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Post-20 Ma motion of the Adriatic plate – new constraints from surrounding orogens and implications for crust-mantle decoupling

Authors

Eline Le Breton[1]*, Mark R. Handy[1], Giancarlo Molli[2], Kamil Ustaszewski[3]

[1]Freie Universität Berlin, Berlin, Germany

[2]Università di Pisa, Italy

[3]Friedrich-Schiller-Universität Jena, Jena, Germany

*Corresponding author: eline.lebreton@fu-berlin.de

Key Points

- Adria has rotated 5 ± 3° counter-clockwise and translated c. 110 km to the NW (azimuth 325°) relative to Europe since 20 Ma.
- Adria motion was associated with 110 km convergence relative to Moesia, 125 km in Eastern Alps and 60 km of extension in Sicily Channel.
- Differences between amounts of shortening and plate convergence suggest crust-mantle decoupling at active Adria-Europe boundaries.

Abstract

A new kinematic reconstruction that incorporates estimates of post-20 Ma shortening and extension in the Apennines, Alps, Dinarides and Sicily Channel Rift Zone (SCRZ) reveals that the Adriatic microplate (Adria) rotated counter-clockwise as it subducted beneath the European Plate to the west and to the east, while indenting the Alps to the north. Minimum and maximum amounts of rotation (2°, 8°) are derived by using, respectively, estimates of crustal extension along the SCRZ (minimum of 30 km) combined with crustal shortening in the eastern Alps (minimum of 115 km), and a maximum amount (140 km) of convergence between Adria and Moesia across the southern Dinarides and Carpatho-Balkan orogens. When combined with Neogene convergence in the western Alps, the best fit of available structural data constrains Adria to have moved 113 km to the NW (azimuth 325°) while rotating 5 ± 3° counter-clockwise relative to Europe since 20 Ma. Amounts of plate convergence predicted by our new model exceed Neogene shortening estimates of several tens of kilometers in both the Apennines and Dinarides. We attribute this difference to crust-mantle decoupling (delamination) during roll-back in the Apennines and to deformation related to the northward motion of the Dacia Unit between the southern Dinarides and Europe (Moesia). Neogene motion of Adria resulted from a combination of Africa pushing from the south, the Adriatic-Hellenides slab pulling to the northeast and crustal wedging in the western Alps, which acted as a pivot and stopped further northwestward motion of Adria relative to Europe.

1. Introduction

The Adriatic microplate (Adria) is a key player in the geodynamics of the western Mediterranean because of its location between two major plates, Europe and Africa (**Fig. 1**), that have been converging since at least Late Cretaceous time [e.g., *Dewey et al.*, 1989; *Stampfli and Borel*, 2002; *Handy et al.*, 2010]. Its boundaries are highly deformed and include the Alps, Apennines, Dinarides, Hellenides and the Calabrian Arc. The Alps-Apennines and Alps-Dinarides junctions are marked by switches in subduction polarity, with Adria being the upper plate in the Alps and the lower plate in the Apennines and Dinarides [**Fig. 1**; e.g., *Carminati and Doglioni,* 2012*; Handy et al.*, 2010; 2015b]. The Apennines have been the site of Oligo-Miocene roll-back subduction, "soft" collision and pronounced back-arc (upper-plate) extension leading to the opening of the Tyrrhenian and Liguro-Provençal Basins [**Fig. 1;** e.g., *Royden and Burchfiel*, 1989; *Patacca et al.*, 1990; *Gueguen et al.*, 1997; *Séranne*, 1999; *Faccenna et al.*, 2003; *Jolivet and Faccenna*, 2000; *Stampfli and Borel*, 2002; *Molli*, 2008].

Reconstructing the motion of Adria remains a challenge, partly because most of it has been subducted [e.g., *Handy et al*., 2010], but also because its eastern and western margins were very deformable [e.g., *Moretti and Royden*, 1988], making it difficult to choose stable reference points for motion studies. Adria is often considered to be a promontory of Africa and thus to have moved with Africa [e.g., *Channell and Horvath,* 1976; *Channell et al.,* 1979; *Dewey et al*., 1989; *Mazzoli and Helmann*, 1994; *Rosenbaum et al.*, 2004; *Gaina et al.*, 2013; *Muttoni et al*., 2013], although independent motion of Adria with respect to both Europa and Africa has been deemed necessary to explain the complex kinematics of orogenesis and basin formation in the Adriatic region [*Biju-Duval et al.,* 1977; *Dercourt et al.,* 1986]. The three-plate hypothesis has been confirmed by recent studies based on restoring shortening in the Alps, indicating that Adria's motion was intermittently independent of Africa since the onset of Adria-Europe convergence in late Cretaceous time [*Handy et al.*, 2010; 2015b]. Reconstructions of the Aegean region also indicate that Adria likely moved some 40 km relative to Africa in the Pliocene [*van Hinsbergen and Schmid*, 2012]. While there is consensus that Adria's motion involved counter-clockwise (CCW) rotation with respect to Europe, the amount of rotation remains controversial. This pertains even to the Neogene part of the history during collision in the Alps, Apennines and Dinarides. Estimates of post-Paleogene CCW rotation range from a few degrees to as much as 20° depending on the authors and approach used [paleomagnetics, e.g., *Márton et al.,* 2010; *van Hinsbergen et al.*, 2014a and references therein; palinspastic reconstructions, *Ustaszewski et al.*, 2008; *Handy et al.*, 2010, 2015b]. The rotation pole today is generally placed within the arc of the western Alps and the western Po Basin as indicated by seismic moment [*Anderson and Jackson,* 1987] and GPS velocity studies [*Calais et al.*, 2002; *Vrabec and Fodor,* 2006; *Bennett et al*., 2012]. All of these studies assume that Adria moved as a single block, though some seismic and geodetic investigations suggest that it may have fragmented into two blocks that are currently rotating with respect to each other, as well as relative to Europe and Africa [*Oldow et al.*, 2002; *D'Agostino et al*., 2008; *Scisciani and Calamita*, 2009; *Sani et al*., 2016].

This paper presents a new motion path for the Adriatic microplate since early Neogene time (≤ 20 Ma). This period saw major changes in the interaction of plates in the western and central Mediterranean, and is therefore key to understanding the forces that drove plate motion [slab-pull, slab-suction, Africa-push; e.g., *Faccenna et al.*, 2004; *Handy et al.*, 2010; *Carminati and Doglioni*, 2012; *Viti et al*., 2016] and ultimately formed the mountains and basins surrounding Adria. After reviewing the Apennines, Alps and Dinarides (section 2), and comparing existing models of Adriatic motion (section 3), we compile new estimates of crustal shortening, continental subduction and extension along transects surrounding Adria (A-A'-A", B-B', C-C', D-D' on **Fig. 1**; section 4). The information is then synthesized to provide a best-fit model of Adriatic motion that reconciles data from all neighboring orogens and basins (section 5). Finally, the motion path is used to draw inferences about the forces that drive the Adriatic plate (section 6).

2. Geological setting

The western Mediterranean area is a highly mobile tectonic system marked by arcuate plate boundaries with highly non-cylindrical orogens and back-arc basins (**Fig. 1**). Adria played a central role in the geodynamics of this region because of its location between two former oceans: the mid-Jurassic-early Cretaceous Alpine Tethys [e.g., *Stampfli and Borel*, 2002; *Schmid et al.*, 2004; *Vissers et al.*, 2013] and the northern branch of Neotethys [e.g., *Ricou*, 1994; *Schmid et al.*, 2008]. Today, the Adriatic microplate comprises mostly continental lithosphere [1300 km in a NW-SE direction, 250 km NE-SW and 80 km thick; *Munzarová et al.*, 2013]. It is surrounded by orogens (**Fig. 1**), from the Alps in the north where Adria is the upper plate and indents the Alpine orogenic edifice [e.g., *Schmid et al.* 2004], to the Apennines and the Dinarides where Adria forms the compliant lower plate descending to the west and east, respectively [e.g., *Moretti and Royden*, 1988]. The Alps are characterized by filled to overfilled foreland basins (Molasse, Po), wholesale accretion of the lower plate including exhumed high-pressure rocks and pronounced topographic relief, whereas the Apennines and Dinarides tend to have narrow foredeeps, low-grade metamorphism of accreted lower-plate units and subdued relief [*Royden et al.*, 1987; *Royden and Burchfiel*, 1989].

Collision in the Apennines involving W-directed roll-back subduction of Adriatic continental lithosphere began no earlier than early Oligocene time [*Molli,* 2008 and references therein] as constrained by the 34-28 Ma age of rifting in the Liguro-Provençal basin [Rupelian; *Séranne*, 1999; *Jolivet et al.,* 2015] and the deposition of continental clastics in the Apenninic foredeep [Chattian-Aquitanian Macigno flysch; *Argnani and Ricci Lucchi,* 2001; *Cerrina Feroni et al*., 2002; *Cornamusini et al.,* 2002; *Cornamusini* 2004]. Prior to collision, the polarity of subduction of the Alpine Tethys ocean is controversial; some authors favor NW-directed "Apenninic" subduction of Adria already since Late Cretaceous time [e.g., *Jolivet and Faccenna*, 2000], whereas others invoke a switch from SE-directed "Alpine" subduction of European lithosphere to NW-directed "Apenninic" subduction of Adriatic lithosphere at about 34 Ma [e.g., *Molli*, 2008 and references therein; *Molli and Malavieille*, 2011 and references therein]. However, the polarity of pre-Neogene subduction is not important for the purposes of this paper, which focuses on post-20 Ma motion of Adria.

The Apennines continue into the Calabrian Arc, where the lithosphere of the Ionian Sea forming the southernmost part of the Adriatic microplate is actively subducting beneath Europe (**Fig. 1**). *Faccenna et al.* [2001] proposed that the Calabrian Arc formed in late Miocene time in response to slab tearing during the advanced stages of slab roll-back, back-arc extension and opening of the Tyrrhenian Sea. The nature of the lithosphere beneath the Ionian Abyssal Plain (**Fig. 1**) remains controversial, with oceanic [e.g., *de Voogd et al.*, 1992; *Speranza et al.*, 2012] or hyper-extended continental lithosphere [e.g., *Hieke et al.*, 2003] proposed so far. However, the length and retreat of the slab under the Calabrian arc and Tyrrhenian Sea suggest that the downgoing lithosphere connected to the Ionian lithosphere is oceanic. Moreover, numerous geophysical studies showed that the 330-km wide [*Catalano et al.,* 2001] Ionian Basin has a 7-9 km thick oceanic crust [*Cowie and Kuznir,* 2012] of Early Mesozoic age [220-230 Ma; *Speranza et al.*, 2012] covered by more than 5 km of Meso-Cenozoic sediments [*de Voogd et al.*, 1992; *Cowie and Kuznir,* 2012]. We will return to this point below, as it has implications for whether Adria was a rigid promontory of Africa or an independent plate during the convergence of Africa and Europe.

