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Structural architecture, tectonic stacking and extensional reactivation of nappe contacts in the southern Middle Tuscan Ridge, Inner Northern Apennines orogenic belt (Italy)

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ABSTRACT

Interpreting tectonic stacking patterns and the nature of contacts between tectonic units is a major challenge in orogenic belts, particularly when mafic rock slices are embedded within the tectonic stack. These occurrences raise fundamental questions about their origin and the tectonic processes responsible for their emplacement. Such complexities, which characterize several orogenic belts worldwide, are especially prominent in the inner Northern Apennines orogenic belt (Italy). This belt is characterized by abrupt metamorphic discontinuities, local omissions of portions of the tectonic stack, significant stratigraphic gaps within individual tectonic units and contains discontinuous mafic bodies within the nappe pile. These features point to a polyphase tectonic evolution, which over the last decades has led to a range of hypotheses concerning the Neogene evolution of the inner Northern Apennines. Testing these models requires integrated structural, petrological, and stratigraphic investigations. This study presents structural, kinematic and stratigraphic data on detailed field mapping in the southern Middle Tuscan Ridge (southern Tuscany), a key area within the inner Northern Apennines. Our results document a polyphase extensional evolution characterised by the sequential development of normal faults during post-orogenic deformation (~19–20 Ma). Based on this evidence, we propose an updated tectonic model that integrates the geometry, timing, and evolution of extensional structures in this part of the chain. The model refines the regional tectonic framework and provides a basis for further investigation into the metamorphic evolution, the chronology of tectonic events, and the origin of mafic bodies within continental units. On a broader scale, it offers a reference for interpreting post-collisional extensional settings in other orogenic belts worldwide.

1. Introduction

The stacking patterns of tectonic units and the nature of their contacts in orogenic belts are often subject to divergent, sometimes conflicting, interpretations. These differences typically arise from uncertainties in the relative timing of deformation events, the direction of tectonic transport, and the internal stratigraphy of the involved units. Such issues become particularly pronounced when ambiguous evidence is not adequately assessed, or when the geological evidence is limited, poorly exposed, or appears opens to multiple interpretations. As a result, contrasting tectonic models are then proposed, without converging toward a coherent and internally consistent tectonic evolution.

This geological issue is common to many orogenic belts worldwide, and it is particularly evident in the inner Northern Apennines orogenic belt (i.e., southern Tuscany and the Tuscan Archipelago; Fig. 1a and b; Vai and Martini, 2001), where continuous exposures are rare and dense vegetation often covers the tectonic contacts. In addition, complete tectonic stacks are only locally preserved, and poor outcrop conditions often prevent direct analysis of deformation patterns, thus hindering regional-scale interpretation.

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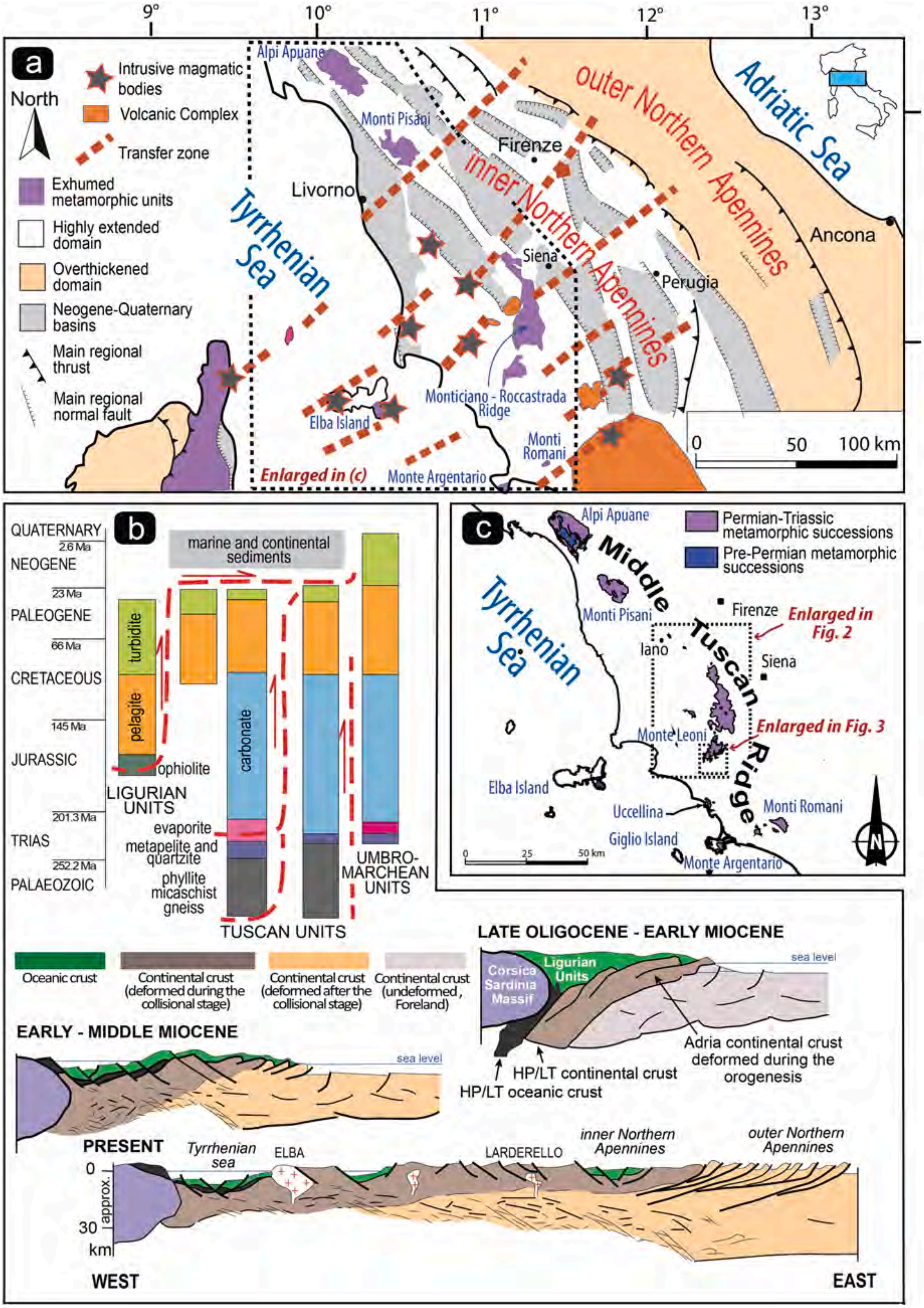

Fig. 1. – (a) Location maps of the study area within the framework of the Northern Apennines and the Northern Tyrrhenian Basin (modified from Brogi, 2020); (b) Tectonic units of the inner Northern Apennines and their palaeogeographic domains, with schematic geological cross-sections illustrating the collisional and post-collisional evolution of the inner Northern Apennines (modified from Brogi et al., 2025); (c) Schematic sketch of the Middle Tuscan Ridge highlighting the distribution of pre-Permian and Permian–Triassic units (modified from Capezzuoli et al., 2021).

The Northern Apennines, which formed following the closure of the Alpine Tethys and the subsequent collision between the European and Adria palaeomargins (Fig. 1b), is characterized by a distinctive feature: post-collisional rifting in the hinterland led to the exhumation of high-pressure (HP) metamorphic units during the Neogene (Jolivet et al., 1998; Brunet et al., 2000; Bianco et al., 2019; Montomoli et al., 2024). Apart from occurrences in the Tuscan Archipelago, these HP units are exposed on land only in localized areas, notably in the Middle Tuscan Ridge (Fig. 1c), a north–south-trending morphotectonic feature that extends across Tuscany (Costantini et al., 1988; Carmignani et al., 1994).

