic soundings (e.g., Finetti et al., 146 2001, 2005a), which do not evidence any well developed lithospheric slab beneath the Apennine-147 Tyrrhenian system. The occurrence of some subcrustal earthquakes beneath the Northern Apennines 148 cannot be used to confirm the results of tomography, since focal depths are mainly lower that 70 km 149 (e.g., Chiarabba et al., 2005) and the magnitudes are very low (ISIDe Working Group, 2016). It is 150 worth noting that the distribution of subcrustal earthquakes is compatible with the geometry of the 151 crustal slivers suggested by CROP sections (Finetti et al., 2005a). 152

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 155 lithosphere with the 670 km-depth mantle discontinuity. The inability of the slab to penetrate across 156 such discontinuity would cause a sudden decrease of the subduction rate and trench retreat. Only 157 after the slab has folded over the mantle discontinuity, subduction and trench migration may resume 158 again, leading to a new phase of back-arc extension (Faccenna et al., 2004, 2007). However, it must 159 be considered that the above results have been obtained by experiments where the upper plate is not 160 present at all, a quite irrealistic condition. Other experiments have shown that the presence of a 161 sufficiently strong upper plate can prevent slab roll-back (see figure 11 by Capitanio et al., 2010 and 162 Shemenda, 1993; Hassani et al., 1997). 163

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165 *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 centralMediterranean region, as listed in the following.

173

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 strikeslip 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).

202 - 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.,
206 2010).

207

Any attempt at explaining the formation of the Central Tyrrhenian basin as an effect of slabpull 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 underthe 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

216 Pliocene-early Pleistocene ? i.e. when crustal stretching ended in the Central Tyrrhenian basin.

217

218 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 231 northern Adriatic foreland (Schio-Vicenza) can hardly be explained as effects of slab-pull forces 232 beneath the Southern Apennines, there remains the problem of identifying which other driving 233 mechanisms were active in the central Mediterranean zone during the Pliocene. In this regard, 234 Faccenna et al. (2004, 2007) suggest that transtensional deformation in the Sicily Channel could be 235 related to the breaking that would have affected the most curved sector of the wide slab formed 236 during the Balearic phase. Such deep break would have caused the Late Miocene alkaline 237 volcanism in northern Tunisia and Sardinia and deformation in the Sicily Channel zone. However, 238 slab breaking and related magmatism (e.g., Lustrino and Wilson, 2007) do not necessarily 239 presuppose passive lithosphere sinking. Moreover, one must consider that tectonic activity in the 240 Sicily Channel relates to transcurrent fault systems, with some sectors of pull-apart extension, 241 which cannot simply be generated by uprising of magma. 242

243

## 244 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).

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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 asan 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. Whenand why did such tears develop ?

285

286 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 normaloblique 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).

325

The present kinematic pattern in the Italian region is fairly well defined by the analysis of 326 geodetic data observed in more than 700 permanent GPS stations in the period running from 327 January 1, 2001 to December 31, 2018. The horizontal velocity field derived by such data (Fig. 7) 328 with respect to a fixed Eurasian frame (Euler pole at 54.23°N, 98.83°W,  $\omega = 0.257^{\circ}/Myr$ , Altamimi 329 et al., 2016) shows that the outer sector of the Apennine belt, including the buried thrusts and folds 330 under the Po Plain, moves considerably faster (4-5 mm/y) and with a greater eastward component 331 with respect to the inner belt (1-2 mm/y). In the Padanian zone that lies west of the Giudicarie fault 332 system velocity values show a significant decrease and a different trend, with respect to the outer 333

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

336

To interpret the drastic change of tectonic style that occurred in the Apennine belt around the 337 middle Pleistocene as an effect of slab-pull forces, one should explain why the effect of such deep 338 driving mechanism on shallow structures has considerably changed at that time. An attempt in this 339 sense has been made by some authors (e.g., Faccenna et al., 2014b), who suggest that the 340 Pleistocene deformation pattern in the Apennine belt has been controlled by changes of deep seated 341 dynamic processes (mantle convection) connected with the development of windows in the western 342 subducted margin of Adria located beneath the Central and Southern Apennines (e.g., Wortel and 343 Spakman, 2000; Piromallo and Morelli, 2003; Faccenna et al., 2007). However, this interpretation 344 cannot easily be reconciled with some major features of the observed deformation pattern, as 345 346 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.

