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Adria microplate: a puzzling key stone in west-central Mediterranean geodynamics

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Abstract

The Mediterranean region denotes a special plate tectonic environment as the two big plates, Africa and Eurasia, primarily provide the main frame while the dominant players are the small oceanic basins and the continental micro plates (MP) that for the past 80 Ma was the Adria MP. In this environment slab rollback subduction, orogenic arc formation and rotation of crustal blocks are common. While the tectonic setting and involvement in geodynamic processes of Adria MP might not be unique in global terms, it presents Adria as an ideal natural laboratory to study the geodynamic processes individually and in their combined effects in a generally well-studied and rather well-accessible region. The current extension of the Adria MP is defined by the continental Moho as far into the bounding orogens as the latter could be confirmed. The slabs surrounding Adria dominate and characterize the geodynamics of this MP and in most cases their geometries and the possible connection with Adria are well defined by tomographic images. The Ionian oceanic lithosphere slab subducting beneath Calabria has been torn off and detached from the very short South Apennines slab remaining attached to Adria. On the southeastern side we observe the Adria slab beneath the Hellenides that seems detached from the Ionian oceanic lithosphere slab of the Hellenic subduction zone. Along the Dinarides a slab gap is observed analogue to the slab window on Adria MP's western side between the South Apennines and the North Apennines. Encircled by three orogens, the Adria continental lithosphere has been and still is strongly affected by the subductions surrounding it. In the northern part of the Adria MP, the North Apennines slab rollback is the obvious dominant geodynamic force acting locally on the plate while in contrast, the slabs beneath the Eastern Alps and beneath the Hellenides seem stagnant. This study presents a brief overview of the wealth of information aiming to summarize the main constraints on Adria MP available and it discusses some of the questions surrounding this key player in west-central Mediterranean geodynamics.

Keywords: Adria Micro Plate; Summary Review; Lithosphere Slab Geometries; Special Plate Tectonic Environment; Slab Rollback Tectonics

1. Introduction

Since Pangea times, the region we now know as the Mediterranean has always been an assembly of relatively small oceanic basins and micro continents or continental slivers caught between the two big plates Africa and

Eurasia (e.g., Stampfli, 2005; van Hinsbergen et al., 2020; Jolivet et al., 2021; Frasca et al., 2024; and references therein). This provides a specific geodynamic setting with multiple small and rather short-lived mainly rollback subduction zones (Malinverno and Ryan, 1986; Royden, 1993; Doglioni, 1994) between the two large plates that seemingly move independently of subducting oceanic lithosphere in the Mediterranean that might be attached to them. Between the two obliquely converging large plates small pieces of oceanic and continental lithosphere interact. The currently largest fragment of continental lithosphere in the Mediterranean is known as the Adria micro plate (Adria MP). Originally a promontory of Africa (Channell et al., 1979), since Permian times the micro-continental plate Adria expands and acquires new oceanic lithosphere, is torn, subducts, rotates and migrates – sometimes in conjunction with one of the big plates but, during the past 20Ma, independently of either (Stampfli and Hochard, 2009; Le Breton et al., 2017; Channell et al., 2022). Considering this geologic record, the current plate tectonic situation of Adria in Central Mediterranean (Fig. 1) while puzzling may not be considered as exceptional. Presently, Adria appears as a narrow and bent strip of continental lithosphere bounded by the three orogens Apennines, Alps, and Dinarides-Hellenides and in the SW by an old oceanic lithosphere (Ionian Sea) attached to Africa and currently involved in two textbook-example rollback subduction zones, i.e., the Calabrian and the Hellenic subduction zones (Fig. 1).

The Mediterranean region denotes a special plate tectonic (PT) environment as the two big plates primarily provide the main frame while the dominant players are the small oceanic basins and the continental micro plates (MP). For the past some 80 Ma Adria MP played this latter role (e.g., Stampfli and Hochard, 2009; Handy et al., 2010; Le Breton et al., 2021). The PT processes characteristic for the Mediterranean environment are notably different from the original concepts (Burke and Wilson, 1972; Dewey and Burke, 1974) that were developed for large plates with long-distance plate boundaries. The early concepts often allow consideration of 2D models that may still be found in textbooks. Those models though were in obvious disagreement with the geologically well-established record of the – at that time – best studied orogen, the Alps as Trümpy (2001) reasoned to explain “why plate tectonics was not

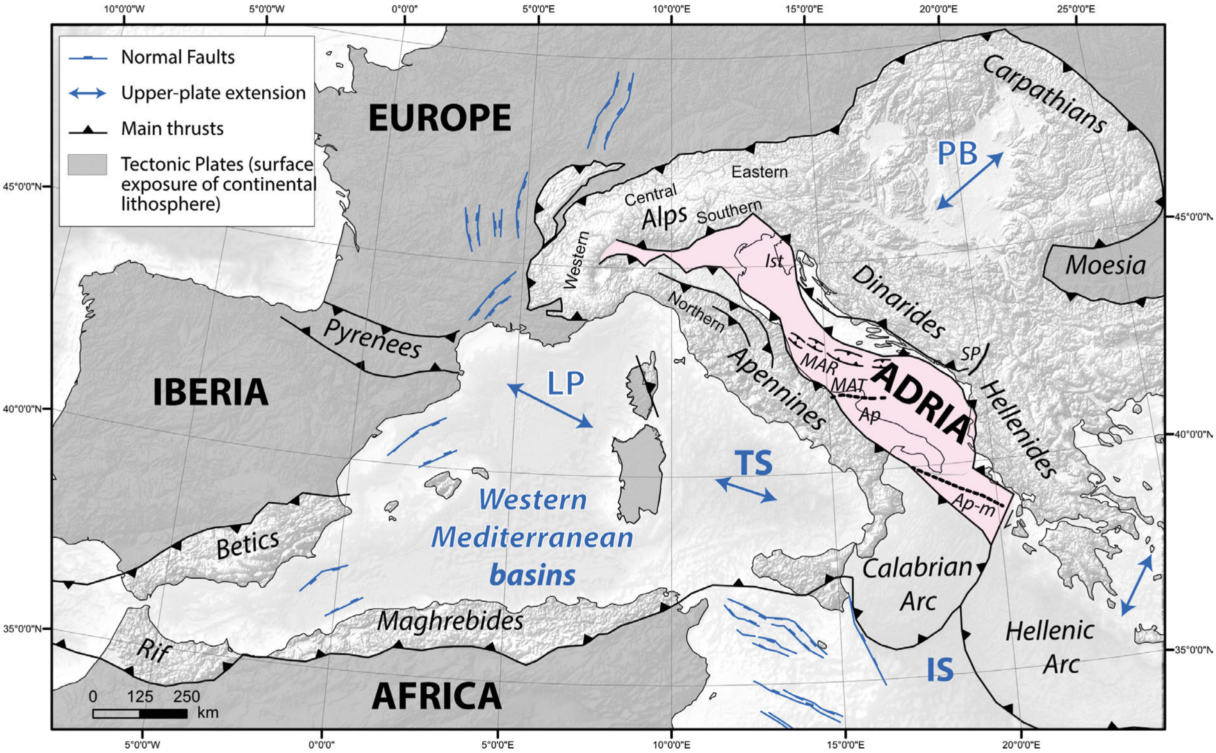

Figure 1. Tectonic map of western Mediterranean with main Cenozoic structures and surface outline of Adria micro plate (modified from Le Breton et al., 2017).

Abbreviations: Ap: Apulia; Ap-m: Apulian passive margin; IS: Ionian Sea; Ist: Istria; LP: Liguro-Provençal Basin; MAR: Mid-Adriatic Ridge; MAT: Mattinata fault system (Turco et al. 2021); PB: Pannonian Basin; SP: Shkoder-Peja normal fault system; TS: Tyrrhenian Sea. Map projection is Transverse Mercator (central meridian 10°E, latitude of origin 43°N).

invented in the Alps". Indeed, the Alps are situated on the "wrong" (subducting) plate compared to the two iconically large orogens Himalaya and Andes (Kissling and Schlunegger, 2018, Fig. 7). Furthermore, the actively northwardly moving upper plate Adria lacked a pulling subducting slab (Royden, 1993; Doglioni and Carminati, 2002) and, therefore, needed to be pushed by Africa or another unknown mechanism. While the rollback orogeny concept for the Alps was trailing behind, the model of back-arc basin evolution by rollback subduction was developed early and Adria served as a prime example (Malinverno and Ryan, 1986; Doglioni, 1991). The Mediterranean setting also stimulated the inclusion of specific asthenospheric mantle processes (e.g., Doglioni et al., 1999, Faccenna et al., 2014) and slab tearing and detachment processes (Carminati et al., 1998; Wortel and Spakman, 2000) in the subduction models. Notably, Adria MP was in the geologically recent past and is currently still involved in all those PT processes (Carminati et al., 2012; Jolivet, 2023 and references therein).

While the tectonic setting and involvement in geodynamic processes of Adria MP might not be unique in global terms, it presents Adria as an ideal natural laboratory to study those PT processes individually and in their combined effects in a generally well-studied and rather well-accessible region. Furthermore, the assessment of seismic and volcanic hazards that are part of those processes request a thorough and detailed understanding of the interplay of these PT processes. In recent years, several mostly disciplinary review papers have been published (Faccenna et al., 2014; van Hinsbergen et al., 2020; Channell et al., 2022; Serpelloni et al., 2022; Chiarabba et al., 2023; Jolivet, 2023; Latorre et al., 2023; Menichelli et al., 2023). The present study is largely based on these reviews and a series of original papers from the past two decades and it aims to focus the results of the different perspectives and methods onto the main geodynamic processes and tectonically active regions constituting Adria MP.

This study provides a brief overview of the wealth of Earth sciences publications to summarize the main constraints on Adria MP we currently have, and to discuss some of the open questions surrounding this still somewhat puzzling key player in west-central Mediterranean geodynamics. I will refer to many papers that seem representative for the topics but inevitably direct references to other papers that deal with Adria s.l. will regretfully be left out. Most of these though may be found in the reference lists of those papers referred to in this article.

2. Lithosphere extent and current motion of Adria plate

Historically (Dal Piaz, 2001; Jolivet, 2023) and – as there seems general agreement – also physically, Adria MP started as a promontory of Africa. The originally kinematically based promontory model of Argand (1924a and b) was supported by early paleomagnetic measurements in several locations from the Southern Alps through the Apennines to Apulia (Channell et al., 1979). Though only the rock units in the latter location could be considered in direct connection with the continental lithosphere of Adria, with appropriate tectonic corrections these sampled pieces of lithosphere seemed to have moved more-or-less synchronously during Mesozoic times and they lead to the interpretation of Adria as a continental sliver or micro plate. Muttoni et al. (2013) reviewed the polar wander paths (PWP) of Africa and Adria and concluded that Adria data may be used to define the Africa PWP, i.e., that Adria was a solidly attached part of Africa since Permian times (280 Ma) including a so-called "monster shift" by the plate of 40° latitude during the Jurassic. The paleolatitudes obtained from the five different locations in Adria, however, between the Permian and the end of Cretaceous show a larger spread than the other data from Africa locations. This could be interpreted either by lateral movements of the Adria locations along lithosphere-displacing faults relative to each other or by locally different internal plate distortions or a combination of both. Recently, several review papers have presented palinspastic reconstructions of Adria since Pangea times combining paleomagnetic and kinematic analyses (van Hinsbergen et al., 2020; Angrand and Mouthereau, 2021; Le Breton et al., 2021; Channel et al., 2022; Romagny et al., 2022; Frasca et al., 2024). These reconstructions paint a largely consistent image of Adria's role in the evolution of the Mediterranean since Pangea times though their differences are significant in terms of dimension, structure and tectonic preconditioning of Adria MP.

All reconstructions agree that Adria MP was much larger in Cretaceous time and lost its oceanic lithosphere in a series of subductions. Alpine Tethys units are found from Sicily to Calabria, all along the Apennines, in northern Corsica, in the Ligurian Alps and around the inner parts of the Western Alpine arc, in the Northern Calcareous Alps and finally around the Carpatians (LeBreton et al., 2021). This defines the main oceanic channel between Eurasia in the North and continental Adria and Africa in the South. The oceanic units in the Dinarides and Hellenides originate from another oceanic basin of the Tethys, called Vardar Ocean, that in the North was connected to the Alpine oceanic channel. The Ionian oceanic lithosphere created during the Jurassic supposedly established a solid mechanical link between the continental lithospheres of Adria and Africa (van Hinsbergen et al., 2020; Channell et al., 2022) at least to late Cretaceous times (Le Breton et al., 2021; Frasca et al., 2024).

The present surface outline of Adria MP is defined as a relatively narrow strip of continental lithosphere (some 200 km wide and about 1300 km long) beneath the Adriatic Sea and the Po Plain (Fig. 1). This small strip is surrounded by the above mentioned three orogens Apennines, Alps and Dinarides/Hellenides. In the South, Adria MP borders the Ionian Sea where the old oceanic lithosphere attached to Africa is currently involved in the Calabria and Hellenic rollback subduction zones. For a more realistic estimate of the current size of Adria MP (Piccardi et al., 2011) one should also include those parts of the Adria continental lithosphere involved in the subduction zones as, f.e., those now subducting beneath the Apennines. For this reason, we need to investigate the Adria crustal thickness variations and, in particular, assess the Adria Moho topography beneath the orogens.

2.1 Moho extent

As a prime first-order discontinuity within the lithosphere, the well-documented and nearly ubiquitous Moho, along with its topography, provides a distinctive fingerprint for the characterization of tectonic plates. The northern part of the Adria continental crust beneath the Po Plain has a thickness of about 30 km forming the W-E oriented ridge (Waldhauser et al., 1998 their Fig. 13) with the Moho descending toward North into the collision zone of the Central and Eastern Alps and descending toward South in the Northern Apennines subduction zone (Spada et al., 2013). The western end of this Moho ridge is formed by the well-known Ivrea body. Here, the Adria mantle lithosphere reaches far up into normal crustal levels, and in a narrow band along the plate bounding Insubric fault system, it reaches the surface (e.g. Schmid et al., 2017; Scarponi et al., 2021 and references therein).

In map view, the Tyrrhenian and the Adria Moho split the Italian peninsula alongside into about half (Di Stefano et al. 2009 their Fig. 6). In regional Moho maps that treat the crust-mantle boundary as a continuous interface (f.e., Grad et al., 2009 their Fig. 5) there seems to exist a Moho trough with maximum depth of 34 km to 38 km along the eastern side of the peninsula. While this simplification of a continuous Moho surface across different plates might be a useful approximation for volumetric 3D crustal velocity reference models (e.g., Tesauro et al., 2008; Molinari and Morelli, 2011) it obviously does not allow to illuminate the Moho topography at plate boundaries. In this study we are interested in the Moho topography of the Adria MP including those regions where Adria is involved in subduction zones. Moho offsets in suture zones are a clear indicator of long past (f.e., Heikkinen and Korja, 2018) and current plate boundaries (f.e., Waldhauser et al., 1998). With the originally applied CSS methods (Nicolich, 1981, 2001; Dal Piaz and Nicolich, 1991; Locardi and Nicolich, 2005), however, the Moho offset along the Apennines could not be well determined except for one favorable profiles constellation (Ponziani et al., 1995). It needed the application of the RF method (Bianchi et al., 2008; Piana Agostinetti et al., 2008; Piana Agostinetti and Amato, 2009) to well illuminate the doubled Moho that characterizes this region. Today, the combination of different seismic methods principally allows to reliably image the Moho topography (e.g., Mooney et al., 2023) and Moho offsets across plate boundaries such as the orogenic collisional belts and subduction zones encircling Adria MP (Di Stefano et al., 2011; Spada et al., 2013).

To assess the current extent of Adria MP we will, therefore, summarize the seismic information available today about the Adria Moho including those parts that define the deep geometries of the suture zones. The map of the Adria Moho (Fig. 2) is based on Di Stefano et al. (2011) and complemented with additional seismic information. The quality of each additional seismic data has been assessed based on the published information. As the depth isolines have been interpolated by hand, the map denotes a zero-order approximation dedicated to the purpose of defining the extent of the Adria lithosphere. For the northwestern part of Adria MP including the Ivrea zone, the reader is referred to Spada et al. (2013 their Fig. 11).

The Moho depth information in the E-Alps-NW-Dinarides region (see Spada et al., 2013, their Fig. 11) mainly result from the ALP2000 CSS experiment (Brueckl et al., 2007; Behm et al., 2007; Sumanovac et al., 2009). Recent RF and LET studies (Stipcevic et al., 2020; Zaillac et al., 2023; Rajh et al., 2022, 2024) confirmed earlier information (Oreskovic et al., 2011; Sumanovac, 2015) and documented a rather thick crustal root beneath the Dinarides. Unfortunately, Stipcevic et al. (2022) present their RF results in a map interpolating a continuous Moho across the suture zone. Since in the Dinarides subduction zone Adria denotes the lower plate, the maximum eastern extent of the Adria Moho (Fig. 2) may be assumed to be represented by the locations of those RF stations where the deepest Moho was measured.