Post-collisional extension began during the Burdigalian (Carmignani et al., 1995; Cavazza et al., 2007), affecting parts of the formed orogenic belt (Molli, 2008; Rossetti et al., 2015; Brogi et al., 2025) and thinning the over-thickened continental crust to 20–24 km (Di Stefano et al., 2011; Moeller et al., 2013), with the lithosphere stretching to approximately 100 km (Le Breton et al., 2017). This extensional tectonic setting led to the development of sedimentary basins (Martini and Sagri, 1993), including the Early Miocene Corsica Basin (Zitellini et al., 1986; Moeller et al., 2013), which evolved into the present-day northern Tyrrhenian Sea (Bartole, 1995; Pascucci et al., 1999). The Corsica Basin formed over the suture zone, further complicating the identification of the complete inner belt. Remnants of the inner zone are now exposed in Corsica (Malavieille et al., 1998; Molli, 2008; Rossetti et al., 2015; Di Rosa et al., 2025), the Tuscan Archipelago (Keller and Pialli, 1990; Pertusati et al., 1993; Bortolotti et al., 2001; Bianco et al., 1995; Brogi et al., 2025) and in southern Tuscany (Fig. 1c), particularly in the Middle Tuscan Ridge (Théye et al., 1997; Giorgetti et al., 1998; Jolivet et al., 1998; Lazzarotto et al., 2003; Brogi, 2008; Montomoli et al., 2009).

Along this ridge, tectonic units derived from oceanic (Ligurian), transitional (Subligurian), and continental (Adria margin) domains are discontinuously exposed, typically stacked from top (oceanic) to bottom (continental). These units record a broad range of metamorphic conditions, from regional blueschist to greenschist facies (Théye et al., 1997; Giorgetti et al., 1998; Brunet et al., 2000; Brogi and Giorgetti, 2012; Giuntoli and Viola, 2020) as well as overprinted low-pressure (LP) facies related to the emplacement of Neogene magmatic bodies (Leoni and Tamponi, 1991; Serri et al., 1993; Vezzoni et al., 2018; Brogi et al., 2021).

These variations in metamorphic grade, combined with the local occurrence of mafic to ultramafic slices within the tectonic stack (e.g., Monte Argentario, Giglio Island, Elba Island; Gianniello et al., 1964; Keller and Pialli, 1990; Rossetti et al., 1999; Lucci et al., 2025) suggest a complex pattern of tectonic juxtaposition.

Several competing models have been proposed to explain this structural configuration which characterizes the whole Northern Apennines. These are based on key field observations, including: (i) sharp metamorphic discontinuities between stacked units (e.g., Carmignani and Kligfield, 1990); (ii) the presence of oceanic crustal slices sandwiched between continental units; (iii) subtractive tectonic contacts that lead to significant omissions in the structural stack and associated stratigraphic successions (Trevisan, 1950; Decandia et al., 1993); and (iv) bowl-shaped Miocene basins not bounded by faults, interpreted as either thrust-top (Bonini et al., 1994; Bonini and Moratti, 1995; Bonini and Sani, 2002) or supradetachment basins (Brogi, 2011, 2020; Martini et al., 2021).

These observations have led to divergent interpretations concerning (i) the timing and duration of orogenic processes (Boccaletti et al., 1971; Dewey et al., 1989), (ii) the direction of tectonic transport (Boccaletti et al., 1980; Carmignani et al., 1994), and (iii) the geodynamic processes that governed the Neogene evolution of the Tyrrhenian–Northern Apennines system (Liotta et al., 1998; Finetti et al., 2001). These diverging views have been debated since the 1970s and remain highly relevant and actively discussed in the current scientific literature. A widely accepted model that reconciles these aspects is still lacking.

The southern sector of the Middle Tuscan Ridge (Fig. 1c) offers a key opportunity to address these issues. Here, both metamorphic and non-metamorphic units derived from oceanic, transitional, and continental domains are exposed, including the distinctive "*Pseudoverrucano*" succession of the Adria margin which records the extreme thinning of the passive margin prior to its involvement in orogenesis (Lotti, 1891; Fucini, 1911; Costantini et al., 1980; Aldinucci et al., 2008; Gandin, 2012). Locally, contacts between metamorphic and overlying non-metamorphic units are hidden by Miocene basin infill, further complicating structural interpretations.

In this study, we present new field-based structural and stratigraphic data from this key area, aimed at reconstructing the geometry of the tectonic stack and the relationships among its units. Our contribution also includes a revised interpretation of the relative position and correlation of the tectonic units, in order to clarify their spatial and structural arrangement within the nappe stack.

The results support a polyphase extensional evolution and proviede a coherent explanation for the current structural architecture and tectonic stacking. More broadly, this case study offers a methodological workflow and insights applicable to other orogenic belts affected by post-collisional extension, offering insights into the structural evolution of similar tectonic settings worldwide.

2. Geology and stacking pattern of tectonic units

Excluding the northern Tyrrhenian Sea (Fig. 1a), in particular Elba Island (Keller and Pialli, 1990; Pertusati et al., 1993; Bortolotti et al., 2001; Brogi et al., 2025), and the subsurface successions encountered by deep drilling in the Larderello and Monte Amiata geothermal areas (Pandeli et al., 1991; Batini et al., 2003), the most complete tectonic stack of the Northern Apennines is exposed along the Middle Tuscan Ridge and surrounding areas. This morphotectonic feature, however, displays significant along-strike variability. In the northern sector of the ridge (e.g., Alpi Apuane and Monti Pisani), the exposed succession is mostly characterized by Jurassic–Eocene metacarbonate formations (e.g., marble and calcschist), with only subordinate Palaeozoic–Triassic metasiliciclastic rocks (Carmignani and Kligfield, 1990; Molli et al., 2002; Pieruccioni et al., 2023). In contrast, the southern sector mainly comprise Palaeozoic–Triassic metasiliciclastic successions with Triassic successions more prominently represented (Costantini et al., 1988; Conti et al., 1991; Giorgetti et al., 1998; Lazzarotto et al., 2003; Aldinucci et al., 2005). An exception occurs in the Montagnola Senese and Roselle areas (Fig. 2), where Late Triassic to Early Oligocene metacarbonate and metapelite successions are locally preserved (Giannini and Lazzarotto, 1970; Moretti, 1991; Liotta, 2002).

The Palaeozoic–Triassic succession in the Middle Tuscan Ridge and in deep geothermal boreholes is subdivided into three main stratigraphic groups (Batini et al., 2003, and references therein) (Fig. 2): (a) the Triassic Verrucano Group (e.g. Perrone et al., 2006; Aldinucci et al., 2008), (b) the Carboniferous–Permian Phyllite–Quartzite Group (Capezzuoli et al., 2021, and references therein), and (c) the pre-Carboniferous tectonic basement, composed mainly of micaschist and gneiss (Elter and Pandeli, 1990; Barelli et al., 1995; Gianelli et al., 1997). The latter does not crop out in the southern Middle Tuscan Ridge and is known mainly from boreholes in the Larderello geothermal field, where it occurs at depths of 3–3.5 km (Puxeddu, 1984; Pandeli et al., 1991, 2005; Bertini et al., 2006).