358

## 359 **3. Proposed geodynamic interpretation**

## 361 *Main concepts*

The observed deformation pattern in the Mediterranean region has been driven by the 362 convergence of the Africa/Adriatic and Eurasia plates and by the roughly westward motion of the 363 Anatolian-Aegean-Pelagonian belt, induced by the indentation of Arabia (e.g., Mantovani et al., 364 2006, 2009, 2014; Viti et al., 2009). The shortening of the interposed Mediterranean structures, 365 constituted by orogenic belts, oceanic zones and the Adriatic continental and thinned continental 366 domains, has been accommodated by a variety of tectonic processes, whose spatio-temporal 367 distribution has been controlled by the well know least-action principle, aimed at minimizing the 368 369 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 370 constricted area is the subduction of lithosphere and that such process is mainly favored when 371 372 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 373 374 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 375 not undergo any subduction beneath the African and Adriatic continental domains. The fact that 376 during such phase the push of Africa was very efficiently transmitted by the Ionian zone to the 377 continental Adriatic domain is testified by the compressional deformations that took place along the 378 northern boundary of that promontory (e.g., Castellarin and Cantelli, 2000; Ceriani and Schmid, 379 2004; Rosemberg and Kissling, 2013; Handy et al., 2015). The physical plausibility of the above 380 evidence is confirmed by the computation of rheological profiles (e.g., Viti et al., 1997), which 381 indicates that in long-term (geological) time intervals the horizontal compressional strength of the 382 oceanic lithosphere is not lower than the one of a continental domain. That old and cold oceanic 383 lithosphere can effectively transmit horizontal compression is also suggested by the persistence of 384 continental collision at the Himalayan-Tibet boundary, without any new subduction zone in the 385

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)

412 is the most convenient shortening process and that in the internal side of an extruding/migrating
413 arc crustal extension may develop. Extension occurs when the divergence between the migrating arc
414 and the stable foreland is faster than the shortening induced by plate convergence.

- 415
- 416 Balearic basin

The development of the Balearic ATBA system (Fig.2) was triggered by the collision between 417 the northern margin of the African continent and the southernmost edge of the Al-Ka-Pe-Ca belt 418 (the Atlas compressional phase, e.g. Benaouali-Mebarek et al., 2006; Tesòn and Teixell, 2008; 419 Frizon de Lamotte et al., 2009). After the remarkable increase of resistance induced by that 420 collision, the prosecution of the Africa-Eurasia convergence was allowed by a peculiar shortening 421 process, given by the eastward bowing/extrusion of the Al-Ka-Pe-Ca-Corsica-Sardinia arc, at the 422 expense of the adjacent Tethyan domain (Fig. 2). Crustal extension developed in the wake of the 423 424 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 425 426 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). 427

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## 429 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 437 the development, in the early-middle Miocene of a weak lateral boundary zone, constituted by the 438 Carpatho-Pannonian ATBA system (e.g., Royden et al. 1983; Tari and Pamic, 1998; Horvath et al, 439 2015, Rèka et al., 2018; Mantovani et al., 2006, 2009). The presence of that tectonized structure 440 allowed the eastward extrusion of buoyant crustal wedges from the Eastern Alps (a process also 441 revealed by the formation of the Tauern window in the wake of the extruding wedges, Fig.4b, e.g., 442 Ratschbacher et al., 1991; Robl and Stuwe, 2005; Wolfler et al., 2011), which favoured the 443 NNEward displacement of the Adriatic domain (Peresson and Decker, 1997; Frisch et al., 2000). 444 However, this displacement could only occur after the decoupling of the main Adriatic domain from 445 its northwestern protuberance, which at that time was deeply stacked beneath the Western Alps. 446 Such decoupling was allowed by the reactivation, around the Tortonian (Martin et al. 1998; 447 Castellarin and Cantelli, 2000; Viola et al., 2001; Fellin et al., 2002), of an old discontinuity in the 448 449 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 450 451 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 452 had accumulated during its oblique collision with the European domain. 453

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.

