Plio-Quaternary interaction between Adria and surrounding orogens: a Central-Northern Apennines perspective

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ABSTRACT
The active interaction of the foreland domain represented by the Adria Foreland Plate and the surrounding orogenic systems is discussed by taking a perspective from the Central-Northern Apennines. The present-day tectono-kinematic framework of the Adriatic and surrounding regions is considered with respect to structural setting of the Central-Northern Apennines, developed as a Pliocene lateral chain relative to the NW-SE Africa-Europe convergence. Within this context, the short-term kinematics of the Adria Plate, characterized by a firm NNE-directed kinematics relative to the stable Europe, seismicity and the crustal structure are taken into account to explain the role of Adria on the kinematics of the Apennine orogenic prism and on the active deformation affecting the retro-belt. In this study, the current central-northern portion of the Adria Plate is considered as dissected into four independent crustal/lithospheric blocks, characterized by distinctive kinematic patterns, structural and seismotectonic characteristics. Notwithstanding the largely debated geodynamic models proposed in the literature, the active interaction among the identified crustal blocks within the framework of the short-term kinematics and seismogenic context of the Adria Plate, characterized by a retro-translational counterclockwise motion, and surrounding orogenic systems is discussed.

1. Introduction
The evolution of the peri-Adriatic Apennine-Alpine-Dinaric-Hellenic orogenic system and Maghrebian chain is associated with the convergence between the European and African plates and their interaction with the interposed Adria microplate (Mantovani et al., 2009; Viti et al., 2011; Carminati & Doglioni, 2012; Le Breton et al., 2017; van Hinsbergen et al., 2020 and references therein). The development of this circum-mediterranean orogenic system is accompanied by the opening of extensional basins rooted on oceanic and/or thinned continental crust, like the Liguro-Provenzal Basin, the Valencia Through, the Alboran Sea and the Tyrrhenian Sea, in the western sector, and the Pannonian and Aegean Sea basins in the eastern sector (Figure 1). Different geodynamic models invoking or not subduction-related processes have been proposed to explain the tectonic evolution that led to the development of these orogenic systems and extensional basins from the Oligocene times onwards (e.g. Carminati et al., 2012; van Hinsbergen et al., 2020).

The Africa-Europe convergence and their interaction with the micro-plates interposed in between (i.e. Adria) resulted in the development of frontal orogenic systems, like the Alps and the Maghrebian chain, as well as of lateral orogens, such as the Apennines, the Dinarides, the Albanides and the Hellenides (Figure 1 and Figure 2); Mantovani et al., 2009; Piccardi et al., 2011; Carminati & Doglioni, 2012; Carminati et al., 2012; van Hinsbergen et al., 2020). Within this context, the Apennines, Alps and Dinarides orogenic systems generated at the expenses of the eastern, northern and western Adria paleomargins, respectively, following the closure of the western Tethyan oceanic arms (Carminati & Doglioni, 2012; Carminati et al., 2012; Mantovani et al., 2009; van Hinsbergen et al., 2020).

In this contribution, the structural evolution of the Central-Northern Apennines, considered as a Pliocene lateral chain (i.e. a chain grown orthogonal/lateral to the plate convergence; Boccaletti et al., 1982, Boccaletti et al., 2005; Mantovani et al., 1997, 2009, 2019, 2020a, b) relative to the NNW-SSE Africa-Europe convergence (Figure 1 and Figure 2), is discussed within the present-day tectono-kinematic framework of the Adria Plate and surrounding thrust belts. Notwithstanding the various models proposed in the literature to explain the geodynamic evolution of the Apennine Orogen (e.g. Boccaletti et al., 1971; Reutter et al., 1989; Boccaletti et al., 1982; Locardi, 1982; Wezel, 1985; Malinverno & Ryan, 1986; Finetti and Del Ben, 1986; Tapponnier, 1997; Royden et al., 1987; Lavecchia, 1988; Lavecchia & Stoppa, 1989; Patacca and Scandone, 1989; Carmignani & Kligefield, 1990; Doglioni, 1991; Faccenna et al., 1996; Mantovani et al., 2009; Piccardi et al., 2011; Carminati & Doglioni, 2012; Carminati et al., 2012; van Hinsbergen et al., 2020).
et al., 1997; Faccenna et al., 2001; Carminati et al., 2010; Carminati & Doglioni, 2012; Mantovani et al., 2009; Johnston & Mazzoli, 2009; Chiarabba & Chioldini, 2013; Chiarabba et al., 2014; Brancolini et al., 2019) the present-day movement of the Adria Plate is characterized by a firm NNE kinematics relative to the stable Europe (e.g. Cenni et al., 2012; Devoti et al., 2011, 2010, 2008; Metois et al., 2015; Pezzo et al., 2020). Within this context and independently from the geodynamic framework, in this study we consider the kinematic pattern, seismicity and the crustal-lithospheric structure of the central-northern portion of the Adria Plate to better understand its active interaction with the Pliocene-Quaternary evolution of the Central-Northern Apennine orogenic system and the building of the peri-Adriatic thrust belts.