During the collisional phase, compressional tectonics caused stacking and duplication of the Verrucano and Phyllite–Quartzite Groups (Puxeddu, 1984; Pandeli et al., 1991). This deformation generated a tectonic wedge structure known as the "*Complesso a Scaglie*" (Pandeli et al., 1991), extensively described from deep drilling in the Larderello geothermal area and adjacent regions (Fig. 2).

The Middle Tuscan Ridge represents to the upper structural level of the *Complesso a Scaglie* and can be subdivided into three principal regional tectonic units (Lazzarotto et al., 2003). From structurally highest to lowest, these are (Fig. 2): (a) the Iano Unit, (b) the Monte

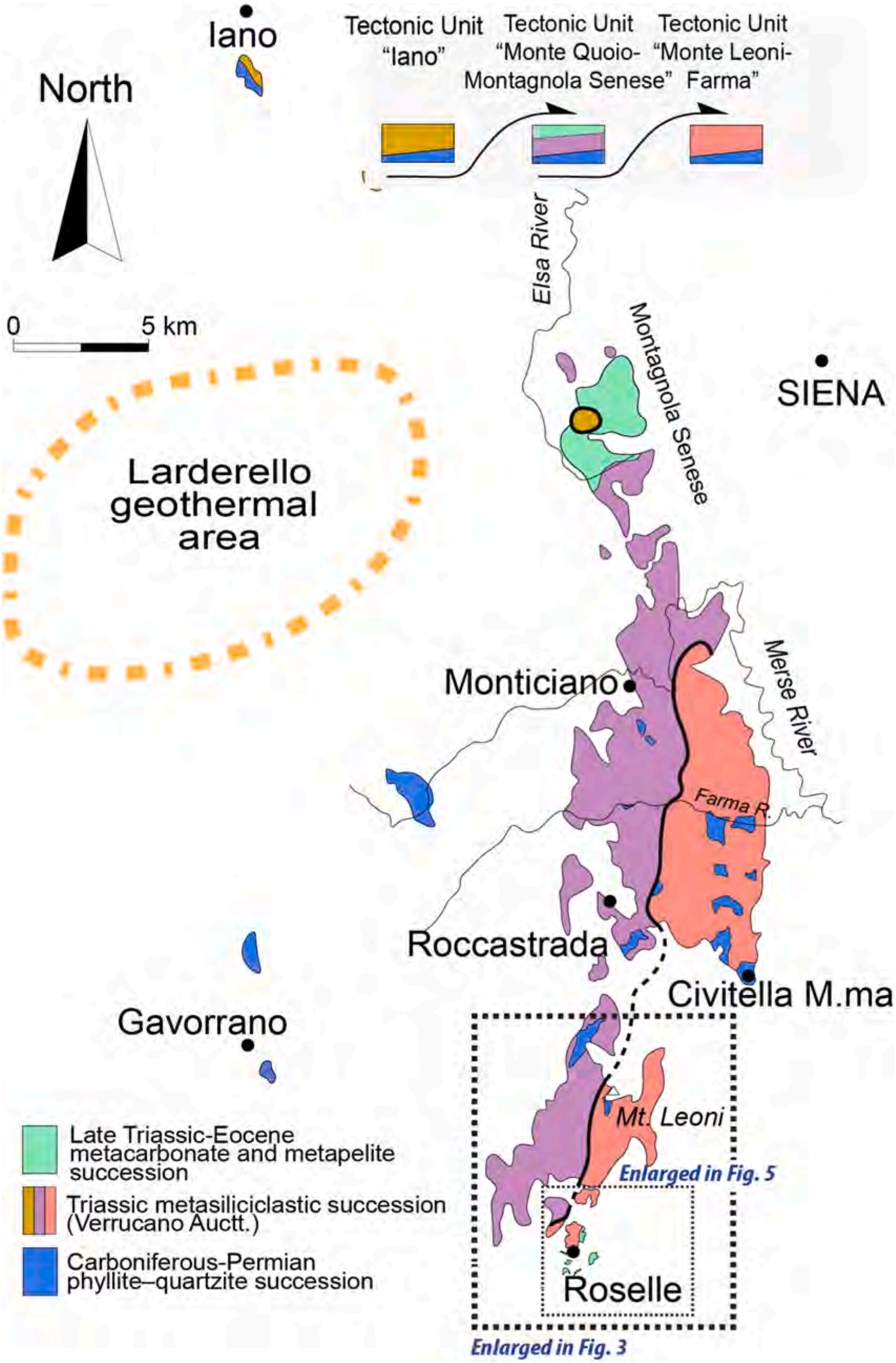

Fig. 2. – Geological sketch of the southern sector of the Middle Tuscan Ridge, showing the location of the study area and the distribution of the three main tectonic units, as defined in the literature by Lazzarotto et al. (2003). The Roselle area is in the southernmost part of this ridge sector, as highlighted in the inset boxes (modified by Brogi and Giorgetti, 2012).

Quoio–Montagnola Senese Unit, and (c) the outer Monte Leoni–Farma Unit. In the southern sector of the ridge, only the Monte Quoio–Montagnola Senese and Monte Leoni–Farma Units are exposed, both preserving evidence of high-pressure (HP) metamorphism and subsequent retrograde overprint (i.e., Giorgetti et al., 1998).

3. The tectonic stack in the Monte Leoni-Roselle area

New geological mapping of this sector of the Middle Tuscan Ridge has enabled a more refined characterization of the tectonic stacking pattern (Fig. 3). This includes not only the deeper structural units previously described by Giorgetti et al. (1998) and Lazzarotto et al. (2003) but also the upper portions of the stack, previously poorly constrained in their geometrical relationships.

The updated stacking pattern of the tectonic units is illustrated in the tectonic sketch shown in Fig. 4. We identify and map eight stacked tectonic units (hereafter abbreviated as TU1–TU8), each derived from distinct palaeogeographic domains. These include: (i) the Adria continental margin (Tuscan Domain: TUs 1–6); (ii) a transitional zone between the thinned Adria margin and the Alpine Tethys oceanic domain (Subligurian Domain: TU7); and (iii) the oceanic Ligurian Domain of the Alpine Tethys (TU8) (Fig. 4).

Among these, Tectonic Units 1 and 3 consist of metamorphic successions. High-pressure (HP) metamorphism has been documented in Units 1 and 2 (Giorgetti et al., 1998), and maximum temperatures (T_max not exceeding 375°C) were determined for these units through organic matter thermal maturity analysis (Spina et al., 2022).

The six continental units from the Tuscan Domain (TUs 1–6), including three metamorphic and three non-metamorphic units, are overlain by the Subligurian Unit (TU7), which is in turn overlain by the Ligurian Unit (TU8). This uppermost unit is unconformably overlain by Tortonian–Messinian continental to brackish sediments, interpreted as the southern continuation of the Ombrone Basin (Bossio et al., 1991), bounded to the west by the Middle Tuscan Ridge.

The Tuscan Domain units are characterized by condensed stratigraphic successions developed during Jurassic pre-collisional extensional tectonics (Costantini et al., 1980; Aldinucci et al., 2008; Gandin, 2012). In addition to this primary feature, all successions (both metamorphic and unmetamorphosed) were affected by post-stacking tectonic elisions of their original stratigraphic successions, commonly referred to as the "Serie Ridotta" (Trevisan, 1950; Decandia et al., 1993).