466

## 467 *Central Tyrrhenian basin and other major coeval tectonic events*

Since the late Miocene, tectonic activity in the Mediterranean region was significantly 468 influenced by the westward displacement of the Anatolian-Aegean-Pelagonian belt (Fig.1). In the 469 previous evolution, this last kinematic boundary condition did not have significant effects in the 470 Central Mediterranean area, because the convergence between the Africa-Adriatic plate and the 471 above belt was mainly accommodated by the consumption of the interposed thinned domain (the 472 Ionian zone in figure 9a, e.g., Robertson and Shallo, 2000). The resistance against this convergence 473 considerably increased in the upper Miocene, when more buoyant domains reached that consuming 474 475 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 476 477 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 478 plate in figure 9c) from Africa, through the activation of a long fracture, the Sicily Channel-479 Medina-Victor Hensen transtensional fault system. Prior to this tectonic phase, the Hyblean-480 Adventure promontory was part of the undeformed African foreland (Pelagian zone, e.g. Finetti and 481 Del Ben, 1986, 2005b; Hieke et al., 2003, 2006; Lentini et al., 2006; Fedorik et al., 2018). The new 482 motion trend of Adria required another major decouplig (at least partial) in the northern Adriatic 483 zone, which was achieved by the reactivation of an old weak zone, the Schio-Vicenza sinistral fault 484 system (Fig. 9c). After that decoupling, the northern Adria domain moved roughly NNW ward, as 485 indicated by a change in the orientation of the compressional axis from SW-NE to SSE-NNW in the 486 eastern Southern Alps (e.g., Castellarin and Cantelli, 2000) and by the reactivation of many thrust 487 zones as right lateral strike-slip faults in the Northern Dinarides (Placer et al., 2010). The 488

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 491 present Algeria-Tunisia zone) required the roughly Northward expulsion of an African fragment 492 (the Adventure block), guided by the Egadi and Sciacca fault systems (Fig. 9c,d), and the E-W 493 shortening of the Hyblean domain. The extrusion of the Adventure block in the early Pliocene may 494 explain the thrusting recognized at the outer front of that wedge (in the Maghrebian belt, Pepe et al., 495 2005), the formation of the Pantelleria trough at the inner side of the same block (Civile et al., 2010, 496 2018) and the dextral shear recognized in the Sciacca fault system (Civile et al., 2018). The E-W 497 shortening of the Hyblean domain, constituted by thick and thin zones (Fig. 9c,d), was 498 accommodated by the southward bending of the Sicilian Apennines, with the consequent formation 499 of the Gela nappe (at the expense of the thinned Hyblean domain), and by fracturation and 500 501 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 502 Malta and Linosa troughs, as tentatively reconstructed in figure 10. 503

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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 515 that discontinuity should also provide a geodynamic justification for the coeval deformations 516 observed in the surrounding zones. For instance, one should consider that a dextral movement at the 517 Sicily Channel fault system would imply a SE ward motion of the Hyblean domain with respect to 518 Africa. However, the deformation predicted by such kinematics in the surrounding zones 519 (shortening in the Ionian zone facing the Hyblean block and extension in the zone lying between the 520 Hyblean promontory and Sardinia) are not compatible with the observed features. No evidence of 521 shortening is recognized in the Ionian area, especially at the Syracuse escarpment, as shown by 522 CROP seismic sections (e.g., Finetti and Del Ben, 2005c) and a considerable shortening, instead of 523 the expected extension, is evidenced by the CROP section crossing the Sardinia and Sicily Channels 524 (Finetti et al., 2005c). We would like to remark that the geodynamic framework we propose as 525 responsible for the formation of the Sicily Channel tectonic zone may provide plausible 526 527 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 528 529 general alternative interpretations so far proposed.

We suppose that the occurrence of crustal extension in the Sicily Channel tectonic zone may be 530 an effect of pull-apart troughs at step-overs of the main transcurrent faults (as suggested by Reuther 531 et al., 1993). This hypothesis is compatible with the occurrence of volcanic activity. In fact, the 532 most plausible genetic mechanism of magma uprise through the crust is generally considered the 533 one involved by pull-apart troughs (e.g., Tamburelli et al., 2000; Gudmundsson, 2001; Acocella and 534 Funiciello, 2006). The normal faults generated by a pure extensional regime (in diverging plate 535 boundaries, for instance) are stressed by a very high compression, which does not allow uprising of 536 magmas. 537