2. The Apennine orogenic system

The Apennines are a NE-verging fold-and-thrust belt that developed from Oligocene time onward in response to the convergence between Africa and Europe (e.g. Boccaletti et al., 1990, 2005, 1971; Carmignani & Kligfield, 1990; Carminati & Doglioni, 2012). The Apennine Orogen extends for ca. 1500 km with a NW-SE trend from the Po Plain, in northern Italy, southward to the Calabrian Arc physically linking the Western and Southern Alps with Sicilian-Maghrebian orogenic systems (Figure 1). It can be defined as a 'lateral' chain (Boccaletti et al., 2005, 1971) relative to the Europe-Africa convergent plate motion, which is NW-directed from the late Tortonian (Mazzoli & Helman, 1994) to present (Argnani et al., 1994; Sella et al., 2002), whereas the roughly E-W-trending Alps and Sicilian-Maghrebian systems can be considered as 'frontal' orogens (Figure 1 and Figure 2).

The present setting of the Apennines results from the interaction between the Corsica-Sardinia continental block, of European affinity, and the Adria continental block, of African affinity. The latter is controversially considered as either an indenter of the African Plate, the so-called 'African promontory' (Argand, 1924; Channel et al., 1979; Dewey et al., 1989; McKenzie, 1972) or as an independent microplate (Anderson, 1987; Anderson & Jackson, 1987; Battaglia et al., 2004; Nocquet & Calais, 2004; Pinter et al., 2006; Ricou et al., 1986).

The geodynamic evolution of the Apennine Orogen has been explained as the result of various driving mechanisms such as: back-arc-related extension (Boccaletti et al., 1971; Malinverno & Ryan, 1986; Royden et al., 1987; Doglioni et al., 1997; Faccenna et al., 2001; Rosenbaum & Lister, 2004), delamination (Chiarabba and Chioldini, 201; Chiarabba et al., 2014), asthenospheric upwelling associated with gravitational collapse (Locardi, 1982; Wezel, 1985) or large-scale wrench faulting (Lavecchia, 1988; Lavecchia & Stoppa, 1989), late-orogenic collapse of an overthickened accretionary wedge (Carmignani & Kligfield, 1990), lateral extrusion of the Apennine orogenic wedge induced by plate convergence (Tapponier, 1977; Boccaletti et al., 1982; Faccenna et al., 1996;
Mantovani et al., 1997, 2009, 2019, 2020a, b; Boccaletti et al., 2005; Viti et al., 2021), or lithospheric buckling (Bertotti et al., 2001; Johnston & Mazzoli, 2009).

The overall Apennine Orogen is composed of stacked tectono-stratigraphic units belonging to different paleogeographic domains. Inner (western) units of both oceanic and continental affinity (allochthonous units) were tectonically superimposed onto the outer (eastern) units belonging and developed on the western Mesozoic continental margin of Adria (Apennine units s.s.; Tuscan, Umbria-Marche, Latium-Abruzzi and Apulian carbonate units; Boccaletti et al., 2005). The

Figure 2. Simplified tectonic map of the Apennine-Adriatic thrust belt-foreland system and surrounding regions, compiled from (Ben Avraham et al., 1990; Carminati & Doglioni, 2012; Mantovani et al., 2009; Scisciani & Calamita, 2009). Olevano-Antrodoco-Sibillini (O-A-S) and Sangro-Volturno (S-V) transverse tectonic lineaments.
allochthonous units can be subdivided into the allochthonous Ligurian units, derived from the subduction of the Alpine Tethys oceanic crust during the Alpine orogeny (Carmignani & Kligfield, 1990), and the allochthonous Apennine units. The latter, which are mainly found in the Southern Apennines, are further divided into the Lagonegro Molise units with Ionian Neo-Tethys affinity and the inner carbonate units (Apenninic and Panormide platforms; Ben Avraham et al., 1990; Finetti et al., 1996) belonging to the continental block located between the Alpine and Ionian Oceans (Finetti & Del Ben, 2005; Stampfli, 2005).

The architecture of the Apennines thrust system is arranged in two major arcs, the Northern Apennines Arc and the Southern Apennines-Calabrian Arc, with NE and SE convexity, respectively (Figure 1). The Central Apennines represent the transitional junction between the Northern and the Southern Apennines arches. Two main transverse structural lineaments, trending approximately N-S, bound the Central Apennines, respectively, towards the NW and SE (Figure 2): the Olevano-Antrodoco-Sibillini and the Sangro-Volturino or Ortona-Roccamonfina cross-strike discontinuities (Calamita et al., 2011; Pace & Calamita, 2014). Because these two important transverse faults intersect the main trend of the structures at a high angle, they compartmentalize both the Apennine thrust system (Butler et al., 2006; Tavarnelli et al., 2004) and the active extensional fault array with annexed seismicity (Di Domenica et al., 2012; Pirzi & Galadini, 2009). Within this context, the cross-trending faults are considered as basement-involved Mesozoic, or probably older, extensional discontinuities that were reactivated during the Neogene as important oblique thrust ramps enveloping the Plio-Quaternary frontal thrusts of the Central-Northern Apennine chain (Calamita et al., 2011; Di Domenica et al., 2012; Pace & Calamita, 2014). The NWW-SSE-trending thrust-and-related folds of the Northern and Central Apennines merge towards the south, respectively, into the NNE-SSW Olevano-Antrodoco-Sibillini and Sangro-Volturino oblique thrust ramps, defining the typical curved shape of the Apennine orogenic belt. Such curved geometries were strongly influenced by the original architecture of the Adria paleo-margin, which developed during the Triassic and Early Jurassic extension (e.g. Butler et al., 2006; Calamita et al., 2018, 2021; Pace et al., 2020, 2017, 2011; Scisciani et al., 2019; Tavarnelli et al., 2019).