The amount of shortening in the Apennines is poorly constrained despite the abundance of seismic data collected over the years. Previous studies estimated shortening by assuming that orogenic shortening during roll-back subduction was compensated entirely by upper-plate extension in the Liguro-Provençal basins, amounting to zero convergence between Adria and Europe [*Faccenna et al.*, 2001]. This resulted in estimates of upper-plate extension (and thus also of maximum orogenic shortening) of 240 km and 780 km, respectively, for northern and southern transects of the Apennines (Gulf of Lion to the northern Apennines via Corsica, and Gulf of Lion to Calabria via Sardinia; *Faccenna et al.*, 2001, their Figure 1]. Although the shortening estimate for the southern transect appears to coincide with the length of the slab anomaly extending to the NW from the Calabrian Arc [e.g., *Piromallo and Morelli*, 2003], there is no reason to assume a priori that Apenninic shortening was equal to extension. Moreover, studies suggested that the mantle lithosphere subducting beneath the Apennines delaminated from the crust [e.g. *Channell and Mareschal*, 1989; *Serri et al.*, 1993; *Chiarabba et al.*, 2009, 2014; *Benoit et al.*, 2011]. Delamination [*Bird*, 1979] involves peeling off of the lithospheric mantle from the crust and does not necessarily entail an equivalent amount of crustal shortening as the lithospheric mantle sinks into the asthenosphere.

The Alps contain the sutured remains of Alpine Tethys [e.g., *Stampfli et al*., 1998; *Schmid et al*., 2004; *Handy et al*., 2010], which opened as an arm of the North Atlantic in two stages, from 170-131 Ma (Piemont-Liguria Basin) and 131 to 93 Ma [Valais Basin; *Frisch* 1979; *Stampfli and Borel*, 2002; *Schmid et al.*, 2004]. Closure of Alpine Tethys occurred during NNW convergence of Adria with Europe between 84 Ma and 35 Ma [*Handy et al.,* 2010]. Collision in the Alps involved SE-directed subduction of the European margin and was punctuated by detachment of the European slab at 35-30 Ma [*von Blankenburg and Davies* 1995; *Schmid et al*., 2004]. This led to crustal wedging and indentation beginning at about 30 Ma and 23-21 Ma, respectively, in the western and eastern Alps [*Handy et al.*, 2015b and references therein]. The difference in the amount of Neogene indentation along strike of the Alps is directly related to the rotation of Adria, a point to which we return below.

The Dinarides are a SW-vergent fold-and-thrust belt (**Fig. 1**), most of which formed during Late Jurassic to early Oligocene time by the progressive closure of the northern branch of Neotethys (Meliata-Maliac-Vardar ocean) and subsequent collision and deformation of the NE Adriatic margin [e.g., *Pamić et al.*, 1998; *Babić et al.*, 2002; *Schmid et al.*, 2008; *Ustaszewski et al.*, 2010]. The part of the history relevant to this paper began with detachment of the NE-dipping Adriatic slab, triggering calc-alkaline magmatism in the Dinaric nappe pile in late Eocene-early Miocene time [37-22 Ma; *Schefer et al.*, 2011]. From Late Oligocene onward, thrusting and folding propagated to the SW into the foreland [e.g., *Tari*, 2002; *Roure et al*., 2004], accompanied by dextral strike-slip faulting [*Picha*, 2002; *Kastelić et al.*, 2008]. The amount of shortening in the Dinarides is poorly constrained at present. Neogene upper-plate extension in the Dinarides [*Matenco and Radivojević*, 2012] is minor compared to the amount of upper-plate extension in the Pannonian Basin [*Ustaszewski et al.*, 2008] and Apennines cited above. Extension in the Pannonian Basin occurs in the upper plate of the zero-convergence Carpathian system [*Royden and Burchfiel*, 1989] and therefore has little effect on the relative motion of Adria and Europe studied here. In the next section, we review the main unresolved problems with existing kinematic models of Adria as a prelude to the new approach used in this study.

3. Existing reconstructions of Adriatic plate motion

The classical approach for reconstructing plate motion is to assume that tectonic plates are rigid, then apply Euler's theorem to describe their rotation on an ideally spherical Earth by fitting magnetic anomalies and fracture zones in oceanic basins, or using paleomagnetic studies on continents [e.g., *Morgan*, 1968; *Le Pichon et al.*, 1977]. The quality of the magnetic database has improved over recent decades to the point where the motions of major plates such as Europe and Africa are reasonably well constrained [e.g., *Doubrovine and Tarduno*, 2008; *Seton et al*., 2012]. However, this approach is inadequate to reconstruct the motion of Mediterranean microplates like Adria, whose oceanic portions have been almost entirely subducted (**Fig. 1**; section 2) or do not have oceanic anomalies of Miocene age [Ionian Sea; *Speranza et al.,* 2012].

The idea that Adria was a rigid promontory of Africa since at least Jurassic time [e.g., *Channell et al*., 1979; *Rosenbaum et al*., 2004*; Speranza et al*., 2012] and moved together with Africa since that time [e.g., *Dewey et al*., 1989; *Capitanio and Goes*, 2006; *Gaina et al.*, 2013] is based primarily on paleomagnetic studies indicating little or no rotation of Adria with respect to Africa [e.g., *Channell et al*., 1979; *Channell*, 1996; *Rosenbaum et al*., 2004]. However, recent paleomagnetic studies on stable parts of Adria (Adige embayment, Istria and Apulia, **Fig. 1**) indicate that Adria may have rotated CCW by as much as 20° relative to Africa since about 20 Ma [*Márton*, 2003; *Márton et al*., 2008; 2010; 2011; *van Hinsbergen et al*., 2014a]. Also, recent magnetic studies suggest that the Ionian crust is oceanic [e.g., *Speranza et al*., 2012] with a continuous lithospheric mantle between the northern margin of Africa and Italy [e.g., *Catalano et al. 2001*; *Mele*, 2001; *Rosenbaum et al*., 2004], implying that Adria has been 'rigidly' connected with Africa since Triassic time [age of the oceanic crust, 220-230 Ma; *Speranza et al.*, 2012]. However, Neogene SW-NE striking thrusts and positive inversion structures in the Ionian abyssal plain [*Gallais et al*., 2011; *Polonia et al*., 2011; *Roure et al*., 2012] are interpreted as reactivated normal and transform faults originally formed at spreading centers of the Ionian Sea [*Gallais et al*., 2011]. These structures indicate that the crust beneath the Ionian Sea is not rigid, but deformable. Moreover, several NW-SE trending rifts opened during Miocene time along the African Margin in the Sicily Channel Rift Zone [SCRZ, **Fig 1**; e.g. *Civile et al*., 2008; 2010]. These structures both in the Ionian Sea and along the African Margin are therefore evidence for possible relative motion of Adria away from Africa in Neogene time.

Moreover, plate motion models invoking Adria as a rigid promontory of Africa are unable to account adequately for the opening and closure of Alpine Tethys, as discussed in Handy et al. [2010]. For one, the E-W and N-S dimensions of Alpine Tethys in such models [e.g., *Capitanio and Goes*, 2006] do not corroborate available estimates of N-S convergence in the Alps [*Schmid et al*., 1996; *Handy et al*., 2010; 2015b]. Either the N–S length of Alpine Tethys was smaller than deduced from such models, and/or the Adriatic microplate moved independently of the African plate [*Biju-Duval et al.*, 1977; *Dercourt et al.*, 1986] for at least part of the period considered above.

To test the different models of Adria motion with respect to Europe, we use the compilation of finite rotations of *Gaina et al.* [2013] for Africa based on a best-fit of magnetic anomalies in the Atlantic, and of *Seton et al.* [2012; using paleomagnetic studies of *Speranza et al.*, 2002] for the Corsica-Sardinia block that best fit the amount and timing of spreading in the Liguro-Provençal Basin (see also section 4.2). We also tested the model of *Handy et al.* [2015b] that accounts for shortening in the Alps and proposes independent motion of Adria relative to Africa. All plate reconstructions and rotation calculations in this paper are performed with GPlates software [*Boyden et al.*, 2011]. Independent motion of Adria is supported by present-day GPS velocities [e.g. *D'Agostino et al.*, 2008] and by the aforementioned extension along the African Margin - and therefore motion of Adria away from Africa - in Neogene time [SCRZ; *Civile et al.,* 2008; 2010].

For the past 20 Ma, motion of Adria together with Africa (**Fig 2**, in green) would necessitate 170 km of NW-SE directed Neogene convergence in the western Alps, which far exceeds current estimates of Neogene shortening in the western Alps, including the recent estimate of c. 30-40 km of *Schmid et al*. [2017] obtained from areal balancing of lithospheric cross sections. It even exceeds the 113 km convergence estimate that *Handy et al.* [2015b] obtained by retro-deforming the Alpine nappe stack in map view, a value that they regarded as an absolute maximum (see also section 4.3). Adria moving together with Africa also calls for 35 km and 65 km of Neogene overall convergence along NE-SW transects in the northern Apennines and southern Dinarides-Carpatho-Balkan respectively, which both seem plausible.

The discrepancy between measured and model-based shortening estimates in the western Alps can only be resolved if Adria is assumed to have moved independently of Africa. We note that the model of *Handy et al.* [2015b] uses Neogene shortening in the southern Alps to obtain a CCW rotation of Adria relative to Europe of some 20°, which would require far too much Neogene convergence in the southern Dinarides-Carpatho-Balkan (350 km, **Fig. 2**, in red) and an implausible 330 km of Neogene extension in the Ionian Sea and/or African Margin. None of these large estimates are supported by available geological data. Therefore, data from the other surrounding orogens (Apennines and Dinarides) and basins (western Mediterranean basins and SCRZ) are needed to better constrain the Neogene motion and amount of CCW rotation of Adria relative to Europe.