The Subligurian Unit is represented exclusively by a Paleocene–Eocene clayey–limestone succession (the Canetolo Formation, or Argille e Calcari Formation; Elter et al., 1966; Plesi, 1975), with the remaining stratigraphic components of the unit missing. The Ligurian Domain is represented by a single tectonic unit of the Inner Ligurian Domain (Ophiolitic Unit, Decandia and Elter, 1969), composed predominantly of oceanic rocks (ophiolites) and their sedimentary cover. This unit consists mainly of shale and siliceous limestone successions attributed to the *Argille a Palombini* Formation of Early Cretaceous age (Decandia and Elter, 1969).

The geometric and stratigraphic relationships between the different tectonic units (particularly those of the Tuscan Domain) were analysed in detail in the Roselle area, where the occurrence of mafic-ultramafic bodies was previously described (Ardigò, 1961; Marinelli, 1964; Ricci, 1968), although their precise geometric setting had not been clarified.

To further investigate the relationships between the tectonic stack and the Neogene sediments, we conducted a kinematic analysis of shear zones exposed along the eastern slope of Monte Leoni (Fig. 2), integrating the results into the overall structural interpretation.

4. Field analyses: a focus on the Roselle area

The Roselle area (Fig. 2) provides an exceptional opportunity to investigate the structural architecture and tectonostratigraphic relationships within the Tuscan Domain, as exposed in the Middle Tuscan Ridge. Through detailed field mapping and structural analysis, this study focuses on deciphering the spatial and genetic relationships between the metamorphic and non-metamorphic units that characterize this segment of the orogenic belt. The revised geological framework resulting from this new mapping is presented in Fig. 5, offering an updated interpretation of the structural configuration of the area. Fig. 6 illustrates the tectonic units identified in the field, with their respective stratigraphic successions clearly highlighted, providing further constraints on their original position within the tectonic stack and their subsequent tectonic evolution.

The deepest exposed tectonic unit (TU2, Figs. 5 and 6) is a metamorphic Mesozoic-Cenozoic succession, likely corresponding to the upper part of the Permian-Triassic succession of the TU2 exposed in Monte Leoni, as documented by Giorgetti et al. (1998) (Fig. 2). This succession includes marble interbedded with calcschist (metamorphic Calcare Selcifero Fm, Rosso Ammonitico Fm, and Marne a Posidonia Fm; Middle-Late Jurassic; Fig. 7a–d), overlain by metaradiolarite and quartz-phyllite (Late Jurassic), and further covered by red and green phyllite, calcschist, and metacarbonate (metamorphic Scaglia Toscana Fm; Cretaceous-Eocene; Fig. 7e).

Overlying TU2 is TU3, a metamorphic succession composed of grey-black quartz-phyllite rich in organic matter, grey metasandstones, and whitish quartz-metaconglomerates formed by white quartz clasts, rare tourmalinites (Fig. 8a–c), and dismembered dolomitic marble (Fig. 8d). The protolith of the metasiliciclastic succession (at least the quartz-siltstone, phyllite and metasandstones), reported here for the first time, is of Permian age, as documented in this study through microfloristic and palynological assemblage analyses, which reveal the presence of taeniate bisaccate pollen grains such as*, Falcisporites* sp. cf. *zapfei*, *Protohaploxypinus limpidus, Striatopodocarpites cancellosus, S. fusus, Sulcatisporites* sp. and *Taeniaesporites noviaulensis*, as well as non-taeniate grains like *Alisporites nuthallensis* and *Platysaccus papilionis*. Trilete spores such as *Calamospora* sp., *Punctatisporites fungosus,* and *Brevitriletes* sp. were also identified (Fig. 1 SM and Table 1 **SM**). This assemblage supports a Permian (Guadalupian-Lopingian) age (e.g., Cirilli et al., 2002; Aldinucci et al., 2008; Spina et al., 2015, 2018, 2019, 2021, 2022; Brogi et al., 2021, 2023; Peruccioni et al. 2023) and southern Alps (Spina et al., 2025a) The succession is highly discontinuous and is associated with isolated exposures of quartz-metaconglomerate (Anagenite Auctt.), interpreted as part of the Triassic continental deposits of the Verrucano tectofacies (Perrone et al., 2006; Aldinucci et al., 2008), along with its carbonate cover predominantly composed of dolomitic marble. Notably, this carbonate level occur exclusively as isolated erratic blocks, found in only a few restricted areas within the archaeological site of the Etruscan Ruins (Fig. 5), suggesting limited preservation of the original sedimentary cover. The extreme discontinuity of the stratigraphic succession of the Tectonic Unit 3 (TU3) suggests that this unit was partially dismembered, omitted as tectonically removed, resulting in the incomplete and fragmented exposures.

TU3 also contains discontinuous metabasite bodies (Fig. 8d–f), a few meters thick, known since the 1960s (e.g., Ardigò, 1961; Marinelli, 1964; Ricci, 1968). These bodies crop out in only two localities (see Fig. 5), specifically at the contact between the tectonic units TU2 and TU3. Initially classified as albite-arfvedsonite alkaline sienite (Ardigò, 1961), they were later reinterpreted by Marinelli (1964), who identified a complex association of mylonitic gabbroic-prasinites and albite-crossitite rocks. Although their preserved fabric locally retains magmatic textures (Fig. 9), these metabasites have clearly undergone metamorphic recrystallization, as indicated by the documented (Marinelli, 1964) widespread development of a pervasive metamorphic paragenesis, including glaucophane-albite-chlorite-epidote, which replaces the primary magmatic plagioclase-clinopyroxene-hornblende assemblage, thus confirming their classification as metabasites.

These metabasite blocks are even associated with dismembered materials composed of dark phyllite and grey quartz-metasandstones. This spatial association supports the interpretation that the mafic

