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Recent evolution of the Mediterranean realm: Exploring the links between deep and shallow processes in a plate convergent setting Christian Gorini, Anouk Beniest, Andréa Billi, Nicolas Chamot-Rooke, Jacques Déverchère and Juan I. Soto (Guest editors)

Structural inheritance within the outer zones of arcuate collisional orogens: A case from the Central-Northern Apennine orogenic system

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Abstract – The evolution of fold-and-thrust systems developed at the expenses of pre-orogenic extensional basins is mainly achieved by reactivation, truncation of precursor structures, or by variable combination of these two distinct modes of propagation of compressional deformation during positive tectonic inversion. An overview of three selected examples from the Central-Northern Apennines of peninsular Italy towards the nearby Adriatic foreland domain illustrates that reactivation, truncation or combinations of these two processes of precursor fault deformation tend to be dominant proceeding from forelands towards orogenic interiors, suggesting a correlation between modes of deformation during inversion and their spatial distribution across orogenic belts.

Keywords: Tectonic inversion / Orogenic belts / Precursor extensional basins / Fault truncation / Reactivation / Structural inheritance

1 Introduction

The advent of the Plate Tectonics theory in the 1970s has illustrated that compressional deformation fronts proceed from the inner orogenic provinces towards adjacent foreland domains (Dewey and Bird, 1970); in case of more-or-less linear converging continental margins, the deriving orogenic belts will consequently have more-or-less linear trends. There are, however, colliding continental blocks with margins far from linear, with highly pronounced salients and recesses, whose geometry does influence the final, complex shape of the growing mountain belts: isolated salients can thus represent a shared foreland domain with respect to distinct, converging orogenic systems flanking it from all sides. The Mediterranean area, due to the Cretaceous-to-Present interaction of small lithospheric plates (microplates: Alvarez *et al.*, 1974) bounded by the main converging Africa and Eurasia plates, has long been considered a very complex tectonic puzzle; yet, thanks to good exposure, it has long represented a natural laboratory for the study of orogenic dynamics. The peri-Mediterranean belts originated from the Africa-Europe collision locally depart from ideally linear trends, especially around Adria, a northerly promontory of the African continent, that represents a common foreland domain shared by the Apennines, the Southern Alps and the Dinarides converging systems. Under these circumstances, it is important to investigate if – and, if so, to what extent – the occurrence of pre-existing structures within otherwise undeformed templates controls the final shape of convergent arcuate mountain belts (Fig. 1). In this contribution we aim at reviewing the evolution of the Northern-Central Apennines, an arcuate segment of the Apennine orogenic belt of peninsular Italy (Lavecchia *et al.*, 1988; Calamita and Deiana, 1988; Billi and Tiberti, 2009), paying particular attention to the controls played by structures present in the Adria foreland as this was incorporated within the advancing orogenic wedge, an issue that has led to the development of the inversion tectonics concept (Williams *et al.*, 1989; Coward, 1994). The arcuate map pattern of the Central-Northern Apennines has classically been interpreted as due to: paleogeographic dishomogeneities within the stratigraphy; the interaction of pre-and post-orogenic structures; the occurrence, thickness and lateral extent of detachment horizons mainly consisting of evaporite layers at the base of, or of pelitic layers within the sedimentary cover; and/or the distribution of gravity anomalies within the crust (Castellarin *et al.*, 1982; Speranza and Chiappini, 2002; Billi and Tiberti, 2009; Barchi, 2010; Livani *et al.*, 2018, and references therein). All these factors combined may help elucidate the

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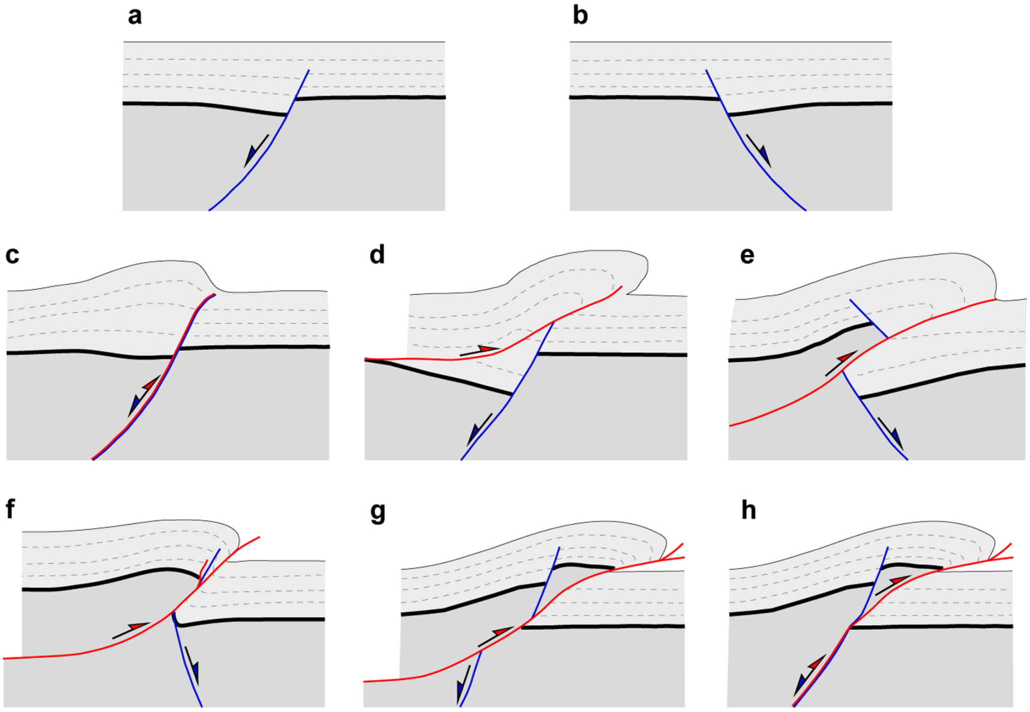

Fig. 1. A comprehensive review of 2D relationships between hinterland- (a) and foreland- dipping (b) precursor normal faults with subsequent thrusts and related folds (c-h). Hinterland-dipping normal faults may be reverse-reactivated (c), truncated (g), or reverse-reactivated to depth and truncated at higher structural levels (h) by upward-propagating thrusts. Foreland-dipping normal faults are generally truncated and passively carried piggy-back in the hangingwall blocks of upward-propagating thrusts (e, f), or may act as loci for thrust ramp nucleation (d).

geometry and deformation history of the stratigraphic sequences during positive tectonic inversion episodes. In the following sections we first review the basic definitions of inversion tectonics as this process was recognized in peninsular Italy and elsewhere, mainly in the circum-Mediterranean orogenic belts. We then describe three thrust-related anticlines reported from the literature, paying attention to the possible, if any, structural controls that have inhibited their location and amplification. Our examples, located in the Adria foreland and in the outer zones of the Central-Northern Apennines (Fig. 1), may ultimately provide sound analogues to model the evolution of analogue structures resulting from positive inversion in other belts of the circum-Mediterranean regions and elsewhere.

2 A short review of Inversion Tectonics concepts in the Central-Northern Apennines

Inversion tectonics is a significant, globally recognized process that applies to regions which have experienced a reversal in deformation regimes from extension to contraction or vice-versa. In the first case, basins developed during the extensional phase are turned inside out becoming structural highs or positive features. Basin-bounding normal faults may reverse their movement during superimposed contractional tectonics. This process accommodates ‘positive inversion’ also known as ‘basin inversion’ (Glennie and Boegner, 1981; Ziegler, 1987; Bally, 1984; Gillcrist *et al.*, 1987; Williams *et al.*, 1989; Letouzey, 1990; Coward, 1994; Buchanan and Buchanan, 1995). Conversely, a switch from compression to extension results in a change from uplift to subsidence leading to what is identified as ‘negative inversion’ (Glennie and Boegner, 1981; Harding, 1985; Cooper and Williams, 1989; Cooper and Warren, 2010; Tari *et al.*, 2023). In this case, former thrusts produced during the compressional episodes may be reactivated as normal faults during the superimposed extensional phase.

At odds with classical concepts of inversion tectonics, resulting from switches in deformation fields, there is much less documentation available about inheritance played by structures developed under the same, or analogue, tectonic regime; these include, for instance, thrust-related folds whose final geometry was influenced by already existing compressional structures. The patterns of these interfering structures are relatively easy to recognize when they trend at high angles (*e.g.*, Doglioni and Siorpaes, 1990), whereas their recognition may be more complex in case of interference of near-parallel structures.