4. New constraints on post-20 Ma Adria motion

To constrain the motion of Adria in Neogene time, we choose 4 transects along which to estimate convergence and divergence of Adria relative to Europe, Corsica and Africa (**Fig. 1, sections 4.1-4.4**): (1) **southern France - Corsica - northern Apennines** (Transect A-A'-A") perpendicular to rifting and spreading of the Liguro-Provençal Basin, and parallel to the CROP03 seismic profile [*Alberti et al*., 1998; *Barchi et al.* 1998a, 1998b, 2003; *Decandia et al.,* 1998]. We choose this transect because upper-plate extension is modest and shortening can be better estimated than in the southern Apennines; (2) **western** (Ivrea) **and eastern Alps** (Transect C-C') where recent restorations are available [*Handy et al*., 2010, 2015b; *Schmid et al*., 2017]; (3) **southern Dinarides-Carpatho-Balkan** (Transect B-B'), where seismic tomography [UU-P07 model from *Amaru*, 2007; *Hall and Spakman*, 2015] and industrial active-source seismic data [*Bega* 2013, 2015] are available to estimate the amount of subducted lithosphere since Oligocene-early Miocene slab breakoff and Miocene crustal shortening, respectively, and where Miocene Pannonian extension is modest [*Matenco and Radivojević*, 2012]; (4) **Africa - southern Italy** (Transect D-D'), perpendicular to the Pantelleria Rift, the main rift of the SCRZ.

It is important to note that estimates of crustal shortening along these transects only correspond to convergence of the Adriatic and European plates if the crust and lithospheric mantle moved coherently during orogeny. Plate convergence is defined here as the decrease in distance between points on undeformed parts of the upper and lower plates of the orogen. Where mantle delamination, intracrustal decoupling or tectonic erosion have occurred, the amount of crustal shortening recorded by folding and thrusting will be less than the amount of plate convergence. As discussed below, these processes all occurred, sometimes together, so that most shortening values below provide minimum estimates of Adria-Europe convergence. Irrespective of the processes at active margins, shortening estimates in fold-and-thrust belts are almost always minima due to erosion of the hangingwall tiplines of thrusts and/or footwall cutoffs.

4.1. Extension vs. shortening in the northern Apennines (Transect A-A'-A")

In the Apennines, contemporaneous Neogene shortening and upper-plate extension were estimated separately to arrive at an overall amount of deformation parallel to A-A'-A". The amount of upper-plate extension was estimated by constructing a crustal-scale profile along transect A-A'-A" from a recent map of Moho depth [*Spada et al*. 2013, their Figure 11], and from topography and bathymetry [global model ETOPO1 of *Amante and Eakins*, 2009]. This involved first removing the 55-km length of oceanic lithosphere (spreading) in the central part of the Liguro-Provençal Basin [*Jolivet et al*., 2015] from transect A-A' and 100-km length at the NE end of transect A'-A", where Adria is the downgoing plate (**Fig. 3a**). The profile was then restored to an assumed pre-extensional crustal thickness of 30 km, as preserved beneath southern France (**Fig. 3b**). However, the crust beneath Corsica and Italy was orogenically thickened prior to the onset of upper-plate extension [*Jolivet et al*., 1998; *Faccenna et al*., 2001], as evidenced by Eocene high-pressure metamorphism exhumed in the footwalls of Alpine thrusts reactivated as Miocene normal faults on Alpine Corsica [e.g., *Martin et al*., 2011 and references therein] and in some Tuscan units of the northern Apennines [Massa unit and along-strike equivalents; e.g., *Theye et al.,* 1997; *Molli et al.*, 2000; *Bianco et al*., 2015]. We have therefore assumed an orogenically thickened crust of 40 km (**Fig. 3b**), in agreement with the present Moho depth in the central Apennines [*Spada et al*., 2013] where the orogenic crust is not deepened by downward pull of the Adriatic slab.

This results in a total of 223 ± 30 km of upper-plate extension along transect A-A'-A" (**Fig. 3**), which can be divided into 61 ± 16 km of rifting from 34-21 Ma [age of syn-rift sediments; *Seranne*, 1999; *Jolivet et al.*, 2015], 55 km of sea-floor spreading from 21-16 Ma [age of post-rift sediments and CCW rotation of the Corsica-Sardinia block; *Seranne*, 1999; *Jolivet et al.* 2015; *Speranza et al*., 2002; *Seton et al*., 2012] in the Liguro-Provençal Basin, and 107 ± 14 km of extension in the Tyrrhenian Sea from 16-0 Ma [age of syn-rift sediments; *Seranne*, 1999; *Jolivet et al.*, 2015]. The large uncertainties reflect the large variation in Moho depths along the section [*Spada et al.*, 2013; their Figure 11]. Note that if the initial thickness of crust beneath Corsica and Italy was assumed to be only 30 km, the amount of extension in the Tyrrhenian Sea (A'-A") would be only 51 ± 18 km instead of 107 ± 14 km. This would in turn yield an average of 77 ± 44 km extension. However, we favor the 107 ± 14 km value which is based on the estimates of orogenic crustal thickness beneath Corsica and Tuscany prior to extension, as explained above. Moreover, our total estimate of 223 ± 30 km Oligo-Miocene extension is in good agreement with the 240 km of total extension that *Faccenna et al.* [2001] obtained for the same transect and time period.

Shortening is difficult to estimate in the northern Apennines due to contractional reactivation of pre-orogenic normal faults as thrusts [e.g. *Tavarnelli et al*., 2001] and to subsequent extensional reactivation of these thrusts during roll-back subduction [e.g. *Brogi and Liotta*, 2006]. This makes tectonostratigraphic markers unreliable for estimating thrust displacement. Early attempts to estimate shortening in the Umbria-Marche belt of the northern Apennines assumed a thin-skinned thrusting with detachment at the sediment-basement interface, yielding up to 100 km of shortening [*Bally et al*., 1986; *Lavecchia et al*., 1987; *Calamita and Deiana.*, 1988; *Calamita et al.,* 1990]. However, more recent studies using active-source seismic data from the CROP-03 profile invoked a thick-skinned thrusting involving the basement and multiple detachment levels, resulting in conservative shortening estimates ranging from 30 to 60 km (average 45 ± 15 km) [*Barchi et al*., 1998b; *Alberti et al*., 1998; *Coward et al*., 1999; *Tavarnelli et al*., 2004; *Mazzoli et al*., 2005; *Butler et al*., 2006]. Shortening in the Umbria-Marche belt initiated in Burdigalian time [c. 20 Ma, *Barchi et al.*, 1998b] as constrained by the age of syn-orogenic foredeep sediments (Marnoso Arenacea Fm). Older foredeep sediments of Oligo-Miocene age (c. 34 – 20 Ma, Macigno Fm) are preserved in Tuscany in the western "Tyrrhenian" segment of the CROP03 transect, where all orogenic structures are overprinted by upper-plate extension [*Barchi et al*., 1998a; *Decandia et al*., 1998; *Brogi and Liotta*, 2006]. However, pre-20 Ma sediments and structures are not directly relevant for the post-20 Ma aforementioned shortening estimates.

To summarize, 107 ± 14 km of post-20 Ma upper-plate extension exceeded an average of 45 ± 15 km of coeval orogenic shortening, resulting in a possible overall divergence of about 62 ± 29 km along transect A'-A" (**Fig. 4**). However, shortening estimates can underestimate plate convergence considerably. Moreover, if we perform the same calculation with the whole range of possible values for both shortening (30-100 km) and extension (77 ± 44 km) along transect A'-A", we end up with an overall divergence of 10.5 ± 80.5 km, with an uncertainty higher than the mean value. In light of this poor constraint, independent estimates of shortening and extension are needed from the other surrounding orogens and basins.

4.2. Neogene convergence in the southern Dinarides-Carpatho-Balkan (transect B-B')

The external part of the Dinarides accommodated only minor Mio-Pliocene shortening (≤ 20 km) according to reflection seismic profiles interpreted from off- and onshore industry data in southern Montenegro and northern Albania [*Bega* 2013, 2015]. Miocene and younger shortening across the orogenic front increases to some 80-100 km as one moves to the southeast into the Tirana foredeep basin of central Albania [*Schmid et al.,* 2014]. This along-strike change in shortening has been attributed to a SE increase in the contribution of Hellenic roll-back subduction [*Handy et al.,* 2014, 2015a]; the Neogene component of this roll-back subduction was accommodated by a combination of post-middle Miocene CCW block rotation and orogen-parallel extension limited to southeast of the Shkoder-Peja Normal Fault

(SPNF, **Fig. 1**), as documented by paleomagnetic studies [*Kissel et al.*, 1995] and structural work [*Handy et al.,* 2014, 2015a]. Thus, for the purposes of this paper, we only regard Neogene shortening north of the SPNF, where effects of Hellenic rollback subduction are negligible.

Neogene opening of the Pannonian Basin in the upper plate of the neighboring Carpathian orogen involved no convergence between Adria and Europe [*Royden and Burchfiel*, 1989] and therefore had little, if any, effect on our estimates of Adria-Europe convergence in the southern Dinarides-Carpatho-Balkan. Moreover, our transect B-B' crosses south of the Pannonian Basin where Neogene extension amounts to less than 10 km based on the geometry of Mio-Pliocene rift basins in the seismic interpretation of *Matenco and Radivojević* [2012; their Fig. 4].

Out-of-sequence thrusting in the internal Dinarides [e.g. *Ustaszewski et al.*, 2008] and strike-slip faulting east of the Sava Suture [Timok Fault, *Fügenschuh and Schmid,* 2005] also occurred along this transect, the latter during the Neogene northward motion of the Dacia Unit around the Moesian promontory of Europe and escape into the Pannonian embayment behind the eastwardly retreating Carpatho-Balkan orogen. The lack of reliable markers precludes quantifying the effect of strike-slip faulting, but given the range of rotations of the Tisza and Dacia units [16-38° clockwise, *Ustaszewski et al. 2008* and references therein], the overall Adria-Europe (Moesia) convergence was significantly more, perhaps on the order of a 100 km, than Neogene shortening in the external Dinarides.

An absolute maximum on the amount of Adria-Europe (Moesia) convergence along our transect B-B' is given by the length (140 km) of a positive P-wave velocity anomaly imaged in seismic tomography [model UU-P07 of *Amaru* 2007; *Hall and Spakman*, 2015; **Fig. 5**]. This can be interpreted as the Adriatic slab dipping beneath the Dinarides; unfortunately, neither the age, the detachment depth, nor the exact location of the slab with respect to the surface geology are known. Slab break-off in the Dinarides occurred between about 37 and 22 Ma as inferred from the distribution of calc-alkaline magmatism [*Schefer et al.*, 2011]. In light of the minor Mio-Pliocene crustal shortening in the external Dinarides, most of this truncated slab length probably accrued during Paleogene Adria-Europe convergence, for which there is abundant geological evidence in the Dinarides [e.g., *Schmid et al.,* 2008].