Two main steps can be identified within the evolutionary history of the Apennine Orogen, which started from the late Oligocene time onwards following the closure of the Alpine Tethys. The ‘Balearic stage’ (late Oligocene-early Miocene) during which the Corsica-Sardinia block detaches from the European margin and rotates counter-clockwise reaching its present-day setting during the early Miocene and undergoing important deformation and migration in the subsequent evolution. This process has been accompanied by the sinistral transtensional opening of the Liguro-Provencal Basin (Finetti et al., 2001) and by the subduction of the Alpine Tethys underneath both the Corsica-Sardinia block and the westernmost European margin. The collision between Corsica and Adria blocks occurred and compressional tectonics started in the Northern Apennines (Finetti et al., 2005). According to some authors, Balearic basin opening was also coupled with the lateral extrusion of the Alpine belt flanked by the Apennine belt (Mantovani et al., 1997, 2009; Tapponier, 1977).

The ‘Tyrrenian stage’ (Middle Miocene to Present) during which the opening of the Tyrrenian Basin occurs with extension progressively increasing from the northern Tyrrenian Sea to the Sicilian-Calabrian margins (Finetti et al., 2001) or with distinct phases (Sartori, 2005). The Apennine imbricate thrust belt started to develop with a chain-foredeep-foreland system progressively migrating towards the foreland as documented by the progressively younger age of siliciclastic foredeep deposits towards the east (Boccaletti et al., 1990). Within this last stage, pre- and post-Pliocene evolutionary phases have been recognized (Boccaletti et al., 2005). Starting from the early Pliocene, the orogenic system, carrying on top far-travelled allochthonous units, rapidly migrates towards the east, giving rise to a continuous and subsiding foredeep basin extending from the Northern Apennines foothills to the Sangro-Volturino oblique thrust ramp (Satolli et al., 2014). This process is related to a lithospheric-scale thrust that envelopes the western curved thrust systems of the Northern and Central Apennines defining the so-called Pliocene-Quaternary neo-chain (Boccaletti et al., 2005). This is the most dynamic phase of the Apennine foreland thrust belt evolution, during which compressional tectonics involves also the innermost basins (Boccaletti et al., 1999). Before these two main stages recognized for the evolutionary history of the Apennine Orogen, earlier contractual events coeval to the Alpine-Dinaric tectonics were also documented as in the outer zone of the Central Apennines (late Cretaceous- middle Miocene; Calamita et al., 2021) and along the Mid-Adriatic Ridge in the foreland (late Cretaceous- Oligocene; Pace et al., 2015; Scisciani, 2009).

During the most recent (late Pliocene-Quaternary) evolution of the orogenic wedge, the outer Apennine thrust front slows down, localizing present-day seismogenic activity in the Northern Apennines, from the Po Plain, through the Adriatic coast-line, to the Conero promontory (Boncio & Bacron, 2009; Costa et al., 2021; Lavecchia et al., 2003; Pezz0 et al., 2020; Pierantoni et al., 2019). Conversely, in the Southern Apennines the thrust front is completely deactivated and buried in the Bradanic foredeep southwestward to the
Apulian region (Patacca & Scandone, 2007; Vezzani et al., 2010). The Quaternary evolution of the Apennine Orogen is characterized by post-orogenic extension in the axial zone of the carbonate ridge (Figure 2). NW-SE trending normal/transtensive active fault systems with associated seismicity (Calamita & Pizzi, 1994; Pizzi et al., 2017; Roberts & Michetti, 2004; Sani et al., 2016) bound Quaternary intermontane basins that are localized in their hanging wall blocks. They are mainly composed of en-echelon SW-dipping high-angle faults with lengths ranging from a few kilometres to 15–35 km and downthrows of hundreds of meters (Pizzi & Galadini, 2009) and some of them rejuvenate the inherited pre-thrusting (Jurassic-Miocene) discontinuities (Pizzi & Scisciani, 2000). Fault slip data measured along Quaternary/active fault planes and earthquake focal mechanisms reveal an ongoing extension driven by a nearly horizontal NE-trending $\sigma_3$ axis (e.g. Calamita et al., 2000; Pizzi et al., 2017; Pizzi & Galadini, 2009; Puliti et al., 2020) as discussed in detail by Sani et al. (2016).

