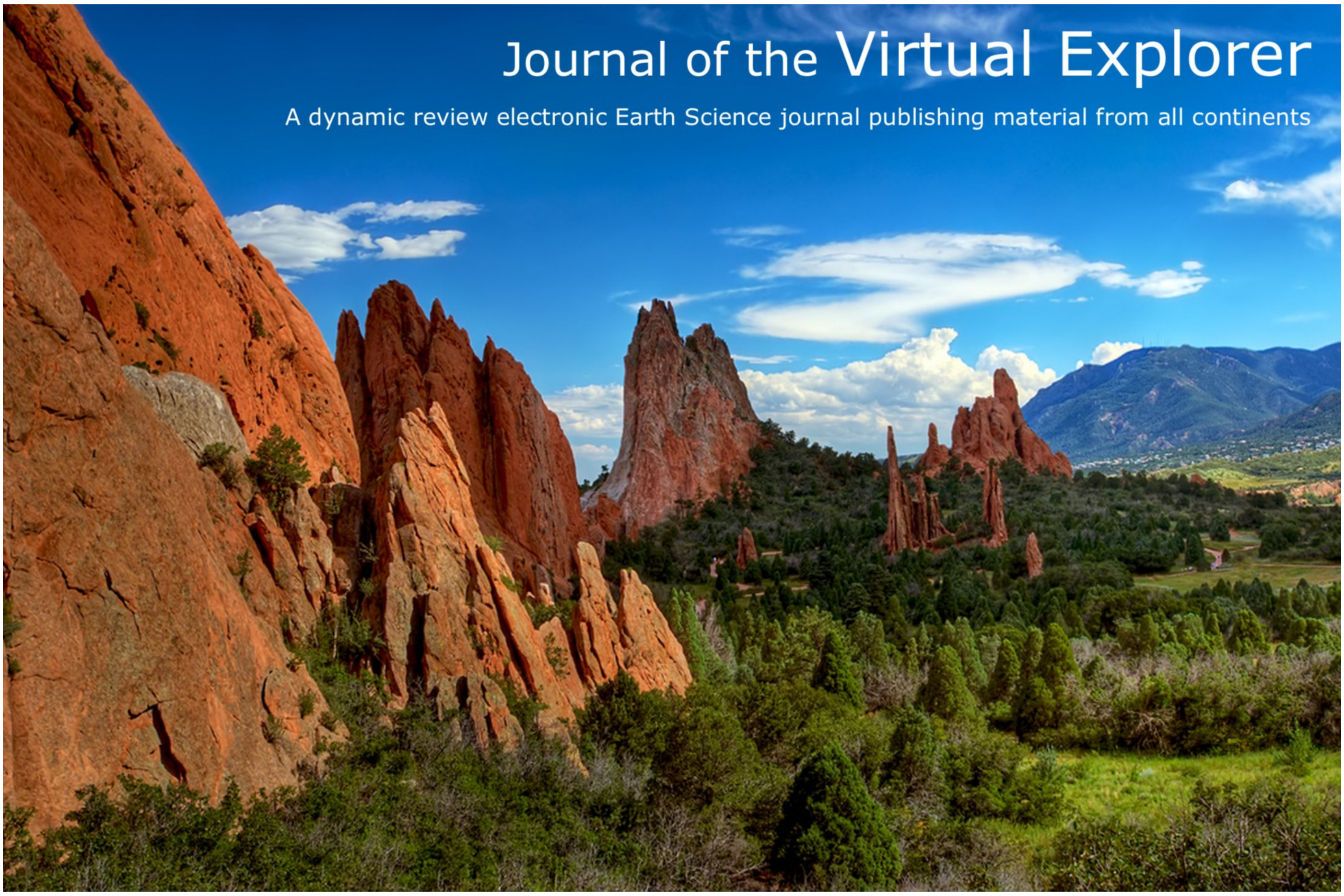

Influence of Inversion Tectonics in the Bending of a Foreland Fold-and-Thrust Belt: The Case of the Northern Apennines (Italy).

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Influence of Inversion Tectonics in the Bending of a Foreland Fold-and-Thrust Belt: The Case of the Northern Apennines (Italy).

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Abstract: The outer Northern Apennines fold-and-thrust belt has been interpreted in the literature either as an orocline, a primary or a progressive arc, with a thin- or thick-skinned tectonic style. This paper reviews prior theories on the origin of the curve-shaped Northern Apennines belt and integrates these past findings with more recent geologic, structural, and paleomagnetic data collected from the Northern Apennines area. Documenting the presence of inversion tectonics is particularly important in identifying the origins of this foreland belt. The inversion tectonics evidences indicate that the foreland Northern Apennines chain is a progressive arc whose shape is strongly influenced by the architecture of the Mesozoic Adria paleomargin, as documented by a correlation between structural units and paleodomains. The arc curvature was accentuated during orogenesis by the occurrence of tectonic rotations. We propose that the curve-shaped Northern Apennines foreland fold-and-thrust belt evolved as a progressive arc under the influence of inversion tectonics and demonstrates a thick-skinned deformation style with a conservative amount of shortening. In the context of the Apennine-Maghrebide orogen, the Northern Apennines Arc is clearly distinguishable from the Southern Apennines-Calabrian Arc by differences in paleogeographic domains, stratigraphic successions, tectonic style and rotations, and geodynamic evolution.

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Introduction

Many mountain belts show curved structural trends in plan-view. The origins and kinematics of these bends are crucial to understanding the tectonic evolution of orogenic belts. However, because orogenic curvature occurs at many different scales, there is an ongoing debate over the formation processes of orogenic belts. Curved orogenic belts are produced by geodynamic forces capable of causing shortening and eventual extension. These geodynamic forces include: 1) slab rollback, where slab retreat and shortening occur close to the trench and extend into the overriding plate (Malinverno and Ryan, 1986; Royden *et al.*, 1987; Lucente and Speranza, 2001; Schellart *et al.*, 2007); 2) gravitational collapse due to potential energy differences (Platt and Vissers, 1989; Carmignani and Klingfield, 1990); 3) orogen-perpendicular compression (Jolivet *et al.*, 1990); and 4) orogen-parallel compression (i.e., extrusion tectonics), where bending or buckling occurs perpendicular to the long axis of the orogen and extension occurs behind the orogen (Faccenna *et al.*, 1996; Mantovani *et al.*, 2002; Johnston and Mazzoli, 2009). It is also important to note that the geodynamics of curved belts depend strictly on their size. Regional-scale curved belts are primarily controlled by lithospheric-scale phenomena (Beck, 1998; Platt *et al.*, 2003; Hall *et al.*, 2004; Jolivet and Faccenna, 2000). Conversely, small-scale arcs are controlled by frictional processes occurring at crustal levels (Davis *et al.*, 1983).

The following types of curved belts can be identified based on their kinematics: 1) oroclines (or rotational arcs), which are originally linear and subsequently bend during a deformation event; 2) primary (or non-rotational) arcs, which acquire their curvature in the initial deformation (Carey, 1955; Marshak, 1988); and 3) progressive arcs, which develop their arcuate nature as they grow (Weil and Sussman, 2004).