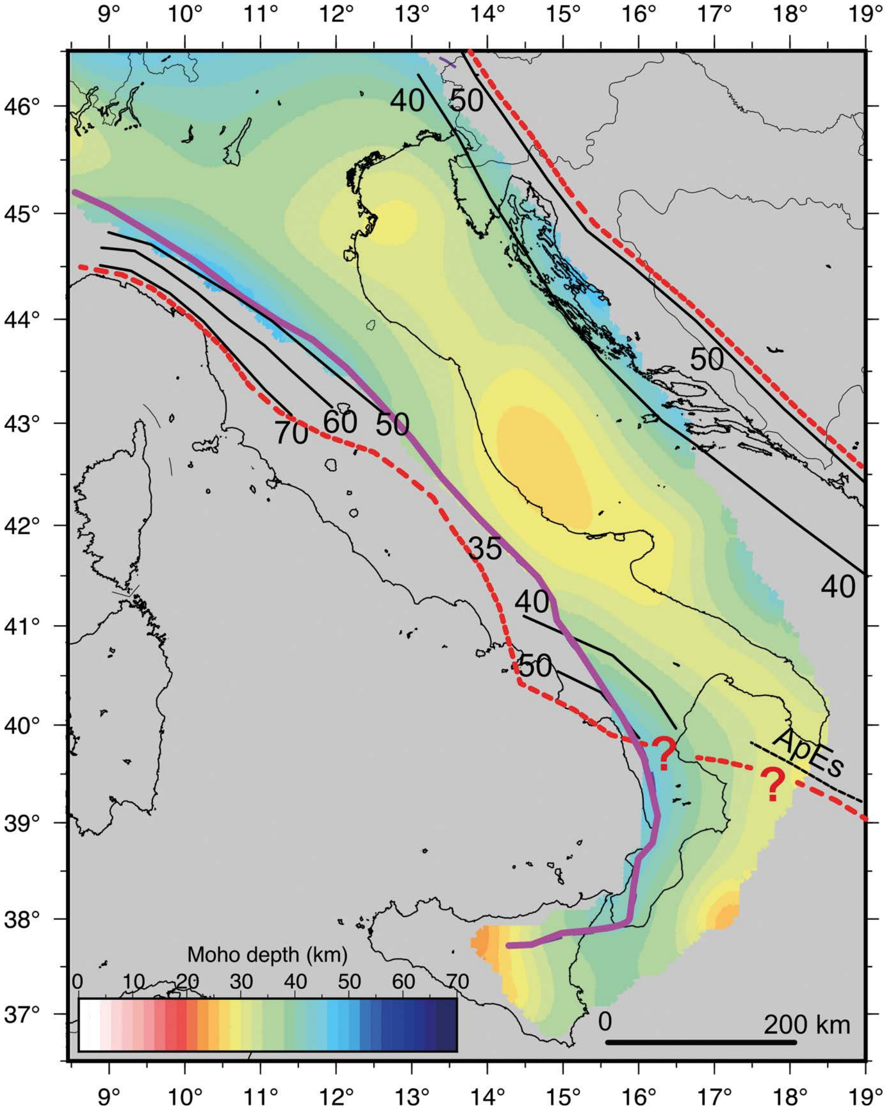

Figure 2. Moho map of Adria MP (modified from Di Stefano et al., 2011). The map has been complemented by additional seismic information that was assessed for its quality as documented in the publications and subsequently the data has been interpolated by hand with the purpose to define the extent of Adria MP (see text for details). Solid black lines denote depth isolines of Adria Moho in km. The red line documents the limits of Adria Moho at depth. Thick purple line shows the eastern limits of Tyrrhenian Moho (Di Stefano et al., 2011). Note the width of continental Adria MP based on Adria Moho is doubled relative to width of continental Adria surface exposure (see Fig. 1).

Scarascia et al. (1994) report a 30 km crustal thickness for Apulia and the southernmost parts of the Adria Sea. The same study also documents the Adria Moho to continuously descend to 40 km beneath Calabria and further into the subduction zone to reach the deepest reported value of 50 km. The crust beneath the NW Ionian Sea between the Apulian escarpment and the Malta one and within the Calabria arc is reported to be 18-20 km thick (Ferrucci et al., 1991; Scarascia et al., 1994; Delong et al., 2018 and references therein). Likely this upper plate crust represents an extended former continental crust whereas in contrast, the crust beneath the Ionian basin is less than 10 km thick and of clear oceanic origin (Tugend et al., 2019 and references therein). However, with the currently available Moho information, it remains unclear if and where exists a former plate boundary or if there exists a propagating tear separating Adria MP and the Ionian Sea lithospheres both descending into the Calabria subduction zone (see, f.e., Turco et al., 2021 their Fig. 23).

According to Scarascia et al. (1994), Di Stefano et al. (2011 and references therein) and Kelemework et al. (2021) the maximum Moho depth of Adria measured beneath the south-central Apennines near 42N/14E denotes 35 km. From this apparent culmination point along its western edge the Adria Moho descends to the South into the Calabria subduction zone and to the North into the Northern-Apennines subduction zone where the Adria Moho has been mapped mainly by RF methods below the Tyrrhenian Moho to reach maximum depth of 70 km (Bianchi et al., 2010; Pauselli et al., 2006; Piana Agostinetti et al., 2011; Chiarabba et al., 2014; Monna et al., 2019). Local earthquake tomography studies confirm this Moho topography beneath the Apennines and complement it with the 3D crustal velocity information (Scafidi et al., 2009; Di Stefano and Ciaccio, 2014; Magnoni et al., 2022; Menichelli et al., 2023).

The map (Fig. 2) shows the topography of Adria Moho as far into the orogenic belts and even below the Tyrrhenian Moho beneath the Apennines where it could be identified with confidence and as such it documents the minimal extent of Adria MP lithosphere today. Note the significant difference in width of the Adria plate between this definition by the Moho interface (400 km across northern and southern and 300 km across central Adria Sea) and the one based on limits of tectonic units at surface (200 km across northern and southern and 125 km across central Adria Sea) that is used in palinspastic reconstructions (e.g., Fig. 1 based on Le Breton et al., 2017; van Hinsbergen et al., 2020) though also the latter do not only count the surface outcrop of autochthonous Adria crust (f.e., Po basin). In the Western, Central and parts of the Eastern Alps Adria denotes the upper plate and the northern and western limits of the Adria Moho have been well mapped (e.g. Kissling et al., 2006 and references therein; Spada et al., 2013 their Fig. 11; Solarino et al., 2018) and they closely follow the Peri-Adriatic fault system (Handy et al., 2014).

Defining the current extent of Adria MP by its Moho serves the purpose to facilitate more precise geodynamic modelling and assessment of plate forces since (1) the density contrast across the crust-mantle boundary defines the first-order gravity effects and (2) the Moho topography and the seismicity distribution within the suture zones provide important information as to what plate a subducting lithosphere slab might be attached to or being in the process of tearing. The involvement of Adria MP into the tectonic evolution of the three orogens obviously includes subduction and collision and consequently, Adria is surrounded by several subduction zones (e.g., Doglioni and Carminati, 2002), at least three of them still very active (Northern Apennines, Calabria, Hellenic). As a result of these and previous subduction processes, over times nearly all formerly attached oceanic lithosphere to Adria (the exception is the Ionian Sea oceanic lithosphere that remains attached to Africa) has been consumed by subduction and likely also some parts of its continental lithosphere. Although of significantly different age and in different tectonic states, the three orogens bounding Adria exhibit lithosphere slabs (e.g., Piromallo and Morelli, 2003; Spakman and Wortel, 2004; Amaru, 2007; Rappisi et al., 2022) still attached to either Adria (Apennines and Dinarides/Hellenides) or to Eurasia (Alps) or to Africa (Calabria and Hellenic subductions).

2.2 Lithospheric mantle and slabs extent

Within the study region, the thickness of the horizontally laying lithosphere ranges from 70 km to 120 km based on surface wave and adjoint tomography (e.g., Panza et al., 1980; Boschi et al., 2010; Schaefer et al., 2011; Kaestle et al., 2018; Magnoni et al., 2022), regional body wave tomography (e.g., Paffrath et al., 2021; Menichelli et al., 2023 and references therein), P and S receiver functions (e.g., Monna et al., 2019; Monna et al., 2022 and references therein), and integrated geophysical-petrological inversions (e.g., Artemieva, 2019; El-Sharkawy et al., 2024 and references therein). In a tomographic cross section at 150 km depth (Fig. 3), therefore, the background velocity (red color) represents the asthenosphere and the high velocity (blue color) anomalies are lithosphere slabs. In this pioneering tomographic image (Piromallo and Morelli, 2003), one may recognize the several slabs – and slab gaps – that circumvent continental Adria MP as defined by the Adria Moho (Figs. 2 and 3). Like Piromallo and Morelli (2003), Koulakov et al. (2009) used the large ISC data set but with a different inversion code. At 150 km depth they found nearly identical slabs around Adria (Koulakov et al., 2009 their Fig. 5) thus documenting the reliability of these regional features.

Although only recognizable by their effects and visible by seismic tomography, the slabs surrounding Adria dominate the tectonics and characterize the geodynamics of this MP (e.g., Kiraly et al., 2018). Since its introduction in the eighties of the past century (Nolet, 1981; Dziewonski and Anderson, 1984) mantle tomography has greatly evolved and analogue to crustal tomography it nowadays includes several different seismic methods. Due to its puzzling and complex tectonic setting (e.g. Handy et al., 2010; Angrand and Mouthereau, 2021; van Hinsbergen et al., 2022; Frasca et al., 2024) the Mediterranean lithosphere-asthenosphere system early has attracted mantle tomography studies (Spakman,1990; Wortel and Spakman, 2000; Piromallo and Morelli, 2003) that have greatly helped to unravel the first-order plate tectonic processes that shape the region (Faccenna et al., 2003 and 2014; Jolivet et al., 2021). Today's greatly increased demands of resolution and reliability (regarding structure, physical state, fluids, lithology and more), however, are very challenging and may possibly be met only by combining different seismic methods that complement each other in strength and limitations.

The important structural targets are the 3D geometries of the slabs and their mechanical connection with the plates. The attachment of a slab to the sub-horizontal lithosphere, slab tears and slab break off are among the primary discussion topics of orogen evolution in the convergence belt around Adria (Handy et al., 2019; Kaestle et al., 2020). However, even in newer teleseismic tomography studies reliable images of sufficient resolution (3D cell-dimensions of 10-15 km) remain rare or more realistically speaking are still missing (e.g., Zhao et al., 2016 their Fig. 5; Kaestle et al., 2018; El-Sharkawy et al., 2020). Furthermore, tomographic images of the lithosphere-asthenosphere boundary depend on the combination of initital and final reference velocity models used for the inversion and presentation of the results and sometimes the images are misleading with regards to the geometric continuity between horizontal lithosphere and the slab (Kissling and Spakman, 1996). Another limitation of importance to geodynamic modeling and our understanding of first-order processes involving subduction zones around Adria regards the slab geometry and its length in particular. While the horizontal dimension of a slab today may be fairly well determined by high-resolution tomography using a large and high quality data set, image distortions as a consequence of vertical smearing effects (mainly as a result of either specific data limitations or the general variation in vertical resolution capabilities due to source-receiver distribution) intrinsic to all currently applied seismic method severely limit reliable assessment of the slab geometry at greater depth. Hopefully, in the near future these problems may be reduced by the availability of large high-quality data sets (as, f.e., the waveform data set corresponding to the seismic catalogue of three decades assembled by INGV, Latorre et al., 2023) and with synoptic combination of different seismic methods with complementary imaging strength (sensitivities to variations of physical parameters across interfaces and in volumes).

The Calabria slab (Fig. 3, anomaly 1) likely represents an exception as its geometries generally are well determined by combination of passive teleseismic, passive local and active sources seismic tomography and the distribution

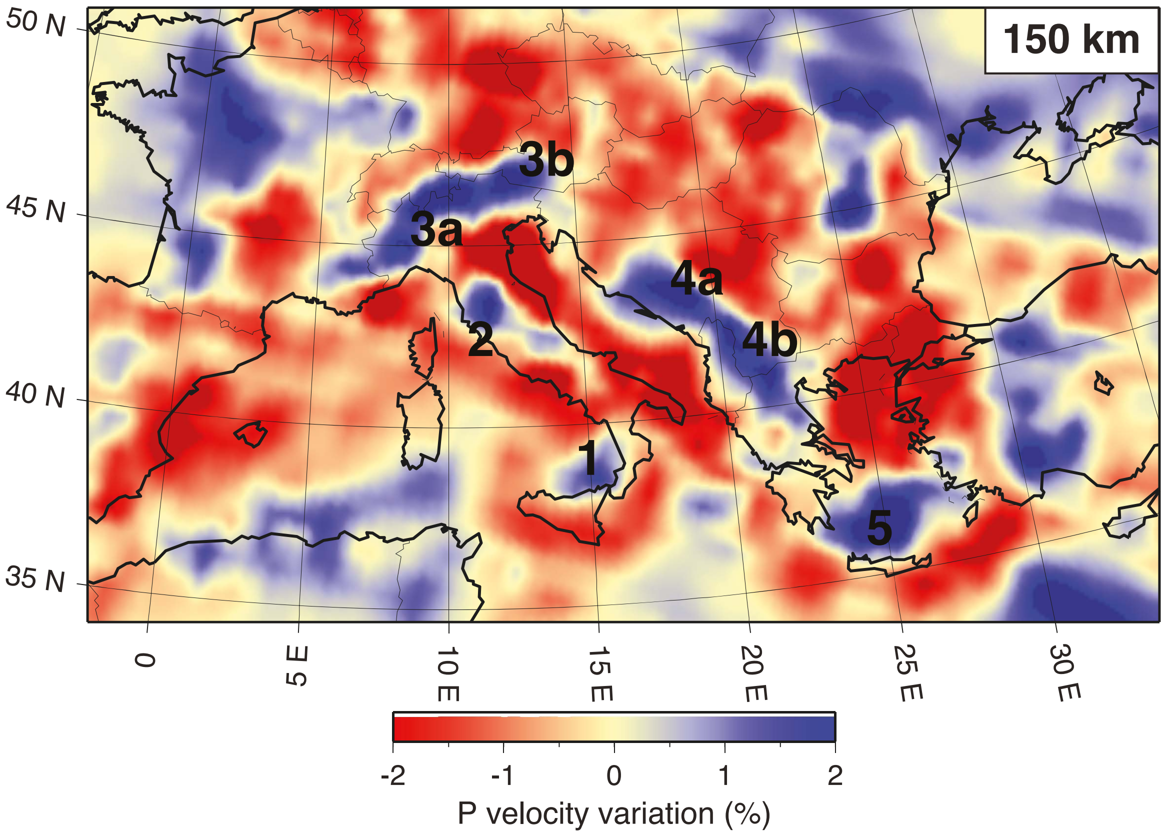

Figure 3. Tomographic map view of P-velocity variations in 150 km depth beneath Adria and adjacent region (modified from Piromallo and Morelli, 2003). The background velocity (in red) denotes the asthenosphere and the high-velocity anomalies (in blue) around Adria represent the following slabs: (1) Calabria, (2) N Apennines, (3a) West-Central Alps, (3b) Eastern Alps, (4a) Dinarides, (4b) Hellenides, (5) Ionian slab in Hellenic subduction zone (see text).

of deep earthquakes. The latter document that the slab is still attached to the Ionian lithosphere (Cimini and Marchetti, 2006; Wortel et al., 2008) and teleseismic tomography revealed a subducted lithosphere descending down to and resting on the 670 km discontinuity with a total length nearly matching the distance between Calabria and Spain (Spakman and Wortel, 2004, their Fig. 2-6; Lucente et al., 2006, their Fig. 2). Presently available tomographic images suggest no remaining mechanical connection between the Calabria slab and Adria lithosphere other than by the link between the Ionian and the Adria lithospheres across the passive margin of the Apulian escarpment. At greater depth, however, the slab anomaly extends further toward N and NW along the S Apennines subduction in direct vicinity of the SW limits of the Adria lithosphere (see Wortel et al., 2009, their Fig. 2) thus suggesting a mechanical connection between the slab and Adria in the recent past. There seems to be general agreement that nowadays there exists a slab gap (gap between Fig. 3, anomalies 1 and 2) beneath the Central Apennines (Racano et al., 2024 and references therein). The currently available tomographic images suggest the N Apennines sub-vertical slab to be attached to Adria (Fig. 3, anomaly 2) though its length remains unclear (Lucente et al., 1999; Margheriti et al., 2006; Cimini and Marchetti, 2006; Rappisi et al., 2022).

Along the Western Alpine arc, the Central Alps and the western parts of the Eastern Alps, Adria denotes the upper plate overriding in collision the European slab (Fig. 3, anomaly 3a) subducting toward SSE. A possible horizontal tear in the European slab beneath the Western Alps propagating toward the Central Alps (Lippitsch et al., 2003; Fox et al., 2015; Monna et al., 2022) is debated by Zhao et al. (2016) (see also Malusa et al., 2021; Pondrelli et al., 2024 and references therein). Beneath the Eastern Alps we note another high-velocity anomaly (Fig. 3, anomaly 3b) that according to the high-resolution teleseismic tomography (see definition by Arlitt et al., 1999) employed by Lippitsch et al. (2003) and confirmed by Karousova et al. (2013) denotes a separate anomaly representing a slab dipping toward NE (Plomerova et al., 2022). A steeply toward NE dipping or nearly vertical (Piromallo and Faccenna, 2004) high-velocity anomaly has also been found in earlier regional and global models (Spakman et al., 1993; Morelli and Piromallo, 1999; Bijwaard and Spakman, 2000; Piromallo and Morelli, 2003; Koulakov et al., 2009) and in more recent studies of similar resolution (Kaestle et al., 2018; Paffrath et al., 2021; Rappisi et al., 2022). While some interpretations assume the slab being attached to Adria (Lippitsch et al., 2003; Karousova et al., 2013; Handy et al., 2014; Salimbeni et al., 2022; Plomerova et al., 2022) Handy et al. (2021) interpret the high-velocity anomaly as a detached remnant European slab and Kaestle et al. (2020) discuss 4 scenarios for the slab evolution with either European or Adria provenance.