4.3. Western (Ivrea) and Eastern Alps (transect C-C')

Adria-Europe convergence in the western Alps is difficult to ascertain because shortening varies around the arc of the western Alps and partly preceded arcuation [*Collombet et al.*, 2002; *Schmid et al.*, 2017]. At the SW end of the arc in the Ligurian Alps, the arcuation was accentuated by eastward rollback subduction of the northern Apennines and counterclockwise rotation of the Corsica-Sardina block [*Vignaroli et al*., 2008]. We considered the approaches of *Handy et al*. [2015b] and *Schmid et al.* [2017] which entail different assumptions and yield different amounts of Neogene convergence (113 km) and shortening (30-40 km) estimates, respectively. Adria-Europe convergence in the Western Alps is defined here as displacement of the city of Ivrea (in the Ivrea Zone) on an undeformed part of Adria relative to a point on stable Europe in the Alpine foreland (the Schwarzwald of southern Germany). *Handy et al.* [2015b] retrodeformed the Alpine thrusts in map view using previously published estimates of shortening (their Fig. A1) and maintaining compatibility around the arc by avoiding overlaps in thrusts during stepwise restoration. Their 113 km of post-20 Ma, Adria-Europe convergence along an azimuth of 325° is a maximum estimate because restoring thrust displacements orthogonally to differently oriented thrust tip lines within the arc leads to a space problem. The authors solved this by translating Adria by an amount greater than the shortening measured along individual cross sections around the arc. Recently, *Schmid et al.* [2017] obtained a shortening estimate of about 30-40 km from areally balanced lithospheric cross sections around the arc. However, this estimate must be regarded as a minimum for Neogene Adria-Europe convergence due to erosion of thrusts tip lines and cutoffs, as well as possible tectonic erosion within the orogen. We also note that any obliquity of the convergence vector to the trend of the thrust belts around the western Alpine arc would result in shortening estimates less than the overall Europe-Adria convergence [*Lacassin*, 1987]. The 30 and 113 km estimates therefore very broadly bracket the actual amount of Neogene Adria-Europe convergence in the Western Alps.

In the eastern Alps, post-20 Ma shortening along transect C-C' amounts to a minimum of 115 km, comprising 65 km [*Linzer et al.* 2002] and 50 km [*Schönborn, 1999*], respectively, north and south of the Periadriatic fault. However, shortening along this transect probably does not represent the entire amount of Adria-Europe convergence, some of which was accommodated by eastward, orogen-parallel extrusion of orogenic crust in the Tauern Window [e.g., *Scharf et al.*, 2013; *Favaro et al*., 2017]. Approximately 150 km of continental subduction can be deduced from the length of the +Vp slab anomaly imaged beneath the eastern Alps [*Handy et al*., 2015b, their Figure B3] though this is only a crude estimate due to the highly variable, drop-like shape of this slab in the tomographic images of *Lippitsch et al.* [2003]. We consider this 150-km amount of subduction as an absolute upper limit on the amount of Adria-Europe Neogene convergence; therefore, post-20 Ma Adria-Europe convergence along transect C-C' ranges from 115 to 150 km.

4.4. Sicily Channel Rift Zone (transect D-D')

The continental margin between Africa and Sicily was stretched by a series of NW-SE trending rifts that developed along the Sicily Channel Rift Zone (SCRZ, **Fig. 1**) during Neogene time [e.g. *Jongsma et al*., 1987; *Argnani* 1990; *Corti et al*., 2006; *Civile et al*., 2008; 2010]. This area shows evidence for both extension in the SCRZ (100 km wide) and dextral transtension along the Malta Escarpment [**Fig. 1**; 3 km vertical relief over 200 km length; *Jongsma et al*., 1987; *Doglioni et al*., 2001]. The reason(s) for this extension are unclear; it may have accommodated shortening in the Maghrebian chain, rollback of the Calabrian slab [*Argnani* 1990] or be related to a change in the rheology of the northern African continental lithosphere [*Civile et al*., 2010]. Here, we propose that this extension accommodated the divergence between Adria and Africa during the post-20 Ma CCW rotation of Adria. The overall amount of extension is still poorly constrained. A crustal profile perpendicular to the main rift of the SCRZ (Pantelleria Rift, south of Sicily) and parallel to our transect D-D' (**Fig. 1**) was published by *Civile et al.* [2008, their Figure 9] based on their interpretation of the CROP seismic lines M-25. The amount of NE-SW extension obtained from balancing this section for an initial thickness of 25 km (present-day thickness on both side of the rift) is about 30 km. Taking into account the other rifts along the SCRZ and the transtensional deformation along the Malta Escarpment, we consider this 30 km of extension to represent the minimum amount of Neogene divergence of Africa and Adria (D-D').

5. Post-20 Ma motion and rotation of Adria relative to Europe

Combining amounts of extension, shortening and subduction obtained above from the orogens and basins surrounding Adria (section 4, **Table 1**) allows us to place tighter constraints on Adria-Europe and Adria-Africa motion. To describe the rotation of Adria, we choose an axis at the aforementioned city of Ivrea [*Handy et al*., 2010, 2015b] due to its location at the northwesternmost stable part of Adria (**Fig. 1**) and its general coincidence with the Miocene-to-recent rotation axis for Adria proposed in previous geodetic and geophysical studies [e.g. *Vrabec and Fodor*, 2006; *D'Agostino et al*., 2008; *Ustaszewski et al*., 2008]. However, we emphasize that the Ivrea rotation axis is not the finite Euler rotation pole for

Adria as a whole because Ivrea has undergone translation relative to Europe since 20 Ma together with Adria; therefore, the finite rotation pole for Adria is a combination of both the motion of Ivrea/Adria and the rotation of Adria about the Ivrea axis (**Fig. 6**).

We test two plate-motion scenarios utilizing either (1) the 113 km of Adria-Europe convergence in the Western Alps discussed above [*Handy et al.*, 2015b] or (2) a smaller amount of 60 km [closer to the minimum shortening estimate of *Schmid et al*., 2017]. For both scenarios, we run a series of tests that account for different amounts of rotation, from 4° clockwise to 20° counter-clockwise (**Fig. 6; Appendix 1**). For each such test, we calculate the amounts of Adria-Europe divergence/convergence along transects A-A'-A", B-B', C-C' and D-D', and compare them with data in section 4 in order to obtain a best-fit model for post-20 Ma Adria motion (**Table 1**; **Appendix 1**).

The post-20 Ma motion of Adria relative to Europe along transect A-A'-A" is divided into two components: (1) the motion of Corsica relative to Europe (transect A-A'); and (2) the motion of Adria relative to Corsica (transect A'-A"). As mentioned in section 4.1, 55 km of sea-floor spreading occurred between 21 and 16 Ma [*Seranne* 1999; *Speranza et al*. 2002; *Gattacceca et al*., 2007; *Jolivet et al*., 2015] in the Liguro-Provençal basin along transect A-A' (**Fig. 3**). This necessitates a CCW rotation of the Corsica-Sardinia block relative to Europe as already demonstrated in paleomagnetic studies [e.g., *Speranza et al*., 2002; *Gattacceca et al.,* 2007]. For a constant spreading rate of 11 km/Ma, Corsica moved about 44 km away from Europe between 20 and 16 Ma along transect A-A'. This is identical within error to the 40 km of Corsica-Sardinia motion predicted along the same transect by *Seton et al.* [2012; Euler pole and rotation angle from *Speranza et al*., 2002; **Fig. 4**]. A more recent model for the Corsica-Sardinia block [*Advokaat et al*., 2014 based on *Gattacceca et al*., 2007 for Neogene time] predicts less than 20 km of post-20 Ma displacement of Corsica along transect A-A'. We believe this underestimates the actual amount of spreading [c. 40 km according to *Jolivet et al*., 2015] and therefore use the *Seton et al.* [2012] plate motion model for the motion of Corsica-Sardinia.

Post-20 Ma motion of Adria (A'') relative to Corsica (A') was associated with some 107 ± 14 km of extension in the Tyrrhenian Sea and Tuscany as shown above and in **Figure 4**. During the same period, a minimum of 45 ± 15 km shortening was accommodated in the northern Apennines (section 4.1). Assuming that this shortening represents the minimum convergence, we obtain an overall maximum divergence of 62 ± 29 km between Adria (A") and Corsica (A). To accommodate this overall divergence, Adria would have rotated at most

15.5 ± 4° CCW (11 to 19.5° CCW) relative to Europe given 113 km of convergence in the western Alps (Model 1), or 14.75 ± 4.25° CCW (10.5 to 19° CCW) for only 60 km of convergence in the western Alps (Model 2). Using the same approach but with the largest uncertainties in our data (77 ± 44 km of extension and 65 ± 35 km shortening along A'-A"; Section 4.1 and Table 1), the range of maximum rotation of Adria relative to Europe increases to 7.75 ± 11.75° (4° CW to 19.5° CCW, Model 1; 4.5° CW to 19° CCW for Model 2; **Appendix 1**).

If the observed Neogene shortening in the southern external Dinarides (c. 20 km along transect B-B'; Section 4.2 and Table 1) represents the true amount of Adria-Europe (Moesia) convergence, then rotation of Adria was negligible, if at all existent (0.6° CW for Model 1, 0.3° CCW for Model 2; **Table 1 and Appendix 1**). In contrast, using the 140-km slab-anomaly length (**Fig. 5**) as a maximum of Adria-Europe (Moesia) convergence would yield maximum CCW rotation of Adria of 7° CCW for Model 1 and 8° CCW for Model 2. In the eastern Alps (transect C-C'), 115-150 km of Adria-Europe convergence corresponds to a CCW rotation of Adria ranging from 6.5 ± 3° (Model 1) to 14 ± 3° (Model 2). A minimum of 30 km divergence between Adria and Africa across the Sicily Rift Zone (SCRZ, transect D-D') corresponds to a minimum CCW rotation of Adria of 3.5° for Model 1 and 4° for Model 2. Therefore, no rotation of Adria – as required for only 20 km of convergence in the southern external Dinarides - would not fit the data in the eastern Alps and SCRZ. Additional convergence along B-B' related to strike-slip faulting and northward motion of Dacia into the Pannonian embayment (section 4.2) therefore fits well with the kinematic constraints imposed by the other orogens surrounding the Adriatic Plate.