The extent to which paleogeography and the architecture of colliding continental margins influence the curvature of an arcuate belt (Weil and Sussman, 2004) depends on the geometry and strength of the detachment horizon, the configuration of the sedimentary basin, the presence of strike-parallel variations in lithology and sedimentary thickness, the occurrence of buttressing (Macedo and Marshak, 1999; Weil *et al.*, 2010; Mitra, 1997; Paulsen and Marshak, 1999), the presence of crustal-scale wrench-faults or indenters, and the geometry of the lithosphere (Marshak, 1988; Marshak *et al.*, 1992; Cunningham, 1993; Platt *et al.*, 2003; Hall *et al.*, 2004; Jolivet and Faccenna, 2000; Schellart and Lister 2004). Small-scale arcs formed after the collision of an orogenic wedge with one or more foreland obstacles, have been paleomagnetically investigated. Such salients usually reveal an oroclinal-type rotation pattern, as observed in the Wyoming-Idaho belt (Schwartz and Van der Voo, 1984) and the Southern Pyrenees (Sussman *et al.*, 2004).

The use of single datasets (e.g., structural data, paleomagnetism, and seismic reflection) to classify curved orogens is not enough to adequately explain their kinematic evolution and can lead to contradictory and incomplete interpretations. Using only geologic/structural data (Martínez Catalán *et al.*, 2002) or paleomagnetic data (Stamatakos *et al.*, 1996; Weil, 2006) have resulted in multiple contradictory interpretations of a primary or rotational arc for several curved belts, including the Appalachians and the Variscan mountain system. Contradictory interpretations also characterize the curved Northern Apennines belt. Although some authors support its primary nature (Channell *et al.*, 1978; Eldredge *et al.*, 1985; Muttoni *et al.*, 1998), others suggest either an oroclinal origin for the outer portion of the arc (Speranza *et al.*, 1997) or a progressive arc mechanism, which acquired its definitive curved shape during the Neogene Period (Calamita and Deiana 1988; Cifelli and Mattei, 2010). As a result, the rotational nature of this fold-and-thrust belt remains controversial.

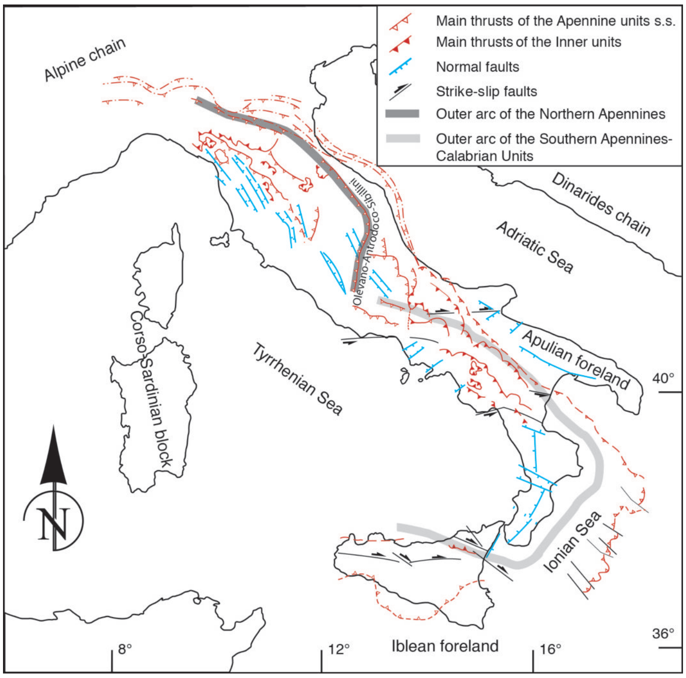
In this paper, we attempt to explain the evolution of the outer Northern Apennines within the context of the Apennine-Maghrebide orogen. The Apennine-Maghrebide orogen can be divided into two arcuate features: the Northern Apennines Arc and the Southern Apennines-Calabrian Arc. They are characterized by differences in paleogeographic domains, stratigraphic successions, structural setting, and geodynamic evolution one respect to another (Satolli and Calamita, 2008, and references therein).

Our methodology includes the integration of geologic, structural, and paleomagnetic data collected in this belt over several decades of geological research. The integration of these data supports a thick-skinned setting of the belt, strongly controlled by the structural inheritance of older faults. These older faults are responsible for the orientation of thrust faults and the overall curved geometry.

The Northern Apennines

The Apennine-Maghrebide orogen is characterized by a curved shape showing the Calabrian units in the apical zone and the Tyrrhenian extensional basin in the inner area (Johnston and Mazzoli, 2009). This first-order curved belt is divided into two arcs: the Northern Apennines Arc and the Southern Apennines-Calabrian Arc, with NE and SE convexity, respectively (Fig. 1). The two arcs are characterized by several differences in paleogeographic domains, stratigraphic successions, structural settings, the amount and sense of vertical-axis rotations, and geodynamic evolution (Boccaletti *et al.*, 1971; Malinverno and Ryan, 1986; Carmignani and Klingfield, 1990; Doglioni, 1991; Boccaletti *et al.*, 2005; Finetti *et al.*, 2005; Satolli and Calamita, 2008). In the Northern Apennines, the carbonate structural units generated by the deformation of the outer Adria paleomargin crop out. Their bounding thrust faults accommodate a maximum shortening of approximately 10 km in the apical zone, as seen in length-displacement profiles across the thrust front (Mazzoli *et al.*, 2005).

Figure 1. Tectonic sketch map.



Tectonic sketch map of the Apennine-Maghrebide thrust front, showing the two main outer arcs of the Northern Apennines and Southern Apennines-Calabrian Arc.

Conversely, in the Southern Apennines, the Apulian units lie in the footwall of the basal thrust, along which the main allochthonous units are far travelled (Liguridi-Sicilidi, inner Carbonate Platform, and Lagonegro-Sannio-Molise Units). The Apulian carbonate units have been interpreted as the Apulian duplex (Mostardini and Merlini, 1986; Patacca and Scandone, 2007), the buried Apulian chain (Cello *et al.*, 1989) with thick-skinned structural setting characterized by the reactivation of Permo-Triassic extensional faults (Shiner *et al.*, 2004), or as the Pliocene Apennine neochain (Boccaletti *et al.*, 2005). Geophysical studies provide evidence that deep-seated reverse faulting involves the basement in the Southern Apennines (Improta & Corciulo, 2006; Steckler *et al.*, 2008). The deformation of the Apulian chain is characterized by limited horizontal displacement (Menardi Noguera & Rea, 2000; Butler *et al.*, 2004; Turrini & Rennison, 2004), whereas large displacements of up to several tens of kilometers are localized at the base of the overlying allochthonous units (Mazzoli *et al.*, 2008).

Paleomagnetic data show a separation between the Northern and the Southern Apennines. In fact, the Northern Apennines Arc is characterized by CCW rotations in the Emilia-Romagna and Marche regions passing to CW rotations in its southern sector. Similarly, the southern Apennines-Calabrian Arc is characterized by CCW rotations in the southern Apennines and strong CW rotations in Sicily.