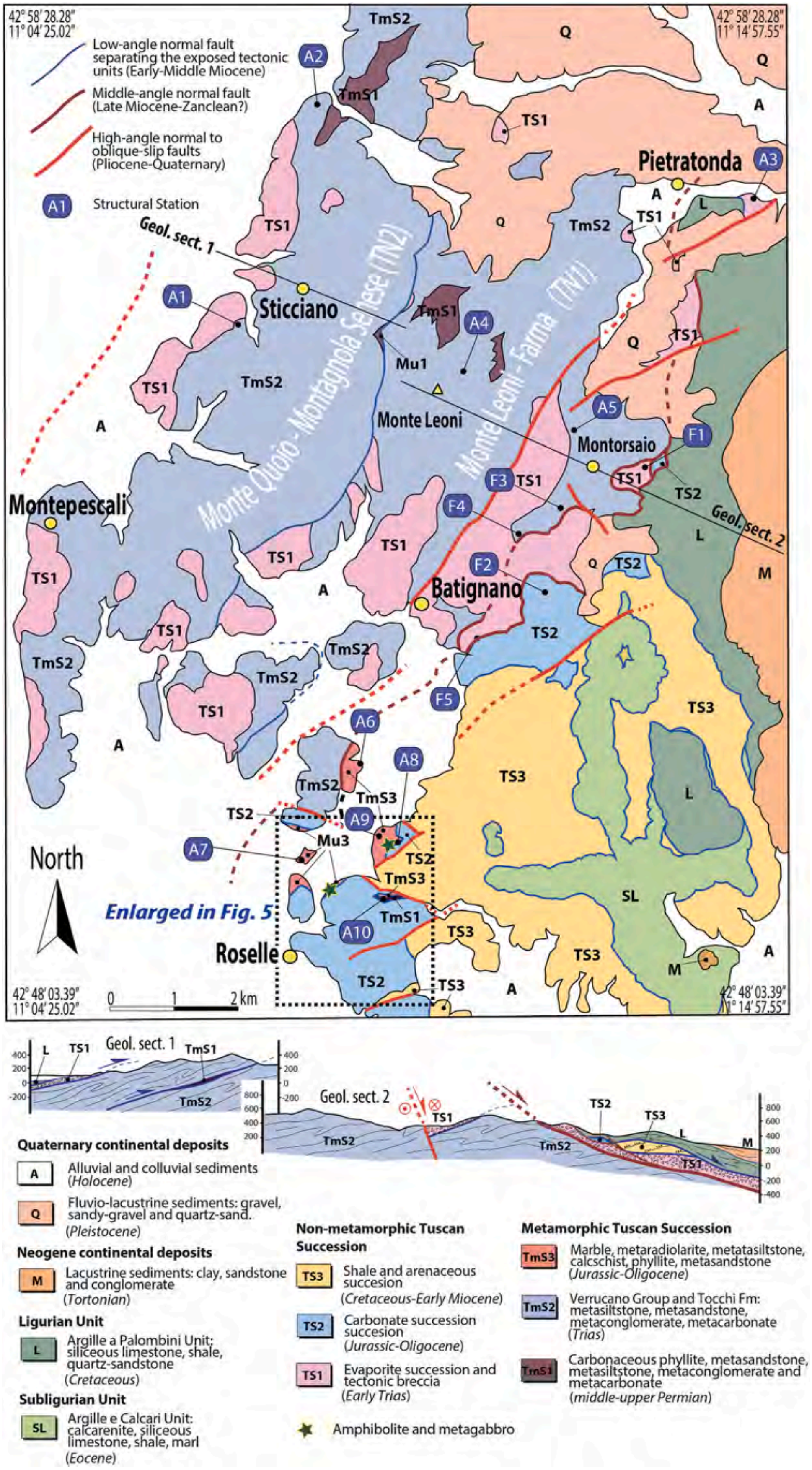

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Fig. 3. – Geological map of the southern sector of the Middle Tuscan Ridge, based on new field mapping conducted at 1:10,000 scales between 2001 and 2025. Geological cross-sections highlight the east-bounding shear zone that defines this sector of the ridge and extends along its entire eastern margin, as discussed in the text. Locations of kinematic analysis stations used to reconstruct shear sense within the exposed shear zone are also shown. The geometrical relations among the different tectonic units and Miocene deposits are also indicated in Fig. 4.

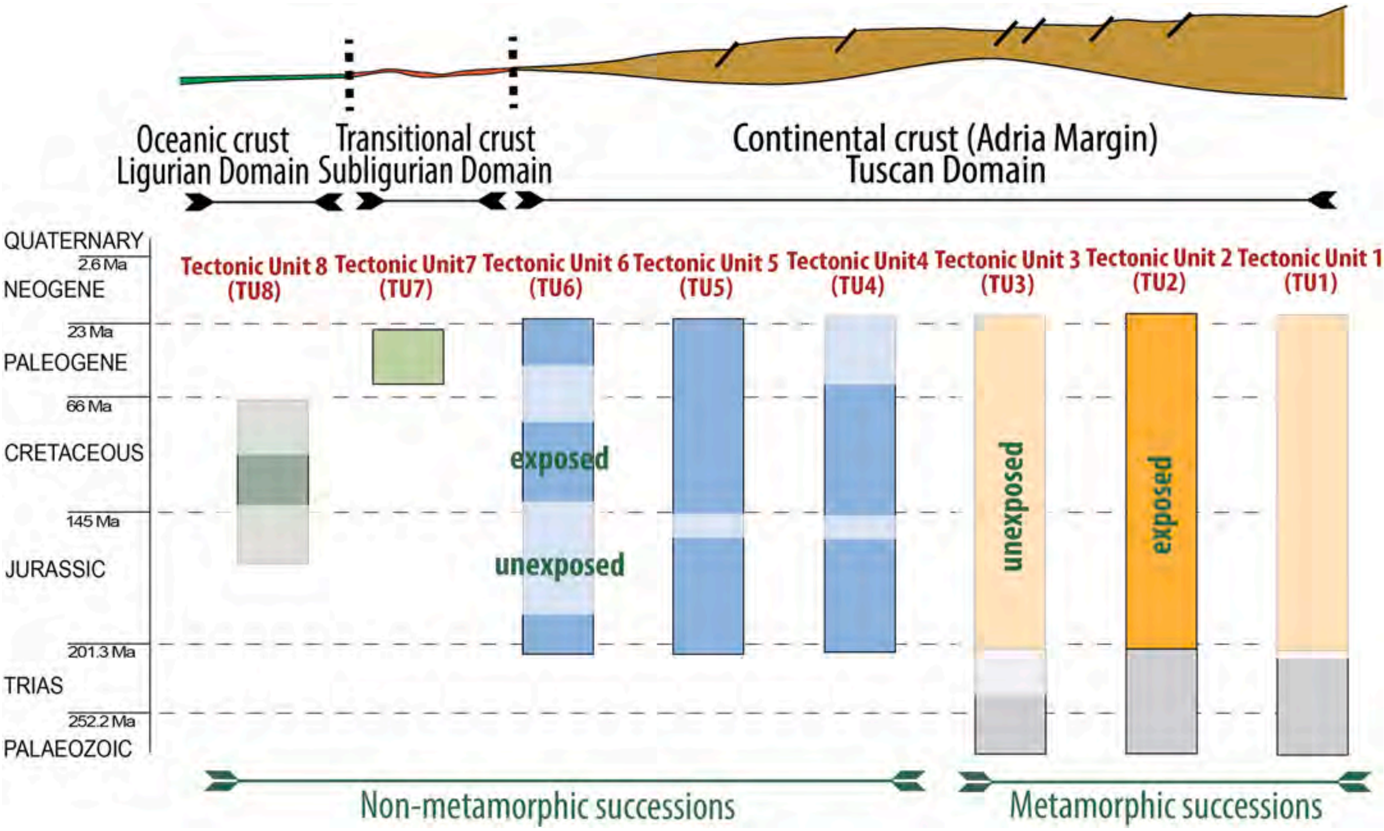

Fig. 4. – Schematic reconstruction of the tectonic units stacked in the study area, showing their inferred original positions along the hyperextended Adria margin and the transitional zone toward the Alpine Tethys Ocean. Lightly shaded coloured portions within the tectonic units indicate the stratigraphic intervals that have been tectonically removed (elided) or unexposed.

bodies are reasonably linked to the lithotypes of the Tectonic Unit 3, and were likely emplaced as intrusions within the Permian-Triassic sedimentary suquence. Additional support for this interpretation comes from the occurrence of metabasite fragments embedded within dolomitic marble, presumed to be part of the Upper Triassic succession, found as an erratic block in the archelogical site (Fig. 8d). However, the absence of an overlying stratigraphic unit of the TU3 prevents a definitive constraint on the relationship between these magmatic bodies and the post-Triassic sedimentary succession.