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 541 Tethys and the thinned margin of the Adriatic domain (Fig. 9c,d). This process may explain why 542 since the late Miocene intense accretionary activity occurred in the Apennine belt, in front of the 543 extruding wedges (Viti et al., 2006 and references therein), and crustal extension developed in the 544 wake of those wedges, with the formation of the central Tyrrhenian basin. The relatively high 545 velocity (up to 5-8 cm/y) of the consequent trench retreat recognized at the related consuming 546 boundary, during the Pliocene (Patacca and Scandone, 1989; Finetti et al., 2005b; Guillaume et al., 547 2010), might be due to the contemporaneous actions of two opposite kinematic boundary 548 conditions, i.e. the roughly NW ward motion of southern Adria and the roughly ESE ward 549 migration of the Alpine-Apennines wedges (Fig.9c,d). 550

During this phase, belt-parallel compression also stressed the central-northern Apennines, 551 causing the formation of arcs, with in-sequence thrusting at external fronts (e.g., Calamita et al., 552 553 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 554 555 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 556 in the Northern Apennines changed from continuous, cylindrical, to highly fragmented, non 557 cylindrical (e.g., Amadori et al., 2019). The hypothesis that in the Pliocene the belt underwent a 558 compressional regime is also suggested by the shortening evidenced by CROP seismic sections 559 (e.g., Finetti et al., 2005a). 560

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

567 expected to occur at the inner side of extruding wedges (e.g., Tamburelli et al., 2000;
568 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).

575 During the Late Miocene-Pleistocene interval, a complex system of elongated foredeeps 576 developed in the eastern sector of the Po Plain and in the northern Adriatic area and severe tectonic 577 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.

584

## 585 Southern Tyrrhenian basin (Early Pleistocene)

586 When the extruding Southern Apennine wedge reached the continental Adriatic domain, the 587 resistance against such consuming process underwent a significant increase, which led to the 588 progressive stop of that wedge, revealed by the end of thrusting at its outer front and of crustal 589 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

619 suggests that since about 10 My two large slab windows have developed beneath that belt, one in 620 the sector running from Tunisia to eastern Sicily and the other beneath the central and southern 621 Apennines. If this reconstruction is reliable, one can hardly understand why the most intense uplift 622 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).

630

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

Since the middle Pleistocene, the gravitational energy accumulated by the southern Adria 632 633 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 634 (Dinarides) and northern (Eastern Alps) boundaries of Adria (Viti et al., 2006 and references 635 therein). A more complex effect of Adria's acceleration has developed along its western boundary, 636 the Apennine belt. Since the external (eastern) sector of that chain was more closely connected with 637 the underlying Adriatic domain, it underwent a more efficent drag from Adria, with respect to the 638 inner belt (which was overlying a much deeper Adriatic lithosphere). This drag has resulted in a 639 greater mobility, stronger deformation and uplift of the outer belt, which has progressively 640 separated from the inner belt, forming the series of troughs located in the axial chain. This 641 mechanism may explain why since the middle Pleistocene the compressional tectonic style in the 642 Apennines was replaced by a dominant left lateral transcurrent regime (Viti et al., 2006 and 643 references therein). The compressional features previously developed in the two main Pliocenic 644

extruding wedges, the Molise-Sannio (MS) and the Romagna-Marche-Umbria (RMU), were cut by 645 a series of longitudinal trastensional fault sytems, as the Irpinia-Benevento-Matese (e.g., Pantosti 646 and Valensise, 1990; Cinque et al., 2000; Ascione et al., 2007) in the MS wedge and the Norcia-647 Colfiorito-Val Tiberina (Calamita et al., 2002; Pizzi and Galadini, 2009) in the RMU wedge, 648 connected by longitudinal transtensional fault systems (Aquila and Fucino) in the Lazio-Abruzzi 649 platform (Fig. 10, Viti et al., 2006 and references therein). This dynamics also induced belt-parallel 650 shortening in the outer belt, accommodated by the formation of arcs (e.g., Maiella, Gran Sasso, 651 Laga Mt.) and a generalized uplift (e.g., Pizzi and Galadini, 2009; Elter et al., 2012; Blumetti et al., 652 2013). 653

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).