This study focuses on the Northern Apennines Arc. This fold-and-thrust belt was formed by the convergence of the African and Eurasian plates, beginning during the Late Cretaceous Period. Starting in the Late Oligocene Period, the convergence caused the formation of the Apennines, as indicated by the age of siliciclastic deposits (Boccaletti *et al.*, 1990). Orogenesis generated a Triassic to Miocene sedimentary multilayer characterized by a strong contrast of competence (Ciarapica and Passeri, 2002; Patacca and Scandone, 2007). From the Middle/Late Miocene to Late Pliocene Periods, coeval occurrence of normal and thrust faults characterized the western and eastern belt margins, respectively (Cavinato and DeCelles, 1999). Consequently, both syn-rift (primarily deposited within intermontane basins) and foredeep (later incorporated into the frontal thrust structures) sediments are exposed in the Apennine belt. Extension and compression continued during the Pleistocene-Holocene Period and still actively occur today, controlling seismicity in the Apennine mountain range and Po plain/Adriatic areas, respectively.

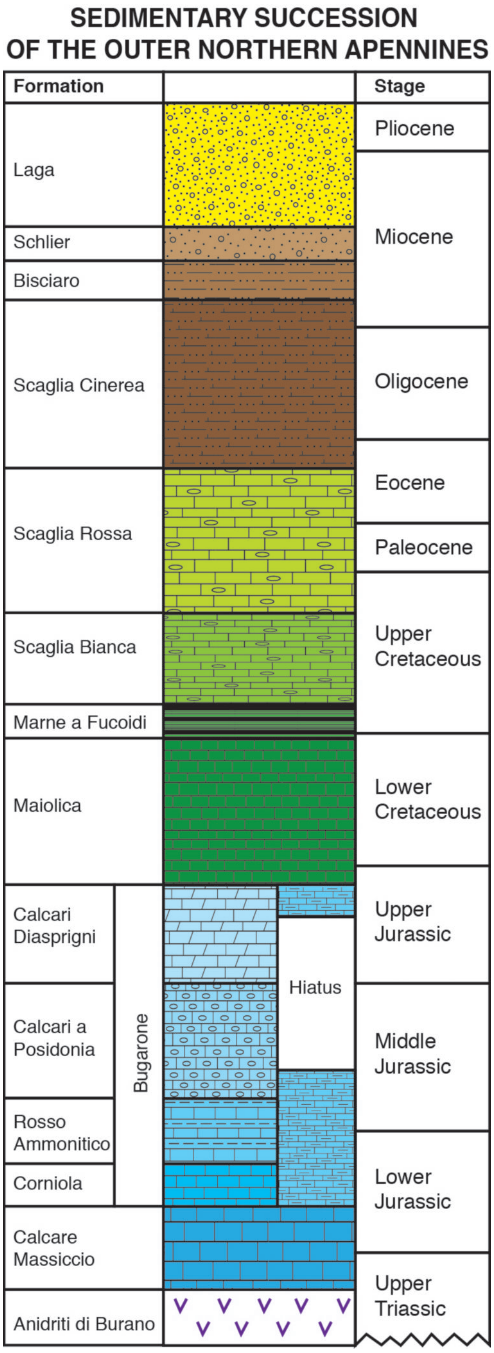
Stratigraphic succession

The Northern Apennines are composed of structural units of European origin, which are tectonically superimposed against units belonging to the Adria and African passive paleomargin within the framework of Alpine-Himalayan orogenesis. Two regional-scale extensional tectonic phases flooded the pre-rifting Triassic-Lower Jurassic peritidal carbonatic shelf (D'Argenio and Alvarez, 1980). The main extensional tectonic phase occurred during the Triassic Period and was followed by a second extensional phase during the Early Jurassic Period.

Extension initially results in the deposition of evaporites (Anidriti di Burano Fm.) or dolomites (Dolomia Principale Fm.) during the Upper Triassic and is followed by the deposition of carbonate platform limestones (Calcare Massiccio Fm.) in the Lower Jurassic. The later extensional tectonic phase is documented by both the presence of pre-orogenic normal faults (Ancona-Anzio line, Castellarin *et al.*, 1978) and changes in the facies and thickness of sedimentary successions deposited above the Adria passive margin (Channell *et al.*, 1979). In fact, during this phase, the Triassic-Lower Jurassic succession was separated into persistent carbonate platform (Lazio-Abruzzo area) and pelagic (Umbria-Marche area, Northern Apennines) domains. These domains were divided by a slope-to-basin transitional domain.

In the pelagic Umbria-Marche domain, the Lower Jurassic to Lower Cretaceous pelagic syn- (Corniola and Rosso Ammonitico Fms.) and post-rift (Calcari Diasprigni to Maiolica Fms.) successions are characterized by highly variable facies and thicknesses due to differential subsidence (Fig. 2). The differential subsidence ended before the Aptian Period, when facies and thickness became uniform (Marne a Fucoidi to Scaglia Rossa Fms.). During the Cretaceous and Paleogene Periods, sedimentation evolved toward hemipelagic lithotypes (Scaglia Cinerea to Schlier Fms.) characterized by carbonate and marls with abundant chert. Sedimentation then became more terrigenous during the Miocene Period. During the Middle Miocene-Pleistocene Period, the convergence of the Africa and Eurasian plates initiated Apennine orogenesis, as indicated by the deposition of siliciclastic turbiditic systems (Laga Fm. in the outer sector of the Northern Apennines; Boccaletti *et al.*, 1990).

Figure 2. Jurassic stratigraphy of the Umbria-Marche pelagic domain.