Following the development of inversion tectonics concepts during the ‘80s and early ’90s, the Apennines of Italy increasingly attracted the interests of many researchers and remarkable examples of both positive and negative inversion tectonics were documented. Specifically, given the spectacular exposures and the mild overprint between repeated episodes of extension and contraction, the outer Central-Northern Apennines represent a natural laboratory to analyse different styles of inversion tectonics. Moreover, the Apennine thrust belt provides different exposure levels and sound stratigraphic constraints within the Meso-Cenozoic carbonate-dominated sequence. This feature makes it possible to understand

and reconstruct how the boundary, passive continental margins of Tethys Ocean deformed under contraction. Therefore, widespread surface geological analyses, realistic stratigraphic templates and balanced cross-sections combined with diverse geophysical data led to the recognition of inversion and to the development of new tectonic models to account for these structures (see comprehensive reviews by Tavarnelli *et al.*, 2004; Butler *et al.*, 2006; Tavani *et al.*, 2015). End-member, relatively simple "inversion anticlines" and "shortcut structures" have been described along with a great variety of more complex and composite structural patterns (*e.g.*, Coward *et al.*, 1999; Tavarnelli 1999; Mazzoli *et al.*, 2002; Calamita *et al.*, 2003; Tavarnelli *et al.*, 2004; Butler *et al.*, 2004; 2006; Centamore *et al.*, 2009; Scisciani, 2009; Scisciani *et al.*, 2014; Tavani *et al.*, 2015; Pace *et al.*, 2015; Calamita *et al.*, 2018; Scisciani *et al.*, 2019; Tavarnelli *et al.*, 2019).

Such complex structural inversion tectonic styles have been documented in a wide range of scales in the outer sector of the Miocene-Pliocene Central-Northern Apennines, where newly-formed, gently-dipping thrusts variously interfere with different sets of pre-existing faults. Pre-thrusting normal faults were inherited from the early Mesozoic rifting, from the Miocene-Pliocene foreland flexuring ahead of the advancing thrust belt, or from a combination of both mechanisms. Significant lateral thickness and facies variations within the pre-orogenic, Jurassic-Eocene stratigraphy are related to the syn-sedimentary Jurassic rifting (Centamore *et al.*, 1969, 1971; Colacicchi *et al.*, 1970; Alvarez, 1990; Santantonio, 1993; Bosellini, 2004) and to the Cretaceous-Paleogene normal faulting episodes (Baldanza *et al.*, 1982; Decandia, 1982; Montanari *et al.*, 1989). In addition, syn-flexural, yet pre-thrusting normal fault systems of Miocene age controlling the development of the depocentres and of the outer edges of syn-orogenic basins have also been reported (*e.g.*, Calamita *et al.*, 1998, 2003; Scisciani *et al.*, 2001; Mazzoli *et al.*, 2002). From Middle-Late Miocene onward, following the onset of the orogenic regime, the switch in deformation from extension to contraction led to positive inversion. As a consequence, all normal faults of Jurassic, Cretaceous-Paleogene and Miocene ages within the pre-thrusting template were modified by upward-propagating thrusts and related folds of Messinian-Lower Pliocene age. The most frequently documented modification by late propagating thrust faults across previously extended templates include reactivation, rotation, truncation and/or passive translation of pre-thrusting normal faults (*e.g.*, Tavarnelli, 1996; Scisciani *et al.*, 2001; Calamita *et al.*, 2018), largely depending on the orientation of the former structures with respect to the subsequent contractional stress field (Calamita *et al.*, 2011). Generally, the inherited normal fault-controlled templates exerted a strong control on thrust ramp nucleation (*e.g.*, Tavarnelli, 1996). Oblique thrust ramps, corresponding to important NNE-SSW-trending regional-scale cross-striking discontinuities, resulted from the transpressional reactivation of precursor basement-rooted faults, giving rise to thrust belt compartmentalization, segmentation and curvature (*e.g.*, Tavarnelli *et al.*, 2004; Butler *et al.*, 2006; Satolli *et al.*, 2014; Barchi and Tavarnelli, 2022). Contrasting styles of positive fault reactivation (*i.e.*, reverse reactivation or footwall thrust shortcut) are documented along the NW-SE-striking low-angle frontal thrust ramps and along the NNE-SSW-striking high-angle oblique thrust ramps (Calamita *et al.*, 2011).

Furthermore, the NW-SE-trending pre-thrusting normal faults that had experienced positive inversion, having been reverse-reactivated to depth and passively carried piggy-back in the hanging-wall of shortcut anticlines at or near the surface, are occasionally recording negative inversion following the onset of the seismogenic Quaternary extensional stress field along the backbone of the Apennines (*e.g.*, Calamita *et al.*, 2003, 2011; Tavarnelli *et al.*, 2004; De Paola *et al.*, 2006; Pizzi and Galadini, 2009; Di Domenica *et al.*, 2012; Pizzi *et al.*, 2017; Porreca *et al.*, 2020).

Re-examining the structural evolution of the outer parts of the Northern Apennines, Coward *et al.*, (1999) reviewed the role of structural inheritance with extension of inversion tectonics concepts also to deeper crustal levels. This opened a new scenario, with changed the interpretation of: i) the deep structure of the thrust belt, from popular detachment-dominated thin-skinned models, largely applied during the 1980s (*e.g.*, Bally *et al.*, 1986; Hill and Hayward, 1988), to more conservative thick-skinned models (*e.g.*, Barchi *et al.*, 1998) only involving basement fault reactivation (*e.g.*, Mazzoli *et al.*, 2000; Butler *et al.*, 2004; Tavarnelli *et al.*, 2004; Calamita *et al.*; Scisciani *et al.*, 2014, 2019; Tavarnelli *et al.*, 2019); and ii) to combinations of detachments located at the base of, and also within the sedimentary cover, locally interfering with deeper faults emanating from the basement that have been reverse-reactivated (Ghisetti *et al.*, 1993; Barchi and Tavarnelli, 2022).

3 Examples of structural controls in the outer Central-Northern Apennines and in the Adriatic offshore

In the following sections we present the results of investigations carried out along three distinct structures that have been extensively described in a wide literature; two are located in the outer zones of the Central-Northern Apennines and one in the adjacent Adriatic foreland domain offshore (Fig. 2). In order to evaluate possible controls in the development of these structures, we proceed from east to west, *i.e.*, from the relatively less deformed Adria foreland domain toward the more intensely deformed interiors of the outer zones of the Central-Northern Apennines thrust system. The first structure corresponds to the Mid-Adriatic Ridge, offshore the Marche coastline; the second structure corresponds to the Montagna dei Fiori Anticline; and the third structure is described along the Mt. Sibillini Thrust (Figs. 2a and 2b).

3.1 – The Mid-Adriatic Ridge

Seismic data from the Marche offshore illustrate the occurrence of a positive compressional structure located midway between the coastlines of Italy and Croatia on both sides of the Adriatic Sea (Figs. 2 and 3). This positive structure, bounded by a system of SW- and NE-dipping high-angle reverse faults, has long been known to the scientific community as the Mid Adriatic Ridge (Figs. 2 and 3).