The Dinarides-Hellenides orogen represents the European upper plate in the subduction zone defining the full length of the eastern limit of Adria MP (Fig. 1). Subduction was active from Early Cretaceous to Paleogene in the North and continued to present in the southernmost Dinarides and Hellenides (Handy et al., 2019 and references therein). In the North-Central Dinarides continent-continent collision occurred in Miocene followed by lithosphere delamination (Ustaszewski et al., 2010; Toljic et al., 2018; Kiraly et al., 2018 and references therein) and slab break-off (Balling et al., 2021). While regional tomography models (Bijwaard and Spakman, 2000; Piromallo and Morelli, 2003; Koulakov et al., 2009) consistently show a gap in the slab anomalies between the easternmost Alps and the southern Dinarides (Fig. 3, anomalies 3b and 4a) Sumanovac (2022) claims there still exists a slab attached to Adria beneath the northern Dinarides. However, in the light of the above-mentioned challenges to illuminate shallow slab structure and their attachment to horizontal lithosphere, a careful inspection of the synthetic test results by Sumanovac (2022, Figs. 5-8 document significant vertical leakage from surface to 400 km depth) raises some doubts about the reliability of the high-velocity anomalies interpreted as a lithosphere slab. For the southernmost Dinarides and the Hellenides (Fig. 3, anomalies 4a and 4b), Handy et al. (2019, their Figs. 1 and 12) present and interpret an updated image of the Adria lithosphere slab obtained by regional P-wave teleseismic tomography (model UU-P07 of Hall and Spakman, 2015). For 150 km depth their model (Handy et al. 2019, their Fig. 12) shows a strongly reduced – in extent and amplitude – high-velocity anomaly beneath the southernmost Dinarides (in comparison to Fig. 3, anomaly 4a) and the northern border of the pronounced and extensive high-velocity anomaly beneath the Hellenides (relating to Fig. 3, anomaly 4b) to coincide with the Shkoder-Peja normal fault system (Fig. 1) that marks the boundary between the Dinarides and the Hellenides. Based on the tomographic results by Hall and Spakman (2015) presented in Handy et al. (2019) and in Balling et al. (2021) we may thus conclude that the slab gap extends from the northern Dinarides to nearly their southern end. The high-velocity anomaly (Fig. 3, anomaly 4b) representing the Adria slab beneath the Western Hellenides actually extends further S (Handy et al., 2019, their Fig. 12; Koulakov et al., 2009) and seemingly is in contact with the northwestern limits of the Ionian slab (Sukale et al., 2009) subducting beneath the Hellenic arc (Fig. 3, anomaly 5).

2.3 Present-day motion

Unsurprisingly, current horizontal plate motion (Serpelloni et al., 2022, their Fig. 6) and level of seismic activity in the Mediterranean (www.emsc-csem.org) exhibit a direct correlation with the activity in the Adria MP region being second only to those in the Hellenic subduction zone and the Aegean (D'Agostino et al., 2008). The analysis of GPS observations from >4000 stations operating in the Euro-Mediterranean, Europe and Africa regions (Serpelloni et al., 2022) allows to reliably assess the horizontal and vertical crustal motions relative to Europe on a subregional scale in the study region encompassing Adria MP (Fig. 4). While there apparently are no significant differences with the results from a study ten years earlier (Serpelloni et al., 2013), the station coverage has greatly increased and for most subregions (except for the eastern margin of Adria) now there exists a high density of measurements with an impressive consistency of vectors allowing to identify and to ignore the outliers.

Continental Adria MP s.s. (Fig. 1) consists of the Po Plain, the sedimentary basin NE of Venezia, Apulia and the Adria Sea. For obvious logistics reasons GPS data for the latter is extremly rare. If we assume the former three subregions to belong to a more-or-less rigid plate, their horizontal velocities (Fig. 4, subregions 1a, 1b, 1c) could possibly be interpreted as documenting a CCW rotation with a pole near Torino (Fig. 4, blue triangle). Notably, the fit by a simple rotation is best just for the two subregions in the N (Fig. 4, subregions 1a, 1b) and without any data in the Adria Sea the combination with the velocities measured in Apulia remains speculative. The majority of the measurements on the Italian peninsula regard the Apennines and Calabria and thus belong to the

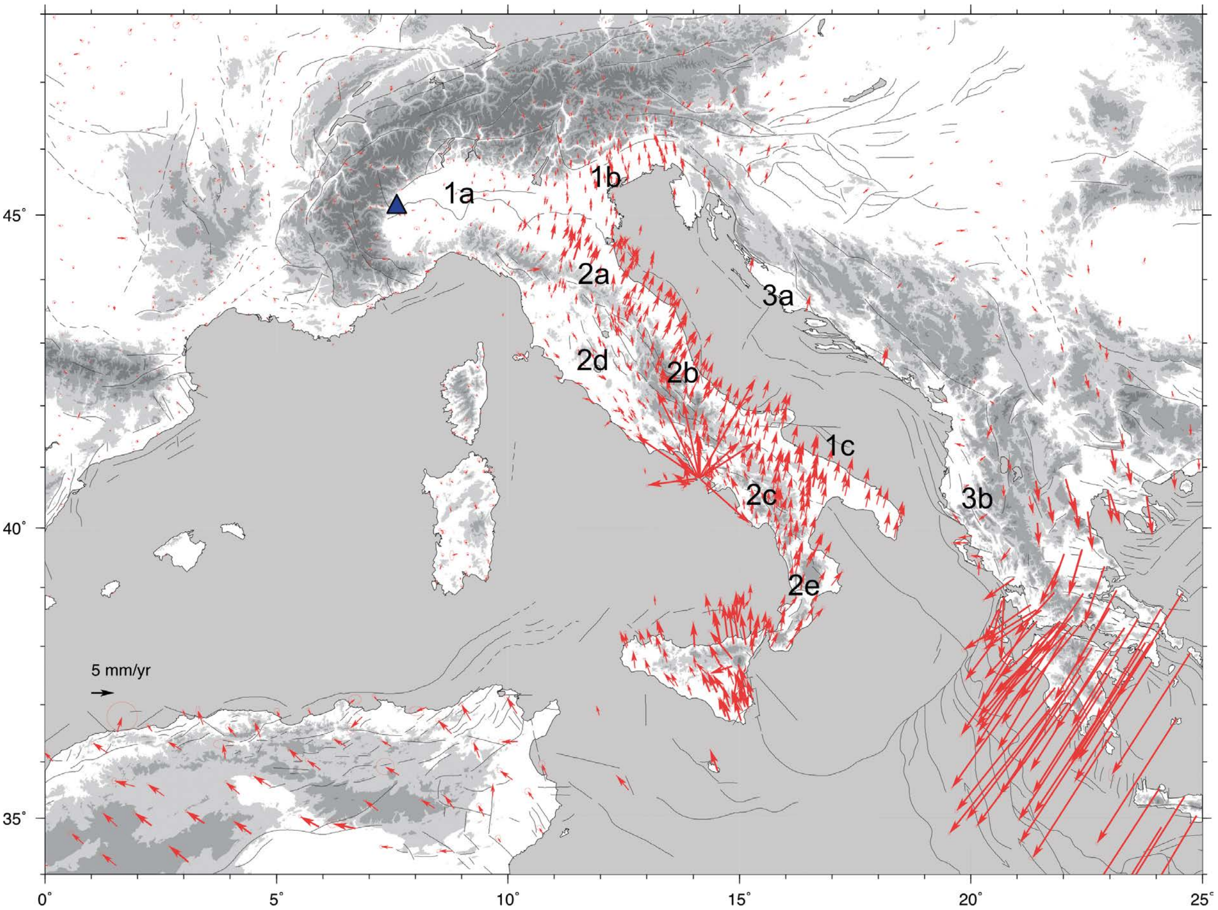

Figure 4. Horizontal velocities relative to Europe (red arrows) based on time series analysis of 25 years of GNSS data (modified from Serpelloni et al., 2022). Numbers refer to subregions of more or less uniform motion within the region of Adria micro plate. (1a, 1b, 1c) refer to subregions defining continental Adria micro plate s.s. (see Fig. 1). If one assumes these three subregions to belong to a single solid plate, one could interpret the data as documenting an CCW rotation around a pole near Torino (solid blue triangle). Subregions (2a-2e) in the Apennines and Calabria represent the Tyrrhenian-Calabria upper plate. (3a) refers to the Adria coast along the Dinarides and (3b) to the Hellenides (see text).

upper plate overthrusting Adria MP. Subregions 2a, 2b and 2c (Fig. 4) along the eastern margin of the Apennines exhibit very consistent velocities of about 5 mm/yr in NNE direction. The western part of the Northern and Central Apennines though (Fig. 4, subregion 2d) shows a rather diffuse pattern of significantly smaller horizontal velocities. This correlates with the observation that compression and extension occur contemporaneously in the Northern Apennines (Barchi et al., 2006). Calabria (Fig. 4, subregion 2e) shows a NE direction, clearly distinguishable from the directions in Apulia and also from the horizontal velocities measured for Sicily that exhibits NW directions. Along the eastern coast of Adria Sea (Fig. 4, subregion 3a) the Dinaride units overlying Adria MP are poorly sampled by GPS stations yet in combination with earthquake slip vectors (D'Agostino et al., 2008) show a NNE direction of about 4 mm/yr. In contrast, the Hellenides (Fig. 4, subregion 3b) exhibit a southerly direction thus documenting the influence of the Ionian slab in the Hellenic rollback subduction zone (D'Agostino et al., 2020).

3. Tectonic state and main tectonic processes in and on Adria plate

Significant moderate to strong seismicity occurs all around the Adria Sea, the Po plain and in the two subduction zones on either side of Ionian Sea (Danciu et al., 2021). The seismicity in Italy (Latorre et al., 2023) is mostly confined to the crust and the uppermost mantle lithosphere with the obvious exception of the Calabria subduction zone and a few deep events in the N Apennines subduction zone (Fig. 5). Thus, the seismicity distribution exemplifies the ongoing tectonic activity along nearly the entire boundary of the Adria MP (Halpapp et al., 2018; Petricca et al., 2019; Eva et al., 2020; Stipcevic et al., 2020; Rajh et al., 2022; Chiarabba et al., 2023; Banko et al., 2024) and it reflects the dominance of the rollback subduction processes throughout the Apennines orogeny.

The different "tectonic styles" of the Alps, Carpathians and Apennines (Royden and Burchfield, 1989; Doglioni et al., 2006) have played important roles in deciphering the main processes involved in rollback subduction orogeny, i.e., the dynamics intrinsic to the subducting slab (negative and positive buoyancy by mantle lithosphere and crust, respectively) attached to a plate not moving toward the trench and its interaction with the asthenosphere including the possibility of a prevailing mantle flow. One could also argue that the Alps (Western, Central and Eastern) prior to continent-continent collision and the Apennines share an analogue orogenic evolution dominated by suction forces of the retreating slab (Kissling and Schlunegger, 2018 and references therein). In the case of the Alps, before the adoption of plate tectonics theory (Trümpy, 2001), this process was typically described as a push from Adria. Clearly, the orogens encircling Adria MP exhibit different tectonic styles and they all currently are in different orogenic stages. The (currently) relatively small size of Adria MP and thus the proximity of these ongoing tectonic processes along the plate boundaries may well lead to interactions between them. An obvious, though geodynamically probably not very important, interaction is the sedimentary infill of the Po basin predominantly from the Alps (Scardia et al., 2006) even if it is the foreland basin to the Northern Apennines. Another interaction between the Alpine collision zone and the Adria slab rollback beneath the Northern Apennines leads to the W-E striking Adria Moho bulge beneath the Po plain (Waldhauser et al., 1998; Di Stefano et al., 2011; Spada et al., 2013). By the exception of a seismicity band traversing the central Adria Sea there seems to be little tectonic interaction between the Apennines and the Dinarides. Further South, however, geodynamic processes forming the Southern Apennines are clearly linked with the Calabria subduction (Fig. 2 and 4) and likewise those forming the Hellenides are linked with the Hellenic subduction (Figs. 3 and 4).

3.1 Apennines

The Apennines are a relatively young and very active orogen. The mountain belt is the result of multi-phase rollback subduction tectonics that started in the Miocene with the activation of frontal thrust faults that propagated eastward and since late Pliocene in the North began to rotate to propagate northeastward and northward (Turco et al., 2021; Chiarabba et al., 2023; Racano et al., 2024; and references therein). The Adria MP acts as the lower plate with the slab currently attached only in the North of the Apennines and in the South the Calabria slab (Fig. 3) attached to the Ionian oceanic lithosphere with a large slab window of 400 km along the Central Apennines (Racano et al., 2024 and references therein). While the slab beneath the Northern Apennines is more-or-less parallel to the Apennines thrust front, in the South the Calabria slab currently subducts in NW direction, i.e., nearly perpendicular to the Apennines trust front in Apulia (Cello and Mazzoli, 1999). Consequently, what started as a single rollback subduction

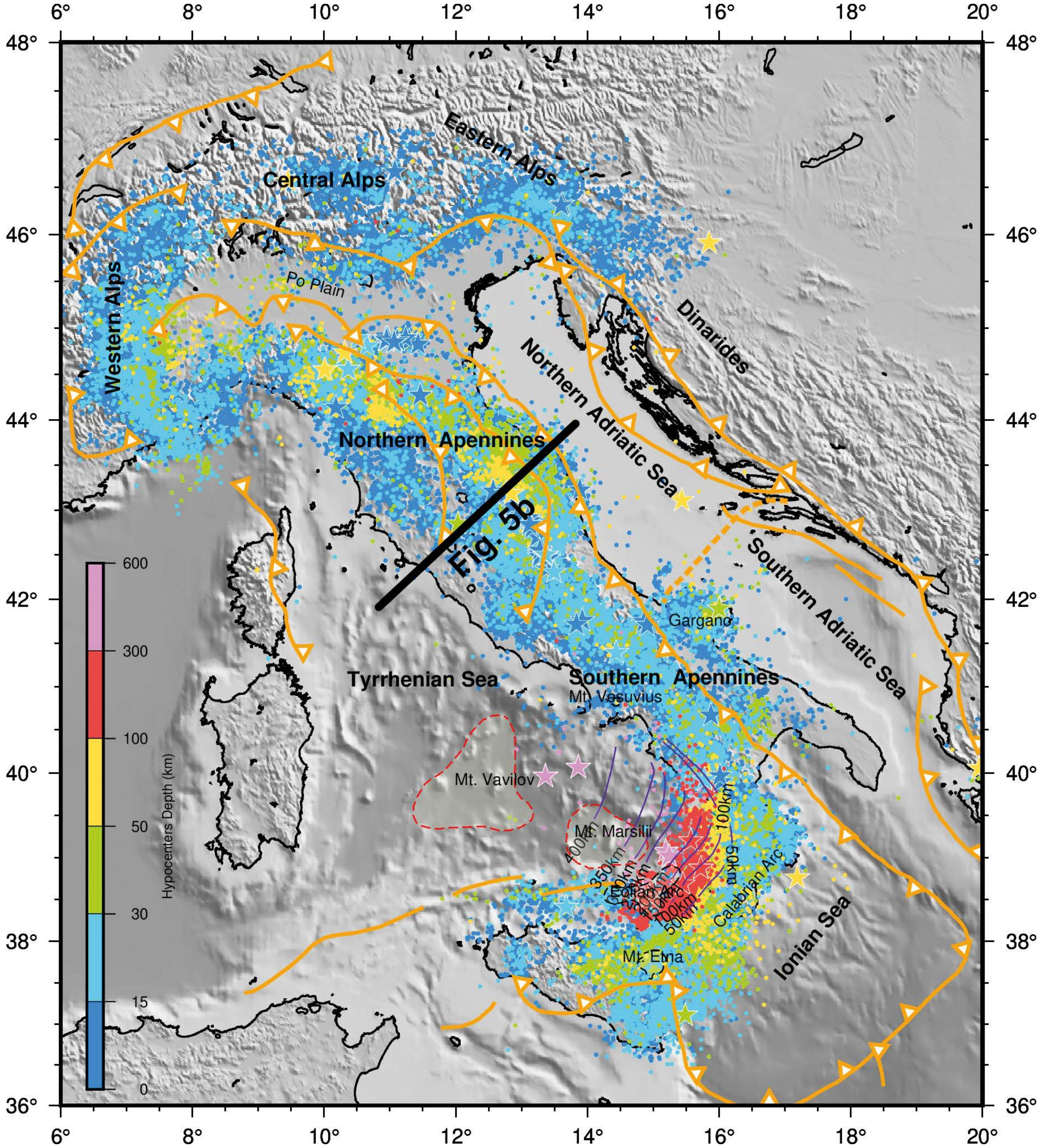

Figure 5a. Instrumental seismicity of Italy for the period 1981-2018 (modified from Latorre et al., 2023). Earthquakes of hypocenter location quality classes A and B are shown for surface to 40 km depth and quality classes A, B and C for deeper events. Yellow lines denote the principal geodynamic features of the region.

leaving similar structure across Northern and Southern Apennines (Chiarabba et al., 2023) turned into two separate subductions at either end of the belt each with their own dynamic and tectonic characteristics.