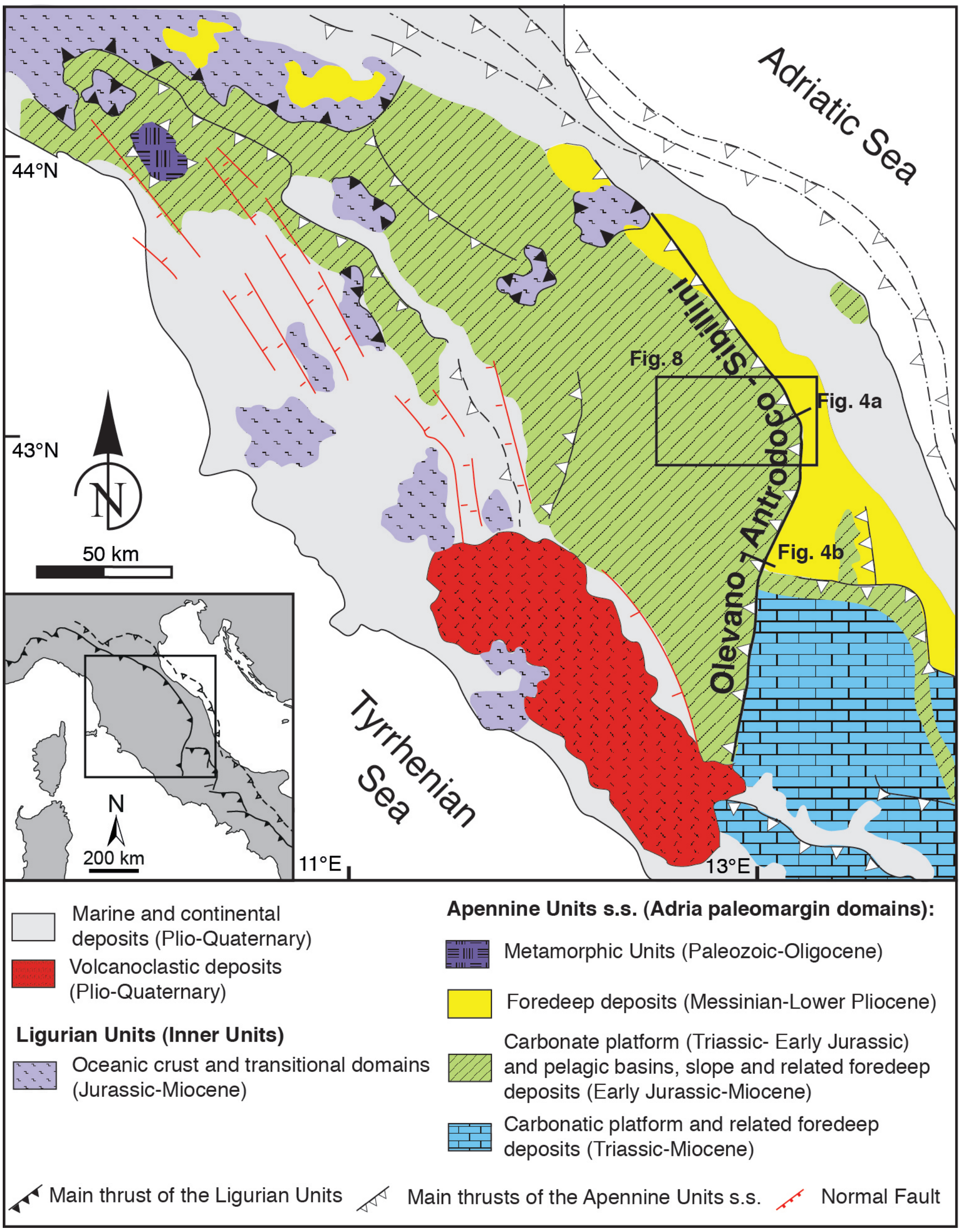


The succession is characterized by variable facies and thicknesses between Lower Jurassic and Aptian Periods.

Structural setting

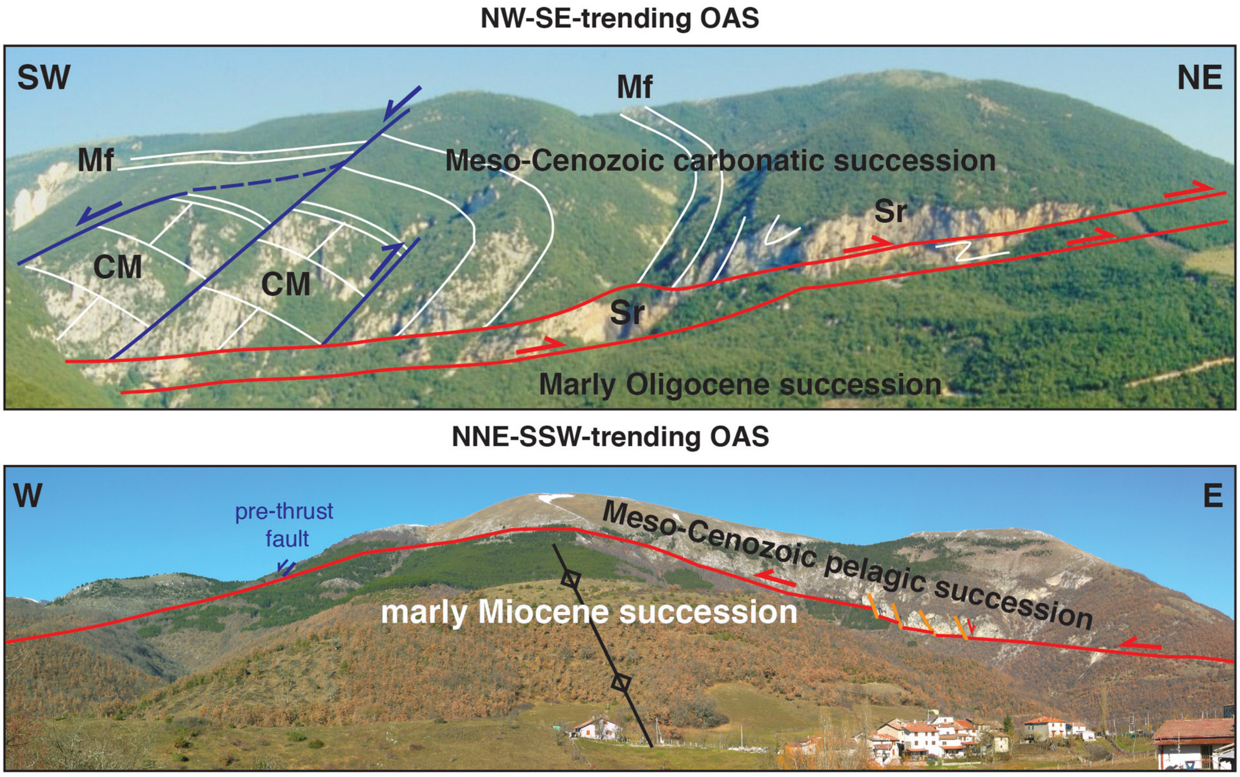
The outer portion of the Northern Apennines is bound by the Pliocene Olevano-Antrodoco-Sibillini (OAS) thrust, cropping out along the mountainous front between the Umbria-Marche mountain ridge and the Marche-Abruzzo pede-Apennines area (Fig. 3). The thrust plane has an irregular structural pattern roughly defined by frontal NW-SE and oblique NNE-SSW trending thrust ramps to the northwest and southwest of the apical zone, respectively (Fig. 4).

Figure 3. Schematic geologic map of the Northern Apennines.



Bold lines indicate the locations of photographs in Fig. 4. Bold squares indicate the location of Fig. 8.