3. Active tectono-kinematic framework of the Central-Northern Apennines-Adriatic thrust belt-foreland system

3.1. Seismicity

Recent seismicity recorded in the peri-Adriatic region suggests that active deformation mainly occurs within the Adria Plate (Figure 3). Several earthquakes are distributed along the thrust belts surrounding the Adriatic region and in particular along the Northern Apennines, in the Southern Alps and along the Dinaric-Albanian-Hellenic thrust fronts. In addition, medium-to-low grade seismicity also affects the Adriatic foreland.

Figure 3. Earthquake focal mechanisms distribution in the peri-Adriatic region, modified from Sani et al. (2016) and references therein. GCMT: Global Centroid Moment Tensor project; ETHZ: Eidgenössische Technische Hochschule Zürich; RCMT: European-Mediterranean Regional Centroid Moment Tensor; TDMT: Time Domain Moment Tensor; EMMA: Earthquake Mechanisms of the Mediterranean Area.
domain with events that are clustered along two main transects across the center of the Adriatic region.

Seismicity across the Apennines is densely distributed along the whole chain, characterized by an active deformation related to the presence of extensional, compressive, and strike-slip tectonics as well as combinations of these as revealed by earthquake focal mechanisms and regional stress field (Carminati & Doglioni, 2012; Montone et al., 2012; Pondrelli et al., 2006; Sani et al., 2016). Focal mechanism and structural data indicate an active compressional deformation along the northeastern portion of the Northern Apennine thrust belt, running from the Po Plain to the Conero Promontory, which is mainly accommodated by crustal and sub-crustal reverse faults connected by subordinate strike-slip and tear faults (Di Bucci & Mazzoli, 2002; Costa et al., 2021; Mantovani et al., 2021; Pezzo et al., 2020; Pierantoni et al., 2019; Zampieri et al., 2021). Beneath the low land of the Po Plain, E-W-striking compressive fault plane solution is consistent with the structural trends of the N/NE-verging blind fold-thrust structures belonging to the thrust front of the Northern Apennines developed in the Miocene-Quaternary foredeep basin (Mantovani et al., 2021). The 2012 Emilia seismic sequence with the largest instrumentally measured earthquakes (Mw = 6.1) represents the most recent expression of the active compressional deformation along the Northern Apennines outer thrust front (Govoni et al., 2014; Pizzi & Scisciani, 2012).

The prevalent compressional, active deformation along the northern outer sector of the Apennines is compensated by widespread and shallower extensional deformation in the inner part, as documented by a crustal seismicity (Mw = 4–6.5) densely distributed along the entire Apennines watershed, with the T-axis oriented generally sub-orthogonal to the axial trend of the mountain belt (Chiarabba et al., 2005). In this sector (Umbria-Marche-Abruzzi), the largest instrumental earthquakes with extensional focal mechanisms were recorded in the 1997 Colfiorito (Mw = 6.0; Amato et al., 1998), the 2009 L’Aquila (Mw = 6.3; Chiarabba et al., 2009), the 2016 Norcia (Mw = 6.5) and Amatrice (Mw = 6.0; Chiaraluce et al., 2017; Pizzi et al., 2017; Puliti et al., 2020), earthquakes.

Conversely, moving southward along the strike of the Apennines, the thrust front is completely deactivated being frozen and buried in the Bradanic foredeep, south to the Maiella Mountain and across the Apulian region (Bertotti et al., 2001; Vezzani et al., 2010), although chain-orthogonal extension persists in the inner part of the mountain belt and in the outer zone (Meletti et al., 2000). In the southern segment of the Apennines, both the inner and outer sectors of the chain and the adjoining Adriatic foreland are dominated by mainly E-W-striking right-lateral strike-slip seismogenic deformation zones (e.g. the Gargano, Benevento and Potenza area; Adinolfi et al., 2015; Boncio et al., 2007; Di Bucci et al., 2010). More complex seismotectonic models suggesting the coexistence of different tectonic styles at distinct crustal depths have also been proposed in this area (De Matteo et al., 2018). The deep crustal/sub-crustal seismicity is concentrated along wide fault zones (e.g. the Martina fault zone), generally reactivating inherited structural discontinuities (Argnani et al., 1994; Boncio et al., 2007). Furthermore, focal mechanisms with NNW-SSE-oriented P-axes along reverse faults have been computed along the Adriatic foreland (e.g. Tremiti Ridge; Scisciani & Calamita, 2009 and references therein).

In the transition zone between the Northern and Southern Apennines, field and seismic data show that the thrust front activity has strongly decreased during the Quaternary (Figure 5). Moreover, seismicity is less frequent or absent in the outer part of the chain, especially as compared to the area to the north. However, diffuse compressional deformation is active in the Adriatic foreland, where earthquakes are clustered in a narrow zone corresponding to the Mid-Adriatic Ridge, with hypocentral locations recorded up to 30 km depth (Di Bucci & Angeloni, 2013; Scisciani & Calamita, 2009). This zone represents the main decoupling area within the chiefly aseismic Adriatic foreland where compressive deformation prevails.