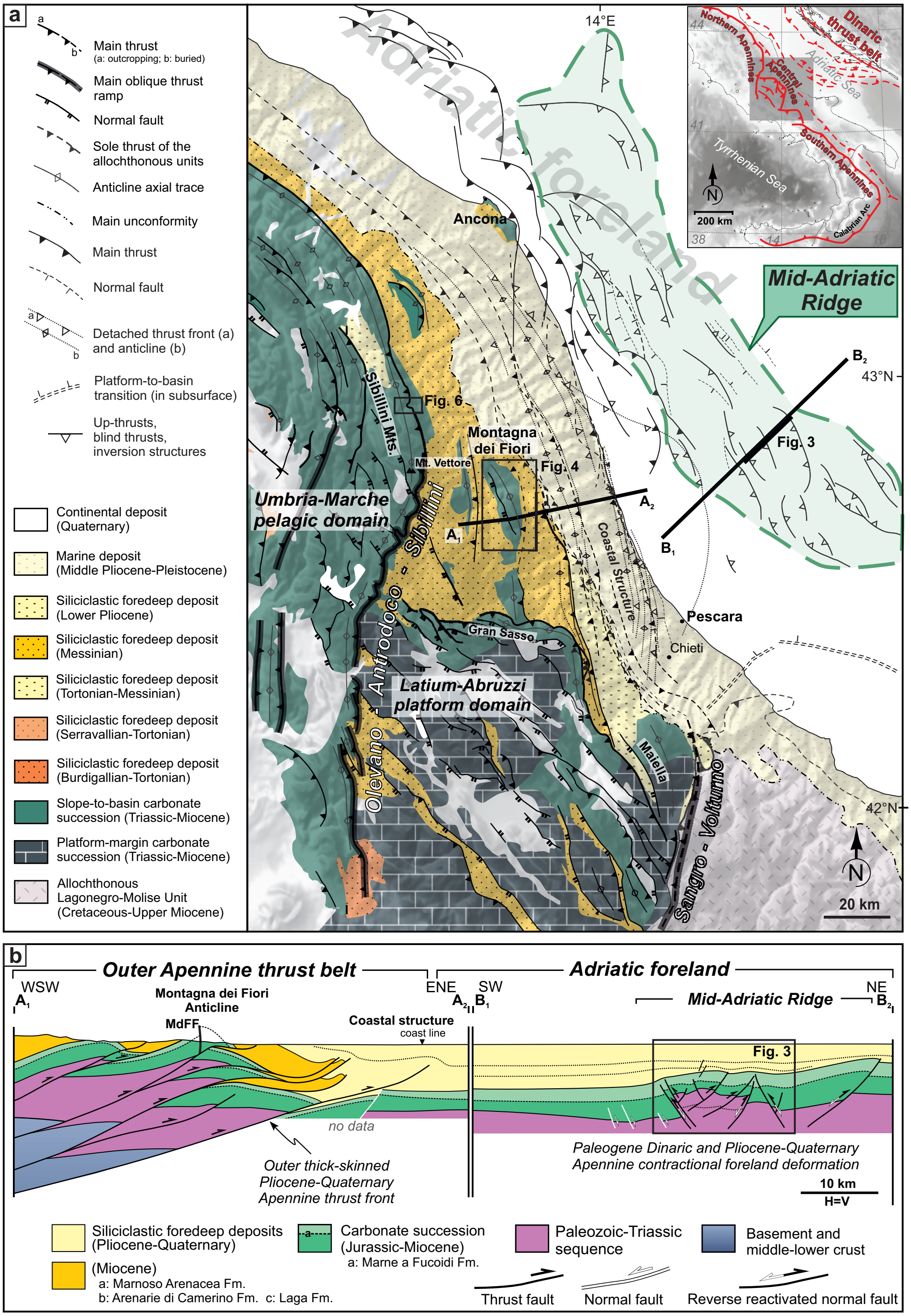

Fig. 2. (a) Simplified structural-geological and related composite geological cross-section (b) of the outer Neogene-Quaternary Central-Northern Apennine fold-and-thrust belt and the doformed sector of the Adriatic foreland (modified after Calamita *et al.* 2021). Please note that the cross-section (b) does not balance: the impossibility to obtain a restored template, essential requirement for balanced cross-sections, is due to the lack of data in the deep parts of the A1-A2 tract (area indicated as "no data"), that prevents to locate footwall cutoff points for the Carbonate succession unit.

Stratigraphic data indicate that the Mid-Adriatic Ridge was uplifted during the latest Cretaceous-Miocene time interval, matching with the deformation events that collectively are indicated to correspond to the Dinaric Phase (*e.g.*, Schmid *et al.*, 2008; Porkoláb *et al.*, 2019; Calamita *et al.*, 2021). This contractional high-angle reverse fault system developed within

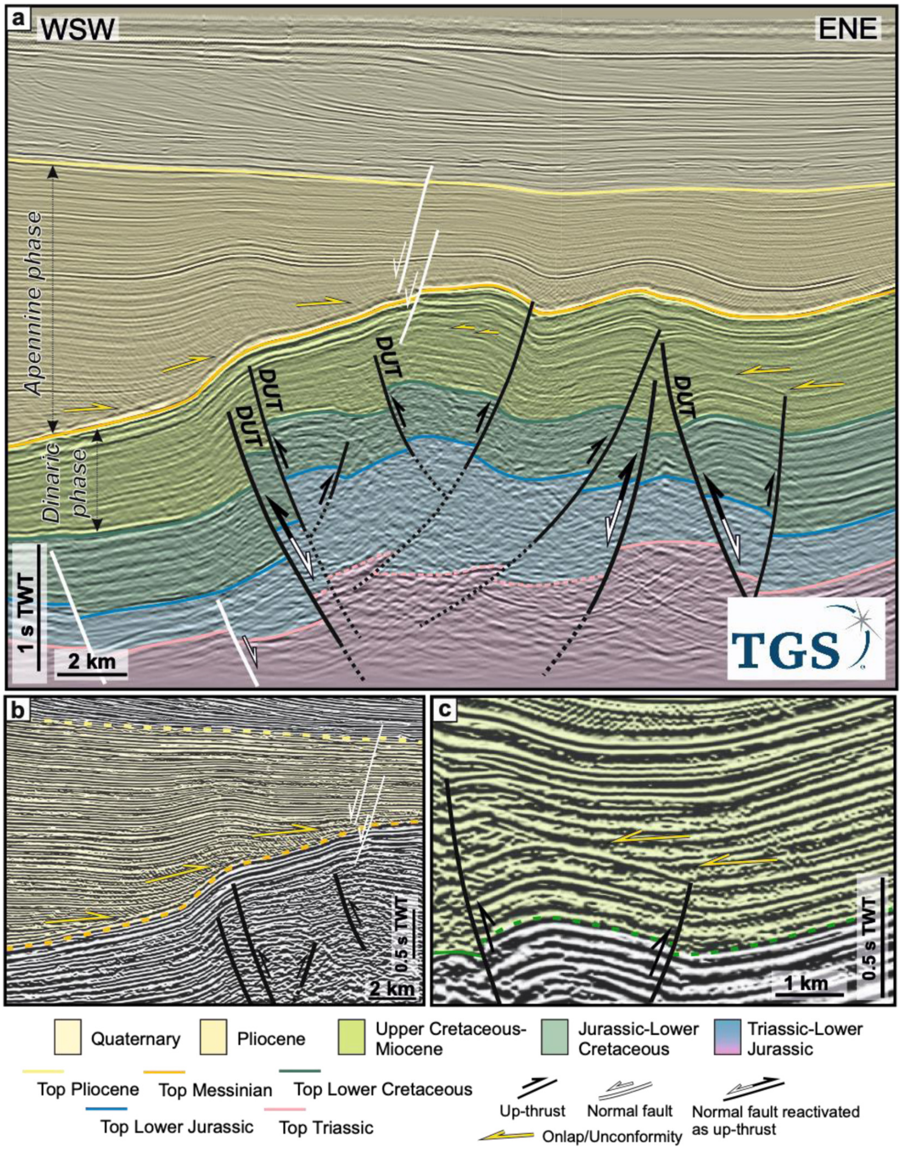

Fig. 3. (**a**) Seismic section from the Mid-Adriatic Ridge (location in Fig. 1) showing a polyphase inversion structure composed of several Dinaric up-thrusts (DUT) and related folds having an Upper Cretaceous-Oligocene (growth coeval with the onset of the Dinaric foreland contractional deformation and a later reactivation during the Pliocene-Quaternary Apennine phase. (**b** and **c**) Close-ups of the seismics with the cosine of phase attribute showing the two phases of growth and inversion (modified after Pace *et al.*, 2015 and Calamita *et al.*, 2021).

the Adriatic foreland ahead of the growing, SW-propagating Dinaric chain (Fig. 3), consists of two main NW–SE trending high-angle reverse faults along which a 5-8 thick succession of marine, Triassic-to-Tertiary rocks are uplifted to define an upward-extruded wedge. This structure is not the only compressional feature recognized within the otherwise less deformed Adria Promontory. Indeed, it seems relevant to stress that evidence for SW-directed, compressional structures belonging to the Dinaric system have long been reported from the eastern margin of the Adriatic Sea and along its north-west ward lateral continuation in the Southern Alps (Doglioni and Siorpaes, 1990); moreover, minor evidence for a further westward extension of SW-directed compressional deformations of Tertiary age is also documented in the Gargano Promontory of Southern Italy (Bertotti *et al.*, 1999). Therefore, it seems likely that the effects, though mild, of the Dinaric Phase are diffused within much of the Adriatic offshore domain.