The Central and Southern Apennines are characterized by an overall extensional tectonic regime, a relatively shallow Moho, a slab window and, consequently, the absence of deep seismicity. The Gran Sasso range in the Central Apennines denotes the highest topography in the mountain belt. The compressional phases date to late Messinian and, since late Pliocene until present, the region is under extension and the range is being uplifted (Cardello and Doglioni, 2015). Based on river-profile inversions, Racano et al. (2024) reconstruct the rock-uplift history in the Central Apennines. Their results document a rock-uplift pulse contemporary with the onset of extension and its relatively fast migration to the South. These observations support the hypothesis of the Central Apennines slab break-off (Faccenna et al., 2014; Chiarabba et al., 2020; Lanari et al., 2023) along a tear migrating southward toward

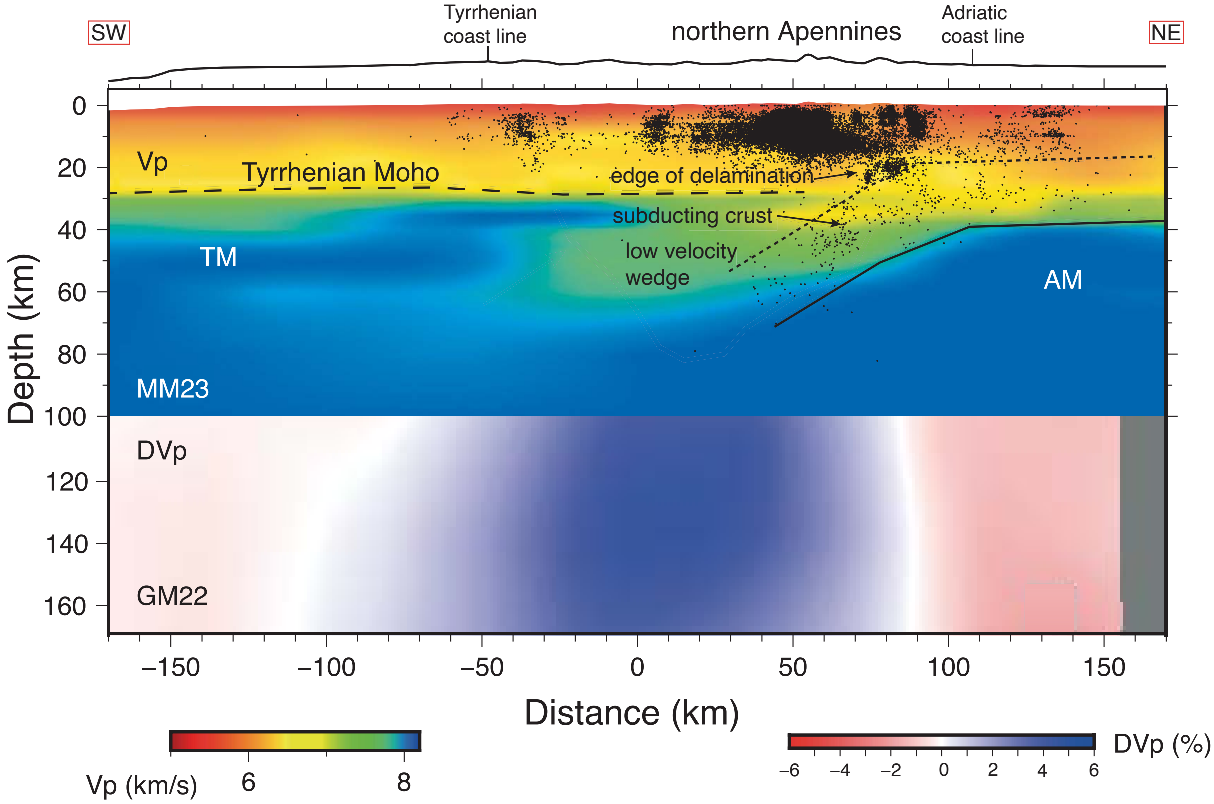

Figure 5b. Seismicity (Chiarabba et al., 2015) superimposed to vertical tomographic cross section of P-velocity model from MM23 (Menichelli et al., 2023) (depth 0-100 km) and a GM22 (Giacomuzzi et al., 2022) (depth 100-180 km) across Northern Apennines (modified from Chiarabba et al. 2023). TM and AM are the Tyrrhenian and Adria mantle, respectively. Dashed line is the Tyrrhenian Moho while small dashed and continuous lines indicate the middle-lower crust shear zone and the Moho of Adria. The purple line indicates the volume of high Vp/Vs observed in GM22. Profile location see Fig. 5a.

the eastern flank of the Calabria subduction zone (Racano et al., 2024, their Fig. 10). Isostatic rebound after slab tearing and break-off beneath the Southern Apennines in the Pleistocene would also correspond with the uplift of the Apennines foreland in the Puglia region during Middle-Late Pleistocene (Doglioni et al. 1996). The slab window beneath the Central Apennines is also characterized by an asthenospheric mantle wedge intrusion below the Tyrrhenian coast (Di Stefano et al., 2009; Monna et al., 2019; Chiarabba et al., 2023).

Differences in the buoyancy and mechanical strength of the subducting Adria lithosphere might play a key role in conditioning the rollback subduction beneath the Northern Apennines where continental delamination is the primary process (Chiarabba et al., 2020; Lo Bue et al., 2021). The originally westward dipping rollback subduction developed a CCW rotation causing the N Apennines deformation front since 23 Ma ago to migrate from the current western coast across the Italian peninsula to beyond the Adria Sea coast and to bend around and migrate N to cover parts of the Po Plain foreland basin (Fig. 1) and to link with the Ligurian Alps (Molli et al. 2010; Channell et al., 2022.

Crustal seismicity is observed throughout the Apennines (Fig. 5a). The Apenninic crust, however, belongs to the Tyrrhenian upper plate and its thickness rarely exceeds 25 km (Chiarabba et al., 2023). Seismicity with hypocenters below 30 km is exclusively found within the Adria crust (Fig. 5b) and hypocenters below 50 km are only observed within the N Apennines slab (Figs. 5a and 6). The slab window in the Central Apennines correlates well with the gap in subcrustal seismicity (Di Stefano and Ciaccio, 2014). Seismicity and tectonics document a change in the stress regime from compression and transpression in a belt along the Apennines frontal thrust to extension in the back-arc region – the so-called Tyrrhenian domain (Barchi et al. 2006; Chiarabba et al., 2023) – that encompasses about two third of the mountain belt (Dragoni et al., 1996; D'Agostino et al., 2011).

Based on interpretation of reflection seismic images in the foreland basin, Brancolini et al. (2019) concluded that the Apennines foredeep in northern Adria Sea does not show evidence of tilting since Early Pliocene and, therefore, the subduction below the Northern Apennines ceased. GPS-derived vertical velocities (Serpelloni et al., 2022, their

Fig. 6B) though provide a different message. Consistent strong regional subsidence (up to 3 mm/yr) is observed in a triangle between Modena – Venezia – Ancona with the maximum values close to the Apennines front. This current subsidence pattern correlates well with the thickness of the Quarternary in the same region (Scrocca et al., 2007; Pezzo et al., 2020). In the Southern Alps along the plate boundary the same data document moderate uplift, regionally again highly consistent. When combined, the vertical motions in these two regions document ongoing tilting of the Adria upper crust in the foreland of the Northern Apennines. For the Apennines mountain belt, Serpelloni et al. (2022) document a lateral variation of subsidence and uplift on a local scale with a tendency to more subsidence in the North-Central Apennines and more uplift in the Southern Apennines.

3.2 Alps

The European Alps are the result of subduction of the Alpine Tethys oceanic lithosphere attached to Europe beneath the Adria MP since the Late Cretaceous, the subsequent continent-continent collision in late Eocene and the post-collisional shortening until recent times (Dal Piaz et al., 2003; Schmid et al., 2004; Handy et al., 2010 and references therein; Pfiffner, 2014; van Agtmaal et al., 2022). The Peri-Adriatic fault system (Handy et al., 2014) marks the plate boundary at the surface leaving more than 90% of the Western, Central and the western parts of the Eastern Alps to rest on the European lower plate. The Alpine orogeny though had a significant impact on the Adria MP, mainly by acting as the backstop to the Southern Alps in connection with the northward migration and CCW rotation of Adria. Furthermore, one might speculate that without the erosional debris in sedimentary infill from the Alps the up to 12 km deep Po basin would be underfilled and nearly all today continental Adria would be below sea level.

Together with the Eastern Alpine nappe system thrusted over the lower plate European crust, the Southern Alpine crustal units were involved in the Mesozoic Alpine orogeny (Bertotti et al. 1993) both as parts of the Adria MP (e.g., Schmid et al., 2004). The current Europe-Adria plate boundary at depth beneath the Eastern Alps and the Southern Alps is best defined by mapping the Moho offset between Adria Moho in the S and Europe Moho in the N. Although geometric details of the deepest levels of the Eastern Alpine crustal root are still a matter of discussion when imaged by different seismic methods (see Brueckl et al., 2010; Bianchi and Bockelmann, 2014; Michailos et al. 2022; Bagagli et al., 2024 and references therein), the reliably resolved northern limit of the Adria Moho in general follows the Peri-Adriatic fault system (i.e., Spada et al., 2013; Bianchi et al., 2021). According to high-resolution seismic tomography (Lippitsch et al. 2003; Karousova et al., 2013; Plomerova et al., 2022) the slab beneath the easternmost parts of the Eastern Alps and the northernmost parts of the Dinarides is attached to Adria (Fig. 6) thus documenting the change in subduction vergency from the Alps to the Dinarides (Handy et al., 2014; Salimbeni et al., 2022).

Owing to the intense fragmentation, the Southern Alps exhibit a moderate seismic activity confined to crustal levels and concentrated in Friuli and along the southern thrust front (Slejko et al., 1989,1999; Bressan et al. 1998; Bressan et al. 2003). The moderately strong seismicity continues across the plate boundary (Fig. 5a) at upper crustal levels in the Austra-Alpine nappe system of the Eastern Alps and in the transition zone between the Eastern Alps and Northern Dinarides (Latorre et al., 2023). There has been no record of deep slab related earthquakes in the Eastern and Southern Alps. The moderate seismic activity in the Western and Central Alps is mainly concentrated within two arcuate zones related to main tectonic lineaments (Giglia et al., 1996; Bertrand and Sue, 2017; Eva et al., 2020; Mathey et al., 2021). Seismicity in the western seismic arc is confined to the upper 25 km of the Alpine crust while the eastern seismic arc along the plate boundary also contains deeper earthquakes originating in the Ivrea body (Scafidi et al., 2009; Schmid et al. 2017 and references therein; Solarino et al. 2018; Menichelli et al., 2023), i.e., the Adria mantle lithosphere (Eva et al. 2020 and references therein; Chiarabba et al., 2023). The two seismic arcs join at the southern tip of the tectonic Alpine Internal Arc (Lardeaux et al., 2006, their Fig. 2) where the former Western Alpine units have been rotated CCW and now form the Ligurian Alps as the transition to the Northern Apennines with the seismicity again being confined to the middle and upper crust (Eva et al., 2020; Mathey et al., 2021).

3.3 Dinarides and Hellenides

The Dinarides and Hellenides consist of nappes detached from the former Adriatic continental margin that sutured with the Tisza and Dacia units of the Neotethys margin during Cretaceous and Cenozoic orogeny (Schmid et al., 2020 and references therein; Vukovski et al., 2024). The Cretaceous orogeny of Austra-Alpine nappe system of the

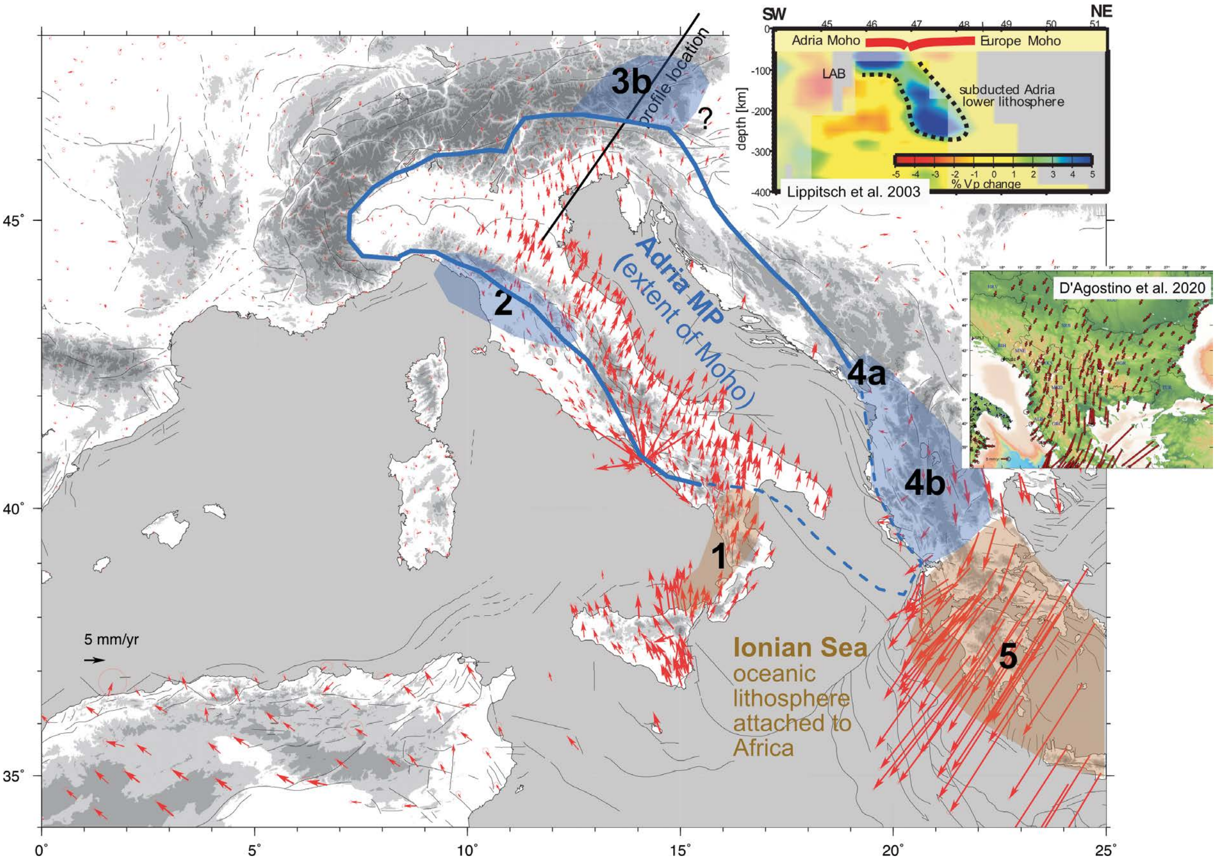

Figure 6. Adria MP with its slabs attached (in blue) with superimposed the current horizontal velocities measured for the surface units (Serpelloni et al., 2022). The extent of the slabs corresponds with that of the high-velocity anomalies illuminated by seismic tomography for the depth 150 km (Piromallo and Morelli, 2003, see Fig. 3; Amaru, 2007, see Fig. 7; Hall and Spakman, 2015). Inset top right: Tomographic cross section by Lippitsch et al. (2003). The profile location is marked by solid black line. Inset center right: horizontal velocities of surface units across the Hellenides relative to Apulia (modified from D'Agostino et al. 2020). Bold blue line marks extent of Adria Moho (see Fig. 2 and text). The numbers refer to the anomalies in Fig. 3. Slabs 1 (Calabria) and 5 (Hellenic) are attached to the Ionian Sea lithosphere (see text).

Eastern Alps can be linked to different episodes of suturing in the Dinarides after closure of the Vardar and Pindos oceans (Argnani, 2018; Toljic et al., 2018; Nirta et al., 2020). Affected by the Hellenic rollback subduction, the Southern Dinarides and the Hellenides were involved in Miocene-to-recent CW oroclinal bending (Handy et al., 2019; van Hinsbergen et al., 2020) that led to ongoing N-S shortening relative to Apulia (Biermanns et al., 2022; D'Agostino et al. 2020) (see also inset in Fig. 6).

The moderate seismicity observed throughout the Dinarides is confined to crustal levels (Stipcevic et al., 2020; Banko et al., 2024). The vast majority of the earthquakes recorded in the western Hellenides are also crustal events with a few exceptions reaching hypocentral depths up to 100 km (Dushi and Havskov, 2023). This corresponds well with the slab window beneath the Northern Dinarides (Fig. 3) documented by the early regional tomography studies (Spakman, 1990; Piromallo and Morelli, 2003; Koulakov et al., 2009) and recent seismic anisotropy measurements (i.e., Salimbeni et al., 2022 and references therein). However, the tomographic images differ significantly in terms of lateral extent and amplitude of the high-velocity anomalies observed in 150 km depth that represent the Southern Dinarides, the Western Hellenides and the Hellenic subduction zone slab (Fig. 3, anomalies 4a, 4b, 5, respectively) (Spakman, 1990; Wortel and Spakman, 2000; Piromallo and Morelli, 2003; Koulakov et al., 2009). Handy et al. (2019) present a map view of the P velocity anomalies at 150 km depth in the Hellenides region extracted from the model P06 (Amaru, 2007) that is available from (https://www.atlas-of-the-underworld.org). Among other improvements, this global model has been derived by complementing the ISC data with regional travel time data and thus it allows higher resolution in some regions, including the Mediterranean, than its predecessors though it has only been published in parts (see, f.e., Hall and Spakman, 2015). The model P06_3Dloc shown in Fig. 7 is another model of Amaru (2007) calculated with rays traced through a 3D hybrid reference model that of all the models calculated by Amaru arguably provides the most reliable information at shallow mantle depth. Below the tectonic plates (the maximum thickness of the lithosphere in the region is approximately 100 km), positive velocity anomalies are interpreted as subducted lithosphere and negative velocity anomalies as representing relatively warmer mantle, i.e., asthenosphere. According to Goes et al. (2005), a P-wave velocity variation of 1% corresponds to a thermal anomaly of about 250°K.

At 120 km depth we clearly see a small slab beneath the Southern Dinarides (Fig. 7, anomaly 4a) and a pronounced high-velocity anomaly representing an apparently continuous slab beneath the Hellenides (Fig. 7, anomaly 4b) and the Hellenic subduction zone (Fig. 7, anomaly 5 representing the Ionian lithosphere slab). While the slab beneath the Southern Dinarides does not reach beyond 150 km depth the slab beneath the Hellenides (Fig. 7, anomaly 4b) possible extends to 180 km depth. At 150 km depth though we see a necking between the Ionian oceanic lithosphere slab (Fig. 7, anomaly 5) and the Adriatic slab beneath the Hellenides approximately coinciding with the projection of the Cefalonia Transform Fault (CF). Below 200 km depth only the Ionian slab remains with a possible remnant of a lithosphere slab below 250 km in the N that has been detached from its shallower parts.

Considering the great suction force exerted by the rollback of the Ionian slab in the Hellenic subduction zone onto the overriding Aegean plate (Sachpazi et al., 2016), the slab geometries revealed by the tomographic images (Fig. 7) of model P06_3Dloc by Amaru (2007) correlate very well with the horizontal velocities measured in the Western Hellenides (D'Agostino et al., 2020) (Fig. 6, inset). On the other hand, rollback of the Adria slab beneath the Hellenides (Fig. 6 and 7, anomaly 4b) seems to have stopped since at present there is no westward directed suction force observed in the Hellenides. Furthermore, the tomographic images document the Adria slab beneath the Dinarides to be very short and the slab beneath the Hellenides to be detached at depth from the Ionian slab of the Hellenic subduction zone.