661 The recent/present kinematic pattern of the Apennine belt inferred from Pleistocene 662 deformation pattern, involving a faster motion of the outer Apennine belt with respect to the inner 663 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 availableevidence 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 673 Adriatic domain (5-6 mm/y) could be connected with a non rigid behaviour of the Adria plate, due 674 to the non uniform time distribution of decoupling earthquakes along the circum Adriatic 675 boundaries (Mantovani et al., 2015a). In this regard, one could suppose that the Pleistocene 676 compressional deformations recognized in the inner part of Adria (such as the Middle Adriatic 677 Ridge, Fig. 6, e.g., Scisciani and Calamita, 2009) may have developed during such transitory 678 phases, characterized by an accelerated motion of southern Adria and a low mobility of the northern 679 680 Adria (Mantovani et al., 2016).

681

The belt-parallel compression and the sinistral shear that affected the Apennine belt during the 682 683 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 684 685 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 686 provide a possible explanation for the two major features, i.e. the location and timing, of the most 687 intense Quaternary volcanic episodes that has developed in the Apennine belt during this 688 evolutionary phase. 689

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 697 accelerated its northward motion, as suggested by the fact that the border with the Ventura block 698 (Sciacca fault) has become a sinistral shear zone (Civile et al., 2018). The fact that magmatic 699 activity in the Sciacca fault system has mainly developed in the Pleistocene could suggest that the 700 inversion of the strike slip sense at that fault may have favoured the development of pull-apart 701 mechanisms. The hypothesis that the Syracuse fault is an active decoupling zone is supported by 702 the occurrence of great damages in the eastern side of Sicily (e.g., 1169 and 1683, Rovida et al., 703 2016). 704

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).

710

## 711 **4.** Conclusions

712

Discussions about Mediterranean geodynamics mainly concern the driving mechanism of the 713 ATBA systems. To overcome the apparent difficulty raised by the occurrence of crustal extension 714 in zones of plate convergence, some authors suggest that such tectonic process may be produced by 715 deep seated forces, mainly induced by gravitational sinking of subducted lithosphere. However, the 716 implications of that genetic mechanism can hardly be reconciled with the observed deformation 717 pattern. In particular, the development of the northern, central and southern Tyrrhenian basins in 718 three well distict phases, would require a discontinuos, very peculiar and scarcely plausible action 719 of gravity on the Adriatic subducted margin. This and other major problems discussed in the text 720 suggest that slab-pull forces can hardly be invoked to explain the surface deformation pattern. 721

So far, many laboratory and numerical experiments, both 2D and 3D, have investigated the 722 dynamics of slab-pull. However, the parameters adopted in various experiments vary over wide 723 ranges, making it difficult to compare among results provided by different works. For instance, one 724 may consider the density difference between the slab and surrounding mantle ( $\Delta \rho$ ), which crucially 725 affects the magnitude of the slab-pull force. Capitanio et al. (2010) use the values  $\Delta \rho = 30$ , 60 and 726 90 kg m<sup>-3</sup> for their numerical experiments. Schellart and Moresi (2013) instead adopt the value  $\Delta \rho =$ 727 80 kg m<sup>-3</sup>. Meyer and Schellart (2013) consider the significantly larger value  $\Delta \rho = 103$  kg m<sup>-3</sup>, 728 729 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., 730 Funiciello et al., 2003a,b, 2004, 2006; Schellart, 2010; Schellart et al., 2011). On the other hand, the 731 upper plate may effectively resist slab retreat and back-arc extension (Shemenda, 1993; Hassani et 732 al., 1997; Capitanio et al., 2010). Thus, the conclusions drawn by the above works cannot be 733 considered as definitive ones, because they depend on questionable experimental settings or on still 734 poorly constrained subduction parameters. 735

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 givenin the following.

- It takes into account a very large set of tectonic features, more complete than the ones consideredin 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 765 geodynamic interpretations so far proposed for this area, underlying the considerable ambiguity that 766 still surrounds this problem. This uncertainty involves many negative implications, even concerning 767 important social problems, as for instance the mitigation of seismic hazard. In fact, it is well known 768 that a reliable attempt at recognizing the zones most prone to next strong shocks can only be made 769 if one can rely on a deep knowledge of the ongoing tectonic processes. Exploiting this knowledge 770 and the seismic history of the zone considered, one could try to recognize the perturbation of the 771 strain/stress fields that may be caused by major earthquakes and how this effect may influence the 772 subsequent spatio-temporal distribution of seismicity (Mantovani et al., 2015b, 2016, 2017; Viti et 773

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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## 1496 **Figure captions**

1497

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).