Pace *et al.* (2015) have described the Mid Adriatic Ridge whose deep geometry is inferred from high-resolution seismic profiles. The occurrence of facies and thickness variations within Triassic-Lower Cretaceous rocks west of the Mid Adriatic Ridge is controlled by syn-sedimentary normal faults that were active prior to the onset of the Dinaric contractional deformations (Fig. 3). Many of the high-angle faults bounding the Mid Adriatic Ridge and within it exhibit evidence for thickness inversion across them at null-points (terminology after Cooper and Williams, 1989), an evidence indicating that many of these structures were originated as Triassic-Lower Cretaceous syn-sedimentary normal faults. These faults were later reverse-reactivated to produce the observed upward extrusion of Upper Cretaceous-Miocene sequences during the Dinaric Phase (Fig. 3). These relationships apply to the Dinaric up-thrust (DUT in Fig. 3) that limits the Mid Adriatic Ridge westwards. It is interesting to note that all reverse-reactivated normal faults fall within the Mid Adriatic Ridge, whereas those west of it do not exhibit evidence for reverse reactivation, maintaining normal offsets. This dual behaviour likely reflects the occurrence along the Mid Adriatic Ridge of deep normal faults emanating from the basement that produced significant offsets within parts of the overlying sedimentary cover sections. These observations and inferences suggest that the location of the Tertiary Mid Adriatic Ridge was controlled by syn-sedimetary normal faults, some of which emanating from the basement, that were reverse-reactivated during the Upper Cretaceous-Miocene contractional events. This inference supports the view of structural inheritance phenomena during the Dinaric Phase.

Careful examination within the upper part of the Mid Adriatic Ridge illustrates two West-dipping normal faults affecting and controlling thickness and facies variations within Pliocene-Quaternary deposits. These faults show no evidence for reactivation, indicating that when they formed the compressional effects of the Dinaric Phase had long waned (Fig. 3).

3.2 The Montagna dei Fiori thrust-related anticline

The Montagna dei Fiori Anticline is the most prominent structure in the outer Central-Northern Apennine fold-and-thrust belt, and consists of a NNW–SSE-trending, thrust-related fold (Figs. 2 and 4).

The anticline is East-verging and is exposed for an along-strike length of c. 25 km. The fold profile is remarkably asymmetric, with a steep-to-overturned forelimb and a gently (30–50°) dipping backlimb, separated by a flat-lying crest zone and by a curvilinear hinge line plunging NNW- and S-wards (Fig. 4). The fold-and-thrust structure involves the pre-orogenic, Jurassic–Miocene, Umbria–Marche pelagic carbonate sequence overlain by Messinian syn-orogenic, foredeep siliciclastic deposits of the Laga Formation (Giannini, 1960; Giannini *et al.*, 1970; Koopman, 1983; Mattei, 1987; Calamita *et al.*, 1998; Scisciani *et al.*, 2001; Scisciani and Montefalcone, 2006; Di Francesco *et al.*, 2010; Storti *et al.*, 2018).

The main thrust surface, exposed in the fold core, is antiformally folded by the growth of a younger and deeper thrust-related anticline, as inferred from several interpretations of seismic reflection profiles (Bally *et al.*, 1986; Ghisetti and Vezzani, 2000; Scisciani and Montefalcone, 2006; Artoni, 2013; Figs. 4a and 4c). Moving eastwards, a gently West-dipping thrust propagates across East-dipping siliciclastic deposits of the Messinian Laga Formation (Calamita, 1990; Scisciani and Montefalcone, 2006). The steeply East-dipping to overturned forelimb of the Montagna dei Fiori Anticline trends NW–SE in the northern sector, changing across the fold axial culmination to a N–S orientation. Pervasive S-C-C' fabrics within shear zones along the thrust that truncates the fold forelimb consistently indicate a top-to-the-NE (60–70° N) tectonic transport direction (Koopman, 1983). Reverse shear zones and detachment folds are also exposed in the anticline backlimb. The shear zones are confined to the upper section of the Miocene marly sequence, whereas the overlying Messinian turbidites (*i.e.*, Laga Formation) appear undeformed (Koopman, 1983; Invernizzi and Ridolfi, 1992; Calamita *et al.*, 1998; Mazzoli *et al.*, 2002; Scisciani and Montefalcone, 2006). The similarity between the geometries and kinematics of the shear zones observed along the flanks of the Montagna dei Fiori Anticline indicates that the Palaeogene–Miocene pre-orogenic succession acted as a regional detachment level (Laga Detachment sensu Koopman, 1983), along which the thick sedimentary wedge of the Laga Formation was translated eastwards with respect to the underlying Mesozoic sequence. The deep (> 10 km) setting of the Montagna dei Fiori structure has been debated by many authors, and both thin- and thick-skinned tectonic models have been used to illustrate the tectonic style of this sector of the outer Central-Northern Apennines (Paltrinieri *et al.*, 1982; Bally *et al.*, 1986; Tozer *et al.*, 2002, 2006; Albouy *et al.*, 2003; Scisciani and Montefalcone, 2006).

The crest of the Montagna dei Fiori Anticline is offset by a steeply SW-dipping normal fault, the Montagna dei Fiori Fault, along which the Miocene Marne con Cerrogna Formation of the hanging-wall is juxtaposed to the pre-orogenic carbonate sequence with an offset of ca. 900m (Mattei, 1987; Calamita *et al.*, 1998; Scisciani *et al.*, 2001; Fig. 4b). The timing of activity of the Montagna dei Fiori Fault with respect to the orogenic deformation event is highly controversial and different interpretations have been proposed. Based on the assumption that the vast majority of normal faults affecting Jurassic-Neogene stratigraphic sequences in the Apennines result from late-to-post-thrusting extension, Koopman (1983), Bally *et al.* (1986) and Mattei (1987) consider the fault as a post-orogenic structure; Ghisetti and Vezzani (2000) and Storti *et al.* (2018), the latter based on geochemical data from veins associated with the main extensional structures, propose that the activity of the Montagna dei Fiori Fault accompanied, and thus was synchronous with, thrusting; and conversely, at odds with other abovementioned interpretations, Calamita *et al.* (1998), Scisciani *et al.*, 2001, Mazzoli *et al.* (2002) and Tozer *et al.*, (2006), based on the occurrence of minor thrusts that accommodate few centimetres of contractional displacements and that truncate the main normal fault surface, consider the Montagna dei Fiori Fault as a pre-thrusting structure, whose development would have accommodated foreland flexuring, the location of the Laga Foredeep Basin and whose occurrence would have inhibited foreland-directed thrust propagation (Fig. 4b).

In more recent accounts, the opening and evolution of the Tyrrhenian Sea to the west of the Apennines has been interpreted as due to, and accompanied by, lithospheric stretching accommodated by subsidence within basins bounded by normal faults that merge downwards into low-angle extensional detachments: these structures have since been referred to as supradetachment faults (Milia and Torrente, 2015; Milia *et al.*, 2017). Consistently with this interpretation, and as a possible alternative to pre-thrusting extension due to foreland flexuring and foredeep development ahead of the advancing Apennine belt (Scisciani *et al.*, 2001; Mazzoli *et al.*, 2002; Tozer *et al.*, 2006) we here propose that the formation of the Montagna dei Fiori Fault could result from location of a supradetachment extensional basin, developed since the Middle-Late Miocene, and later affected by thrusting of Upper Messinian age during its incorporation in the Apennine belt.