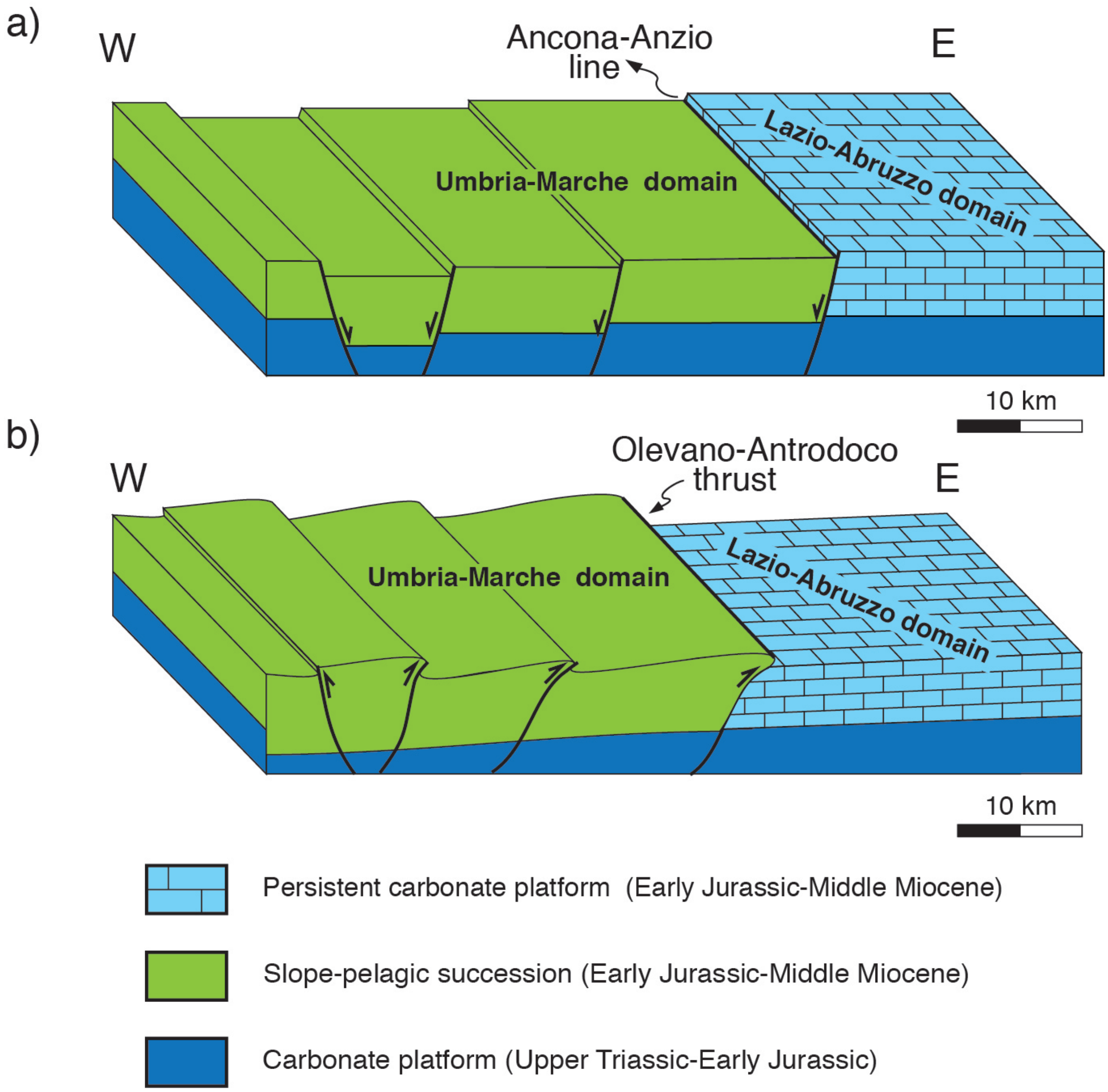
Figure 4. OAS thrust front



Photographs of the OAS thrust front, showing the frontal NW-SE trending (a) and the oblique NNE-SSW trending (b) thrust ramps, located north and south of the apical zone, respectively (for location, see Fig. 3).

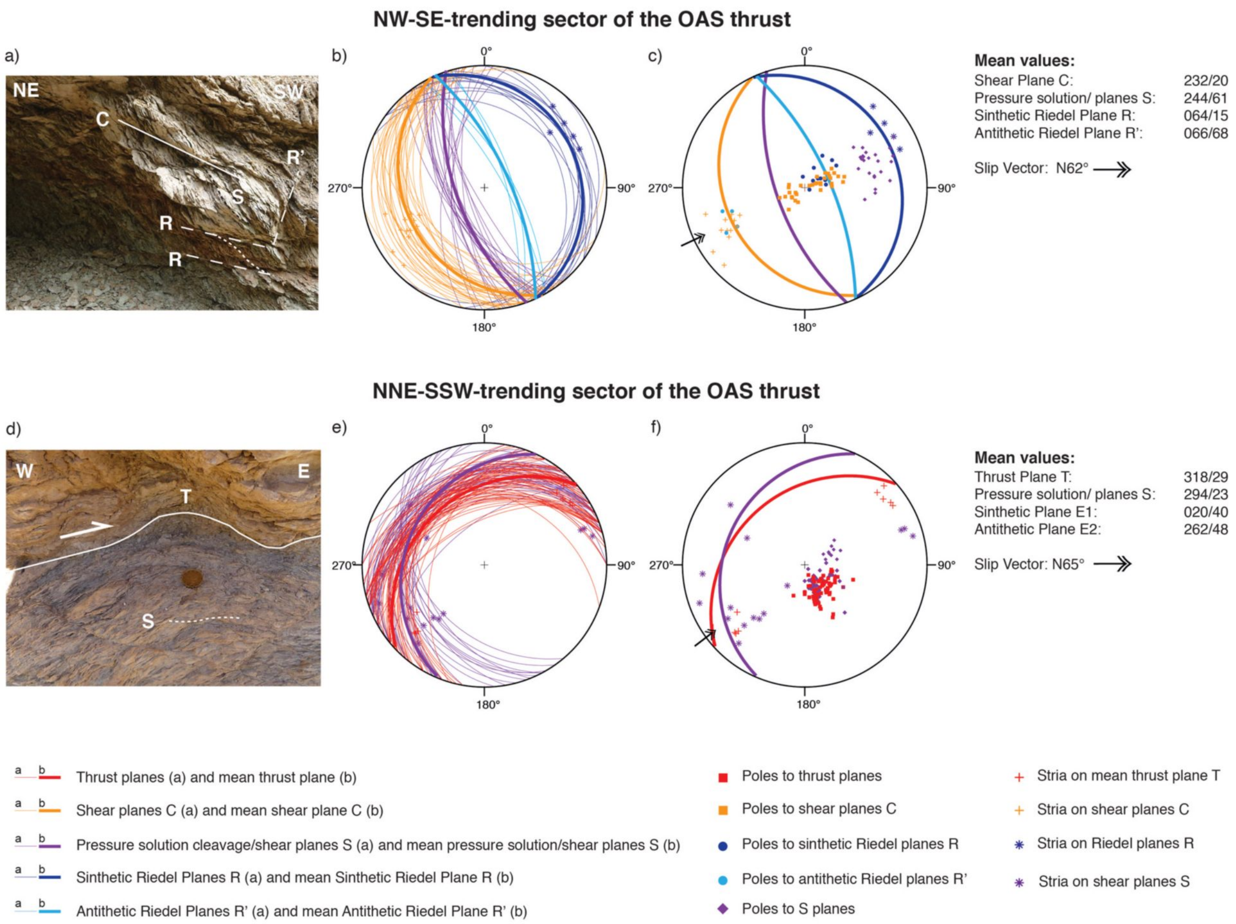
The OAS oblique thrust ramp (NNE-SSW trending sector) reactivated the Ancona-Anzio line (Fig. 5) that separated the Umbria-Marche pelagic domain and the Lazio-Abruzzo carbonate platform (Calamita *et al.*, 2011; Di Domenica *et al.*, 2012, and references therein). The Neogene kinematics of the OAS has been long debated, with special concern being given to the presence of a dextral component of shear (Castellarin *et al.*, 1978; Salvini and Vittori, 1978; Coli, 1981; Koopman, 1983; Satolli and Calamita, 2008). Fold profiles are controlled by structural heritage. In fact, the NNE–SSW trending anticlines show a fault-bend reactivation mechanism, whereas the NW–SE trending anticlines develop with a fault-propagation shortcut (Calamita et al, 2012). The OAS thrust shows shear zones characterized by foliated fault rocks, which are produced by pressure-solution, cataclastic, and slip deformation mechanisms (Koopman, 1983;). In the NW-SE trending sector of the OAS frontal thrust ramp, SC tectonites are developed in centimeter-thick bands and show N60° tectonic transport within a simple shear-dominant deformation. Here, the S fabric is parallel to the XY plane of the strain ellipsoid. In the NNE-SSW trending oblique ramp of the OAS thrust, S-tectonites parallel to the thrust plane are characterized by a slip vector, oriented *ca.* N65°, within a pure shear-dominant deformation (Fig. 6). This fabric is compatible with the kinematics of the NW-SE trending sector of the OAS thrust (Calamita *et al.*, in press).