Using 60 km of convergence in the western Alps (Model 2) requires much more CCW rotation of Adria (14 ± 3°) to fit the data in the Eastern Alps which in turn requires far too much convergence in the southern Dinarides-Carpatho-Balkan (240 ± 50 km; Fig. A9 of Appendix 1) and too much divergence between Adria and Africa (215 ± 55 km; Fig. A11 of Appendix 1). Therefore, the best fit to all the available data involves convergence according to Model 1 in the western Alps (113 km; Step 1 in **Fig. 6**) and CCW rotation of Adria of 5.25 ± 1.75° about the Ivrea axis (Step 2 in **Fig. 6**, **Table 1**). The error associated with all our reconstructions and measurements amounts to 10 km, corresponding to 0.5-1.5° of rotation, depending on the distance to the rotation pole. Thus, the CCW rotation of Adria that fits all the available data is 5 ± 3° about the Ivrea axis. The mean value corresponds to a CCW rotation of 5.35° about a finite Euler rotation pole located in Spain at 38.20°N, 3.16°W.

6. Discussion

6.1. Assessing the model

The range of CCW Adria rotation of 5 ± 3° is within error of the 9.8 ± 9.5° CCW rotation proposed by *van Hinsbergen et al*. [2014a] based on their paleomagnetic study of the Apulian peninsula, southern Italy (**Fig. 1**), but much less than the 20° previously obtained from shortening values in the southern Alps [*Ustaszewski et al*., 2008; *Handy et al*., 2015b]. These shortening estimates come from near the Ivrea rotation axis in the western part of the southern Alps [Bergamasche Alps, 70 km of *Schönborn,* 1992] where some of the shortening attributed to the Neogene may actually be older [e.g. *Doglioni and Bosellini*, 1987; *Fantoni et al.,* 2004]. Certainly, applying 20° of CCW rotation to the entire Adriatic plate can be ruled out on the grounds that it would require far too much Neogene convergence in the southern Dinarides-Carpatho-Balkan and Neogene extension in the Ionian Sea (**Fig. 2**).

In a test of different plate scenarios for Adria, *van Hinsbergen et al.* [2014a] concluded that either Neogene shortening in the western Alps has been underestimated by as much as 150 km or Neogene extension in the Ionian Basin has been underestimated by as much as 420 km. However, Neogene shortening in the western Alps certainly does not exceed 113 km of convergence [our Model 1; section 4.3; *Handy et al*., 2015b], an amount that is much greater than usually proposed for shortening in the western Alps [c. 30-40 km; *Schmid* et al., 2017]. If one assumes only 60 km of convergence (our Model 2), then this would require 14 ± 3° of CCW Adria rotation to fit the data in the eastern Alps, implying too much convergence in the southern Dinarides-Carpatho-Balkan and too much divergence along the SCRZ (Section 5 and Table 1). Obviously, this is strongly dependent on the location of the rotation pole for Adria; here, we used the city of Ivrea for our first reconstruction step (section 5; **Fig. 6**). The rotation pole may have changed through time but this was not tested in this study. We recall that using another rotation pole such as that for Africa relative to Europe (so that Adria would move together with Africa) would require far too much convergence in the Western Alps (170 km, **Fig. 2**).

Our proposed best-fit CCW Adria rotation of about 5° relative to Europe calls for about 60 km of post-20 Ma NE-SW directed extension between Africa and Adria, which is much less than the 420 mentioned by *van Hinsbergen et al*. [2014a]. The actual amount of extension accommodated there is difficult to assess because most of the Ionian lithosphere was subducted beneath the advancing Calabrian and Hellenic arcs in Pliocene time [e.g., *Malinverno and Ryan*, 1986; *Royden*, 1993; *Faccenna et al*., 2003; *Gutscher et al*., 2016]; only a small triangular patch of the Ionian abyssal plain remains unsubducted (**Fig. 1**).

Seismic profiles of this remnant basin indicate Neogene tectonic inversion along NE-SW striking thrust faults rather than extensional deformation [*Gallais et al*., 2011; *Polonia et al.,* 2011; *Roure et al*., 2012]. However, Neogene NE-SW directed extension along the SCRZ [e.g. *Civile et al*., 2008] and right-lateral transtension along the Malta Escarpment [e.g. *Jongsma et al*., 1987; *Doglioni et al*., 2001] on the African Margin of the Ionian Sea (**Figs. 1 and 7**) accommodated the southeastward advance of the Calabrian Arc [e.g., *Jongsma et al*., 1987; *Frizon de Lamotte et al*., 2011; *Roure et al*., 2012] and most likely the NE-SW divergence of Adria and Africa (section 4.4; **Fig. 7**). In sum, evidence of Neogene NW-SE directed extension along the African margin of the Ionian Sea is compatible with the NE-SW divergence of Adria and Africa as featured in our best-fit model for CCW Adria rotation. More data from the SRCZ are needed to refine this model.

A possible solution to the dilemma above is that the Adriatic plate fragmented, with the northern part rotating independently of the southern part [*Oldow et al*., 2002; *D'Agostino et al*., 2008; *Sani et al*., 2016]. Indeed, seismic reflection profiling (CROP M15), GPS velocities and diffuse seismicity in the central Adriatic Sea have been interpreted as evidence for NW-SE striking thrusts and dextral strike-slip faults along the so-called Mid-Adriatic Ridge or MAR [**Fig. 1;** *Scisciani and Calamita*, 2009]. If we split Adria into two blocks along the MAR and move the northern block as in our best-fit model and the southern block together with Africa, the resulting deformation along the MAR would be 50-100 km (eastwardly increasing) of dextral strike-slip with a transtensional component (≤ 10 km of extension) to accommodate CCW rotation of the northern block relative to the southern block. However, the structures imaged along CROP M15 transect are only contractional and/or transpressive; there is no evidence for transtension or for 50-100 km of dextral strike-slip deformation [*Scisciani and Calamita*, 2009]. In order to allow simultaneous Neogene CCW rotation of Adria relative to Europe and independent motion of Adria relative to Africa, the Ionian Sea and/or its adjacent margins must have accommodated Neogene extension.

6.2. Discrepant shortening and convergence as evidence for crust-mantle decoupling?

The best-fit CCW Adria rotation of about 5° relative to Europe entails c. 8 km of overall Adria-Europe convergence in the northern Apennines (A-A'-A"), c. 110 km of across the southern Dinarides-Carpatho-Balkan (B-B"), 113 km of convergence in the western Alps (Ivrea), c. 125 km of convergence in the eastern Alps (C-C') and c. 60 km of divergence between Africa and Adria (D-D"). Predicted Adria-Europe convergence in the best-fit model exceeds measured shortening in all three orogens surrounding the Adriatic plate. These discrepancies tell us something about mechanisms of orogeny in the circum-Adriatic mountain belts.

Continental roll-back subduction in the northern Apennines involved nearly zero Adria-Europe convergence, with about 115 km ± 14 km of continental subduction if we use the 107 km ± 14 km of extension obtained by areal balancing (section 4.1). This would be close to the amount of crustal shortening obtained from the 'thin-skinned' interpretations (c. 100 km, section 4.1), but far greater than the favored 'thick-skinned' interpretations (30-60 km, section 4.1). We attribute this deficiency of crustal shortening to tectonic erosion and/or to lithospheric and lower crustal delamination in the Apennines.

Likewise, the discrepancy between observed Miocene crustal shortening and inferred Adria-Europe (Moesia) convergence along transect B-B′ implies wholesale vertical decoupling. The zone of decoupling is most probably located between the Dinarides and the Moesia promontory of Europe, where arcuate strike-slip faults [e.g., Timok Fault of *Fügenschuh and Schmid*, 2005] accommodated Miocene northward extrusion and clockwise rotation of the Dacia part of the Tisza-Dacia Unit [e.g. *Ustaszewski et al.*, 2008].

6.3. Possible forces driving Adriatic motion in Neogene time

Neogene motion of the Adriatic plate raises the question of its driving forces, indeed, of whether its motion was at all independent of that of the larger plates. Certainly, pull of the slab beneath the Apennines can be ruled out as a driving force because the Adriatic plate rotated CCW to the NE, i.e., away from the westward direction of its subduction beneath Europe. Likewise, pull of an Adriatic slab segment beneath the eastern Alps is probably negligible due to its limited length [≤ 150 km in the eastern Alps, *Lippitsch et al.,* 2003]. So far, P-wave tomography shows no evidence of a slab anomaly in the northern Dinarides [*Wortel and Spakman*, 2000; *Piromallo and Morelli*, 2003], precluding a component of slab pull to the NE.

This leaves eastward pull of the Adriatic slab beneath the northwestern Hellenides and/or northward push of the African plate as the only viable drivers of post-20 Ma Adria motion (**Fig. 7**). P-wave tomography has shown that the Hellenic slab descends through the Mantle Transitional Zone into the lower mantle [*Piromallo and Morelli*, 2003; *van Hinsbergen et al.*, 2005]. Similar directions (to the NW) and rates [7 mm/yr; *Gaina et al.*, 2013 for Africa and our best-fit model for Adria] of motion of Adria and Africa relative to Europe during Neogene time indicate that Adria was pushed to the northwest by Africa, as proposed by *Handy et al.* [2010, 2015b]. However, the northwestward motion of Adria most likely slowed – if not stopped – as Adria indented and wedged in the western Alps along the Ivrea Body [*Handy and Zingg,* 1991; *Zingg et al.,* 1990; *Schmid et al*., 2017]. Then, pull of the NE-dipping slab beneath the northwestern Hellenides, to which the eastern part of the Adriatic plate was (and still is) attached, drove the CCW rotation of Adria and divergence from Africa, while the Apenninic-Calabrian trench retreated rapidly. Today, the remaining Adriatic plate is squeezed between Europe and Africa while the latter still pushes to the north. In response to that push, Adria most likely started to fragment internally, as indicated by the present-day seismicity and deformation within Adria [*Oldow et al*., 2002; *D'Agostino et al*., 2008; *Scisciani and Calamita*, 2009; *Sani et al*., 2016].