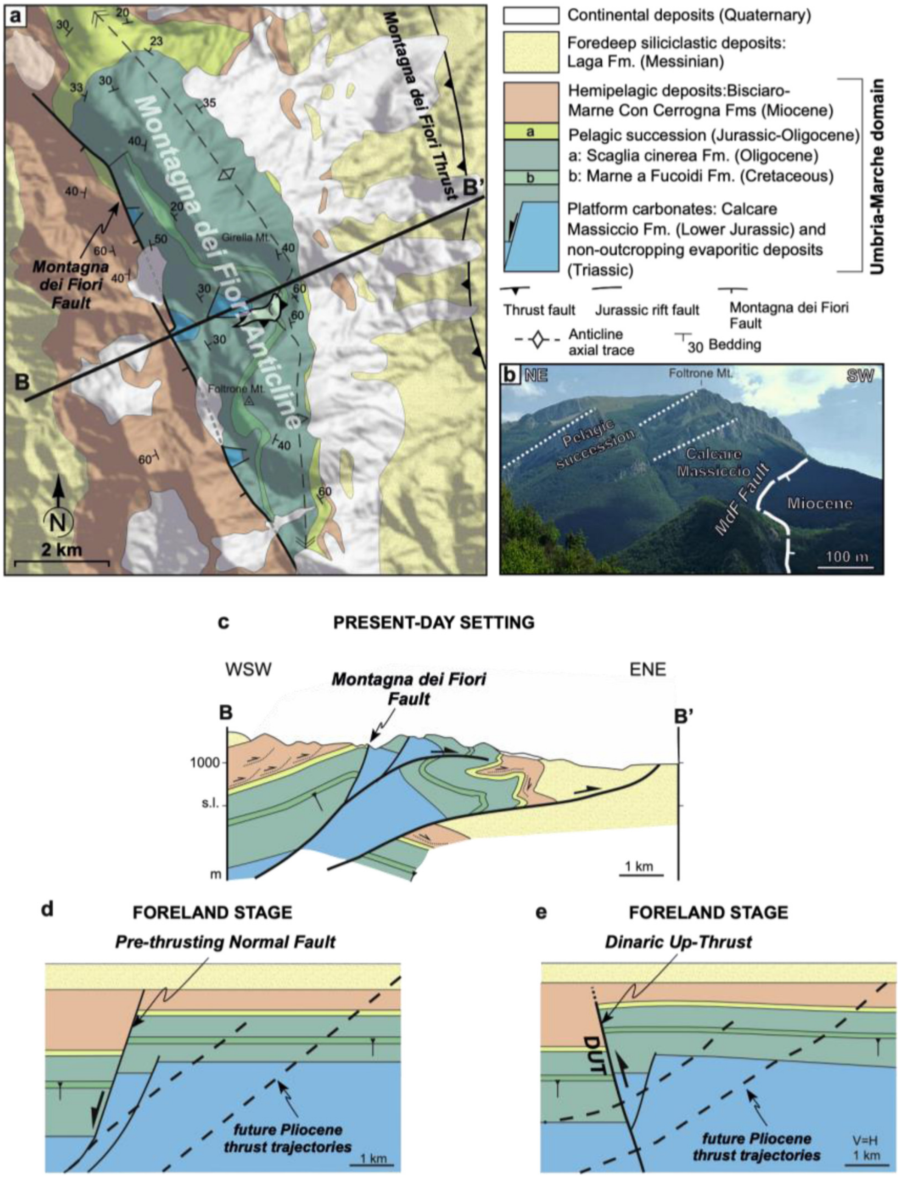

Fig. 4. (**a**) Geological map of the Montagna dei Fiori structure (modified from Mattei, 1987; Calamita *et al.*, 2011). (**b**) Panoramic view of the Montagna dei Fiori fault along the forelimb/hinge zone of the anticline, showing the attitude of the footwall strata characterized by 30–40° dip towards the NE. (**c**) Geological cross-section (trace B-B' in Fig. 4a). (**d**) Speculative template showing the interpretation of the Montagna dei Fiori Fault as a syn-orogenic, pre-thrusting normal fault (Calamita *et al.*, 1998; Scisciani *et al.*, 2001). **(e)** Speculative template showing the interpretation of the Montagna dei Fiori Fault as a NE-directed, high-angle upthrust (DUT) developed during the latest Cretaceous–Middle Miocene time interval (Calamita *et al.*, 2021). Note that the cross-section (c) does not balance, due to the paucity of data to constrain its deeper parts, which prevents its quantitative restoration; however, it is presented here with the only purpose of illustrating the alternative, qualitative interpretations given for the same structure, the Montagna dei Fiori Fault, as a pre-thrusting normal fault (d) or as a West-directed upthust (e). One slightly different, third interpretation for the Montagna dei Fiori Fault, that is yet geometrically and kinematically consistent with the hypothesis of a pre-thrusting normal fault illustrated in Figure 4d, is that this tructure could represent the relicts of a supradetachment fault (terminology after Milia & Torrente, 2015), inherited during the episodes of extension that have accompanied the opening of the Tyrrhenian Sea and preceeded the upward-propagation of the Montagna dei Fiori Thrust (see the text for explanation).

Even more recently, Calamita *et al.* (2021) propose a different model predicting that the fault represents an originally, steeply NE-dipping, SW-propagating high-angle up-thrust of Teriary age developed during the Dinaric Phase (Fig. 4e); this upthrust would have later been truncated by the NE-propagating Montagna dei Fiori Thrust and rotated to its current SW-dip, that consequently mimics the geometry of a normal fault.

Given the documented occurrence of small low-angle thrusts offsetting the main fault surface – and regardless of the pre-thrusting fault origin as due: i) to foreland flexure (Calamita *et al.*, 1998; Scisciani *et al.*, 2001; Mazzoli *et al.*, 2002;

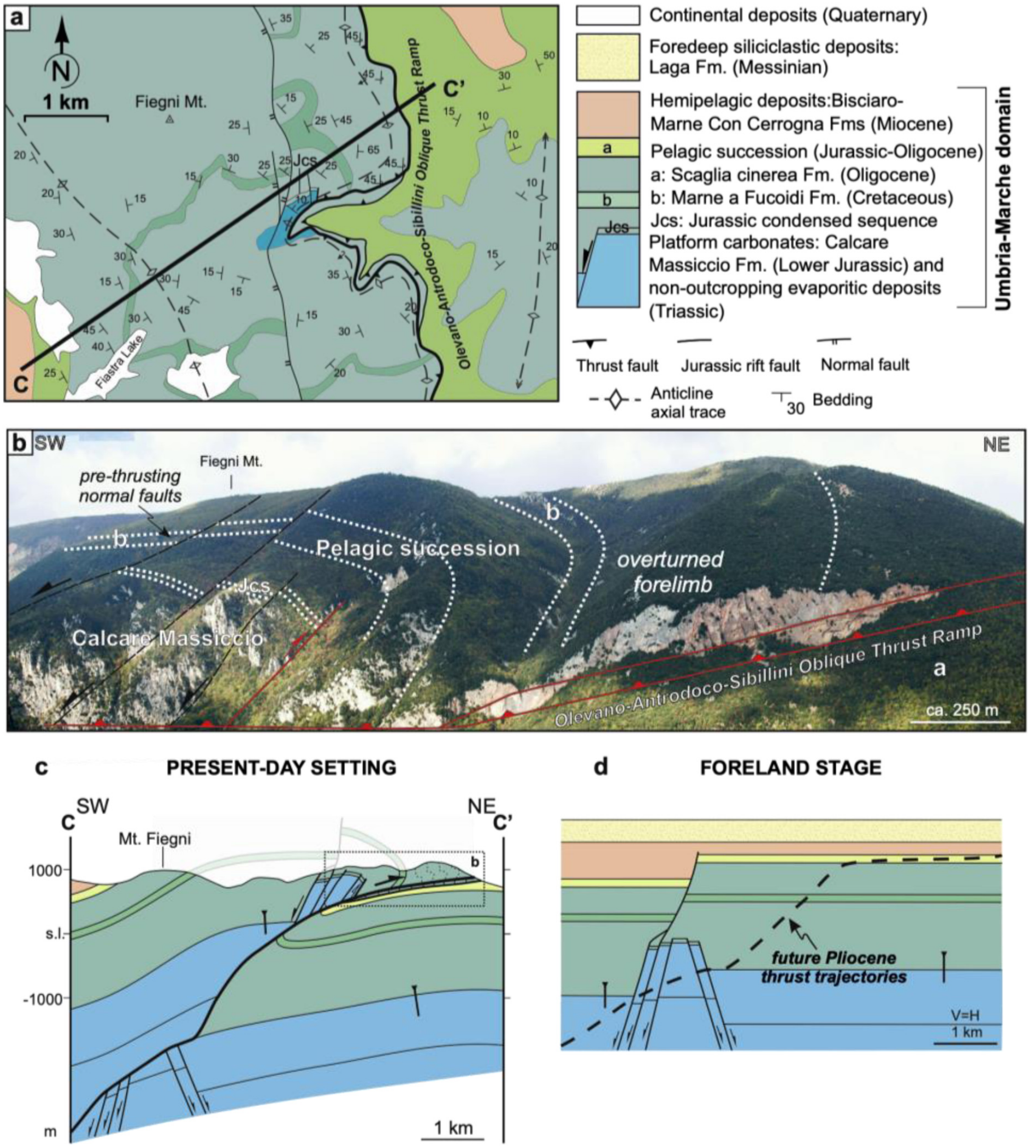

Fig. 5. (**a**) Geological map of the Mt. Sibillini frontal thrust ramp in the area of Mt. Fiegni. (**b**) Panoramic view of the structure along the Fiastra valley. (**c**) Geological cross-section and (**d**) restored template showing the thrust ramp localization during Pliocene thrusting and positive inversion stage (modified after Calamita *et al.*, 2012).