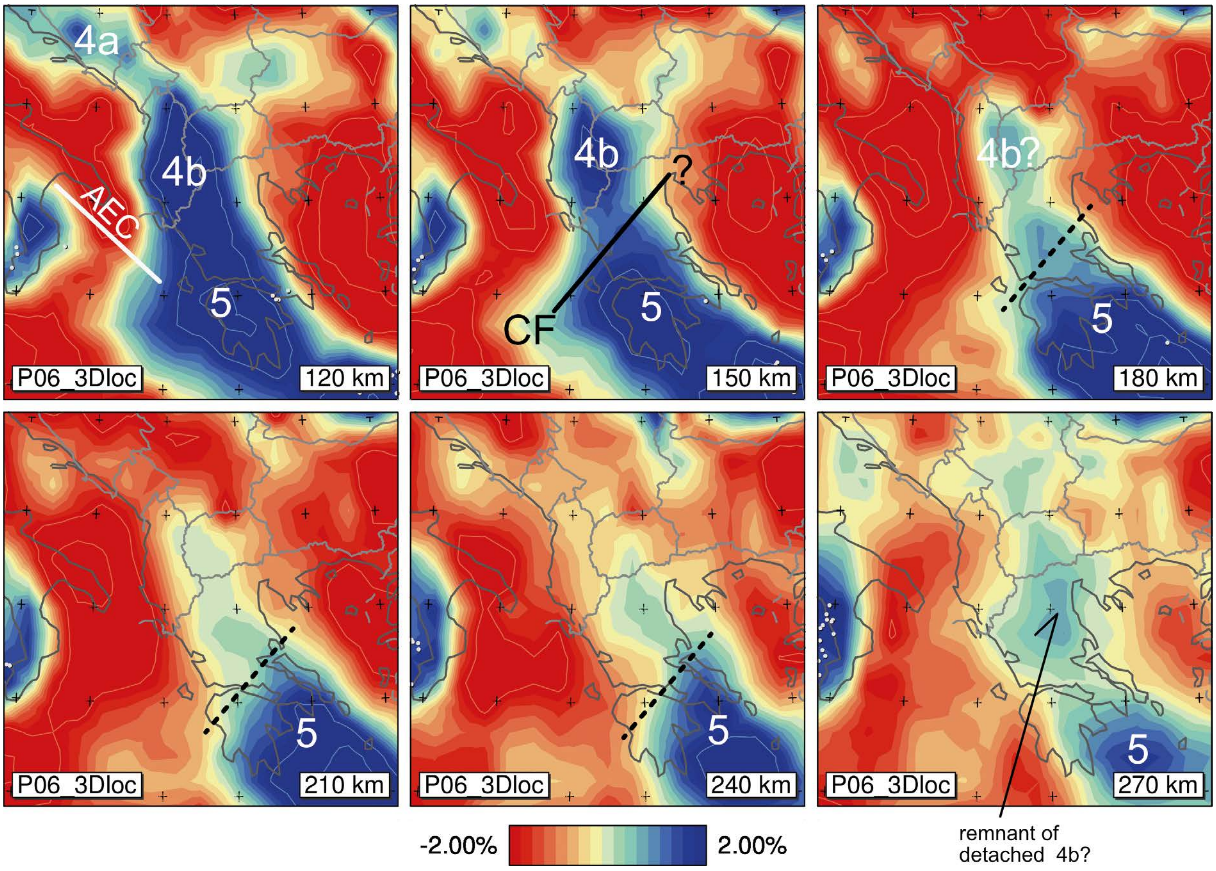

Figure 7. Tomographic images of P-wave velocity anomalies beneath the Southern Dinarides, the Hellenides, the Ionian Sea and the Aegean (modified from Amaru, 2007, courtesy of W. Spakman). For interpretation see text. Numbers refer to velocity anomalies representing lithosphere slabs listed in Fig. 3. CF marks the projection of the Cefalonia Transform Fault and AEC the projection of the Apulian Escarpment. The broken lines mark the likely NW limits of the Ionian oceanic lithosphere slab (anomaly 5).

3.4 Calabria subduction zone and Ionian Sea

The relatively old oceanic lithosphere (Catalano et al., 2001; Dannowski et al., 2019 and references therein) beneath the Ionian Sea is part of the Africa plate. Currently, the Ionian lithosphere subducts in the Calabria and the Western Hellenic subduction zones (Fig. 1). Both subduction zones are characterized by fast slab retreat and by strong and deep reaching seismicity (see Fig. 3 for Calabria subduction). The slab rollback is a consequence of the old age (and strong negative buoyancy) of the oceanic lithosphere in combination with the attachment of relatively small slabs to a very large plate that does not move toward the trench. There are, however, notable differences between the two subduction zones. The Hellenic arc is relatively wide and long and the slab rollback exerts great suction forces upon the overriding Aegean plate that shows some of the fastest horizontal plate motions (Fig. 4, Serpelloni et al., 2022) perpendicular to the retreating trench. In fact, the suction forces are strong enough to influence the motions of upper plates beyond the extension of the trench as the Hellenides document (Fig. 6, inset, D'Agostino et al., 2020). The Calabria arc in contrast is one of the narrowest subduction zones (Dellong et al., 2020 and references therein) and the horizontal velocity vectors of the upper plate vary along the arc and they are significantly different than the apparent slab retreat direction (Fig. 4, Serpelloni et al., 2022).

The Apulian escarpment traversing the Gulf of Taranto and continuing to the Cefalonia transform fault system (Fig. 7) denotes the passive margin between the continental Apulian platform and the oceanic Ionia Sea (Tugend et al., 2019). The northeastern branch of the Calabria trench (Turco et al., 2021) follows this prominent topographic feature (Fig. 1). Seismic studies (Merlini et al., 2000; Volpi et al., 2017 and references therein) revealed the accretionary wedge is deeper and subsided with respect to the foreland that is uplifted and emerging in the Puglia region. Cicala et al. (2021) interpreted the well-documented Apulian swell as the consequence of the proximity of the two opposed subduction zones in the Hellenides and the Southern Apennines. The tomographic images, however, do not show any sign of a long slab attached to Adria (Fig. 7). Consequently, we must assume the remaining very short Southern Apennines slab of Adria lithosphere to be fully detached from the Calabria subduction (Fig. 8) and the uplift of the Apulian platform being possibly caused by the tearing along the passive margin across the Gulf and the northern Ionian Sea between the positively buoyant continental Adria and the negatively buoyant oceanic Ionia-Africa (see Volpi et al., 2017, their Fig. 1).

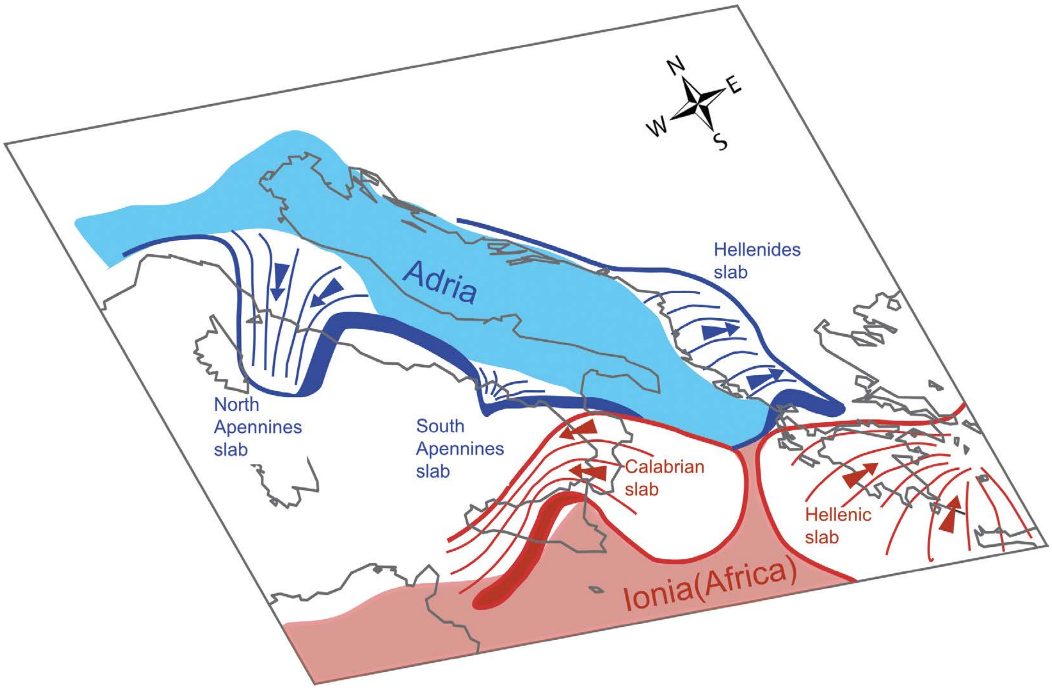

Figure 8. Cartoon illustrating the proposed slab geometries and the plate boundary at the southern edge of the Adria MP (blue). The Ionian Plate, considered part of the African Plate, is shown in red. Horizontal lithosphere is represented by light shading, while the dipping slabs are marked with stripes along the dip direction. Arrows indicate the direction of subduction. This sketch was created with the contribution of C. Piromallo.

4. Discussion of open questions

The many review papers – some topically, other disciplinary – recently published about Adria MP and its surroundings allow to get an unprecedented insight into the evolution, state and geodynamics of this region. In the two previous chapters, I tried to compile and summarize from them some of the key issues regarding the three orogens and three active rollback subduction zones encircling and encroaching onto the small remnant strip of continental Adria visible on the surface (Fig. 1). Following some previously published ideas I also tried to discuss some likely and possible interactions between documented processes on different sides and/or in the interior of the rather small and tectonically very active plate. However, a few important questions about the Adria MP as an entity are still under discussion and they are briefly addressed below.

4.1 Is Adria still attached to or detached from Africa?

This relates to the discussion of Adria being a microplate of its own or just a promontory of Africa as proposed by Channell et al. (1979) based on paleomagnetic data. Platt et al. (1989) opposed this notion and argued for an independent Adria MP since Neogene times. Ward (1994) and Oldow et al. (2002) based on early GPS data argued for Adria MP today moving independently from Africa. The opening of the Neotethys around 250 Ma ago separated the continental lithosphere sliver of Apulia from the Africa plate only to eventually amalgamate it again to Africa after the rifting seized in the oceanic lithosphere later to become known as the Ionian Sea (Stampfli, 2005). Around 230 Ma ago, after the westernmost part of the Paleotethys completely subducted, the two slivers of continental lithosphere Adria (northern part) and Apulia were juxtaposed and joined by transpression along the Mattinata tectonic lineament (Stampfli, 2005; Schettino and Turco, 2011; Speranza et al. 2012; Carminati et al., 2012; van Hinsbergen et al., 2020; Le Breton et al., 2021; Angrand and Mouthereau, 2021; Frasca et al., 2024). Hence, there exists general agreement that continental Adria MP as we know it today was attached to the Africa plate by 230 Ma ago and remained as such for about 200 Ma.

Van Hinsbergen et al. (2020) and Channell et al. (2022) based on paleomagnetic Polar Wander Path (PWP) comparison for the points measured in supposedly “stable Adria” with the PWP of Africa argue for an attachment of Adria MP until recent times thus meaning Adria remaining the promontory of Africa (Muttoni et al., 2013). Le Breton et al. (2021) though based on a new kinematic reconstruction for Adria MP considering all geological and geophysical data from the Alps, Apennines, Dinarides and the Sicily Channel Rift Zone argue for a detached Adria since 20 Ma including a small CCW rotation of 5° relative to Europe. Close inspection of the PWP from “stable Adria” (van Hinsbergen et al., 2020) shows the points from different regions to diverge significantly from each other during two periods, one from 135 Ma-85 Ma and another from 52 Ma-40 Ma. If one assumes these variations to represent scatter from normal data errors and thus defines an uncertainty for the entity of the Adria points, the Africa and the Adria PWP’s overlap nearly all times since at least 180 Ma ago. This scatter, however, would also allow significant relative movements between the points of “stable Adria” (significant movements with respect to the size of Adria MP). Either side arguments are well established though in my view neither are providing convincing proof of Adria as a separate MP or as a solidly attached promontory of Africa.

From a mechanical plate tectonic point of view though proximity and motion consistency are not enough to make Adria a promontory. Carminati et al. (2012, their Fig. 6) show a plate configuration of Central Mediterranean for 31 Ma where todays continental Adria in nearly its full length is attached to the oceanic lithosphere of Africa, the remaining parts of what we now know as the Ionian Sea. There can be little doubt that such a long and old passive continental margin is mechanically strong enough to have Adria being moved with its big plate Africa and even acting as indenter in the Alpine collision zone. Considering the situation at 5 Ma ago (Carminati et al., 2012, their Fig. 9) and certainly the present situation (Fig. 1, 6, 7) though it seems unlikely that the remaining short passive continental margin would allow a solid mechanical connection between the Ionian Sea oceanic lithosphere as part of Africa and the continental Adria. Finally, the current velocity vectors (D’Agostino et al., 2008; Serpelloni et al., 2022) in my view request an Adria MP detached from Africa. In any case, over the past 20 Ma Adria MP has been geodynamically active as an independent entity yet still much influenced by its two large neighbor plates Africa and Europe.

4.2 Did and does Adria rotate relative to Europe?

The question about rotation of Adria is obviously linked with the above discussion about Adria being a promontory of Africa. Following the conclusions of the previous sub-chapter it is clear and generally accepted that Adria as promontory moved and rotated with Africa relative to Europe since Jurassic times (Handy et al., 2010; Le Breton et al., 2021; Jolivet et al., 2021; Frasca et al., 2024; for a review of the paleomagnetic data see Channell et al., 2022). Rotation of Adria relative to Africa and Europe since about 30 Ma are mainly based on paleomagnetic data from the Southern Alps (Marton et al., 2010) and Apulia (van Hinsbergen et al., 2014) even though these interpretations are disputed by Channell et al. (2022). Rotation of the "Adria indenter" have long been discussed and used to explain kinematic indicators from tectonics in the Alps (e.g., Platt et al., 1989; Molli et al., 2010; Handy et al., 2010 and references therein; Luth et al., 2013; Bertrand and Sue, 2017; van Gelder et al., 2020; Romagny et al., 2020). Current CCW rotation of Adria relative to Europe has also been postulated based on stress measurements in Friuli and Istria (Bressan et al., 1998; Willingshofer et al., 2003) and based on GPS measurements (e.g., Devoti et al., 2008). Present-day kinematics derived from inversion of large GPS data set (Fig. 4) (Serpelloni et al., 2022) could indeed be interpreted as documenting a small CCW rotation around a pole in the western Po Plain if one considers the various Adria parts with measurements to belong to a rigid plate. GPS signals, however, are also affected by non-tectonic components and the surface units the stations locate upon might not be mechanically fully linked with the middle and lower crustal layers of the plate. Although it is intriguing that the possible GPS-derived pole of rotation nearly perfectly corresponds with the paleo-kinematic pole of rotation, I remain unconvinced that an ongoing CCW rotation of northern Adria MP represents a conclusive and the most likely interpretation. Rather, the GPS data could document Adria-internal surface deformation (Nucci et al., 2023, their Fig. 12).

Beyond any doubt, Adria did rotate relative to Europe in the distant past as a promontory of Africa and in my view, Breton et al. (2017) and van Hinsbergen et al. (2014) based on their reviews of all available geophysical and geological data convincingly documented a post-Oligocene CCW rotation of Adria MP relative to Africa and Europe.

4.3 Status and geodynamic effects of slabs around Adria

Adria MP is surrounded by lithosphere slabs and subduction zones (Fig. 6). The slabs attached to Adria beneath the Eastern Alps and the Hellenides seem currently not to be subducting any further even though they will still exert a pull force to the Adria continental lithosphere (possibly in parts compensated by the orogenic buoyancy forces) and they might interact with asthenospheric mantle flow (Handy et al., 2015, 2019). In the recent past, the slabs on the western side of Adria have dominated the geodynamic evolution of the western Mediterranean (Faccenna et al., 2004, 2014, 2020; Piccardi et al., 2011; Romagny et al., 2020; Jolivet et al. 2021; Salimbeni et al., 2022). At present the oceanic lithosphere slab subducting beneath Calabria seems to be detached from Adria (Fig. 7) and "only" the N Apennines slab remains attached to Adria. Rollback dynamics from this slab, however, are currently active and continue to deform and stress the Adria plate and the overriding orogenic wedge (e.g. Cuffaro et al., 2010; Pezzo et al., 2020; Chiarabba et al., 2020, 2023). Exact dimensions, composition and physical constitution of the Northern Apennines slab unfortunately are still poorly known.

To further our process-oriented understanding of the Adria MP geodynamic system requires geodynamic modeling (i.e., Kiraly et al., 2018; Lo Bue et al., 2021; Schuler et al., 2024) encompassing the wealth of information from several disciplines presently available. Yet, also some additional constraints are required regarding the geometries, buoyancy and mechanical state of the slabs as the main drivers of geodynamics both by their linkage to the plate as by their interaction with asthenospheric flow.

4.4 Is Adria lithosphere one single MP?

At present we recognize five subducting slabs interacting with the Adria MP – tearing in the Calabria and Hellenic subduction zones and pulling beneath the Northern Apennines, the Hellenides and the Eastern Alps. Additionally, the Adria MP is in continent-continent-collision along a 1000 km long boundary with Europe and there exist inherited zones of mechanical weakness across the central Adria Sea. There seems general agreement (Frasca et al., 2024 and references therein) that in Late Cretaceous-Paleogene times the Mattinata tectonic lineament (Fig. 1) was active as a transform fault between Adria northern part and Apulia (Schettino and Turco, 2011). This transform fault's former western continuation plays an important role in the model of Turco et al. (2021) for the segmented Apennines slab rollback. Tectonic deformations by reactivation of pre-existing structures are also observed along the so-called Mid-Adriatic Ridge (Fig. 1) further North (Scisciani and Calamita, 2009). Furthermore, strike-slip deformation and reactivation of Jurassic structures during Cretaceous and Neogene times have also been reported from the Southern Alps (Le Breton et al., 2021 and references therein).

Plate-internal deformation on a scale significant in relation to the size of the MP have obviously occurred in the past and some have seen recent reactivation, consequence of the ongoing tectonic forcing. While such plate-internal deformation prohibits modeling Adria MP as a rigid block in kinematic models, it does not immediately follow that Adria MP is in the process to be torn apart or has already separated into a northern and a southern part. Rather, in my understanding the current strain vectors (Nucci et al., 2024) suggest Adria MP to mechanically represent a single lithospheric plate stressed by the well-known locally different geodynamic sources. Of course, this should better be tested by 4D geodynamic modeling. Additional constraints related to Adria being a single MP with inherited deep reaching internal structure and variations in lithosphere thickness could be obtained by detailed mapping of the LAB.