TU3 is overlain by Tectonic Unit 4 (TU4) primarily composed of the Late Triassic–Oligocene Tuscan succession. At the base of this unit, highly altered, brecciated dolomite and dolomitic limestone form a tectonic breccia, derived from the Burano Formation. Above this, a bedded limestone interbedded with marl (Calcare a *Rhaetavicula contorta* Fm - Rhaetian) occurs, with a thickness of several meters. This transitions into massive limestone (Calcare Massiccio Fm, Early Jurassic), several tens of meters thick, which gradually changes into pink nodular limestone with marly layers (Calcare Rosso Ammonitico Fm, Middle Jurassic). The nodular limestone is further overlain by cherty limestone, which is restricted to the eastern sector of the map (Calcare Selcifero Fm, Middle Jurassic). In some locations, several meters of radiolarite (Diaspri Fm, Late Jurassic) are present, composed mainly of red and green siliceous beds, alternating with millimeter-thick layers of shale (Fig. 10).

The radiolarite, ammonitic limestone, and massive limestone are unconformably overlain by the Scaglia Toscana Fm (Cretaceous–Oligocene), which consists of red and green siliceous claystones and siltstones at the base. These gradually pass into siliceous limestones and calcarenites interbedded with yellow and green siltstones. This succession is overlain by Tectonic Unit (TU5), which shows a similar stratigraphic succession but includes Nummulite-bearing calcarenites in its upper portion, indicating an Eocene age. The upper part of TU5 consists of Oligocene–Early Miocene Macigno Fm, characterized by a thick turbiditic sequence of sandstones and siltstones.

The uppermost Tectonic Unit (TU6) is composed of a siliciclastic succession that begins with a basal conglomerate featuring siliceous clasts interbedded with reddish siliceous sandstones and siltstones. This lithological association, known in the historical literature as the Pseudoverrucano Fm (Lotti, 1891; Fucini, 1910; Merla, 1952; Fazzini and Parea, 1966; Signorini, 1967), is referred to the Late Triassic (Aldinucci et al., 2008; Gandin, 2012). The Pseudoverrucano passes upward into the Montebrandoli Limestone Fm through mixed carbonate–siliciclastic deposits. The Montebrandoli Limestone Fm, composed of metre-thick beds of limestone and calcarenite, also dates to the Late Triassic–Jurassic interval (Aldinucci et al., 2008; Gandin, 2012). The Montebrandoli Limestone Fm is unconformably overlain by the Scaglia Toscana Fm (Cretaceous–Oligocene), which is similar to that in TU4 and TU5 in terms of association of lithotypes. Nevertheless, it is composed primarily of calcarenite beds, with local intercalations of conglomerate, marl, and siltstone.

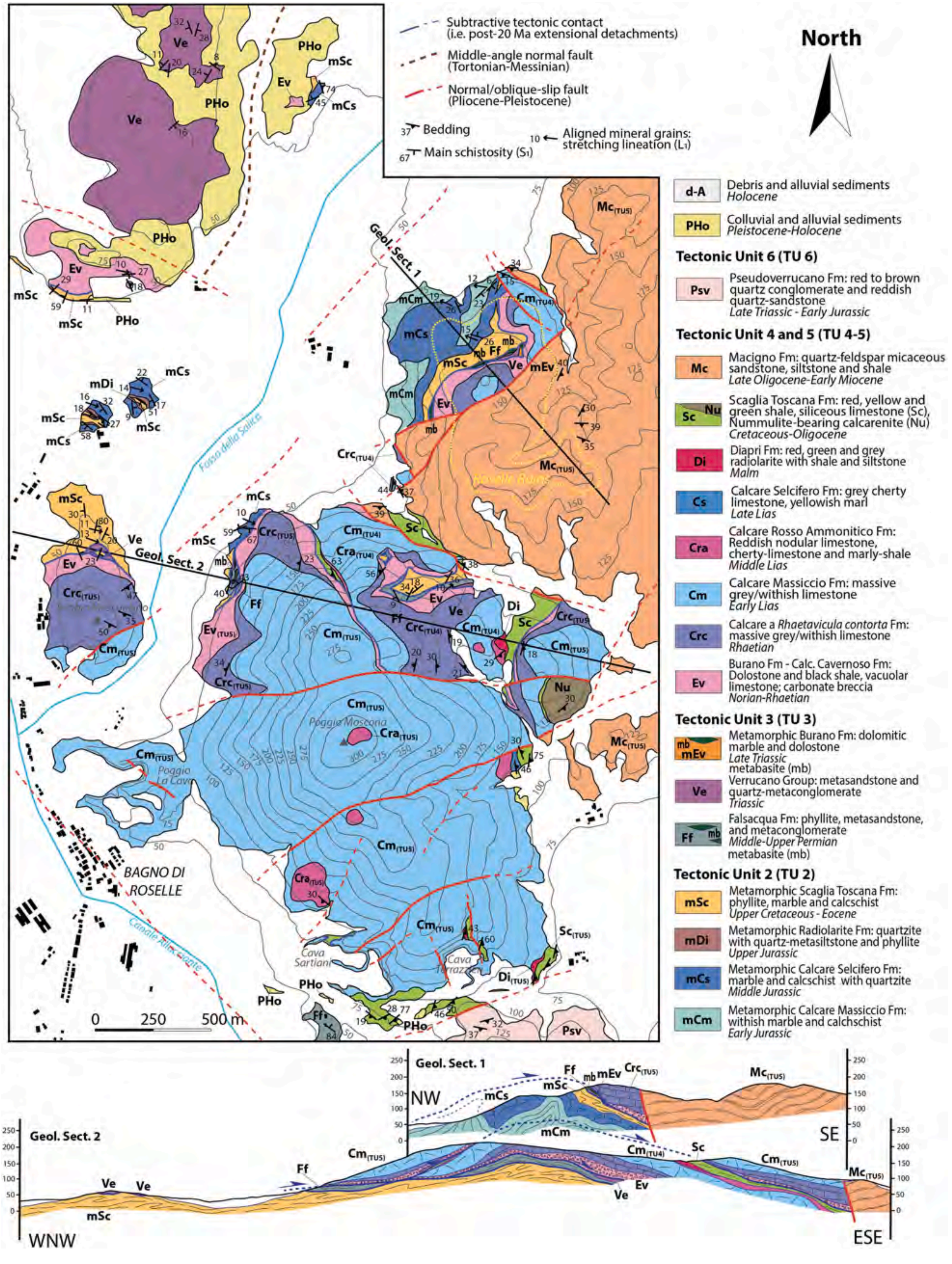

Fig. 5. – Detailed geological map of the Roselle area, based on field surveys at 1:5000 and 1:10,000 scales, carried out between 2020 and 2025. The geometric relationships between the different tectonic units are illustrated in the legend and geological cross-sections and are further constrained by the tectonic framework shown in Fig. 6. Many detrital cover deposits on the Poggio Moscona slopes have not been mapped in order to preserve greater geometric continuity of the contacts.