Tozer *et al.*, 2006); ii) to a supradetachment basin-driven process (terminology after Milia and Torrente, 2015; this study); or alternatively: iii) to the Dinaric up-thrust (Calamita *et al.*, 2021) interpretation – we here maintain that the steeply dipping fault running along the crest line of the Montagna dei Fori Anticline predated its growth, juxtaposing rocks with different rheological properties. We conclude that this inherited structure represented a fundamental geometrical and mechanical control on the development of the Montagna dei Fiori thust ramp during the Apennine orogenic event.

3.3 The Mt. Sibillini Thrust

The Mt. Sibillini Thrust is a prominent, first-order arcuate structure representing the main front of the Central-Northern Apennines belt (Calamita and Deiana 1988). The thrust consists of a NW-SE-trending segment deviating into a N-S and then NNE-SSW trend, respectively north, east and south of Mt. Vettore (Figs 2, 4 and 6).

The thrust is traced continuously for over 150 km and is characterized by a maximum displacement of ca. 10 km achieved in the salient apex zone near Mt. Vettore (Mazzoli *et al.*, 2005; Pierantoni *et al.*, 2005; Pierantoni *et al.*, 2013) progressively decreasing towards the NW and SSW. Well-developed kinematic indicators, namely S-C-C’ fabrics and R-R’ Riedel shears, reveal a N60–70° mean tectonic transport direction, defining for the thrust a frontal ramp geometry to the north, and an oblique-lateral ramp geometry to the south (*e.g.*, Calamita *et al.*, 1987; Bigi *et al.*, 1995; Pace *et al.*, 2017, 2022a, b). The thrust hanging-wall and footwall, along with the thrust surface itself, are antiformally folded. In the thrust hanging-wall, folds have an axial trend running parallel to the thrust system orientation, while some NW-SE folds are developed in the footwall (Koopman 1983; Calamita and

Deiana 1988). To the south of Mt. Vettore, the NNW-SSE footwall anticlines involve also the NNE-SSW-trending oblique thrust ramp surface and the hanging-wall anticlines, indicating a general piggy-back, hinterland-to-foreland thrust propagation sequence (*e.g.*, Calamita *et al.*, 2012). Along the NNE-SSW-trending segment, the Neogene oblique-lateral thrust ramp surface transpressionally reactivated a pre-existing normal fault system of Lower Jurassic age (Calamita and Deiana 1988; Tavarnelli, 2004; Butler *et al.*, 2006; Calamita *et al.*, 2011; Pace and Calamita 2014). This Lower Jurassic normal fault system (*i.e.*, Ancona-Anzio Line, Castellarin *et al.*, 1982) acted as a regional paleogeographic boundary separating the Mesozoic Latium-Abruzzi carbonate platform from the Umbria-Marche pelagic domain (Figs. 2a, 2b, and 5a). The pre-orogenic, Mesozoic-Tertiary platform-to-basinal limestones, marly limestones, and marls are thrust onto the Messinian syn-orogenic siliciclastic foredeep deposits of the Laga Fm. along the salient apex segment of the Mt. Sibillini Thrust.

Regional-scale faults, corresponding to 15-35 km-long, NW-SE-striking high-angle segmented normal fault arrays, affect the carbonate ridge of the thrust belt both in the hanging-wall (Figs. 2 and 6a) and in the footwall of the Mt. Sibillini Thrust (Pizzi and Galadini 2009; Di Domenica *et al.*, 2012). Detailed mesoscopic structural analyses carried out along these faults (Figs. 2 and 6a) illustrate their pre-thrusting activity (*e.g.*, Pizzi and Galadini 2009; Di Domenica *et al.*, 2012; Calamita *et al.*, 2018). Some of these NW-SE-trending inherited normal fault arrays were reactivated during the post-orogenic, ENE-directed Quaternary extension. This reactivation process was responsible for controlling the distribution of the seismicity along the axial zone of the thrust belt and locally truncated and offset the NNE-SSW-trending Mt. Sibillini oblique thrust ramp, as highlighted during the strong (Mw 6.5) 2016 seismic sequence (Pizzi *et al.*, 2017; Porreca *et al.*, 2020).

The present geometry of the Mt. Sibillini Thrust, therefore, results from a double switch in deformation regimes, with an episode of positive inversion followed by an episode of negative inversion. During positive inversion, the main NW-SE-trending pre-orogenic normal faults mapped north of the Mt. Vettore apex were reverse-reactivated to depth, whilst they were truncated and carried piggy-back towards the foreland along the frontal ramp portion of the Mt. Sibillini Thrust, defining a short-cut fault geometry (Figs. 5b, 6c, and 6d; Pace *et al.*, 2022a, b). At odds with this dual behaviour along the main Mt. Sibillini frontal thrust ramp north of Mt. Vettore, with fault reactivation to depth and fault truncation in more elevated parts of the section, the NNE-SSW-trending normal faults south of the Mt. Vettore apex (Fig. 2a) were almost entirely transpressionally reactivated, to define the Mt. Sibillini oblique-lateral thrust ramp along the so-called Ancona-Anzio Line (Castellarin *et al.*, 1982) or the Olevano-Antrodoco-Sibillini lateral thrust front (terminology after Salvini and Vittori, 1982; Figs. 2a and 5b). This duality of patterns indicates that the pre-orogenic architecture of the extensional fault array significantly influenced and controlled the geometry of the superimposed, up-propagating thrust surface during positive inversion. The main controlling factors for fault reacticvation appear related to pre-orogenic fault orientation and dip (Fig. 2a) whereas a possible additional control exerted by the occurrence, thickness and lateral extent of evaporites to depth remains speculative. The frontal ramp was produced at the expenses of a WSW-, hinterland-dipping, pre-orogenic normal fault with listric geometry, whose deep part was easily reactivated due to its favourable orientation during subsequent thrusting, whereas the steeper, upper part was trimmed by thrusting and passively carried piggy-back in the thrust hanging-wall block. As a consequence, the fault reactivation process took only place to depth along the frontal ramp. At odds with this mode of inversion, the SSW-NNE pre-orogenic extensional faults south of Mt. Vettore, trending at a small angle with respect to the dominant N60°–70° thrusting direction, were almost entirely transpressionally reactivated resulting in the development of an oblique-lateral thrust ramp segment (Fig. 2a). It appears that the geometry, map pattern and orientation of pre-orogenic extensional faults exerted a role in defining the reactivation *vs.* truncation styles during the positive inversion event responsible for the development of the Mt. Sibillini Thrust. Similarly, during negative inversion, several parts of the Mt. Sibillini Thrust were extensionally reactivated (Di Domenica *et al.*, 2012), indicating that the orogenic architecture achieved during the construction of the Apennine belt, in turn, played a role in focussing the location and current geometry of post-orogenic normal faults responsible for the diffuse seismicity in the area.

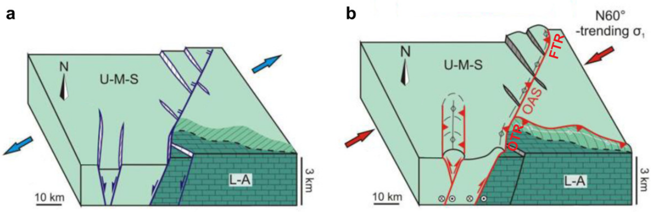

Fig. 6. Schematic 3D block diagrams illustrating the main structural controls of extensional fault arrays on thrust ramp propagation, resulting in the development of frontal and of oblique-lateral ramps depending on the orientation of precursor faults with respect to the superimposed direction of thrust tectonic transport (inspired to the case of the Olevano-Antrodoco-Mt. Sibillini Thrust. (a) Pre-thrusting template; (b) Thrust distribution as it results from the onset and evolution of orogenic contraction. U-M-S: Umbria-Marche-Sabina Basin; L-A: Latium-Abruzzi Platform; OTR: Olevano Thrust; OAS: Olevano-Antrodoco oblique-lateral thrust ramp; FTR: Mt. Sibillini frontal thrust ramp.