3.2. GNSS kinematics

Several studies estimated the present-day short-term kinematics and velocity field in the Apennines-Adriatic area from geodetic measurements and analysis of continuous GNSS observations (e.g. Cenni et al., 2012, 2013; DAgostino et al., 2008; Devoti et al., 2011, 2010, 2008; Farolfi & Del Ventisette, 2016; Pezzo et al., 2020; Sani et al., 2016).

The geodetic horizontal velocity field (Cenni et al., 2012; Devoti et al., 2011, 2010, 2008) reveals that there is a gradual increase of the velocity values moving from the hinterland of the thrust belt (Tyrrhenian side) to the foreland along the Adriatic coastal area (Figure 4). The outer sector of the Central-Northern Apennines is moving significantly faster (3–5 mm/yr) and more easterly/northeastly with respect to the inner area, where velocities are mostly lower than 2 mm/yr and directed mostly towards the north/northwest (Cenni et al., 2012; Devoti et al., 2011, 2010, 2008; Pezzo et al., 2020). Diverging velocity vectors are located in a velocity transition zone occurring approximately along the chain-parallel mountain belt watershed (Figure 4).

The present-day moving sector of the outer Apennine has been characterized by greater mobility since the early Pleistocene as documented by Mantovani et al. (2009). The dynamic context that acted in the most recent tectonic evolution, caused
Figure 4. Geodetic horizontal velocity field in the Central-Northern Apennines, compiled from (Devoti et al., 2008, 2010, 2011; Cenni et al., 2012; Pezzo et al., 2020).

Figure 5. Long-term uplift/exhumation rates (Balestrieri et al., 2003; Calamita et al., 2004; Rusciadelli et al., 2005) and short-term geodetic vertical uplift (Cenni et al., 2013) in the Central-Northern Apennines.
the lateral escape of the Central-Northern Apennine wedge, a process that is still ongoing and very likely active since the early Pleistocene being compatible with a lateral extrusion process, as proposed by some authors (e.g. Boccaletti et al., 2005; Mantovani et al., 2009).

This kinematic pattern may account for the occurrence of major earthquakes in the axial zone of the belt and for the active deformation along the outer thrust front (Cenni et al., 2012; Pezzo et al., 2020). The estimated horizontal strain rate field (Cenni et al., 2012; Devoti et al., 2010, 2008) suggests the presence of strain rate regimes that are coherent with the various seismogenic tectonic zones. A compressional regime, with a NNW-SSE shortening P-axis, dominates in the Eastern Alps, at the northern collisional border of the Adria Plate with the Eurasian domain.

A roughly N-S/NNE-SSW compression occurs in the Po Valley over the active outer buried sector of the Northern Apennine thrust belt system. A dominant extensional/transtensional regime, with a NE-SW lengthening T-axis is diffuse over the extensional seismogenic domain along the backbone of the Central-Northern Apennine chain. A strike-slip regime mainly occurs in the Southern Apennines (Adinolfi et al., 2015; Boncio et al., 2007; Di Bucci et al., 2010; Corrado et al., 1997).

The vertical velocity pattern derived from geodetic measurements evidences a dominant uplift prevails in the Alpine (up to 5 mm/yr) and Apennine (1–2 mm/yr) orogenic belts (Cenni et al., 2013). These sectors of short-term present-day uplifting approximately correspond to the sectors where the higher values of long-term uplift and exhumation rates have been documented (Figure 5). Strong uplift characterize the orogen triggering exhumation and unroofing of the allochthonous units with rates of 0.7–0.9 mm/yr in the inner Northern Apennines (Balesstrieri et al., 2003), 0.75 mm/yr in the Central Apennines (Calamita et al., 2004; Rusciadelli et al., 2005) and 1.14–1.4 mm/yr in the Southern Apennines (Mazzoli et al., 2008). This strong uplift/exhumation process, which is still ongoing as revealed by the vertical GNSS velocities, is related to the most dynamic phase of the Apennine foreland thrust belt evolution with lithospheric-scale thrusting that envelops the curved thrust systems of the Northern and Central Apennines defining the so-called Plio-Quaternary neo-chain (Boccaletti et al., 2005).

### 3.3. Kinematic blocks

By comparing and combining the present-day short-term kinematics, derived from geodetic measurements (Cenni et al., 2012, 2013; Devoti et al., 2010, 2008; Pezzo et al., 2020) and the seismotectonic framework, considering the directions of P and T axes obtained from focal mechanisms solutions and stress data (Di Bucci & Mazzoli, 2002; Carminati & Doglioni, 2012; Mantovani et al., 2021; Montone et al., 2012; Pondrelli et al., 2006; Sani et al., 2016), with the tectonic setting across the Central-Northern Apennines and Adriatic foreland (Carminati & Doglioni, 2012; Scisciani & Calamita, 2009) four main independent kinematic blocks can be identified for the Adria Plate:

1. The Adria foreland plate (Block 1 in Figure 6). The foreland domain that extends form Istria and the Po Plain, in the north, to the south through the Adriatic up to the southernmost sector with the carbonate units cropping out in the Gargano promontory and over the Murge area. This present-day foreland domain represents the remnant of the Adria Plate that has been affected along its western, northern and eastern margins by the Apennine, Alpine and Dinaric thrust belt developments, respectively (Di Bucci & Angeloni, 2013; Scisciani & Calamita, 2009). This crustal block is characterized by a NNE-directed counterclockwise reto-translational movement that is faster in the southern sector (Gargano) slowing down northward with a N-directed kinematics in the Veneto-Friuli Plain, east of the Schio-Vicenza Line (Figure 2 and Figure 4). An active transpressional deformation is localized in the central sector of the Adriatic foreland domain (Mid-Adriatic Ridge) (Di Bucci & Angeloni, 2013; Scisciani & Calamita, 2009) and also in the northern sector accommodated by internal deformation, with N-S and E-W trending fault systems (Brancolini et al., 2019). The kinematic pattern of the Adria foreland domain is also triggering the active compressional deformation along the Southern Alps (e.g. Brückl et al., 2010; Poli et al., 2008) and Dinarides (e.g. Kastelic & Carafa, 2012; Schmitz et al., 2020) as well as the strike-slip transitional zone north to Istria (e.g. Brückl et al., 2010; Tondi et al., 2021).

2. The Pliocene-Quaternary Apennine orogenic wedge (Block 2 in Figure 6). The Pliocene-Quaternary Apennine orogenic wedge is characterized by an active thrust front in the Northern Apennines north to the Conero promontory and in the Po Plain (Boncio & Bracone, 2009; Mantovani et al., 2021). The northeastern boundary is constituted by the active thrust front, whereas the western boundary is represented by the easternmost NW-SE-trending alignment of the active W-dipping extensional faults extending over the Apennine watershed. This orogenic block is characterized by a NNE-directed (N10-20°) kinematics reaching the maximum velocities (4–5 mm/yr) along the apex
Figure 6. Major crustal/lithospheric kinematic blocks over the Central-Northern Apennines-Adriatic thrust belt-foreland system inferred from the present-day short-term GPS kinematics (Cenni et al., 2012; DAgostino et al., 2008; Devoti et al., 2010, 2008; Pezzo et al., 2020), the seismotectonic framework (Boccaletti et al., 2005; Pondrelli et al., 2006; Sani et al., 2016), stress data (Montone et al., 2012) and structural-geological setting (Boccaletti et al., 1990, 2005; Scisciani & Calamita, 2009). The simplified crustal-scale cross-sections show the interactions among the identified kinematic blocks.
zone of the Central-Northern Apennine active curved thrust front (Figure 4). In this sector of the orogenic block, P-axis directions indicate an active shortening and compressional deformation directed towards the NE (N40-50°).

(3) The Quaternary extensional/transstensional domain (Block 3 in Figure 6). This retro-belt domain extending in the hinterland of the chain westward to the Apennine carbonate ridge. This retro-belt block is characterized by a markedly active extensional/transstensional deformation resulting in the development of N-S- and NW-SE-oriented Quaternary extensional basins with annexed diffuse seismicity (e.g. Calamita et al., 2000; Pizzi et al., 2017; Puliti et al., 2020; Roberts & Michetti, 2004; Saccorotti et al., 2022). Focal mechanisms solutions indicate a lengthening T-axis oriented from NNE-SSW to NE-SW (Figure 3). Kinematics from the GNSS data show slow (<3 mm/yr) N-and NW-directed horizontal velocities (Figure 4).

(4) The inner compressive domain (Block 4 in Figure 6). It represents an interaction zone between the Ligurian Alps and the inner retro-Apennine block occurring northwestward to the Apuan Alps. This interaction zone is characterized by a chiefly contractual deformation (e.g. Mantovani et al., 2021).

These blocks, characterized by distinct kinematic patterns, have a crustal to lithospheric significance that is represented in the cross-sections in Figure 6. In general, all the identified kinematic blocks and their boundaries are considered to be crustal since they are mainly identified above the Moho discontinuity and the associated seismicity is crustal to sub-crustal. Moreover, different geophysical data (Barchi et al., 1998; Mele & Sandvol, 2003; Mele et al., 2006; Ponziani et al., 1995; Spada et al., 2013; Di Stefano et al., 2011) revealed an overlap of the Moho underneath the Apennine chain running roughly parallel to the boundary between the kinematic blocks 2 and 3 (Figure 6). The duplication of the Moho has been interpreted both in terms of subduction of the Adriatic slab beneath the Apennines (Carminati & Doglioni, 2012; Royden et al., 1987) or in terms of crustal shortening achieved by lithospheric thrust faults (Boccaletti et al., 2005; Calamita et al., 2004; Finetti et al., 2005; Lavecchia et al., 2003). Within this context, the boundary between the Block 2, the Apennine orogenic wedge, and the Block 1, the Adria foreland plate, in the Northern and Central Apennines sector can be considered as lithospheric. It corresponds to the Moho overlap caused by the fast (4–5 mm/yr) NNE-directed (N10-20°) lateral escape of Block 2 associated also with active shortening and compressional deformation directed towards the NE (N40-50°) as represented in the cross-section S1 of Figure 6. In the same sector, the inner boundary of the Block 2 with Block 3, the Quaternary extensional/transstensional domain, is of crustal significance with a markedly active extensional/transstensional deformation and annexed diffuse crustal seismicity (e.g. Carannante et al., 2013; De Luca et al., 2009; Saccorotti et al., 2022) localized in the hanging wall of the lithospheric boundary between the Block 2 and Block 1 (cross-sections S1 and S2 in Figure 6). In the Southern Apennines, the eastern boundary of the Apennine orogenic wedge is corresponding with a thrust system that is no longer active (Figure 6 and Figure 7) and therefore the W-dipping, high-angle boundary between block 2 and 3 is of crustal to lithospheric significance corresponding at depth to the Moho offset that can be interpreted as a lithospheric-scale negative inversion of the Pliocene-Pleistocene deep thrust front of the Southern Apennines (cross-section S3 in Figure 6).