5. Conclusions

The amount of literature, information, models and ideas published about Adria MP is staggering and, admittedly, in this summary review I must have missed many, for what I apologies. Obviously, the tectonically and seismically active region poses significant natural hazards that demand research attention. The study of the geodynamics in, on, around and below Adria MP though is additionally attractive for Earth sciences research because it presents itself as a natural laboratory for regional-scale plate tectonics and by slab rollback dynamics, in particular.

A continuously "rigid" (solid) connection of Adria MP with Africa across the narrow strip of oceanic Ionian lithosphere between the Calabria and Hellenic subductions since 20 Ma ago as assumed by some paleo-kinematic models (e.g., van Hinsbergen et al., 2020) in my view seems unlikely. Before the onset of the Calabria and Hellenic subductions, Adria apparently was solidly attached to Africa (Carminati et al., 2012) since Jurassic times (Channell et al. 2022). Almost encircled by the three orogens Apennines, Alps, and Dinarides/Hellenides, the Adria continental lithosphere has been and still is strongly affected by the subducting slabs surrounding it. Some of these slabs are still attached, others have recently been torn off. In the northern part of the Adria MP, the N Apennines slab rollback is the obvious dominant geodynamic force acting locally on the plate (e.g., Pezzo et al., 2020; Chiarabba et al. 2023). In contrast, the slabs beneath the Eastern Alps and beneath the Hellenides seem stagnant with a notable slab window beneath the Dinarides between them (Fig. 6). The Southern Apennines slab has been torn off and separated from the Calabria slab by the latter's rollback and it remains as a relatively short length slab attached to Adria MP (Fig. 8). The forearcs of the two very active Calabria and Hellenic subduction zones have nearly met in the western Ionian Sea. Subduction of this old oceanic lithosphere will completely detach Adria MP from Africa plate likely along the Apulian escarpment (Fig. 8).

Documented by mapping the Moho beneath the orogens, the continental lithosphere of Adria is at least twice as wide as the Adria Sea. As the discussion about the motions of Adria since Neogene times document, pure kinematic approaches may not suffice for unravelling the plate tectonic history of this micro plate caught in between two large plates. Rather, we will have to include the likelihood of significant plate-internal deformation. Local and temporally variable distortions in the overriding as well as the subducting plate seem not only possible but are very likely considering the slabs tearing and rotations during Apennines rollback subduction processes.

Data availability statement. The data used in this study has been published and is referenced in the text.

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References

Amaru, M. L. (2007). Global travel time tomography with 3-D reference models, Utrecht University (PhD Thesis).

Amato, A., I. Bianchi and N. Piana Agostinetti (2014). Apulian crust: Top to bottom, J. Geodyn., doi:10.1016/j.jog.2014.09.007.

Angrand, P. and F. Mouthereau (2021). Evolution of the Alpine orogenic belts in the Western Mediterranean region as resolved by the kinematics of the Europe-Africa diffuse plate boundary, BSGF Earth Sci. Bull., 192, 42, doi:10.1051/bsgf/2021031.

Argand, E. (1924a). Des Alpes et de l'Afrique, Bull. Soc. Vaudoise Sci. Nat. 55, 214, 233-236.

Argand, E. (1924b). La tectonique de l'Asie, Proc. Int. Geol. Congr. XIII, 171-372.

Argnani, A. (2018). Subduction evolution of the Dinarides and the Cretaceous orogeny in the Eastern Alps: Hints from a new paleotectonic interpretation, Tectonics, 37, 621-635, doi:10.1002/2017TC004632.

Artemieva, I. M. (2019). Lithosphere structure in Europe from thermal isostasy, Earth Sci. Rev., 188, 454-468, doi:10.1016/j.earscirev.2018.11.004.

Balling, P., C. Grützner, B. Tomljenović, W. Spakman et al. (2021). Post-collisional mantle delamination in the Dinarides implied from staircases of Oligo-Miocene uplifted marine terraces, Sci. Rep., 11, 2685, doi:10.1038/s41598-021-81561-5.

Banko, A., F. Mihelin, T. Bankovic and M. Pavasovic (2024). Preliminary Derived DInSAR Coseismic Displacements of the 2022 M w 5.7 Stolac Earthquake, Remote Sens., 16, 1658, doi:10.3390/rs16101658.

Barchi, M. R., C. Pauselli, C. Chiarabba, R. Di Stefano et al. (2006), Crustal structure, tectonic evolution and seismogenesis in the Northern Apennines (Italy), Boll. Geof. Teor. Appl., 0006-6729(47), 249-270.

Behm, M., E. Bruekl and U. Mittelbauer (2007a). CELEBRATION 2000 and ALP 2002 Working Groups, A new seismic model of the Eastern Alps and its relevance for geodesy and geodynamics, Vermessung and Geoinformation, 2, 121-133, http://www.ovg.at/index.php?id=822.

Behm, M., E. Brueckl, W. Chwatal and H. Thybo (2007b). Application of stacking and inversion techniques to three-dimensional wide-angle reflection and refraction seismic data of the Eastern Alps, Geophys. J. Int., 170, 275-298, doi:10.1111/j.1365-246X.2007.03393.x.

Bertotti, G., V. Picotti, D. Bernoulli and A. Castellarin (1993), From rifting to drifting: tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous, Sediment. Geol., 86, 53-76, doi:10.1016/0037-0738(93)90133-P.

Bertrand, A. and C. Sue (2017). Reconciling late faulting over the whole Alpine belt: from structural analysis to geochronological constrains, Swiss J. Geosciences, 110, 565-580, doi:10.1007/s00015-017-0265-4.

Bijwaard, H. and W. Spakman (2000). Non-linear global P-wave tomography by iterated linearized inversion, Geophys. J. Int., 141, 71-82, doi:10.1046/j.1365-246X.2000.00053.x.

Bianchi, I., N. Piana Agostinetti, P. De Gori and C. Chiarabba (2008). Deep structure of the Colli Albani volcanic district (central Italy) from receiver functions analysis, J. Geophys. Res., 113, B09313, doi:10.1029/2007JB005548.

Bianchi, I., J. Park, N. Piana Agostinetti and V. Levin (2010). Mapping seismic anisotropy using harmonic decomposition of receiver functions: An application to Northern Apennines, Italy, J. Geophys. Res., 115, B12317, doi:10.1029/2009JB007061.

Bianchi, I. and G. Bokelmann (2014). Seismic signature of the Alpine indentation, evidence from the Eastern Alps, J. Geodynam., 82, 69-77, doi:10.1016/j.jog.2014.07.005.

Bianchi, I., E. Ruigrok, A. Obermann and E. Kissling (2021). Moho topography beneath the European Eastern Alps by global-phase seismic interferometry, Solid Earth, 12, 1185-1196, doi:10.5194/se-12-1185-2021.

Biermanns, P., B. Schmitz, S. Mechernich, C. Weismüller et al. (2022). Aegean-style extensional deformation in the contractional southern Dinarids: incipient normal fault scarps in Montenegro, Solid Earth, 13, 957-974, doi:10.5194/se-13-957-2022.

Boschi, L., C. Faccenna and T. W. Becker (2010). Mantle structure and dynamic topography in the Mediterranean Basin, Geophys. Res. Lett., 37, L20303, doi:10.1029/2010GL045001.

Brancolini, G., D. Civile, F. Donda, L. Tosi et al. (2019). New insights on the Adria plate geodynamics from the northern Adriatic perspective, Marine and Petr. Geol., 109, 687-697, doi:10.1016/j.marpetgeo.2019.06.049.

Bressan, G., A. Snidarcig and C. Venturini (1998). Present state of tectonic stress of the Friuli area (eastern Southern Alps), Tectonophysics 292, 211-227, doi:10.1016/S0040-1951(98)00065-1.

Bressan, G., P. L. Bragato and C. Venturini (2003). Stress and strain tensors based on focal mechanisms in the seismotectonic framework of the Friuli-Venezia Giulia region (Northeastern Italy), Bull. Seism. Soc. Am., 93, 1280-1297, doi:10.1785/0120020058.

Broerse, T., B. Norder, R. Govers, D. Sokoutis et al. (2019). New analogue materials for nonlinear lithosphere rheology, with an application to slab break-off, Tectonophysics, 756, 73-96, doi:10.1016/j.tecto.2018.12.007.

Brueckl, E., F. Bleibinhaus, A. Gosar, M. Grad et al. (2007). Crustal structure due to collisional and escape tectonics in the Eastern Alps region based on profiles Alp01 and Alp02 from the ALP 2002 seismic experiment, J. Geophys. Res., 112, B06308, doi:10.1029/2006JB004687.

Brueckl, E., M. Behm, K. Decker, M. Grad et al. (2010). Crustal structure and active tectonics in the Eastern Alps, Tectonics 29 (TC2011), doi:10.1029/2009TC002491.

Burke, K. and J. Wilson (1972). Is the African Plate Stationary?, Nature 239, 387-390, doi:10.1038/239387b0.

Carminati, E., M. J. R. Wortel, W. Spakman and R. Sabadini (1998). The role of slab detachment processes in the opening of the western-central Mediterranean basins: some geological and geophysical evidence, Earth Planet. Sci. Lett., 160, 651-665, doi:10.1016/S0012-821X(98)00118-6.

Carminati, E. and C. Doglioni (2012). Alps vs. Apennines: The paradigm of a tectonically asymmetric Earth, Earth Sci. Rev., 112, 67-96, doi:10.1016/j.earscirev.2012.02.004.

Carminati, E., M. Lustrino and C. Doglioni (2012). Geodynamic evolution of the central and western Mediterranean: Tectonics vs. igneous petrology constraints, Tectonophysics, 579, 173-192, doi:10.1016/j.tecto.2012.01.026.

Catalano, R., C. Doglioni and S. Merlini (2001). On the Mesozoic Ionian Basin, Geophys. J. Int., 144, 49-64, doi:10.1046/j.0956-540X.2000.01287.x.

Cello, G. and S. Mazzoli (1999). Apennine tectonics in southern Italy: a review, J. Geodyn., 27, 191-211. doi:10.1016/S0264-3707(97)00072-0.

Channell, J. E. T., B. D'Argenio and F. Horvath (1979). Adria, the African promontory, in Mesozoic Mediterranean palaeogeography, Earth Sci. Rev., 15, 213-292, doi:10.1016/0012-8252(79)90083-7.

Channell, J. E. T., G. Muttoni and D. V. Kent (2022). Adria in Mediterranean paleogeography, the origin of the Ionian Sea and Permo-Triassic configuration of Pangea, Earth Sci. Rev., 230, doi:10.1016/j.earscirev.2022.104045.

Chiarabba, C., G. Giacomuzzi, I. Bianchi, N. Piana Agostinetti et al. (2014). From underplating to delamination-retreat in the Northern Apennines, Earth Planet. Sci. Lett., 403, 108-116, doi:10.1016/j.epsl.2014.06.041.

Chiarabba, C., P. De Gori and F. M. Mele (2015). Recent seismicity of Italy: active tectonics of the central Mediterranean region and seismicity rate changes after the Mw 6.3 L'Aquila earthquake, Tectonophysics, 638, 82-93. doi:10.1016/j.tecto.2014.10.016.

Chiarabba, C., I. Bianchi, P. De Gori and N. P. Piana Agostinetti (2020). Mantle upwelling beneath the Apennines identified by receiver function imaging, Sci. Rep., 10, 1, 19760, doi:10.1038/s41598-020-76515-2.

Chiarabba, C., I. Menichelli, I. Bianchi, G. Giacomuzzi et al. (2023). Continental subduction of Adria in the Apennines and relation with seismicity and hazard, Front. Earth Sci., 11, 1253443, doi:10.3389/feart.2023.1253443.

Cicala, M., V. Festa, L. Sabato, M. Tropeano et al. (2021). Interference between Apennines and Hellenides foreland basins around the Apulian swell (Italy and Greece), Mar. Pet. Geol., 133, doi:10.1016/j.marpetgeo.2021.105300.

Cimini, G. B. and A. Marchetti (2006). Deep structure of peninsular Italy from seismic tomography and subcrustal seismicity, Ann. Geophys., 49, 1, 331-345.

Cuffaro, M., F. Riguzzi, D. Scrocca, F. Antonioli et al. (2010). On the geodynamics of the northern Adriatic plate, Rend. Fis. Acc. Lincei, 21, 1, S253-S279, doi:10.1007/s12210-010-0098-9.

D'Agostino, N., A. Avallone, D. Cheloni, E. D'Anastasio et al. (2008). Active tectonics of the Adriatic region from GPS and earthquake slip vectors, J. Geophys. Res., 113, B12413, doi:10.1029/2008JB005860.

D'Agostino, N., S. Mantenuto, E. D'Anastasio, R. Giuliani et al. (2011). Evidence for localized active extension in the central Apennines (Italy) from global positioning system observations, Geology, 39, 4, 291-294, doi:10.1130/G31796.1.

D'Agostino, N., M. Métois, R. Koci, L. Duni et al. (2020). Active crustal deformation and rotations in the southwestern Balkans from continuous GPS measurements, Earth Planet. Sc. Lett., 539, 116246, doi:10.1016/j.epsl.2020.116246.

Dal Piaz, G. V. and R. Nicolich (1991). Carta della Moho e lineamenti tettonici, in Structural Model of Italy,1:500,000, CNR P.F. Geodinamica, sheet 2.

Dal Piaz, G. V. (2001). History of tectonic interpretations of the Alps, J. Geodyn., 32, 99-114, doi:10.1016/S0264-3707(01)00019-9.

Dal Piaz, G. V., A. Bistacchi and M. Massironi (2003). Geological outline of the Alps, Episodes, 26, 3, 175-180, doi:10.18814/epiiugs/2003/v26i3/004.

Danciu, L., S. Nandan, C. Reyes, R. Basili et al. (2021). The 2020 update of the European Seismic Hazard Model – ESHM20: Model Overview, EFEHR, Nat. Hazards Earth Syst. Sci., 24, 3049-3073, doi:10.12686/A15.

Dannowski, A., H. Kopp, F. Klingelhoefer, D. Klaeschen et al. (2019). Ionian Abyssal Plain: A window into the Tethys oceanic lithosphere, Solid Earth, 10, 2, 447-462, doi:10.5194/se-10-447-2019.

Dellong, D., F. Klingelhoefer, A. Dannowski, H. Kopp et al. (2020). Geometry of the Deep Calabrian Subduction (Central Mediterranean Sea) From Wide-Angle Seismic Data and 3-D Gravity Modeling. Geochemistry, Geophysics, Geosystems, 21, doi:10.1029/2019GC008586.

Devoti, R., F. Riguzzi, M. Cuffaro and C. Doglioni (2008). New GPS constraints on the kinematics of the Apennines subduction, Earth Planet. Sci. Lett., 273, 163-174, doi:10.1016/j.epsl.2008.06.031.

Dewey, J. F. and K. Burke (1974). Hot Spots and Continental Break-up: Implications for Collisional Orogeny, Geology, 2, 2, 57-60, doi:10.1130/0091-7613(1974)2<57:HSACBI>2.0.CO;2.

Di Stefano, R., E. Kissling, C. Chiarabba, A. Amato et al. (2009). Shallow subduction beneath Italy: Three-dimensional images of the Adriatic European-Tyrrhenian lithosphere system based on high-quality P wave arrival times, J. Geophys. Res., 114, B05305, doi:10.1029/2008JB005641.

Di Stefano, R., I. Bianchi, M. G. Ciaccio, G. Carrara et al. (2011). Three-dimensional Moho topography in Italy: new constraints from receiver functions and controlled source seismology, Geochem. Geophys. Geosyst., 12, Q09006, doi:10.1029/2011GC003649.

Di Stefano, R. and M. G. Ciaccio (2014). The lithosphere and asthenosphere system in Italy as inferred from the Vp and vs 3D velocity model and Moho map, J. Geodyn., 82, 16-25, doi:10.1016/j.jog.2014.09.006.

Doglioni, C. (1991). A proposal for the kinematic modelling of W-dipping subductions-possible application to the Tyrrhenian-Apennines system, Terra Nova, 3, 423-434, doi:10.1111/j.1365-3121.1991.tb00172.x.

Doglioni, C. (1994). Foredeeps versus subduction zones, Geology, 22, 271-274, doi:10.1130/0091-7613(1994)022<0271:FVSZ>2.3.CO;2.

Doglioni, C., M. Tropeano, F. Mongelli and P. Pieri (1996). Middle-Late Pleistocene uplift of Puglia: an "anomaly" in the Apenninic foreland, Mem. Soc. Geol. It., 51, 101-117.

Doglioni, C., P. Harabaglia, S. Merlini, F. Mongelli et al. (1999). Orogens and slabs vs their direction of subduction, Earth Sci. Rev., 45, 167-208, doi:10.1016/S0012-8252(98)00045-2.

Doglioni, C. and E. Carminati (2002). The effects of four subductions in NE Italy, Mem. Sci. Geol., 54, 1-4.

Doglioni, C., E. Carminati and M. Cuffaro (2006). Simple kinematics of subduction zones, Int. Geol. Rev., 48, 6, 479-493, doi:10.2747/0020-6814.48.6.479.

Dragoni, M., C. Doglioni, F. Mongelli and G. Zito (1996). Evaluation of Stresses in tow geodynamically different areas: stable foreland and extensional backarc, PAGEOPH, 146, 2, 0033-4553/96/020319-22.

Dushi, E. and J. Havskov (2023). 1D crustal structure of Albania region, Ann. Geophys., 66, 1, SE103, doi:10.4401/ag-8805.

Dziewonski, A. M. and D. L. Anderson (1984). Seismic tomography of the Earth's interior, Am. Sci., 72, 483-494.

El-Sharkawy, A., T. Meier, S. Lebedev, J. H. Behrmann et al. (2020). The slab puzzle of the Alpine-Mediterranean Region: Insights from a new, high-resolution, shear wave velocity model of the upper mantle, Geochem. Geophys. Geosyst., 21, e2020GC008993, doi:10.1029/2020GC008993.

El-Sharkawy, A., T. H. Hansteen, C. Clemente-Gomez, J. Fullea et al. (2024). Cenozoic volcanic provinces and shallow asthenospheric volumes in the Circum-Mediterranean: Evidence from magmatic geochemistry, seismic tomography, and integrated geophysical-petrological thermochemical inversion, Geochem. Geophys. Geosyst., 25, e2023GC011017, doi:10.1029/2023GC011017.