In summary, we propose that Adria's northward motion in Neogene time was driven by Africa's advance, while the CCW rotation of Adria resulted from a combination of wedging of its rigid northwestern end in the western Alps and northeastward pull of the Adriatic slab descending beneath the northwestern Hellenides. This left Adria's eastern edge free to swing northeastward, out of the way of Africa

7. Conclusions

Neogene motion of the Adriatic plate is key to understand how contrasting orogenic styles develop within the same overall convergent tectonic regime. This study provides a new post-20 Ma motion path for the Adriatic microplate that fits available geological and geophysical data from the Alps, Apennines, Dinarides and Sicily Channel Rift Zone (SCRZ). During the last 20 Ma, upper-plate extension (107 ± 14 km) has exceeded shortening (c. 30-60 km) in the northern Apennines, while Adria subducted beneath the southern Dinarides (> 20 km) and indented both the western Alps (c. 30-113 km) and eastern Alps (c. 115-150 km). The best-fit for Adria motion is a CCW rotation relative to Europe of c. 5° about a finite Euler rotation pole located in Spain at 38.20°N, 3.16°W. This motion calls for almost no overall Neogene Adria-Europe convergence in the northern Apennines, 113 km in the western Alps, 125 km in the eastern Alps, and 110 km between Adria and Moesia, mostly across the Carpatho-Balkan orogen. Furthermore, the estimated divergence between Africa and Adria of 60 km was accommodated by extension along the SRCZ and dextral transtension along NW-SE striking transform faults (Malta escarpment).

Plate convergence exceeds crustal shortening in all orogens surrounding Adria. We attribute this difference to tectonic erosion and crust-mantle decoupling of the Adriatic lithosphere, expressed differently in the three orogens: (1) delamination during roll-back in the Apennines; (2) northward motion of the Dacia Unit between the Dinarides and Europe (Moesia); and (3) eastward lateral extrusion of the Tauern Window in the Eastern Alps during northward indentation of Adria into Europe.

The main driving force of Adria motion was a push from Africa to the northwest until the Adriatic plate slowed and stopped as it indented Europe in the western Alps. Then the main force was a pull to the east by the slab beneath the northwestern Hellenides. This triggered a slight CCW rotation of Adria relative to Europe and divergence from Africa. As Africa still pushes to the north, the Adriatic plate most likely started to fragment internally as documented by GPS and seismic studies cited above.

Supporting information

Appendix 1 presents the results of the two series of tests for Model 1 and Model 2 of post-20 Ma amount of Adria rotation. Appendix 2 (Movie S1) is an animated map-reconstruction of the western Mediterranean based on our favored Model 1 (5.35° CCW rotation about a finite Euler rotation pole located at 38.20°N, 3.16°W).

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Table

<table>
<tr><th></th><th>Dataset used to determine amount of post-20 Ma Adria rotation</th><th>Rotation (R2) for Model 1: 113 km convergence in western Alps (R1)</th><th>Rotation (R2) for Model 2: 60 km convergence in western Alps (R1)</th></tr>
<tr><td>Liguro-Provençal Basin (A-A')</td><td>40 km spreading</td><td rowspan="3">Maximum 7.75 ± 11.75° (from 4° CW to 19.5° CCW)</td><td rowspan="3">Maximum 7.25 ± 11.75° (from 4.5° CW to 19° CCW)</td></tr>
<tr><td>Tyrrhenian Sea – Tuscany (A'-A")</td><td>107 ± 14 km extension assuming 40 km initial thickness
51 ± 18 km extension assuming 30 km initial thickness
⇨ 33-121 km divergence</td></tr>
<tr><td>Northern Apennines (A'-A")</td><td>30-60 km shortening assuming thick-skinned
100 km assuming thin-skinned
⇨ minimum 30-100 km convergence</td></tr>
<tr><td>Southern Dinarides – Carpatho-Balkan (B-B')</td><td>20 km crustal shortening
140 km slab-length
⇨ 20-140 km convergence</td><td>Minimum 0.6° CCW
Maximum 7° CCW</td><td>Minimum 0.3° CCW
Maximum 8° CCW</td></tr>
<tr><td>Eastern Alps (C-C')</td><td>115-150 km convergence</td><td>6.5 ± 3° CCW</td><td>14 ± 3° CCW</td></tr>
<tr><td>SCRZ (D-D')</td><td>Minimum 30 km divergence</td><td>Minimum 3.5° CCW</td><td>Minimum 4° CCW</td></tr>
<tr><td colspan="2">Best-fit rotation</td><td>5.25° ± 1.75° CCW</td><td>No possible fit!</td></tr>
</table>

Table 1. Compilation of crustal shortening, extension, and Adria-Europe divergence and convergence along transects A-A'-A", B-B', C-C' and D-D' (location on Fig. 1) used to constrain post-20 Ma Adria rotation relative to Europe (R1 and R2 refers to Fig. 6). Note that a viable fit of those data is only obtained for Model 1 (involving 113 km convergence in western Alps). More details on calculation of rotations are given in Appendix 1.

Figure Captions

Figure 1. Tectonic map of western Mediterranean with main Cenozoic structures and geological-geophysical transects in this study. Tectonic structures compiled from *Seranne* [1999], *Handy et al.* [2010; 2015b], *Civile et al.* [2010], *Frizon de Lamotte et al.* [2011] and *Polonia et al.* [2011]. Background topographic-bathymetric map from ETOPO1 model [*Amante and Eakins*, 2009]. Dashed black line in the Ionian Sea is the 4000 m depth isobath delimiting the abyssal plain to the south [*Gallais et al.* 2011]. Abbreviations: Ad - Adige Embayment; Ap - Apulia; CS - Corsica-Sardinia; Ga - Gargano; IS - Ionian Sea; Ist - Istria; LP - Liguro-Provençal Basin; MAR - Mid-Adriatic Ridge; ME - Malta Escarpment; PB - Pannonian Basin; SCRZ – Sicily Channel Rift Zone; SPNF, Shkoder-Peja Normal Fault; TS - Tyrrhenian Sea. Map projection is Transverse Mercator (central meridian 10°E, latitude of origin 43°N).

Figure 2. Comparison of Adria locations at 20 Ma depending on whether it moved together with Africa (light green) or independently thereof based on data from the Alps [red; *Handy et al*., 2010; 2015b] relative to Europe (grey). Finite Euler rotation poles for Africa (dark green) from *Gaina et al*. [2013] and Corsica-Sardinia (orange) from *Seton et al.* [2012]. Numbers indicate post-20 Ma overall divergence (+) and convergence (-) in the models. Present-day location of plates and coastline are shown in black. Map projection on Figure 1.

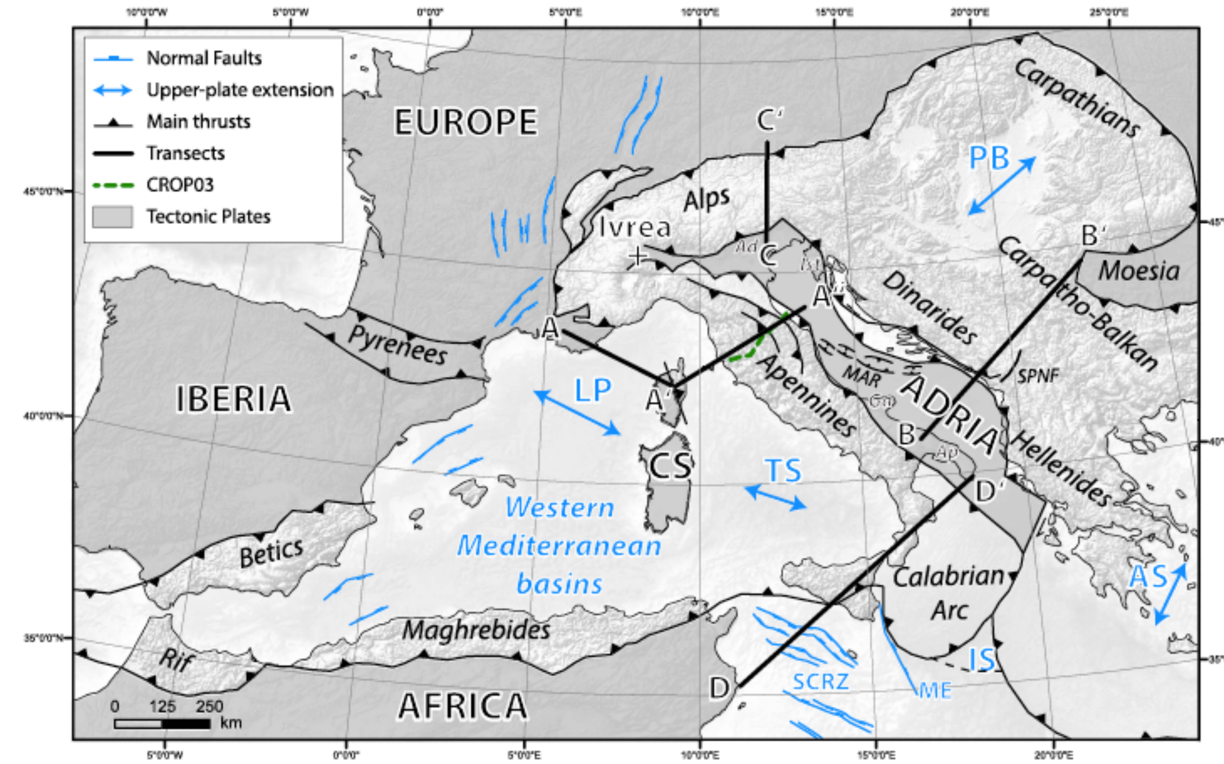
Figure 3. a. Transect A-A'-A'' with Moho depth from *Spada et al.* [2013], topography/bathymetry from ETOPO1 model [*Amante and Eakins*, 2009] and width of oceanic crust (55 km, 21-16 Ma) in Liguro-Provençal Basin from *Jolivet et al.* [2015]. Location of transect on Figure 1. **b.** Transect A-A'-A'' after areal balancing of the crust shows total extension in Liguro-Provençal and Tyrrhenian Sea. Note that the crust under southern France was restored back to normal thickness (30 km), whereas under Corsica and Italy the crust was restored to an orogenic thickness of 40 km (see text).

Figure 4. Tectonic map of the western Mediterranean showing post-20 Ma extension along transect A-A'-A'' in red (Fig. 3) and post-20 Ma shortening in the northern Apennines along the CROP03 profile, parallel to transect A'-A'', in green (location on Fig. 1). Map projection shown on Figure 1.