4. Discussion

Various geodynamic models have been applied to explain the evolution of the Apennine orogenic belt, starting from the early Pliocene, invoking: i) different subduction processes with slab retreat (Boccaletti et al., 1971; Malinverno & Ryan, 1986; Reutter et al., 1989; Finetti and Del Ben, 1986; Royden et al., 1987; Patacca and Scandone, 1989; Doglioni, 1991; Faccenna et al., 2001; Rosenbaum & Lister, 2004; Devoti et al., 2011; Carminati & Doglioni, 2012), ii) lateral extrusion induced by plate convergence (Tapponier, 1997; Boccaletti et al., 1982; Faccenna et al., 1996; Mantovani et al., 1997, 2009, 2015), iii) lithospheric buckling (Bertotti et al., 2001; Johnston & Mazzoli, 2009) related to the Africa-Europe convergence, iv) asthenospheric upwelling associated with gravitational collapse (Locardi, 1982; Wezel, 1985), large-scale wrench faulting (Lavecchia, 1988; Lavecchia & Stoppa, 1989) either related to a passive or an active plume-related rifting (Lavecchia & Creati, 2006); v) late-orogenic collapse of an overthickened accretionary wedge (Carmignani & Klugfield, 1990), or vi) mantle delamination of Adria associated with dehydration of the material subducted during the Europe-Adria collision (Chiarabba & Chiodini, 2013; Chiarabba et al., 2014). However, despite the huge amount of studies, many questions on the geodynamics of the Adria Plate are still unsolved, particularly the post-Miocene interaction, along its western margin, between the Adria Plate and the Apennine chain (Brancolini et al., 2019).

Within this wide spectrum of proposed geodynamic models, the NNE-directed kinematics of the Adria Plate plays a fundamental role during the Pliocene-Quaternary evolution of the Apennine thrust belt, a lateral chain with respect to the Africa-Europe convergence.

The Adria Plate motion has been interpreted as the combination of two blocks with independent kinematics (Battaglia et al., 2004) or as the relative motions of two blocks attached to the major plates (Oldow
et al., 2002). These different interpretations arise from the fact that the Adriatic boundaries are still not completely understood and the Adriatic motion is only weakly constrained (Devoti et al., 2008).

The main driving force of Adria motion has been proposed to be a push from Africa to the northwest until the Adriatic plate slowed and stopped as it indented Europe in the western Alps. Then the main force was a pull to the east by the slab beneath the northwestern Hellenides, triggering a counterclockwise rotation of Adria relative to Europe and divergence from Africa (Le Breton et al., 2017). Mantovani et al., 2020b) suggested that Adria has moved as an independent microplate in the Pliocene. After the Early Pliocene, when the Adria subduction beneath the northern Apennines ceased, the kinematics of the Adria Plate has been almost totally driven by the surrounding plates kinematics (Brancolini et al., 2019). With the continuous push from Africa to the north, the Adria Plate most likely started to fragment internally as documented mostly by GPS data (e.g. Le Breton et al., 2017; DAgostino et al., 2008; Oldow et al., 2002; Sani et al., 2016).

Independently from the geodynamic context and the driving forces behind the Adria Plate motion, the active interaction of the foreland domain represented by the Adria block and the surrounding orogenic systems is here discussed by taking a perspective from the Central-Northern Apennines.

The evolutionary reconstruction of the Central Mediterranean region (Mantovani et al., 2009, 2020) suggests that since the middle Pleistocene the kinematic pattern of the Central-Northern Apennines has mainly been characterized by the lateral NE-directed escape of the orogenic wedge at the expense of the Adriatic domain (Mantovani et al., 2019). The NNE-directed motion of the Adria Plate strongly influenced

Figure 7. Tectonic sketch showing the interaction of the Adria foreland domain with the surrounding orogenic systems with reference on the kinematic and deformational patterns of the Central-Northern Apennines.
the Pliocene-Quaternary evolution of the Apennine orogenic system. Specifically, the roto-translational counterclockwise motion of the Adria Plate has been directly conditioning the building of the peri-Adriatic thrust belts. In fact, the short-term kinematics from geodetic measurements reveals that a fast (4–5 mm/yr) N/NNE-directed kinematics characterizes the central-southern sector of the Adria Plate (Figure 4 and Figure 6), where the thrust front segment of the Central and Southern Apennines is inactive. Conversely, the slower (2–3 mm/yr) motion in the northern sector (Figure 4 and Figure 6) relates to the active segment of the thrust front in the Northern Apennines, north to the Conero promontory along the coastal area and into the Po Plain (Figure 3).