Figure 5. N-S trending Jurassic normal faults



Sketch illustrating the N-S trending Jurassic normal faults between the Lazio-Abruzzo carbonate platform and the Umbria-Marche slope-to-pelagic domains (A). These faults were reactivated during the Neogene Period compressive event (B). The vertical scale is exaggerated.

Figure 6. Geometric and kinematic analyses of the OAS thrust shear zones.



Kinematic compatibility between the frontal (a-c) NW-SE- and oblique (d-e) NNE-SSW-trending ramps; photographs of the shear zones (a, d); equal angle projections in the lower hemisphere of all structural features (b, e); and equal angle projections of the lower hemisphere of averaged structural features (c, f).

Thin- vs. thick-skinned tectonic styles

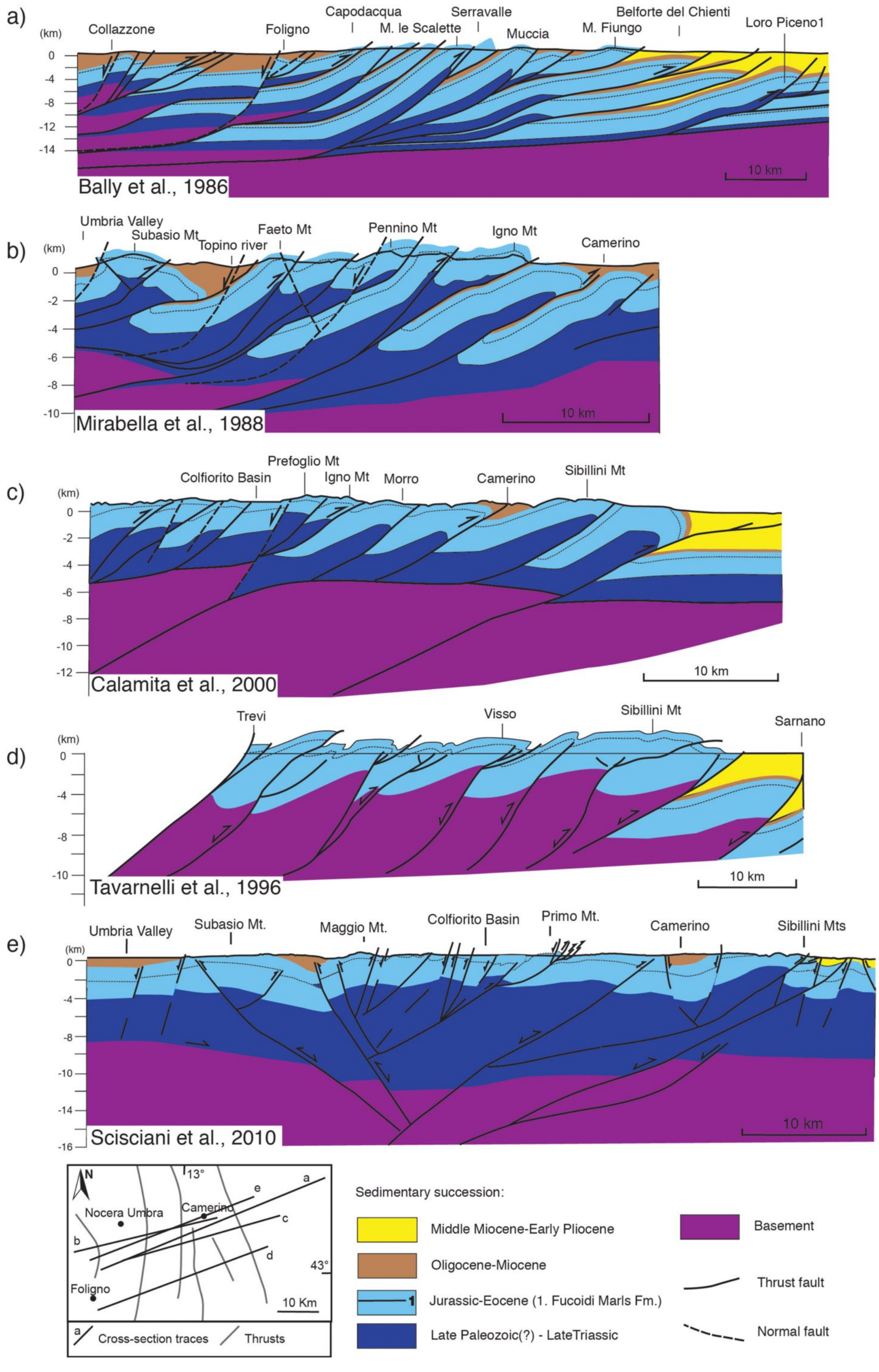
The structural setting of the central Mediterranean region has been widely investigated by deep seismic reflection and refraction profiles. However, contradictory readings of seismic reflection/refraction data still lead to different interpretations of the thickness involved during orogenesis (Bally *et al.*, 1986; Mostardini and Merlini, 1986; Finetti, 2005). During the 1980s, a thin-skinned tectonic style was proposed for the Apennines (Fig. 7a), based on seismic profiles (Bally *et al.*, 1986; Mostardini and Merlini, 1986; Calamita and Deiana, 1988; Hill and Hayward, 1988). Moreover, the first magnetic anomaly map of Italy (AGIP SpA. Italia, 1981) showed a SW-dipping regional monocline in the axial northern Apennines at a depth of 10-15 kilometers (Arisi Rota and Fichera, 1987). This monocline supported the interpretation of the foreland Apennines as a thin-skinned orogen (Bally *et al.*, 1986; Mostardini and Merlini, 1986). During the 1990s, the interpretation of different arrays of seismic profiles (CROP 03, Menichetti *et al.*, 1991; Barchi *et al.*, 1998; Morgante *et al.*, 1998; Finetti, 2005), and the integration of surface and subsurface datasets made available by the oil industry (Coward *et al.*, 1999; Butler *et al.*, 2004) lead to thick-skinned models of the Northern Apennines (Mirabella *et al.*, 2008; Boccaletti *et al.*, 2005; Finetti *et al.*, 2005; Fig. 7b, c) that appealed to structural inheritance (Tavarnelli *et al.*, 2004; Scisciani *et al.*, 2010; Calamita *et al.*, 2011; Fig. 7d, e). Furthermore, interpretation of a recent magnetic anomaly map of the Apennines-Adriatic foreland system showed that the basement is incorporated in the foreland Apennine thrust structures and is involved in high-angle thrust ramps, likely reactivating pre-existing extensional faults (Speranza and Chiappini, 2002).