Figure 5. P-wave tomography [model UU-P07 from *Amaru*, 2007 and *Hall and Spakman*, 2015] along transect B-B' through the southern Dinarides-Carpatho-Balkan (location in Figs. 1 and 6) showing a positive anomaly (blue) interpreted as subducted Adriatic lithosphere. Abbreviation: LAB – Lithosphere Asthenosphere Boundary.

Figure 6. Steps for reconstructing post-20 Ma motion path of Adria (yellow) relative to Europe: (1) translate Ivrea to the SE by 113 km (Model 1) or 60 km (Model 2); (2) test different rotations of Adria (20° CCW to 4° CW) around an axis located at translated Ivrea; (3) calculate convergence and divergence along transects A'-A", B-B', C-C', D-D' and compare with dataset (Table 1). The finite Euler rotation pole (calculated with GPlates) for Adria motion is a combination of Adria translation (R1) and rotation (R2). Post-20 Ma motion of the Corsica-Sardinia block (blue) from *Speranza et al.* [2002; in compilation of *Seton et al*., 2002] and of Africa (green) from *Gaina et al.* [2013] are taken into account when calculating deformation along transect A-A'-A" (blue arrows) and D-D' (green arrows), respectively.

Figure 7. Tectonic map of the central Mediterranean region showing location of the Adria microplate and main front thrusts today (black) and at 20 Ma (pink, favored Model 1) relative to Europe. Blue indicates the proposed force vectors driving the motion of Adria (push of Africa from the south, pull of the Adriatic-Hellenic slab to the northeast) during crustal wedging in the Alps that slowed and ultimately stopped Adria NW motion. Note the Neogene NE-SW directed extension along the African margin that has accommodated divergence of Adria and Africa. Abbreviations: CS - Corsica-Sardinia; LP - Liguro-Provençal; ME - Malta Escarpment; PR - Pantelleria Rift; TS - Tyrrhenian Sea. Map projection on Figure 1.



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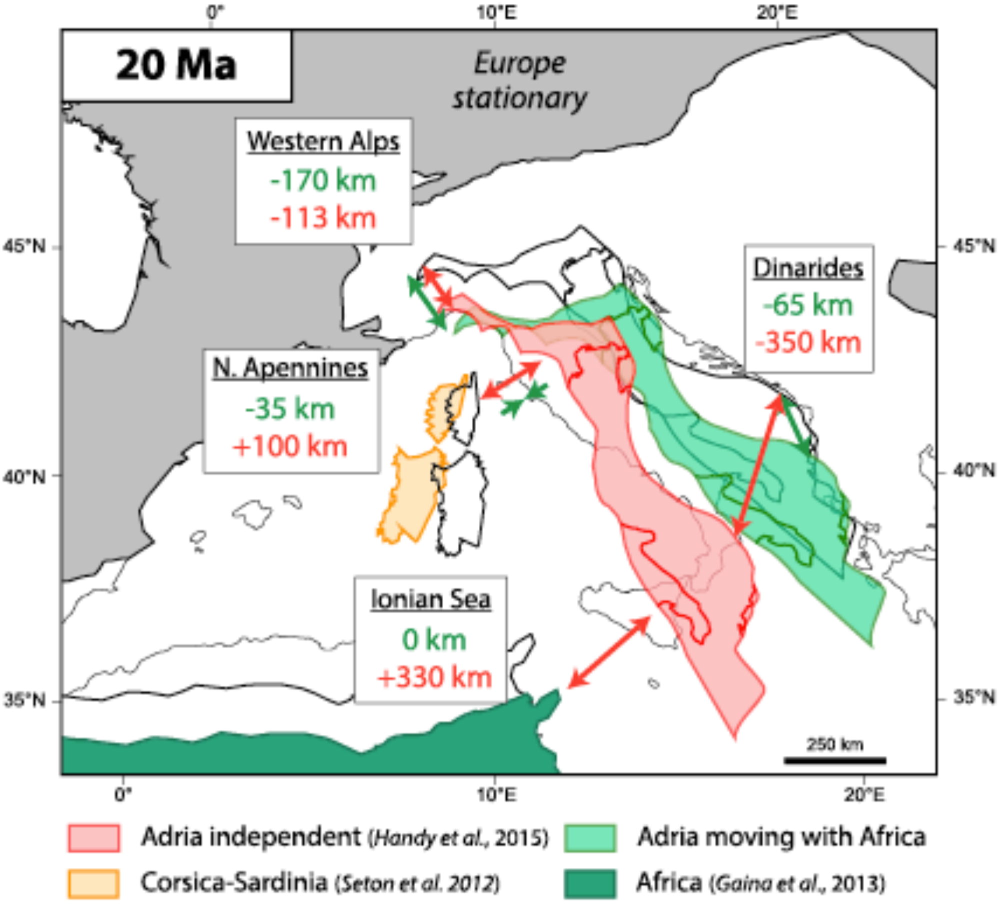

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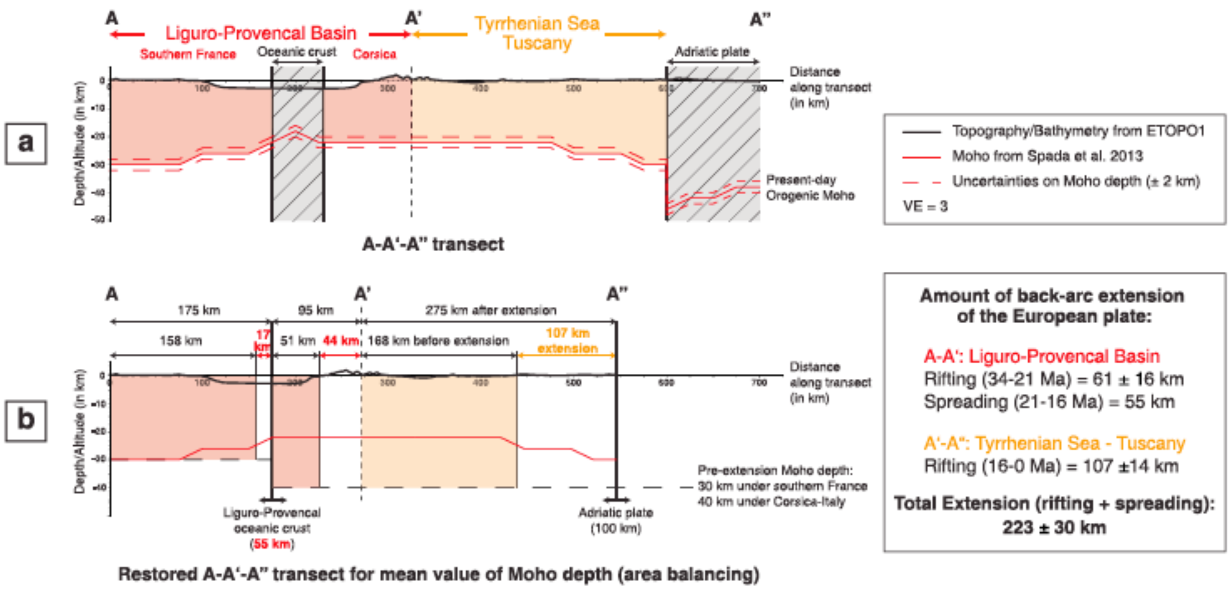

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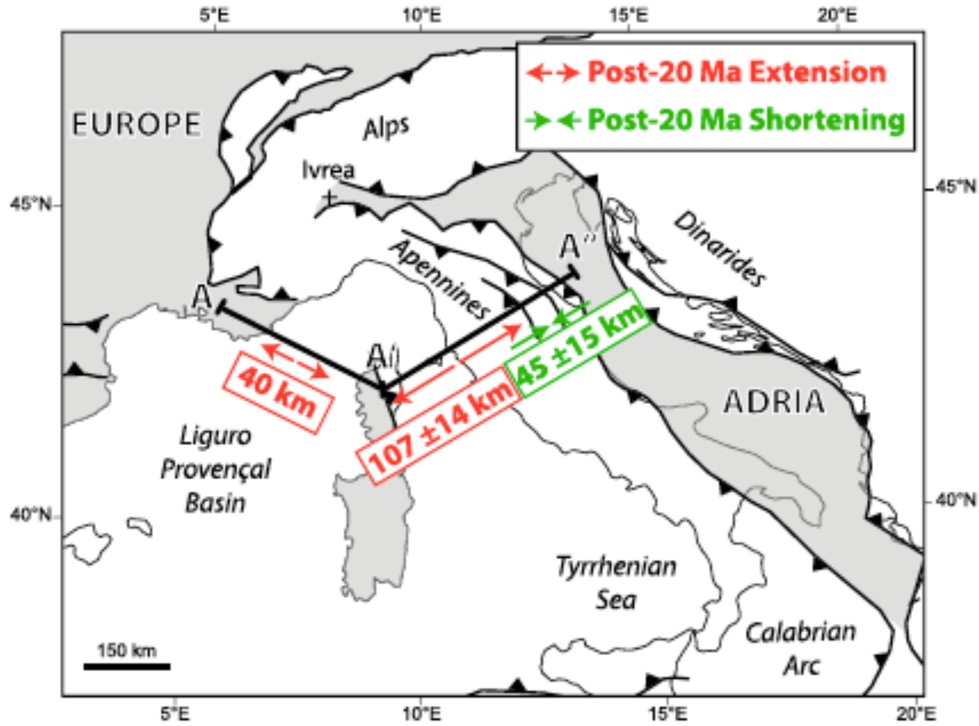