The inconsistency between the NE-SW-oriented (N40-50°) compressional P-axis, as indicated by the focal mechanisms solutions of the compressional events along the active outer Apennine thrust front, and the NNE-SSW-directed (N10-20°) kinematics of the Pliocene-Quaternary Apennine orogenic wedge (Block 2 in Figure 6), as revealed by GPS data, can be related to the dragging effect of the underlying Adria foreland plate (Block 1 in Figure 6) directed to the north in this northern sector and characterized by much slower velocities (Figure 4 and Figure 6). Moreover, the NNW-directed movement of the inner Quaternary extensional/transitional domain (Block 3 in Figure 6) indirectly reflects the Africa-Europe direction of convergence with markedly slower velocity vectors due to the northern confinement represented by the contractional interaction zone with the Ligurian Alps in the inner compressive domain (Block 4 in Figure 6). The remarkable difference in velocities and kinematics between Blocks 2 and 3 is coherent with the active extensional/transitional deformation characterizing the inner retro-Apennine domain. This deformation is pure normal along the boundary segment between Blocks 2 and 3 whereas is more transtensional, mostly left-lateral, in the westward inner sector (Bonini et al., 2011; Brogi & Fabbrini, 2009).

5. Conclusions

In this study, the current central-northern portion of the Adria Plate is considered as dissected into independent crustal/lithospheric blocks of various size and kinematics, which are behaving differently under the indirect influence of the NNW-SSE-oriented convergence between Europe and Africa plates. The differential relative movements of these blocks are the main responsible for the current seismicity at both the margins and within the Adria Plate, having also strongly influenced the Pliocene-Quaternary evolution of the Central-Northern Apennine orogenic system and the building of the peri-Adriatic thrust belts.

By comparing and combining the present-day short-term kinematics, derived from geodetic measurements and the seismotectonic framework, considering the directions of P and T axes obtained from focal mechanisms solutions and stress data, with the tectonic setting across the Central-Northern Apennines and Adriatic foreland four main blocks were identified:

1. The Adria foreland plate (Block 1 in Figure 6);
2. The Pliocene-Quaternary Apennine orogenic wedge (Block 2 in Figure 6);
3. The Quaternary extensional/transitional domain (Block 3 in Figure 6);
4. The inner compressive domain (Block 4 in Figure 6).

Collectively, the active interaction among the kinematic blocks identified in this study within the framework of the short-term kinematics and seismotectonic framework of the Adria Plate and surrounding orogenic systems can be summarized as follows:

1. Deactivation, during Quaternary, of the Central-Southern Apennine thrust front and coupling of the orogenic wedge with the Apulian foreland domain (Figure 7).
2. Dragging and drifting towards NNE of the Northern Apennine orogenic wedge having an active thrust front from the Conero promontory, through the coastal area up to the Po Plain (Figure 7).
3. Differential velocities and kinematics between Blocks 2 and 3 triggering the seismogenic extensional deformation along the inner retro-Apennine domain (Figure 7).
4. Differential velocities within the foreland domain of Block 1 between the faster southern area (e.g. Gargano) and the slower northern sector (e.g. Po Plain, compensated by an active intra-plate deformation in the Central Adriatic (i.e. Mid-Adriatic Ridge), characterized by E-W-trending strike-slip and curved transpressional structures (Figure 7). The kinematic pattern of the Adria foreland domain is also triggering the active contractional deformation along the Southern Alps and Dinarides as well as the strike-slip transitional zone north to Istria.

In conclusion, starting from the early Pliocene, the rate of the Central-Northern Apennine thrust belt development decelerates and the NNW-directed Africa-Europe convergence, 8–9 mm/yr (DeMets et al., 1994), may have influenced the counterclockwise roto-translational movement of the Adria Plate. Alternatively, this movement could have been related to the drastic change of the tectonic setting in the
whole central Mediterranean region since the early Pliocene explained as an effect of the westward push of the Anatolian-Aegean system, after its collision with the continental Adriatic domain (e.g. Mantovani et al., 2020, Viti et al., 2021). Within this context, the characteristic counterclockwise roto-translational motion of the Adria Plate rules the kinematic and deformational patterns directly into the foreland domain (Block 1) and indirectly onto the blocks 2 and 3. The dragging of the Northern Apennine orogenic wedge (Block 2) towards the north and northeast causes the lateral escape of the active Apennine outer thrust system at the expenses of the Adria foreland domain, which is also affected by an active transpressional intraplate deformation, and triggers the seismogenic extensional deformation along the inner retro-Apennine domain (Block 3).

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**Data availability**

Data available within the article or its supplementary materials

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