Gravimetric models can help complete the picture of the geologic setting of the Northern Apennines. Gravity analyses in the Northern Apennines are complicated by the similar densities of Mesozoic shelf limestones, Triassic evaporites, and upper basement rocks (Mostardini and Merlini, 1986). Gravity-magnetic modeling confirms that reflectors associated with the basement in seismic interpretation correspond to the bottom of sedimentary cover. The duplication of the Moho beneath the hinterland of the Apenninic chain (Scarascia *et al.*, 1998) has been explained as a consequence of the westward subduction of the Adria lithosphere (Royden *et al.*, 1987; Doglioni, 1991). An alternative interpretation is that the Moho is imbricated along a main lithospheric thrust fault (Finetti *et al.*, 2005) that, in the outer part of the Apennines, could be an expression of the Neo-lithospheric chain (Boccaletti *et al.*, 2005). Different amounts of shortening have been proposed for the OAS thrust, depending on structural style. The thin-skinned style supposes large-scale displacements and duplication of the sedimentary sequence, decoupled from the undisturbed basement along Triassic evaporites. Conversely, the amount of shortening is more conservative in a thick-skinned context, especially if it is involved in inversion tectonics (Fig. 7).

Paleomagnetism

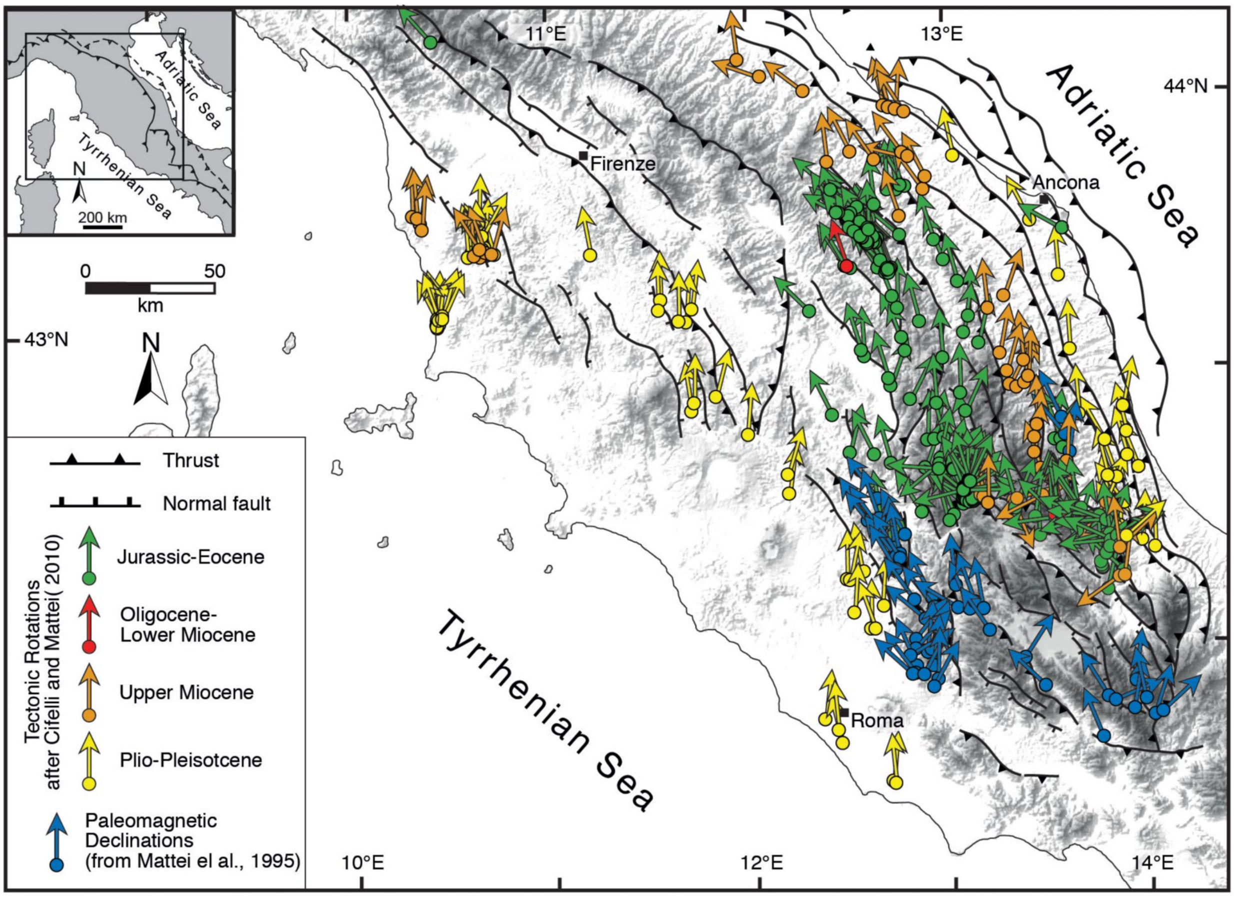
The Northern Apennines have been widely investigated by paleomagnetists since the 1970s. Initially, a *ca.* 40° counterclockwise (CCW) rotation was inferred for the entire Italian peninsula using data from the Umbria-Marche (Lowrie and Alvarez, 1975). However, the autochthonous hypothesis was discarded as soon as paleomagnetic data became available. This new data documented different sense and degree of rotations along the Northern Apennines arc (Channell *et al.* 1992). These rotations were attributed to thrust emplacement, which occurred during the Plio-Pleistocene Period (Speranza *et al.* 1997). Paleomagnetic data from the Northern Apennines (Fig. 8) document a change in vertical-axis rotations from counter clockwise (CCW) to clockwise (CW), as one moves from north to south. Strong CCW rotations have been documented in the Emilia-Romagna region, whose 28° CCW rotation is due to Pliocene thrusting (Muttoni *et al.*, 2000). Rotations decrease toward the arc apex and switch to CW rotations in the southern sector (Speranza *et al.*, 1997). Data from Miocene sediments in the foreland domains indicate that the Northern Apennines represent an oroclinal arc (Speranza *et al.*, 1997). However, a test of the orocline hypothesis, based on data from the internal sheets, shows that the Northern Apennines are a progressive arc (Cifelli and Mattei, 2010). Confined strong rotations, which do not fit either the oroclinal or progressive arc model, are due to the presence of local deformation (e.g., Mazzoli *et al.*, 2001) or strike-slip faults, as described for the southern sector of OAS thrust (Turtù *et al.*, submitted).

Figure 7. Geologic sections reconstructed across the outer sector of the Northern Apennines.



Thin (a) vs. thick- skinned tectonic styles (b, c), also referred to an inversion tectonics context (d, e), have been proposed in the literature.