4 Variability of structural inheritance during inversion: a discussion

Pre-existing faults, shear zones or other heterogeneities may be modified in two end-member modes during positive inversion: reactivation and truncation (Butler, 1989; Tavarnelli, 1999; Butler *et al.*, 2006). The three main structures – the Mid-Adriatic Ridge, the Montagna dei Fiori Anticline and the Mt. Sibillini Thrust – described in the previous sections illustrate different controls exerted by heterogeneities in the Adria foreland domain as this experienced orogenic contraction.

The Mid-Adriatic Ridge was mainly achieved by reverse-reactivation of syn-sedimentary, pre-orogenic normal faults that had controlled thickness and facies variability during deposition of the Meso-Cenozoic stratigraphic sequences within the Adria foreland domain. Most of these faults were reverse-reactivated as Adria experienced compression due to the onset of the Dinaric and of the Apennine orogenic events on its eastern and western margins, respectively, showing that the fault reactivation process plays a fundamental role during positive inversion in foreland domains. These relationships, first documented by Pace *et al.* (2015), are confirmed in this study.

The Montagna dei Fiori Anticline, west of the Mid-Adriatic Ridge, illustrates more complex structural patterns, mainly driven by truncation (associated, or not, to simple shear components) of pre-existing faults during thrust propagation. The steeply-dipping Montagna dei Fiori Fault running along the crest line of the main anticline was modified as orogenic compressional deformation progressively affected the foothills zone of the Central-Northern Apennines. This steeply-dipping fault may have had an original extensional character (Fig. 4d) and could have developed in the Late Messinian during foreland flexuring ahead of the advancing Apennine deformation front. The normal fault would have been later truncated and carried piggy-back by the NE-propagating Montagna dei Fiori thrust, as proposed by Calamita *et al.* (1998), Scisciani *et al.* (2001) Mazzoli *et al.* (2002) and Mazzoli *et al.* (2002). Alternatively, the fault could have developed as an original, steep up-thrust of Late Tertiary age during the southwestward migration of the Dinaric orogenic front (Fig. 4e); it may then have been tilted due to simple shear and truncated by the NE-propagating Montagna dei Fiori thrust during the subsequent onset of the Apennine orogenic event maintaining high cutoff angle relationships with bedding, to mimic an apparent extensional character, as more recently proposed by Calamita *et al.* (2021). Either way – foreland extensional faulting or SW-directed up-thrusting, followed by NE-directed low-angle thrusting – the Montagna dei Fiori Thrust and related anticline provide an example to illustrate that fault truncation represents an effective mode to accommodate thrusting across heterogeneous foreland domains. Both interpretations (SW-dipping, foreland-flexure induced pre-thrusting normal fault, or high-angle, SW-directed Dinaric Upthrust thrust later tilted to mimic a high-angle SW-dipping normal fault) are consistent with the available documentation and thus represent viable solutions. However, given that recent interpretation of seismic lines across the Mid-Adriatic Ridge reveals hig-angle upthrusts induced by the SW-directed migration of the Dinaric orogenic front (Pace *et al.* (2015)), in this contribution we favour and support Calamita *et al.* (2021)'s view of the Montagna dei Fiori Fault as a Dinaric upthrust later affected by a younger NE-directed thrust during the easterly propagation of the Apennine deformation front.

The Mt. Sibillini Thrust west of the Montagna dei Fiori Anticline and the most internal structure of the outer zones of the Central-Northern Apennines investigated in this contribution, illustrate yet more complex structural patterns with respect to the more external, easterly examples. North of Mt. Vettore the Thrust frontal ramp reactivated the lower part of a presumably listric, hinterland-dipping pre-orogenic normal fault, yet truncating its upper section to produce a short-cut thrust geometry (Calamita *et al.*, 2012). On the other hand, south of Mt. Vettore, the Thrust oblique-lateral ramp transpressionally reactivated the SSW-NNE trending pre-orogenic normal fault, with little or no evidence for fault truncation phenomena (Pace and Calamita, 2014; Di Domenica *et al.*, 2014). It appears that the arcuate geometry of the Mt. Sibillini Thrust was controlled by the attitude, pattern, geometry and orientation of pre-orogenic extensional faults within the pre-thrusting template. More recently, Pace *et al.* (2022a) have shown that an additional control on the final geometry of the Mt. Sibillini Thrust might have been represented and played by the displacement distribution along the pre-thrusting extensional faults, that may have been hard- or soft-linked, respectively (see Fig. 13 in Pace *et al.* (2022a)). Under these circumstances, the structures within the transition zone between the shortcut-related frontal thrust ramp, to the north, and the reactivation-related oblique thrust ramp, to the south, may help discern if, and to what extent, the pre-thrusting extensional faults were hard- or soft-linked, representing a single fault with an original arcuate geometry, or two separate, more linear fault segments with different trends whose growth by coalescence produced a more complex arcuate pattern. Either way, it appears that the evolution of the Mt. Sibillini Thrust during positive inversion related to the onset of the Apennine orogenic event was characterized by structural control variability, resulting in combinations of reactivation and truncation patterns of pre-thrusting extensional faults.

The results illustrated above from the Central-Northern Apennines of Italy, the Marche Foothills and the Adriatic Foreland domains (*e.g.*, see Bigi *et al.*, 2012; this study) can be compared and contrasted with those from other areas that have experienced positive tectonic inversion in other provinces of the Apennine-Maghrebide system, such as those widely described in central and southern Italy (Roure *et al.*, 1990; Mazzoli *et al.*, 2000; Calabrò *et al.*, 2003; Mazzoli *et al.*, 2000), in the northernmost part of Adria around the southern Alps (Casero, 2004; Cassinis *et al.*, 2008), in Sicily and in the North African margin (Casero *et al.*, 1991; Roure *et al.*, 2012, and references therein). As for the foreland domains ahead of the Apennine belt in the Adriatic offshore, the most common and extensively documented examples of positive inversion illustrate a simple reverse-reactivation of pre-contractional normal faults with consequent upward graben extrusion phenomena (*e.g.*, Argnani and Gamberi, 1995). Proceeding from the foreland domains towards the orogenic interiors of the Apennine belt in peninsular Italy, the recognition of structures due to positive inversion tends to be progressively more complex (*e.g.*, Butler *et al.*, 2006).

One relevant aspect regarding the deep structure of the Apennine focusses on the deformation style, that has been alternatively interpreted in terms of thin-skinned (Bally *et al.*, 1986) or thick-skinned (Speranza and Chiappini, 2002) models, or of various combinations of both styles (Mazzoli *et al.*, 2000; Calabrò *et al.*, 2003; Barchi and Tavarnelli, 2022). Regardless of the real deep geometry of the belt, that is still poorly constrained having led to different and often contrasting interpretations, of particular interest in comparing the geometries of structures resulting from positive inversion within the Apennines is a terminology issue: while the use of a thick-skinned style in the central-northern parts of the belt describes the upward extrusion of Permo-Triassic basins that involve slices of the underlying Hercynian basement (Pace *et al.* (2015); Tavarnelli *et al.*, 2019), the use of thick-skinned concepts in southern Italy mainly illustrates the upward extrusion by thrusts reverse-reactivating pre-orogenic normal faults developed across relevant parts of a carbonate platform of Mesozoic-Tertiary age (the so-called "Apulian belt" by Cello and Mazzoli, 1999; Scrocca *et al.*, 2005), thus limited to the tectonically buried parts of the sedimentary cover, yet with little information on the involvement (or not) of underlying basement slices.

The interest in the tectono-sedimentary setting and on the deep structure of the Apennine-Maghrebide system, especially in terms of the controls played by inherited structures during positive inversion, has further increased starting from the 1980s with an extensive exploration campaign, since the belt and the adjacent Adriatic-African foreland domains have been recognized and exploited as important petroleum plays (Bally *et al.*, 1986; Roure *et al.*, 1990, 2012; Casero, 2004; Patacca and Scandone, 2004; Casero and Bigi, 2013). These studies, some of which investigate lithospheric-scale processes, have outlined the prominent role of reverse-reactivation of pre-orogenic normal faults during the transition from inherited rifting to mountain building, yet with some documented local deviation with examples of pre-thrusting normal faults truncated by upward-propagating thrusts, especially located in the deeply buried parts of the outer provinces and of the adjacent foreland domains.