Eva, E., M. G. Malusà and S. Solarino (2020). Seismotectonics at the transition between opposite-dipping slabs (western Alpine region), Tectonics, 39, doi:10.1029/2020TC006086.

Faccenna, C., L. Jolivet, C. Piromallo and A. Morelli (2003). Subduction and the depth of convection in the Mediterranean mantle. J. Geophys. Res., 108

Faccenna, C., C. Piromallo, A. Crespo-Blanc, L. Jolivet et al. (2004). Lateral slab deformation and the origin of the Western Mediterranean arcs, Tectonics, 23, TC1012, doi:10.1029/2002TC001488.

Faccenna, C., T. W. Becker, L. Auer, A. Billi et al. (2014). Mantle dynamics in the Mediterranean, Rev. Geophys., 52, 283-332, doi:10.1002/2013RG000444.

Faccenna, C. and T. W. Becker (2020). Topographic expressions of mantle dynamics in the Mediterranean, Earth. Sci. Rev., 209, 103327, doi:10.1016/j. earscirev.2020.103327.

Fantoni, R. and R. Franciosi (2010). Tectono-sedimentary setting of the Po Plain and Adriatic foreland, Rend. Fis. Acc. Lincei, 21, 1, 197-209, doi:10.1007/s12210-010-0102-4.

Ferrucci, F., G. Gaudiosi, A. Hirn and R. Nicolich (1991). Ionian Basin and Calabria Arc: some new elements from DSS data, Tectonophysics, 195, 411-419.

Ficini, E., L. Dal Zilio, C. Doglioni and T. V. Gerya (2017). Horizontal mantle flow controls subduction dynamics, Sci. Rep., 7, 7550, doi:10.1038/s41598-017-06551-y.

Fox, M., F. Herman, E. Kissling and S. D. Willett (2015). Rapid exhumation in the Western Alps driven by slab detachment and glacial erosion, Geology, 43, 379-382, doi:10.1130/G36411.1.

Frasca, G., G. Manatschal and P. Chenin (2024). Kinematic reconstruction of the Alpine Tethys and surrounding Mesozoic rifted margins, Int. J. Earth Sci., 113, 1053-1065, doi:10.1007/s00531-024-02407-9.

Funiciello, F., M. Moroni, C. Piromallo, C. Faccenna et al. (2006). Mapping mantle flow during retreating subduction: Laboratory models analyzed by feature tracking, J. Geophys. Res., 111, B03402, doi:10.1029/2005JB003792.

Garzanti, E., G. Radeff and M. G. Malusà (2018). Slab breakoff: A critical appraisal of a geological theory as applied in space and time, Earth Sci. Rev., 177, 303-319, doi:10.1016/j.earscirev.2017.11.012.

Giacomuzzi, G., C. Chiarabba and P. De Gori (2011). Linking the Alps and Apennines subduction systems: New constraints revealed by high-resolution teleseismic tomography, Earth Planet. Sci. Lett., 301, 3-4, 531-543, doi:10.1016/j.epsl.2010.11.033.

Giacomuzzi, G., M. Civalleri, P. De Gori and C. Chiarabba (2012). A 3D Vs model of the upper mantle beneath Italy: Insight on the geodynamics of central Mediterranean, Earth Planet. Sci. Lett., 335-336, 105-120, doi:10.1016/j. epsl.2012.05.004.

Giacomuzzi, G., P. De Gori and C. Chiarabba (2022). How mantle heterogeneities drive continental subduction and magmatism in the Apennines, Sci. Rep., 12,1, 13631, doi:10.1038/s41598-022-17715-w.

Giglia, G., G. Capponi, L. Crispini and M. Piazza (1996). Dynamics and seismotectonics of the West-Alpine arc, Tectonophysics, 267, 1-4, 143-175, doi:10.1016/S0040-1951(96)00093-5.

Goes, S., F. J. Simons and K. Yoshizawa (2005). Seismic constraints on temperature of the Australian uppermost mantle, Earth Planet. Sci. Lett., 236, 227-237, doi:10.1016/j.epsl.2005.05.001.

Grad, M., T. Tiira and ESC Working Group (2009). The Moho depth map of the European Plate, Geophys. J. Int., 176, 279-292, doi:10.1111/j.1365-246X.2008.03919.x.

Hall, R. and W. Spakman (2015). Mantle structure and tectonic history of SE Asia, Tectonophysics, 658, 14-45, doi:10.1016/j.tecto.2015.07.003.

Handy, M., S. Schmid, R. Bousquet, E. Kissling et al. (2010). Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps, Earth Sci. Rev., 102, 121-158, doi:10.1016/j.earscirev.2010.06.002.

Handy, M. R., K. Ustaszewski and E. Kissling (2015). Reconstructing the Alps-Carpathians-Dinarides as a key to understanding switches in subduction polarity, slab gaps and surface motion, Int. J. Earth Sci. (Geol. Rundsch.), 104, 1-26, doi:10.1007/s00531-014-1060-3.

Handy, M. R., J. Giese, S. M. Schmid, J. Pleuger et al. (2019). Coupled crust-mantle response to slab tearing, bending, and rollback along the Dinaride-Hellenide orogen, Tectonics, 38, 2803-2828, doi:10.1029/2019TC005524.

Handy, M., S. Schmid, M. Paffrath, W. Friederich et al. (2021). Orogenic lithosphere and slabs in the greater Alpine area – interpretations based on teleseismic P-wave tomography, Solid Earth, 12, 2633-2669, doi:10.5194/se12-2633-2021.

Halpaap, F., S. Rondenay and L. Ottemöller (2018). Seismicity, deformation, and metamorphism in the Western Hellenic Subduction Zone: New constraints from tomography, J. Geophys. Res, Solid Earth, 123, 3000-3026, doi:10.1002/2017JB015154.

Heikkinen, P. J. and A. Korja (2018). BABEL4: Crustal Structures of the Precambrian Svecofennian Accretionary Orogen in the Fennoscandian Shield. In: Atlas of Structural Geological Interpretation from Seismic Images, A. A. Misra and S. Mukherjee (eds), Wiley Blackwell, Chichester, 197-199, doi:10.1002/9781119158332.ch38.

Jolivet, L., C. Faccenna, B. Huet, L. Labrousse et al. (2013). Aegean tectonics: Strain localisation, slab tearing and trench retreat, Tectonophysics, 597-598, 1-33, doi:10.1016/j.tecto.2012.06.011.

Jolivet, L., T. Baudin, S. Calassou, S. Chevrot et al. (2021). Geodynamic evolution of a wide plate boundary in the Western Mediterranean, near-field versus far-field interactions, Earth Sci. Bull., 192, 48, doi:10.1051/bsgf/2021043.

Jolivet, L. (2023). Tethys and Apulia (Adria), 100 years of reconstructions, C. R. Geosci., 355, S2, 1-20, doi:10.5802/crgeos.198.

Kaestle, E. D., A. El-Sharkawy, L. Boschi, T. Meier et al. (2018). Surface Wave Tomography of the Alps Using Ambient-Noise and Earthquake Phase Velocity Measurements, J. Geophys. Res. 123, 1770-1792, doi:10.1002/2017JB014698.

Kaestle, E. D., C. Rosenberg, L. Boschi, N. Bellahsen et al. (2020). Slab break-offs in the Alpine subduction zone, Int. J. Earth Sci. (Geol Rundsch), doi:10.1007/s00531-020-01821-z.

Karousová, H., J. Plomerová and V. Babuška (2013). Upper mantle structure beneath the southern Bohemian Massif and its surroundings imaged by high-resolution tomography, Geophys. J. Int., 194, 1203-1215, doi:10.1093/gji/ggt159.

Kelemework, Y., M. Milano, M. La Manna, G. de Alteriis et al. (2021). Crustal structure in the Campanian region (Southern Apennines, Italy) from potential field modeling, Sci. Rep., 11, 14510, doi:10.1038/s41598-021-93945-8.

Király, Á., C. Faccenna and F. Funiciello (2018). Subduction zones interaction around the Adria microplate and the origin of the Apenninic arc, Tectonics, 37, 3941-3953, doi:10.1029/2018TC005211.

Kissling, E. and W. Spakman (1996). Interpretation of tomographic images of uppermost mantle structure: Examples from the western and central Alps, J. Geodyn., 21, 1, 97-111, doi:10.1016/0264-3707(95)00029-1.

Kissling, E. and F. Schlunegger (2018). Rollback orogeny model for the evolution of the Swiss Alps, Tectonics, 37, 1097-1115, doi:10.1002/2017TC004762.

Koulakov, I., M. Kaban, M. Tesauro and S. Cloetingh (2009). P-and S-velocity anomalies in the upper mantle beneath Europe from tomographic inversion of ISC data, Geophys. J. Int., 179, 1, 345-366, doi:10.1111/j.1365-246X.2009.04279.x.

Lanari, R., R. Reitano, C. Faccenna, N. P. Piana Agostinetti et al. (2023). Surface and crustal response to deep subduction dynamics: Insights from the Apennines, Italy, Tectonics, 42, 3, e2022TC007461, doi:10.1029/2022TC007461.

Lardeaux, J. M., S. Schwartz, P. Tricart, A. Paul et al. (2006). A crustal-scale cross-section of the south-western Alps combining geophysical and geological imagery, Terra Nova, 18, 6, 412-422, doi:10.1111/j.1365-3121.2006.00706.x.

Latorre, D., R. Di Stefano, B. Castello, M. Michele et al. (2023). An updated view of the Italian seismicity from probabilistic location in 3D velocity models: the 1981-2018 Italian catalog of absolute earthquake locations (CLASS), Tectonophysics, 846, 229664, doi:10.1016/j.tecto.2022.229664.

Le Breton, E., M. R. Handy, G. Molli and K. Ustaszewski (2017). Post-20 Ma motion of the Adriatic plate: New constraints from surrounding Orogens and implications for crust-mantle decoupling, Tectonics, 36, 3135-3154, doi:10.1002/2016TC004443.

Le Breton, E., S. Brune, K. Ustaszewski, S. Zahirovic et al. (2021). Kinematics and extent of the Piemont-Liguria Basin – implications for subduction processes in the Alps, Solid Earth, 12, 885-913, doi:10.5194/se-12-885-2021.

Lo Bue, R., M. Faccenda and J. Yang (2021). The role of Adria plate lithospheric structures on the recent dynamics of the Central Mediterranean region, J. Geophys. Res., Solid Earth, 126, e2021JB022377, doi:10. 1029/2021JB022377.

Locardi, E. and R. Nicolich (2005). Crust-mantle structures and Neogene-Quarternary magmatism in Italy, Boll. Geof. Teor. Appl., 46, 169-180.

Lucente, F. P., C. Chiarabba, G. B. Cimini and D. Giardini (1999). Tomographic constraints on the geodynamic evolution of the Italian region, J. Geophys. Res., 104, 20307-20327, doi:10.1029/1999JB900147.

Lucente, F. P., L. Margheriti, C. Piromallo and G. Guilhem Barruol (2006). Seismic anisotropy reveals the long route of the slab through the western-central Mediterranean mantle, Earth Plan. Sci. Lett., 241, 3-4, 517-529, doi:10.1016/j.epsl.2005.10.041.

Luth, S., E. Willingshofer, M. ter Borgh, D. Sokoutis et al. (2013). Kinematic analysis and analogue modelling of the Passeier and Jaufen faults: implications for crustal indentation in the Eastern Alps, Int. J. Earth Sci., doi:10.1007/s00531-012-0846-4.

Magnoni, F., E. Casarotti, D. Komatitsch, R. Di Stefano et al. (2022). Adjoint tomography of the Italian lithosphere, Comm. Earth Environ., 3, 1, 69, doi:10.1038/s43247-022-00397-7.

Malinverno, A. and W. B. F. Ryan (1986). Extension in the Tyrrhenian Sea and shortening in the Apennines as a result of arc migration driven by sinking of the lithosphere, Tectonics, 5, 227-245, doi:10.1029/TC005i002p00227.

Malusà, M. G., C. Faccenna, S. L. Baldwin, P. G. Fitzgerald et al. (2015). Contrasting styles of (U)HP rock exhumation along the Cenozoic Adria-Europe plate boundary (Western Alps, Calabria, Corsica), Geochem. Geophy. Geosy., 16, 1786-1824, doi:10.1002/2015GC005767

Malusà, M. G., S. Guillot, L. Zhao, A. Paul et al. (2021). The deep structure of the Alps based on the CIFALPS seismic experiment: A synthesis, Geochem. Geophys. Geosyst., 22, e2020GC009466, doi:10.1029/2020GC009466.

Margheriti, L., S. Pondrelli, D. Piccinini, N. Piana Agostinetti et al. (2006). The subduction structure of the Northern Apennines: results from the RETREAT seismic deployment, Ann. Geophys., 49, N4/5, 1119-1131, doi:10.4401/ag-3107.

Markušic, S., Z. Gülerce, N. Kuka, L. Duni et al. (2016). An updated and unified earthquake catalogue for the Western Balkan Region, Bull. Earthq. Eng., 14, 321-343, doi:10.1007/s10518-015-9833-z.

Márton, E., D. Zampieri, P. Grandesso, V. Ćosović et al. (2010). New Cretaceous paleomagnetic results from the foreland of the Southern Alps and the refined apparent polar wander path for stable Adria, Tectonophysics, 480, 57-72, doi:10.1016/j.tecto.2009.09.003.

Mathey, M., C. Sue, C. Pagani, S. Baize et al. (2021). Present-day geodynamics of the Western Alps: new insights from earthquake mechanisms, Solid Earth, 12, 1661-1681, doi:10.5194/se-12-1661-2021.

Menichelli, I., P. De Gori, F. P. Lucente, L. Improta et al. (2023). Lithosphere structure, processes, and physical state of the alpine-apennine system, J. Geophys. Res. Solid Earth, 128, 4, e2023JB026411, doi:10.1029/2023jb026411.

Merlini, S., G. Cantarella and C. Doglioni (2000). On the seismic profile Crop M5 in the Ionian Sea, Boll. Soc. Geol. It., 119, 227-236.

Michailos, K., G. Hetényi, M. Scarponi, J. Stipčević et al. (2022). Moho depths beneath the European Alps: a homogeneously processed map and receiver functions database. Earth Syst. Sci. Data Discuss., 1-32, doi:10.5194/essd-15-2117-2023.

Molinari, I. and A. Morelli (2011). EPcrust: A reference crustal model for the European Plate, Geophys. J. Int., 185, 352-364, doi:10.1111/j.1365-246X.2011.04940.x.

Molli, G., L. Crispini, P. Mosca, P. Piana et al. (2010). Geology of the Western Alps-Northern Apennine junction area: a regional review, J. Virtual Explorer, 36, 1-49, doi:10.3809/jvirtex.2010.00215.

Monna, S., C. Montuori, C. Piromallo and L. Vinnik (2019). Mantle structure in the central Mediterranean region from P and S receiver functions, Geochem. Geophys. Geosyst., 20, doi:10.1029/2019GC008496.

Monna, S., C. Montuori, F. Frugoni, C. Piromallo et al. (2022). Moho and LAB across the Western Alps (Europe) from P and S receiver function analysis, J. Geophys. Res., Solid Earth, 127, doi:10.1029/2022JB025141.

Mooney, W. D., C. Barrera-Lopez, M. G. Suarez and M. A. Castelblanco (2023). Earth Crustal Model 1 (ECM1): A 1° × 1° Global Seismic and Density Model, Earth Sci. Rev., 243, doi:10.1016/j.earscirev.2023.104493.

Muttoni, G., E. Dallanave, J. E.T. Channell (2013). The drift history of Adria and Africa from 280Ma to Present, Jurassic true polar wander, and zonal climate control on Tethyan sedimentary facies, Palaeogeogr. Palaeoclimatol. Palaeoecol., 386, 415-435, doi:10.1016/j.palaeo.2013.06.011 .

Nicolich, R. (1981). Crustal structures in the Italian Peninsula and surrounding seas: a review of DSS data, in Sedimentary basins of Mediderranean margins, Wezel, F.C. (ed.), CNR Italian Project of Oceanography, Tecnoprint, Bologna, 3-17.

Nicolich, R. (2001). Deep seismic transects, in Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins, G. B. Vai and I. P. Martini (eds.), Springer, Dordrecht, 47-52, doi:10.1007/978-94-015-9829-3.

Nirta, G., M. Aberhan, V. Bortolotti, N. Carras et al. (2020. Deciphering the geodynamic evolution of the Dinaric orogen through the study of the ‘overstepping’ Cretaceous successions, Geol. Mag., 157, 1238-1264, doi:10.1017/S001675682000045X.

Nolet, G. (1981). Linearized inversion of (teleseismic) data, in The Solution of the Inverse Problem in Geophysical Interpretation, R. Cassinis (ed.), Plenum, New York, 9-37.

Nucci, R., E. Serpelloni, L. Faenza, A. Garcia et al. (2023). Comparative Analysis of Methods to Estimate Geodetic Strain Rates from GNSS Data in Italy, Ann. Geophys., 66, 5, DM531, doi:10.441/ag-9015.

Oldow, J. S., L. Ferranti, D. S. Lewis, J. K. Campbell et al. (2002). Active fragmentation of Adria, the north Africa promontory, central Mediterranean orogen, Geology, 30, 779-782.

Orešković, J., F. Šumanovac and E. Hegedűs (2011). Crustal structure beneath Istra peninsula based on receiver function analysis, Geofizika, 28, 247-263.

Paffrath, M., W. Friederich, S. M. Schmid, M. R. Handy et al. (2021). Imaging structure and geometry of slabs in the greater Alpine area – a Pwave travel-time tomography using AlpArray Seismic Network data, Solid Earth, 12, 2671-2702, doi:10.5194/se-122671-2021.

Panza, G. F., S. T. Mueller and G. Calcagnile (1980). The gross features of the Lithosphere-Asthenosphere system in Europe from Seismic Surface Waves and Body Waves, Pageoph, 118, 1209-1213, doi:10.1007/BF01593061.

Pauselli, C., R. M. Barchi, F. Costanzo, M. B. Magnani et al. (2006). The crustal structure of the Northern Apennines (Central Italy): An insight by the CROP03 seismic line, Am. J. Sci., 306, 6, doi:10.2475/06.2006.02.