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Fig. 2. A) Late Oligocene-Early Miocene. The outward migration of the Norhern Al-Ka-Pe-Ca 1508 Arc (NA) and the Corsica-Sardinia block (CS), at the expense of the Tethyan domain, builds up the 1509 Apennine accretionary belt, while crustal extension occurs in the wake of the Arc, forming the 1510 Balearic basin (BB). A more limited rotation is undergone by the Southern Al-Ka-Pe-Ca arc (SA) 1511 and the Balearic Promontory (BP), generating the relatively small Valencia trough (VT). The 1512 relative motion between NA and SA is accommodated by the North Balearic fault (NBF). B) 1513 Middle Miocene. The NA stops rotating after its collision with the continental Adriatic domain, 1514 1515 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 1516 1517 extension develops in the wake of SA, generating the Eastern Algerian basin (EAB). (From Viti et 1518 al., 2009, modified). Colours and symbols as in figure 1.

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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.

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Fig. 4. A) Late Miocene-Early Pliocene (about 5 My). Crustal stretching occurs in the AlpineApennine 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.

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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.

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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.

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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.

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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 aboveprocess.

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Fig. 9. Proposed evolutionary reconstruction. A) Middle-Upper Miocene (15-9 My). Blue arrows 1558 indicate the proposed kinematic pattern (Mantovani et al., 2007a, 2009, 2015a; Viti et al., 2009, 1559 2011) B) Upper Miocene (9-6 My). After the reactivation of the Giudicarie fault system, the 1560 northern Adriatic promontory undergoes a NE ward motion and clockwise rotation, releasing its 1561 previous internal deformation. The divergence between that promontory and the stable Corsica-1562 Sardinia block induces crustal extension in the interposed Alpine-Apennine belt, with the formation 1563 of the Northern Tyrrhenian basin. C) Pliocene (5-2 My). A large part of the Adriatic promontory 1564 decouples from Africa, by the activation of major discontinuities in the Pelagian and Ionian zones, 1565 the Sicily Channel-Medina (Me)-Victor Hensen (VH) fault systems and from its Padanian sector 1566 1567 (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 1568 1569 block and the northern African foreland (Tunisia) causes the roughly NW ward extrusion of a 1570 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 1571 Alpine-Apennine belt lying south of the Selli fault, at the expense of the Tethyan domain and the 1572 1573 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 1574 Tyrrhenian basin (CT). D) Early Pleistocene. After the stop of the Southern Apennines wedge 1575 against the continental Adriatic domain, the convergence of the confining plates is accommodated 1576 by the outward extrusion of the CP wedge, at the expense of the Ionian domain, and the upward 1577 1578 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 1579 side forms the Southern Tyrrhenian basin (ST). The Calabrian wedge undergoes strong uplift, 1580

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.

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Fig. 10. Tentative reconstruction of the E-W shortening processes in the Hyblean-Adventure 1589 that determined the formation of troughs in the Sicily Channel. A) Late Miocene. 1590 domain Configuration of the Hyblean-Adventure domain just after the activation of the Victor-Hensen-1591 Medina-Sicily Channel discontinuity, when the shortening of that zone, induced by the E-W 1592 convergence between the decoupled Adria plate and the Tunisian protuberance (Fig.9c) started to 1593 develop. Present geographical contours are reported for reference. B) Present tectonic setting 1594 (modified after Finetti and Del Ben, 1986). The Adventure block, decoupled from the Hybelan 1595 domain by the Sciacca fault system, has undergone a roughly NNWward escape, forming the 1596 1597 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 1598 been forced to bend southward, forming the Gela nappe. In the southern side, the original NW-SE 1599 plateau, in the Sicily channel zone, has undergone a considerable fragmentation, in order to 1600 accommodate E-W shortening. Local crustal extensions, induced by the divergence between 1601 fragments, have formed the Malta and Linosa grabens and other minor troughs. Toothed lines 1602 1603 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 1604 1605 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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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

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## **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:

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