In addition to studies from the Apennines, other remarkable examples of positive inversion have been widely reported from Europe, North Africa and are particularly abundant in the peri-Mediterranean belts. Examples from continental Europe include the North Sea, the East Shetland Platform and other provinces of the UK, with cases of partial reverse-reactivation of normal faults described by Bally (1984), Corfield *et al.* (1996), Platt and Cartwright (1998), Connolly *et al.* (2024) and also by De Paola *et al.* (2005), although the latter interpreted these reactivated structures in terms of transtensional, rather than inversion-induced deformations.

Further examples of positive inversion in many peri-Mediterranean belts, such as the Pyrenees, the Alps, the Dynarides, the Carpathians, the Albanides, the Hellenides, the Maghrebides and the Kabylides, involve not only simple fault reactivation, but also different and even more complex modifications of pre-thrusting normal faults (*e.g.*, Roure *et al.*, 1989, 1990, 2004, 2012; Butler *et al.*, 2006; Van Unen *et al.*, 2019; Tari *et al.*, 2020; Soto *et al.*, 2024; Zelilidis *et al.*, 2024, and references therein). From a historic point of view, the French Alps have played a fundamental role in the study of inversion tectonics. A spectacular array of pre-orogenic normal faults preserved at the level of the basement-cover contact is reported from the Ecrins region (Lemoine *et al.*, 1986). In a seminal study, Gidon (1981) illustrated that the pre-thrusting normal faults affecting the basement did not only reactivate as thrusts, but also served to partition thrust-related compression into zones of dominantly vertical stretching within mechanically and rheologically weak layers located at different levels within the overlying sedimentary cover, a behaviour that has since been referred to as "buttressing" (Gillcrist *et al.*, 1987). As a consequence, De Graciansky *et al.* (1989) suggest that many of the Mesozoic basins bounded by pre-thrusting normal faults, well exposed in the Ecrins region, have been penetratively shortened by buttressing during the Alpine inversion. Other examples of complex structures due to positive inversion at a regional scale, specifically interpreted as buttressed pre-thrusting extensional basins with half graben geometry, have been reported in the northern flank of the Aar massif in the central Swiss Alps (Butler and Mazzoli, 2006; Butler *et al.*, 2006).

In summary, one very common feature recognized in many collision belts in the peri-Mediterranean domain due to positive inversion is that, proceeding from the outermost parts towards the orogenic interiors there appears to be a tendency towards progressively complex structural relationships, where simple normal fault reverse-reactivation phenomena dominate in the foreland and outer zones. On the other hand, reactivation of late thrusts at the expenses of pre-existing normal faults bounding precursor basins, although potentially present and important, tends to be sequentially obscured. This is probably due to combinations of factors including, but not necessarily restricted to, pervasive shearing, mechanical-rheological properties and presence or absence of fluids during deformation as dominant tectonic controls within orogenic interiors (*e.g.*, Butler *et al.*, 2006).

Most thrust belts mentioned in this discussion share all the features outlined above (Fig. 7). On the other hand, one feature that appears peculiar of the Outer Zones of the Central-Northern Apennines, and in particular of its western sector, is the common occurrence of formerly foreland-, *i.e.*, east-dipping pre-thrusting faults (be these normal faults or early back –thrusts) that were basculated and/or partly folded to acquire a westerly dip, prior to be reactivated or truncated and passively carried piggy-back within east-directed, regionally important thrust-bounded stacked units. This evolution has been documented for the West-directed up-thrusts recognised in Adriatic foreland (Figs. 2 and 3) and proposed for the Montagna dei Fiori Fault by Calamita *et al.* (2021) within the Apennine thrust belt (Figs. 2 and 4; Second inversion phase in Thrust belt of Fig. 7). Future investigations may reveal additional, though hitherto not recognised, East-dipping, West-directed backthrusts or East-dipping normal faults somewhere in the Adriatic foreland domains, thus rendering these structures as plausible candidates for modification, truncation and involvement within East-directed Apennine thrust-bounded tectonic units. This history, that requires a modification of pre-existing faults prior to their involvement within thrust sheets, complicates the common view of simple reverse-reactivation of pre-thrusting faults during positive inversion in the outer zones of orogenic systems.

5 Concluding remarks

The brief review of positive inversion structures illustrated in this contribution outlines an increasing complexity in fault reactivation *vs.* truncation patterns proceeding from distal foreland domains towards orogenic interiors. In the Central-Northern Apennines orogenic belt, that extends along the "backbone" of peninsular Italy flanking the less intensely deformed Adria microplate, positive inversion tends to be accommodated and taken up by: i) reverse-reactivation of pre-existing faults in the distal provinces; ii) fault truncation in the intermediate zones; and iii) combinations of fault reactivation, associated or not to truncation components – depending on the

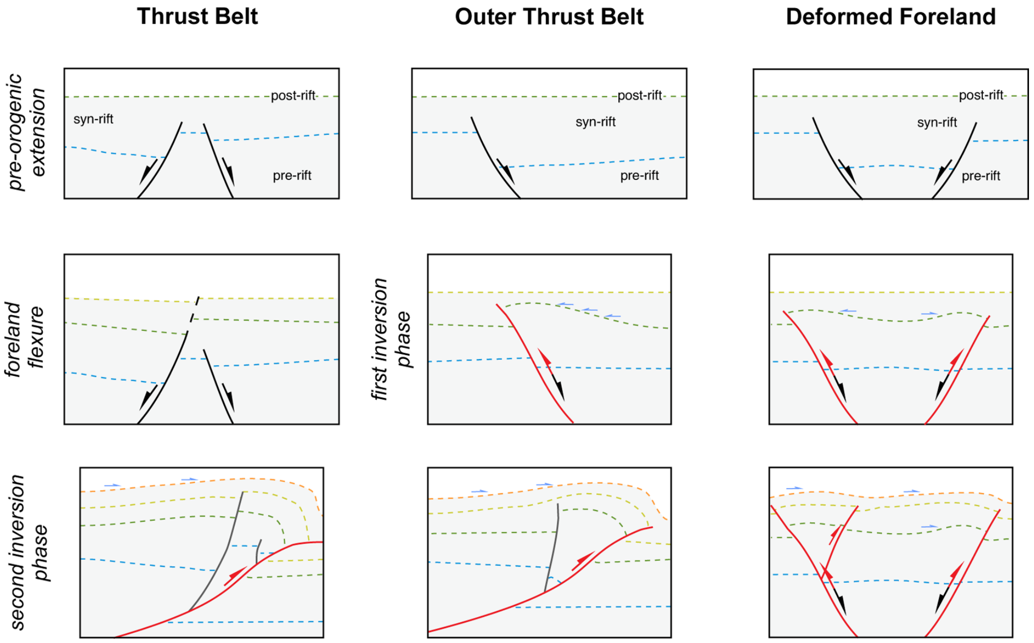

Fig. 7. Generalized, synoptic evolutionary model to account for the modes of positive inversion in the Central-Northern Apennines and within the mildly deformed Adria foreland domain, based on the structures and situations illustrated in this contribution. Note that the light blue little arrows indicate stratal onlap relationships of syn-tectonic (syn-inversion) deposits onto deformed substrata.

geometry of precursor faults – in the more internal parts of the orogen. A synthetic 2D evolutionary model to account for the interaction between compressional and extensional deformations described in this contribution, and for the degrees of reactivation *vs.* truncation modes of positive inversion in the outer zones of the Central-Northern Apennine during migration of the NE-directed orogenic front towards the Adriatic foreland, is illustrated in Figure 7. The geometry and kinematics of structures produced during sequentially younger deformation stages of Figure 7 might tentatively represent a key to interpret the transition from the outer parts of collision orogens towards their mildly deformed foreland domains of other fold-and-thrust belts that have experienced the effects of positive inversion. Of course, each orogenic belt retains its local peculiarities; therefore, a generalization of the model derived from the Apennines and its use to account for the evolution of other belts must only be taken as a gross, first-order indication. However, a comparison between the structures described in this contribution and analogue structures resulting from positive inversion in other, adjacent or distant orogenic belts in the circum-Mediterranean realm, and elsewhere, could represent a useful test to try to unravel their complex geometry and kinematic history. Yet, the evolution of structures investigated in this contribution sheds new light in the history of involvement of pre-existing faults within thrust belts, adding complexity to otherwise well-known and well-documented positive inversion styles. In addition to this cautionary statement, further investigation is necessary to highlight additional controlling factors of positive inversion structures, such as mechanical, thermal and/or rheological properties of the deformed rock sequences, as well as the presence or absence of fluid circulation during the incorporation of extensional basins into thrust-dominated orogenic systems.

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