Figure 8. Digital elevation map of the Northern Apennines, showing major thrust and normal fault traces.



Arrows represent tectonic rotation (Satolli *et al.*, 2005; Cifelli and Mattei, 2010) and paleomagnetic declinations (Mattei *et al.*, 1995) from prior work. Digital evaluation model data were obtained from CGIAR-Consortium for Spatial Information.

Inversion tectonics

Studies on inversion tectonics are an important contribution to the thin- vs. thick-skinned debate. (Fig. 7 d, e). The outer zones of thrust belts are commonly characterized by pre-orogenic faults that control the geometry of thrusts and associated folds (Butler, 1989; McClay, 1989) and have been reactivated or partially translated by thrusts (Tavarnelli *et al.*, 2004; Butler and Mazzoli, 2006). The role of pre-thrusting normal faults in the evolution of the Apennines has been investigated by several authors; such faults were either truncated by thrusts with a shortcut trajectory (sensu McClay, 1989; Coward, 1994) or reactivated with reverse kinematics (Butler, 1989; Scisciani *et al.*, 2002; Tozer *et al.*, 2002; Tavarnelli *et al.*, 2004; Scisciani, 2009; Calamita *et al.*, 2011). Contradictory styles of fault are linked to the same inversion event, and are related to the trend of pre-existing extensional faults with respect to the subsequent compressional NE-SW trending stress field (Calamita *et al.*, 2011; Di Domenica *et al.*, 2012). The N-S trending Ancona-Anzio pre-orogenic normal fault, which controlled the Mesozoic Adria paleomargin, was reactivated during the Neogene Period as an oblique thrust ramp (Fig. 5).

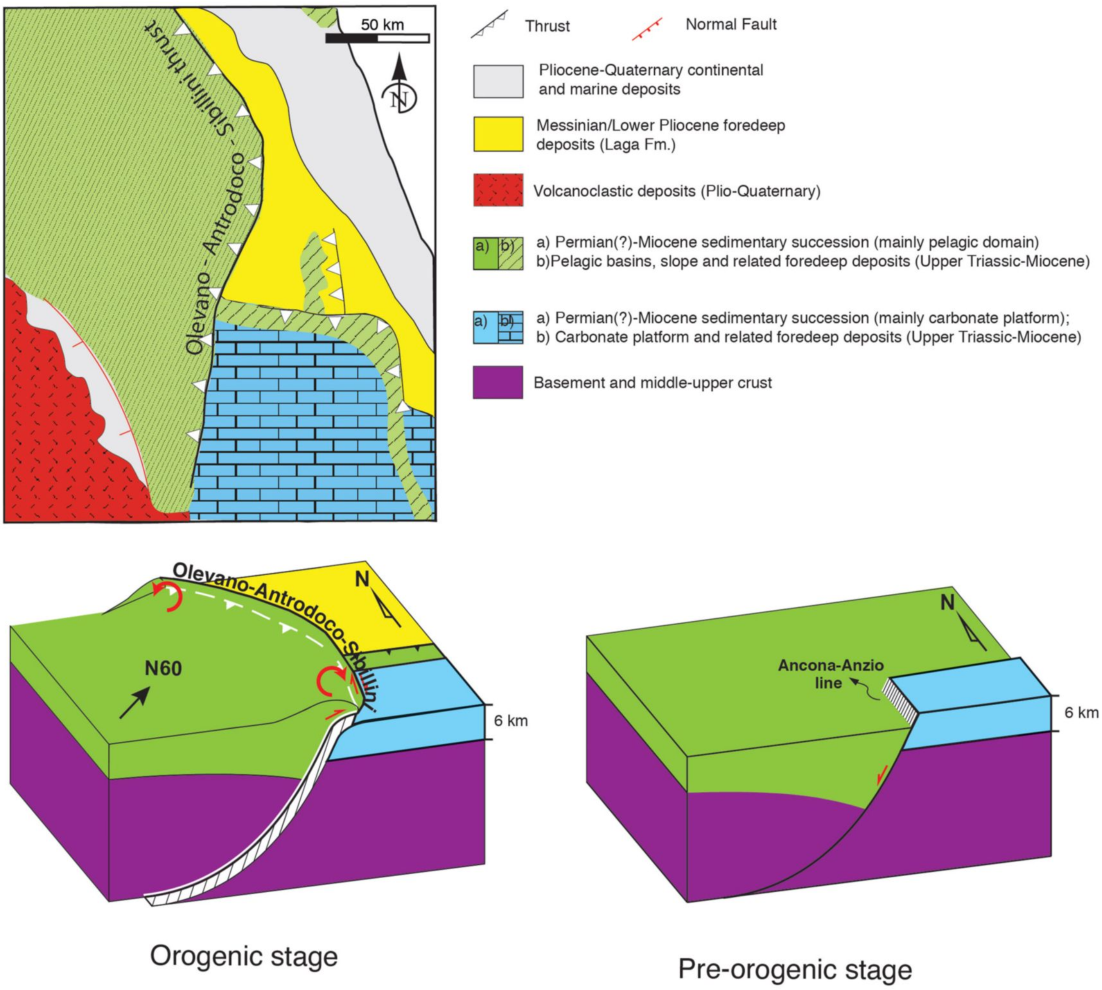
Conclusions

Thin- or thick-skinned models provide contradictory interpretations of orogenic belts. Each model is associated with different amounts of shortening, patterns of rotation around vertical axes, and origins of their curved shapes. Integrating paleomagnetic, geologic, and structural data, with particular attention to inversion tectonics, provides an important contribution to this discussion. This methodological approach has been applied to explain the structural style and origin of the outer Northern Apennines' curved-shape fold-and-thrust belt, within the larger context of the Apennine-Maghrebide belt. The

Northern Apennines Arc can be investigated independently of the rest of the chain because of its numerous differences from the Southern Apennines-Calabrian Arc, including paleogeographic domains, stratigraphic successions, structural setting, tectonic rotations, and geodynamic evolution.

Paleomagnetic and structural data indicate that the foreland Northern Apennines is a progressive arc whose development was influenced by inversion tectonics, involving the reactivation of pre-thrusting normal faults, which trended *ca.* N-S as oblique thrust fronts (the Ancona-Anzio line reactivated as part of the Olevano-Antrodoco-Sibillini thrust; Fig. 9). The architecture of the Mesozoic Adria paleomargin strongly influenced the curved shape of the Northern Apennines, as documented by the relationship between structural units and paleodomains (the OAS thrust separates the carbonate platform from the pelagic domains). The Northern Apennines' curvature was accentuated during orogenesis by CCW and CW tectonic rotations in its northern and southern limbs, respectively. Based on the results of this study, we propose that primary or progressive curve-shaped foreland fold-and-thrust belts are likely to have evolved in an inversion tectonics context. Thrust location was influenced by pre-orogenic normal faults with a thick-skinned deformation style.

Figure 9. Schematic geologic map and 3D model.



Schematic geologic map and 3D model showing the crustal inversion tectonic model proposed for the development of the progressive outer arc of the Northern Apennines (Olevano-Antrodoco-Sibillini thrust).

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