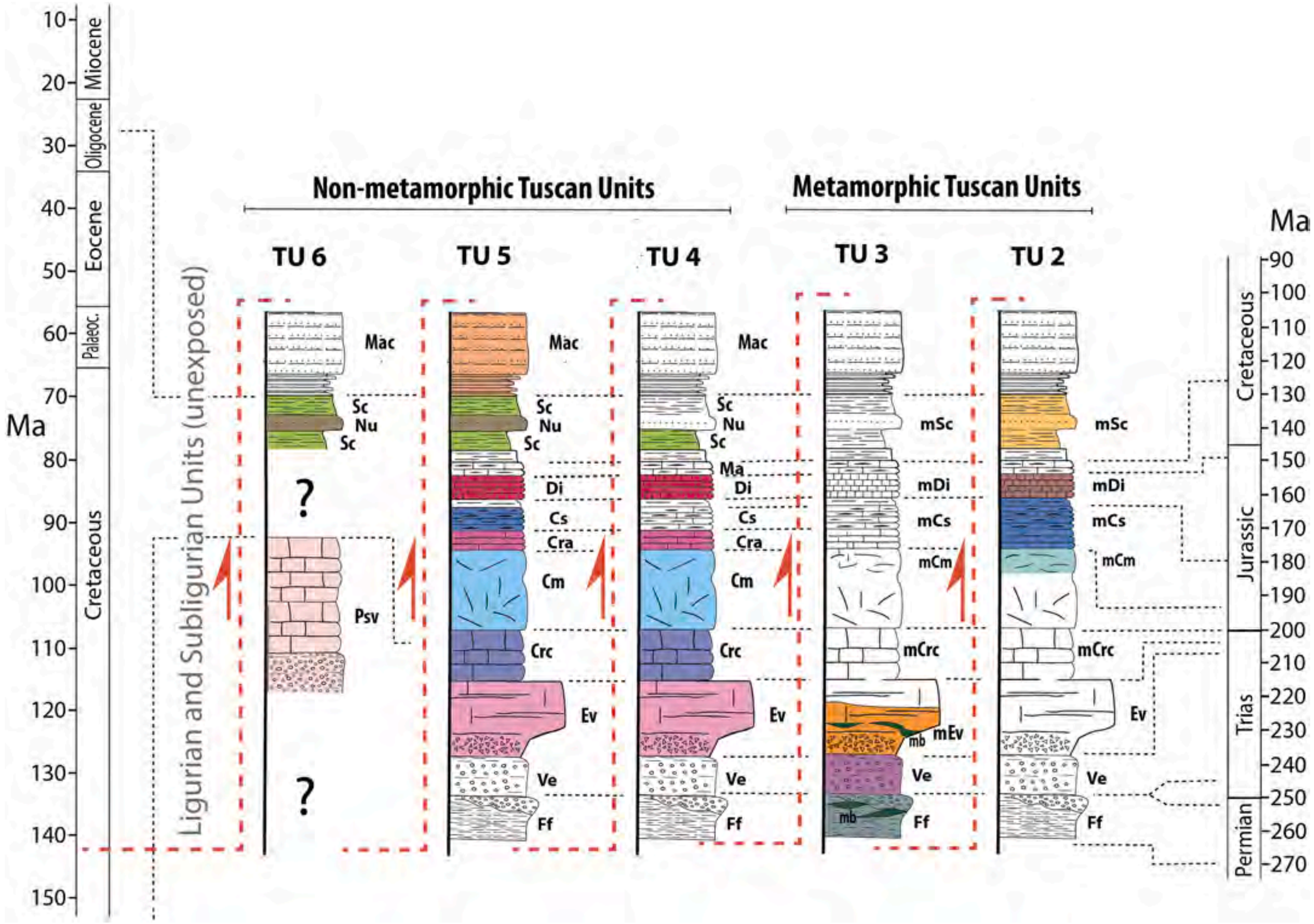

Fig. 6. – Stratigraphic logs of the tectonic units cropping out in the Roselle area. The exposed parts of the different units are indicated with a darker shade of the colour. **Symbols are the same as those used in the geological map shown in Fig. 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)**

5. Deformation, kinematic analyses and nature of the tectonic contacts

Despite dense vegetation, scattered outcrops in the study area have made it possible detailed structural analysis, enabling the reconstruction of deformation histories and the characterization of the tectonic contacts separating the different tectonic units (TU1 - TU7).

In the lower units (TU1 - TU3), peak metamorphic conditions produced S–L tectonites, marked by a dominant planar foliation (S_1) and a well-developed mineral lineation (L_1) (Fig. 11a and b). These fabrics result from intense shear and compressional deformation, leading to the reorientation and transposition of the original primary foliation (i.e. bedding). The mineral lineation, particularly well-developed in meta-carbonates, is represented by the alignment of minerals such as calcite (in calcschists) and quartz and white mica (in metapelites), providing insights into the deformation processes (Fig. 11c and d).

Kinematic analysis indicates a progressive variation in shear sense across these three units: top-to-ENE shear in TU1, top-to-ESE in TU2, and top-to-NNE in TU3, based on shear-sense indicators observed in thin sections and on outcrops (mostly σ-type) as analysed in the stereoplots (Fig. 12).

The S_1/L_1 fabric underwent subsequent deformation during F_2 folding, resulting in open to tight folds observable at the outcrop scale (Fig. 11e and f). The F2 folding event generated a secondary foliation (S_2), formed mainly through mechanical reorientation of the $S_1//S_0$ foliation, without new mineral growth. At the microscopic scale, S_2 is typically expressed as a locally developed crenulation cleavage (Fig. 11g and h).

In the overlying sedimentary units (TU4–TU8), deformation is expressed by decametric-scale fold systems, many of which show detached (unrooted) geometries. In limestone-rich lithologies, stylolitic foliation occurs near fold hinges, while pelitic rocks develop a spaced cleavage that often results in pencil cleavage, produced by high-angle intersections of $S_0//S_1$ and S_2 and producing elongated, pencil-shaped fragments.

The contacts between TU4–TU6 are typically marked by brittle shear zones. These zones exhibit cataclastic textures of varying maturity, often with a clay-rich matrix derived from sheared clayey lithologies. In carbonate-dominated intervals, these zones consist of carbonate breccias composed of limestone and dolostone clasts embedded in a fine-grained carbonate matrix (commonly referred to as Calcare Cavernoso Auctt., e.g. Martini et al., 1989; Cornamusini et al., 2024) (Fig. 13). Shear zone thickness ranges from a few meters to several tens of meters.

At the eastern margin of the Middle Tuscan Ridge, near Monte Leoni, a composite shear zone bounds the ridge, juxtaposing the Ligurian Units (TU7) on the deepest exposed metamorphic unit (TU1) and the intermediate units (TU2–TU6) (Fig. 3). This shear zone contains laterally discontinuous lithons derived from TU 4 and/or TU 5, which lie between the Ligurian Units (TU 7) and the deeper Tuscan Units (TU 1 and 2). These lithons are only sporadically exposed and are not included in the geological map.