Pearce, F. D., S. Rondenay, M. Sachpazi, M. Charalampakis et al. (2012). Seismic investigation of the transition from continental to oceanic subduction along the western Hellenic subduction Zone, J. Geophys. Res., 117, B07306, doi:10.1029/2011JB009023.

Petricca, P., E. Carminati and C. Doglioni (2019). The Decollement depth of active thrust faults in Italy: implications on potential earthquake magnitude, Tectonics, 38, 3990-4009, doi:10.1029/2019TC005641.

Pezzo, G., L. Petracchini, R. Devoti, R. Maffucci et al. (2020). Active fold-thrust belt to foreland transition in northern Adria, Italy, tracked by seismic reflection profiles and GPS offshore data, Tectonics, 39, e2020TC006425, doi:10.1029/2020TC006425.

Pfiffner, O. A. (2014). Geology of the Alps, John Wiley and Sons, New York, NY, 400, ISBN:10:1118708121 .

Piana Agostinetti, N., V. Levin and J. Park (2008). Crustal structure above a retreating trench: Receiver function study of the northern Apennines orogen, Earth Planet. Sci. Lett., 275, 211-220, doi:10.1016/j.epsl.2008.06.022.

Piana Agostinetti, N., I. Bianchi, A. Amato and C. Chiarabba (2011). Fluid migration in continental subduction: The Northern Apennines case study, Earth Plan. Sci. Lett., 302, 267-278, doi:10.1016/J.EPSL.2010.10.039.

Piana Agostinetti, N. and A. Amato (2009). Moho depth and Vp/V sratio in peninsular Italy from teleseismic receiver functions, J. Geophys. Res., 114, B06303, doi:10.1029/2008JB005899.

Piccardi, L., F. Sani, G. Moratti, D. Cunningham et al. (2011). Present-day geodynamics of the circum-Adriatic region: An overview, J. Geodyn., 51, 81-89, doi:10.1016/j.jog.2010.09.002.

Piromallo, C. and A. Morelli (2003). P wave tomography of the mantle under the Alpine-Mediterranean area, J. Geophys. Res., 108, B2, 2065, doi:10.1029/2002JB001757.

Piromallo, C. and C. Faccenna (2004). How deep can we find the traces of Alpine subduction? Geophys. Res. Lett., 31, L06605, doi:10.1029/2003GL019288.

Platt, J. P., J. H. Behrmann, P. C. Cunningham, J. F. Dewey et al. (1989). Kinematics of the Alpine arc and the motion history of Adria, Nature, 337, 158-161, doi:10.1038/337158a0.

Plomerová, J., H. Zlebcíková, G. Hetényi, L. Vecsey et al. (2022). Two subduction-related heterogeneities beneath the Eastern Alps and the Bohemian Massif imaged by high-resolution P-wave tomography, Solid Earth, 13, 251-270, doi:10.5194/se-13-251-2022.

Pondrelli, S., S. Salimbeni, P. Baccheschi, J. M. Confal et al. (2023). Peeking inside the mantle structure beneath the Italian region through SKS shear wave splitting anisotropy: a review, Ann. Geophys., 66, 2, doi:10.4401/ag-8872.

Pondrelli, S., S. Salimbeni, J. M. Confal, M. G. Malusa et al. (2024). Highlights on mantle deformation beneath the Western Alps with seismic anisotropy using CIFALPS2 data, Solid Earth, 15, 827-835, doi:10.5194/se-15-827-2024.

Ponziani, F., R. De Franco, G. Minelli, G. Biella (1995). Crustal shortening and duplication of the Moho in the Northern Apennines: a view from seismic refraction data, Tectonophysics, 252, 391-418, doi:10.1016/0040-1951(95)00093-3.

Racano, S., P. A. van der Beek, T. F. Schildgen, C. Faccenna et al. (2024). Slab driven Quaternary rock-uplift and topographic evolution in the northern-central Apennines from linear inversion of the drainage system, Geochem. Geophys. Geosyst., 25, e2024GC011592, doi:10.1029/2024GC011592.

Rajh, G., J. Stipčević, M. Živčić, M. Herak et al. (2022). One-dimensional velocity structure modeling of the Earth's crust in the northwestern Dinarides, Solid Earth, 13, 177-203, doi:10.5194/se-13-177-2022.

Rappisi, F., B. P. VanderBeek, M. Faccenda, A. Morelli et al. (2022). Slab geometry and upper mantle flow patterns in the Central Mediterranean from 3D anisotropic P-wave tomography, J. Geophys. Res., Solid Earth, 127, e2021JB023488, doi:10.1029/2021JB023488.

Romagny, A., L. Jolivet, A. Menant, E. Bessière et al. (2020). Detailed tectonic reconstructions of the Western Mediterranean region for the last 35 Ma, insights on driving mechanisms, Earth Sci. Bull., 191, 37, doi:10.1051/bsgf/2020040.

Royden, L. H. and B. C. Burchfiel (1989). Are systematic variations in thrust belt style related to plate boundary processes? (The Western Alps versus the Carpathians), Tectonics, 8, 51-62, doi:10.1029/TC008i001p00051.

Royden, L. H. (1993). Evolution of retreating subduction boundaries formed during continental collision, Tectonics, 12, 629-638, doi:10.1029/92TC02641.

Sachpazi, M., M. Laigle, M. Charalampakis, J. Diaz et al. (2016). Segmented Hellenic slab rollback driving Aegean deformation and seismicity, Geophys. Res. Lett., 43, 651-658, doi:10.1002/2015GL066818.

Salimbeni, S., S. Pondrelli, I. Molinari, J. Stipčević et al. (2022). Seismic anisotropy across Adria plate, from the Apennines to the Dinarides, Front. Earth Sci., 10:881138, doi:10.3389/feart.2022.881138.

Scafidi, D., S. Solarino and C. Eva (2009). P wave seismic velocity and Vp/Vs ratio beneath the Italian Peninsula from local earthquake tomography, Tectonophysics, 465, 1-23, doi:10.1016/j.tecto.2008.07.013.

Scarascia, S., A. Lozej and R. Cassinis (1994). Crustal structures of the Ligurian, Tyrrhenian and Ionian seas and adjacent onshore areas interpreted from wide-angle seismic profile, Boll. Geofis. Teor. Appl., 36, 5-19.

Scardia, G., G. Muttoni and D. Sciunnach (2006). Subsurface magnetostratigraphy of Pleistocene sediments from the Po Plain (Italy): Constraints on rates of sedimentation and rock uplift, Geol. Soc. Am. Bull., 118, 1299-1312, doi:10.1130/B25869.1.

Scarponi, M., G. Hetényi, J. Plomerová, S. Solarino et al. (2021). Joint Seismic and Gravity Data Inversion to Image Intra-Crustal Structures: The Ivrea Geophysical Body along the Val Sesia Profile (Piedmont, Italy), Front. Earth Sci., 9, 671412, doi:10.3389/feart.2021.671412.

Schaefer, J. F., L. Boschi and E. Kissling (2011). Adaptively parametrized surface wave tomography: Methodology and a new model of the European upper mantle, Geophys. J. Int., 186, 3, 1431-1453, doi:10.1111/j.1365-246X.2011.05135.x.

Schettino, A. and E. Turco (2011). Tectonic history of the Western Tethys since the Late Triassic, Bull. Geol. Soc. Am., 123, 89-105, doi:10.1130/B30064.1.

Schmid, S. M., B. Fügenschuh, E. Kissling and R. Schuster (2004). Tectonic map and overall architecture of the Alpine orogen, Eclogae Geol. Helv., 97, 1, 93-117, doi:10.1007/s00015-004-1113-x.

Schmid, S. M., E. Kissling, T. Diehl, D. J. J. van Hinsbergen et al. (2017). Ivrea mantle wedge, arc of the Western Alps, and kinematic evolution of the Alps-Apennines orogenic system, Swiss J. Geosci., doi:10.1007/s00015-016-0237-0.

Schmid, S. M., B. Fügenschuh, A. Kounov, L. Matenco et al. (2020). Tectonic units of the Alpine collision zone between Eastern Alps and Western Turkey, Gondwana Res., 78, 308-374, doi:10.1016/j.gr.2019.07.005.

Schuler, C., B. Kaus, E. Le Breton and N. Riel (2024). Investigating the plate motion of the Adriatic microplate by 3D thermomechanical modelling, EGU General Assembly 2024, Vienna, Austria, 14-19 Apr 2024, EGU24-5274, doi:10.5194/egusphere-egu24-5274.

Scrocca, D., E. Carminati, C. Doglioni and D. Marcantoni (2007). Slab retreat and active shortening along the central-northern Apennines, in Thrust belts and foreland basins, Springer, Berlin, Heidelberg, 471-487. doi:10.1007/978-3-540-69426-7_25

Serpelloni, E., C. Faccenna, G. Spada, D. Dong et al. (2013). Vertical GPS Ground Motion Rates in the Euro-Mediterranean Region: New Evidence of Velocity Gradients at Different Spatial Scales along the Nubia-Eurasia Plate Boundary, J. Geophys. Res. Solid Earth, 118, 6003-6024, doi:10.1002/2013JB010102.

Serpelloni, E., A. Cavaliere, L. Martell, F. Pintori et al. (2022). Surface velocities and strain-rates in the Euro-Mediterranean region from massive GPS data processing, Front. Earth Sci., 10, doi:10.3389/feart.2022.907897.

Slejko, D., G. B. Carulli, R. Nicolich, A. Rebez et al. (1989). Seismotectonics of the eastern southern Alps: a review, Boll. Geof. Teor. Appl., 31, 109-136.

Slejko, D., G. Neri, I. Orozova, G. Renner et al. (1999). Stress Field in Friuli (NE Italy) from fault plane solutions of activity following the 1976 main shock, Bull. Seismol. Soc. Am., 89, 1037-1052, doi:10.1785/BSSA0890041037.

Solarino, S., M. G. Malusà, E. Eva, S. Guillot et al. (2018). Mantle wedge exhumation beneath the Dora-Maira (U) HP dome unraveled by local earthquake tomography (Western Alps), Lithos, 296, 623-636, doi:10.1016/j.lithos.2017.11.035.

Spada, M., I. Bianchi, E. Kissling, N. P. Agostinetti et al. (2013). Combining controlled-source seismology and receiver function information to derive 3-D Moho topography for Italy, Geophys. J. International, 194, 1050-1068, doi:10.3929/ethz-b-000070318.

Spakman, W. (1990). Tomographic images of the upper mantle below central Europe and the Mediterranean, Terra Nova, 2, 542-553, doi:10.1111/j.1365-3121.1990.tb00119.x.

Spakman, W. and R. Wortel (2004). A Tomographic View on Western Mediterranean Geodynamics, in W. Cavazza, F. Roure, W. Spakman, G. M. Stampfli et al. (Eds.), The TRANSMED Atlas. The Mediterranean Region from Crust to Mantle: Geological and Geophysical Framework of the Mediterranean and the Surrounding Areas, Springer Berlin Heidelberg, Berlin, Heidelberg, 31-52, 0.1007/978-3-642-18919-7_2.

Stampfli, G. M. (2005). Plate Tectonics of the Apulia-Adria Microcontinents, in CROP PROJECT: Deep Seismic Exploration of the Central Mediterranean and Italy, I. R. Finetti (ed.), Elsevier, The Netherlands, 747-766, ISBN: 9780080457604.

Stampfli, G. M. and C. Hochard (2009). Plate tectonics of the Alpine realm. In: Ancient Orogens and Modern Analogues, J. B. Murphy and A. J. Hynes (eds.), Geol. Soc. Spec. Publ., 327, 89-111, doi:10.1144/SP327.6

Stipčević, J., M. Herak, I. Molinari, I. Dasović et al. (2020). Crustal thickness beneath the Dinarides and surrounding areas from receiver functions, Tectonics, 37, doi:10.1029/2019TC005872.

Suckale, J., S. Rondenay, M. Sachpazi, M. Charalampakis et al. (2009). High-resolution seismic imaging of the western Hellenic subduction zone using teleseismic scattered waves, Geophys. J. Int., 178, 775-791, doi:10.1111/j.1365-246X.2009.04170.x.

Šumanovac, F., J. Orešković, M. Grad and ALP2002 Working Group (2009). Crustal structure at the contact of the Dinarides and Pannonian Basin based on 2-D seismic and gravity interpretation of the Alp07 profile in the ALP2002 experiment, Geophys. J. Int., 179, 615-633, doi:10.1111/j.1365-246X.2009.04288.x.

Šumanovac, F. (2015). Lithosphere of the Pannonian-Adriatic overthrusting, Tectonophysics, 665, 79-91, doi:10.1016/j.tecto.2015.09.032.

Šumanovac, F. (2022). Lithosphere Structure of the Southern Dinarides and Continuity of the Adriatic Lithosphere Slab Beneath the Northern Dinarides Unravelled by Seismic Modelling, Geosciences, 12, 439, doi:10.3390/geosciences12120439.

Tesauro, M., M. K. Kaban and S. A. P. L. Cloetingh (2008). EuCRUST-07: A new reference model for the European crust, Geophys. Res. Lett., 35, L05313, doi:10.1029/2007GL032244.

Toljic, M., L. Matenco, U. Stojadinovic, E. Willingshofer et al. (2018). Understanding fossil fore-arc basins: Inferences from the Cretaceous Adria Europe convergence in the NE Dinarides, Glob. Planet. Change, 171, 167-184, doi:10.1016/j.gloplacha.2018.01.018

Trümpy, R. (2001). Why plate tectonics was not invented in the Alps, Int. J. Earth Sci., 90, 477-483, doi:10.1007/s005310000175.

Tugend, J., N. Chamot-Rooke, S. Arsenikos, C. Blanpied et al. (2019). Geology of the Ionian Basin and margins: A key to the East Mediterranean geodynamics, Tectonics, 38, 2668-2702, doi:10.1029/2018TC005472.

Turco, E., C. Macchiavelli, G. Penza, A. Schettino et al. (2021). Kinematics of Deformable Blocks: Application to the Opening of the Tyrrhenian Basin and the Formation of the Apennine Chain, Geosciences, 11, 177, doi:10.3390/geosciences11040177.

Ustaszewski, K., S. M. Schmid, B. Fügenschuh, M. Tischler et al. (2008). A map-view restoration of the Alpine-Carpathian-Dinaridic system for the Early Miocene, Swiss J. Geosci., 101, 273-294. doi:10.1007/s00015-008-1288-7.

Ustaszewski, K., A. Kounov, S. M. Schmid, U. Schaltegger et al. (2010). Evolution of the Adria-Europe plate boundary in the northern Dinarides: From continent-continent collision to back-arc extension, Tectonics, 29, TC6017, doi:10.1029/2010TC002668.

Van Agtmaal, L., Y. Van Dinther, E. Willingshofer and L. Matenco (2022). Quantifying continental collision dynamics for Alpine-style orogens, Front. Earth Sci., 10:916189, doi:10.3389/feart.2022.916189.

Van Gelder, I. E., E. Willingshofer, P. A. M. Andriessen, R. Schuster et al. (2020). Cooling and vertical motions of crustal wedges prior to, during and after lateral extrusion in the Eastern Alps: new field kinematic and fission track data from the Mur-Mürz fault system, Tectonics, 39, e2019TC005754, doi:10.1029/2019TC005754.

Van Hinsbergen, D. J. J., M. Mensink, C. G. Langereis, M. Maffione et al. (2014). Did Adria rotate relative to Africa?, Solid Earth, 5, 611-629, doi:10.5194/se-5-611-2014.

Van Hinsbergen, D. J. J., T. H. Torsvik, S. M. Schmid, L. C. Matenco et al. (2020). Orogenic architecture of the Mediterranean region and kinematic reconstruction of its tectonic evolution since the Triassic, Gondwana Res., 81, 79-229, doi:10.1016/j.gr.2019.07.009.

Volpi, V., A. Del Ben, D. Civile and F. Zgur (2017). Neogene tectono-sedimentary interaction between the Calabrian accretionary wedge and the Apulian foreland in the northern Ionian Sea, Mar. Pet. Geol., 83, 246-260, doi:10.1016/j.marpetgeo.2017.03.013.

Vukovski, M., M. Spelic, D. Kukoc, T. Troskot-Corbic et al. (2024). Unravelling the tectonic evolution of the Dinarides-Alps-Pannonian Basin transition zone: insights from structural analysis and low-temperature thermochronology vom Ivanscica Mt., NW Croatia, Swiss J. Geosc., 117, 16, doi:10.1186/s00015-024-00464-5.

Waldhauser, F., E. Kissling, J. Ansorge and S. T. Mueller (1998). Three-dimensional interface modelling with two-dimensional seismic data: the Alpine crust-mantle boundary, Geophys. J. Int., 135, 264-278, doi:10.1046/j.1365-246X.1998.00647.x.

Ward, S. (1994). Constraints on the seismotectonics of the central Mediterranean from very long baseline interferometry, Geophys. J. Int. 11, 441-452, doi:10.1111/j.1365-246X.1994.tb03943.x.

Willingshofer, E. and S. Cloetingh (2003). Present-day lithospheric strength of the Eastern Alps and its relationship to neotectonics, Tectonics, 22, 6, 1075, doi:10.1029/2002TC001463.

Wortel, M. J. R. and W. Spakman (2000). Subduction and slab detachment in the Mediterranean-Carpathian region, Science, 290, 1910-1917, doi:10.1126/science.290.5498.191.

Wortel, M. J. R., W. Spakman and R. Govers (2009). Continental Collision and the STEP-wise Evolution of Convergent Plate Boundaries: The Mediterranean Region, in Subduction Zone Geodynamics S. Lallemand and F. Funiciello (Eds.), Front. Earth Sci., Springer, 47-59, doi:10.1007/978-3-540-87974-9_3.

Zailac, K., B. Matos, I. Vlahovic and J. Sptipcevic (2023). Reference seismic crustal model of the Dinarides, Solid Earth, 14, 1197-1220, doi:10.5194/se-14-1197-2023.

Zhao, L., A. Paul, M. G. Malusà, X. Xu et al. (2016). Continuity of the Alpine slab unraveled by high-resolution P wave tomography, J. Geophys. Res., 121, 8720-8737, doi:10.1002/2016JB013310.

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