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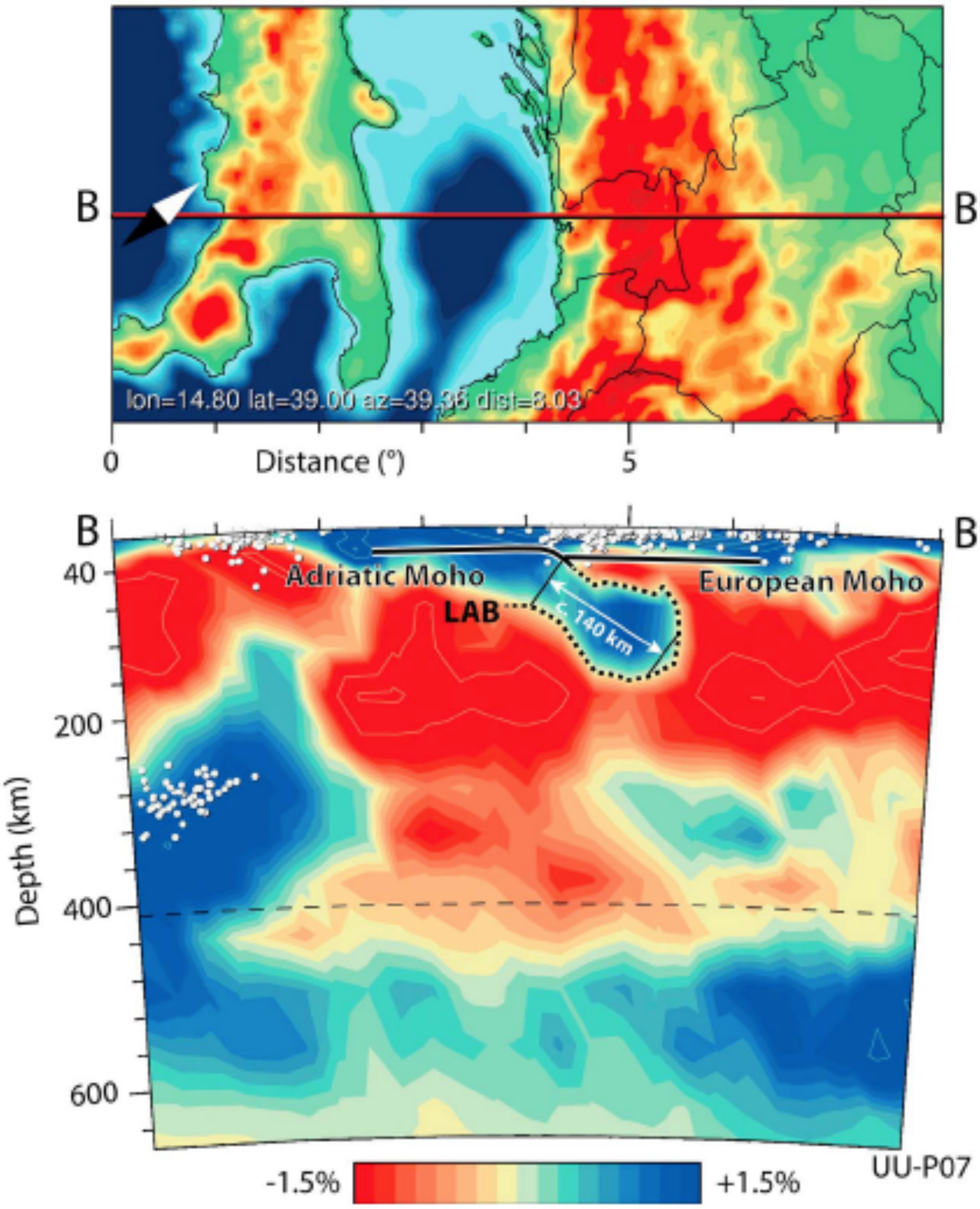

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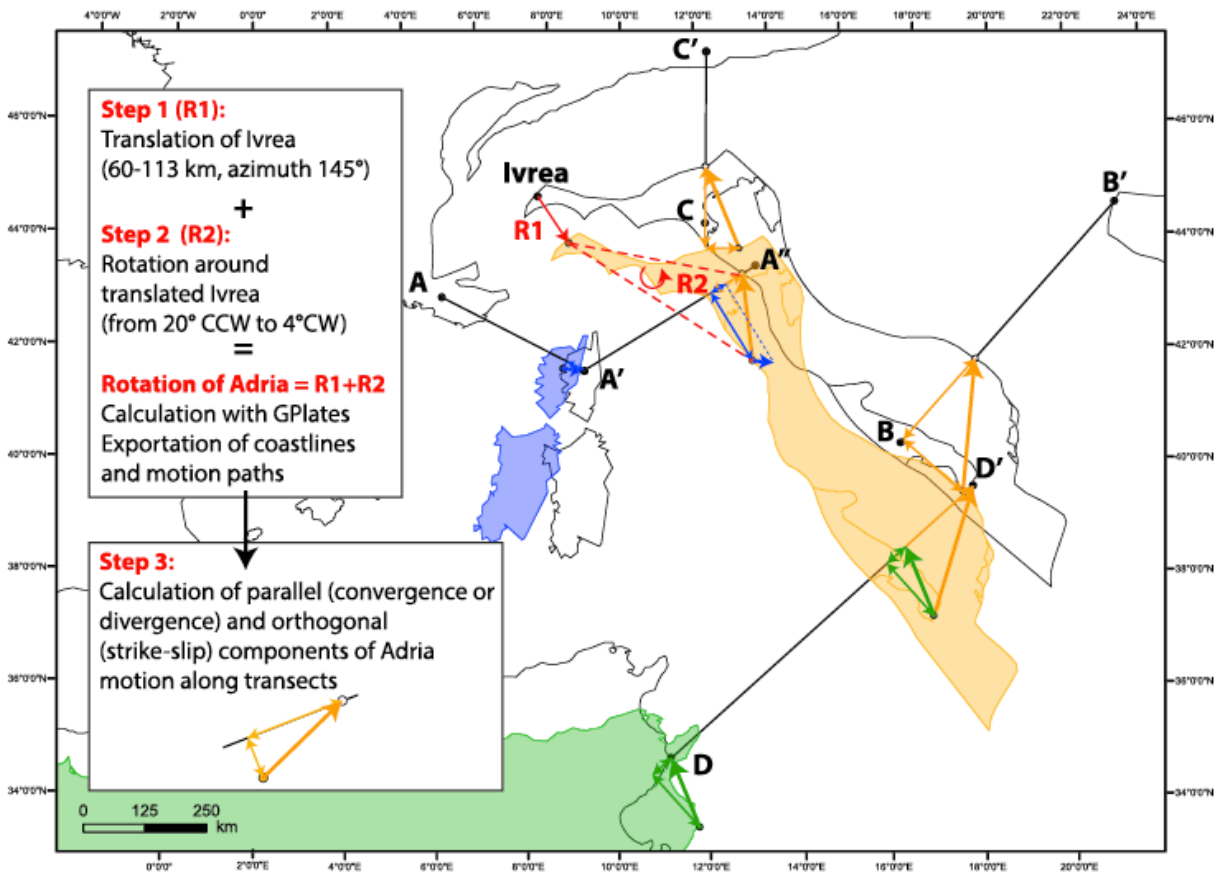
Table 1

Compilation of Crustal Shortening, Extension, and Adria-Europe Divergence and Convergence Along Transects A-A′-A″, B-B′, C-C′, and D-D′ (Location in Figure 1) Used to Constrain Post-20 Ma Adria Rotation Relative to Europe (R1 and R2 refers to Figure 6)

	Dataset used to determine amount of post-20 Ma Adria rotation	Rotation (R2) for Model 1: 113 km convergence in Western Alps (R1)	Rotation (R2) for Model 2: 60 km convergence in Western Alps (R1)
Liguro-Provençal Basin (A-A′) Tyrrhenian Sea-Tuscany (A′-A″) Northern Apennines (A′-A″)	40 km spreading 107 ± 14 km extension assuming 40 km initial thickness 51 ± 18 km extension assuming 30 km initial thickness = 33–121 km divergence 30–60 km shortening assuming thick skinned 100 km assuming thin skinned = Minimum 30–100 km convergence	Maximum 7.75 ± 11.75° (from 4° CW to 19.5° CCW)	Maximum 7.25 ± 11.75° (from 4.5° CW to 19° CCW)
Southern Dinarides-Carpatho-Balkan (B-B′)	20 km crustal shortening 140 km slab length = 20–140 km convergence	Minimum 0.6° CCW; maximum 7° CCW	Minimum 0.3° CCW; maximum 8° CCW
Eastern Alps (C-C′)	115–150 km convergence	6.5 ± 3° CCW	14 ± 3° CCW
Sicily Channel (D-D′)	Minimum 30 km divergence	Minimum 3.5° CCW	Minimum 4° CCW
Best fit rotation		5.25° ± 1.75° CCW	No possible fit!

Note. A viable fit of those data is only obtained for Model 1 (involving 113 km convergence in western Alps). More details on calculation of rotations are given in the supporting information.



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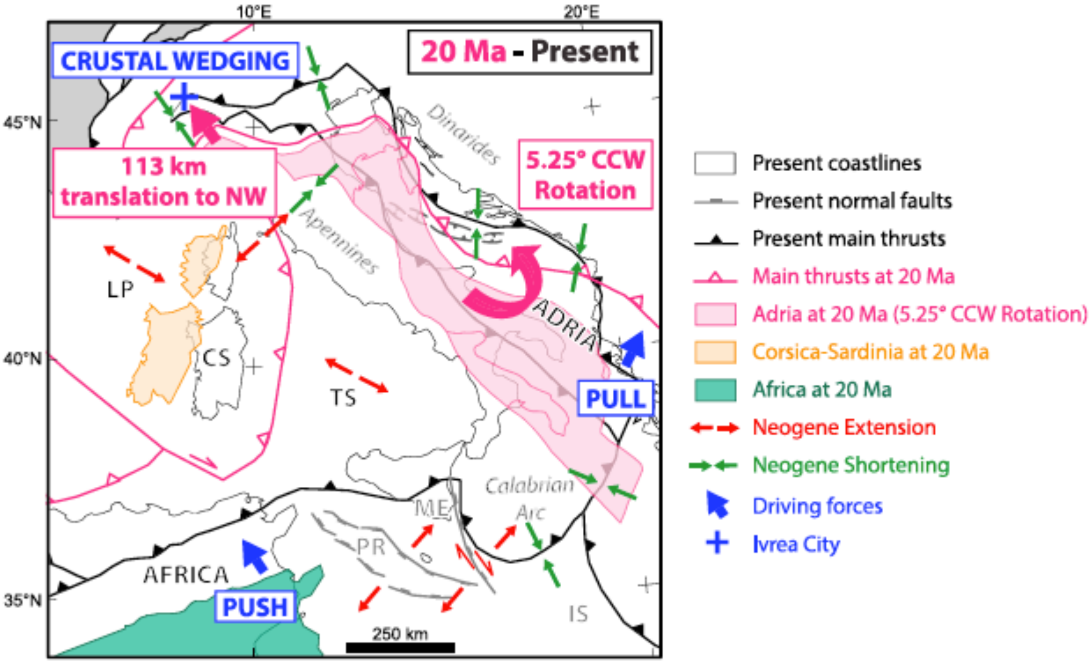

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