The shear zones comprise a broad cataclasite, predominantly

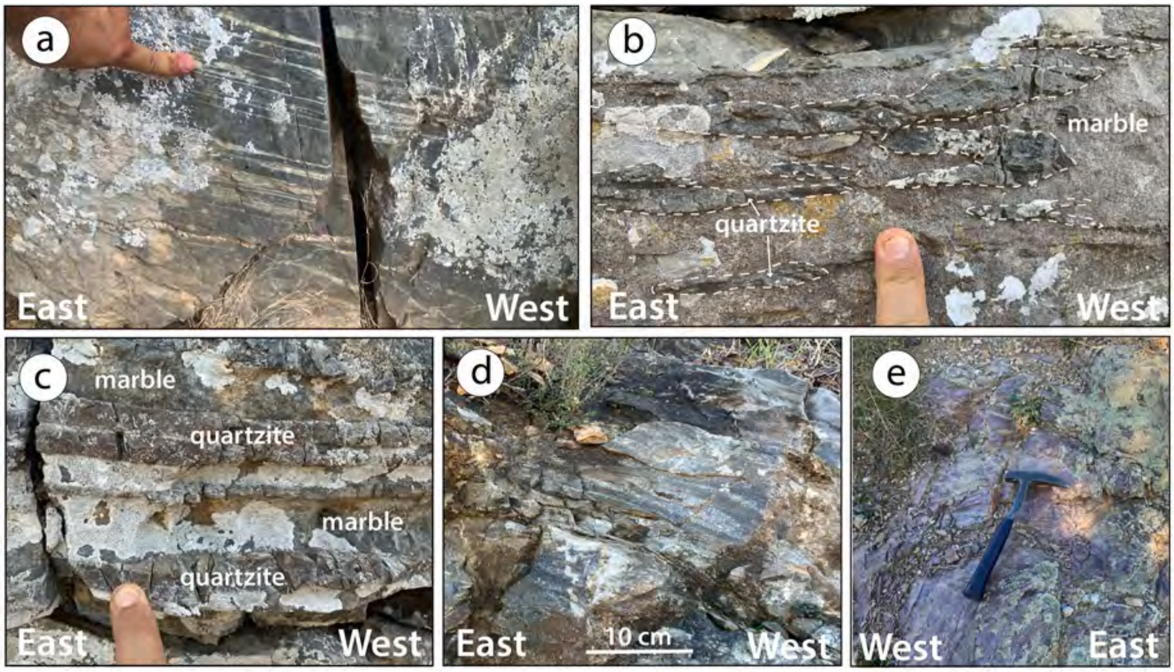

Fig. 7. Outcrop photographs of rocks from the Roselle area. a) Mylonitic marble showing clear alternations of grey and white layers, the latter consisting of newly recrystallized portions; b) Grey marble with former chert layers visibly folded into tight, asymmetric fold systems; c) Detail of marble with quartzites (former cherts) exhibiting a mylonitic fabric; d) Mylonitic marble derived from Eocene calcarenites of the Scaglia Toscana Formation; e) Alternation of phyllites and metasiltstones from the basal portion of the metamorphic Scaglia Toscana Formation.

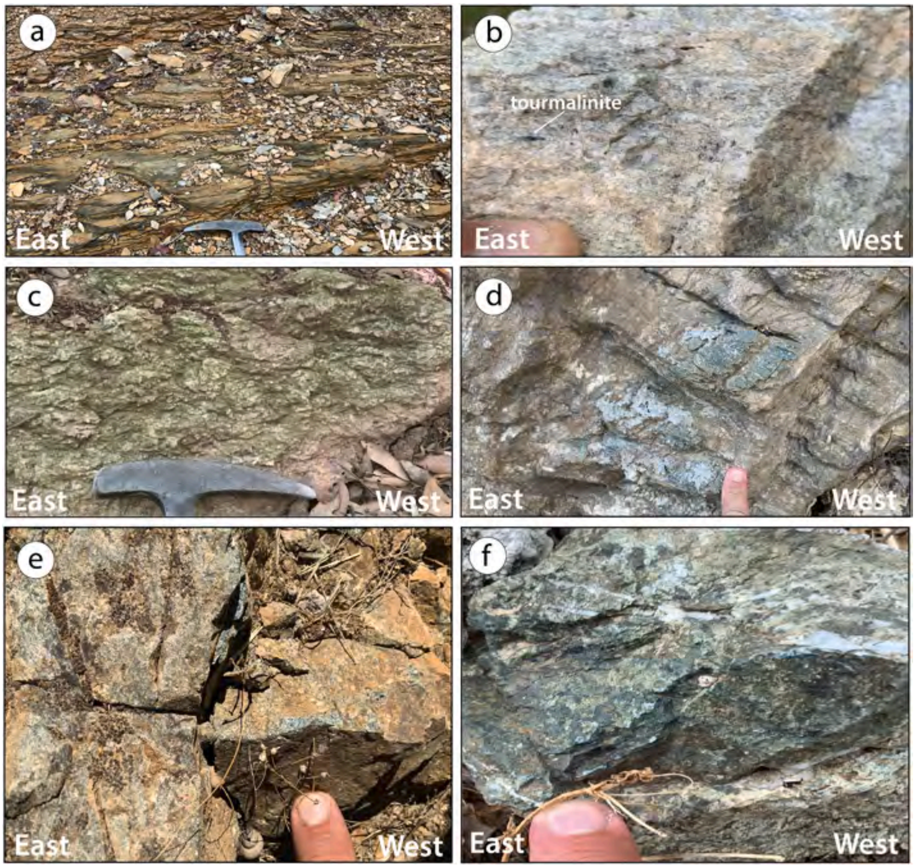

Fig. 8. – Outcrop photographs of rocks from the Roselle area. a) Detail of the phyllite and metasiltstone succession rich in organic matter of Late Permian age, which yielded the microfloral assemblages shown in Fig. 1 of the Supplementary Material; b) Detail of the metarenite succession within the Paleozoic sequence; c) Detail of the metaconglomerate succession with white quartz and tourmalinite clasts within the Paleozoic sequence; d) Detail of a grey dolomitic marble with a decimetre-thick layer of metabasite, sampled from the archaeological site of Roselle; e–f) Details of the texture of the metabasites cropping out within the archaeological area.

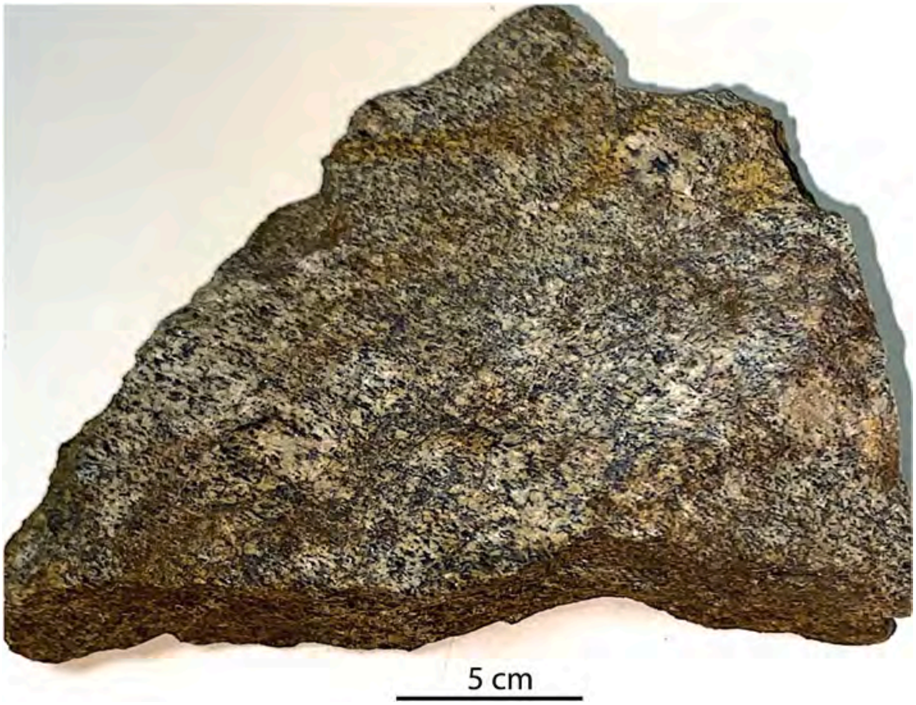

Fig. 9. – Hand specimen of gabbroic rock collected west of Poggio Moscona (see Fig. 5 for location), showing a foliation overprinting a well-preserved magmatic fabric, defined by the preferred orientation of both mafic and felsic mineral phases.

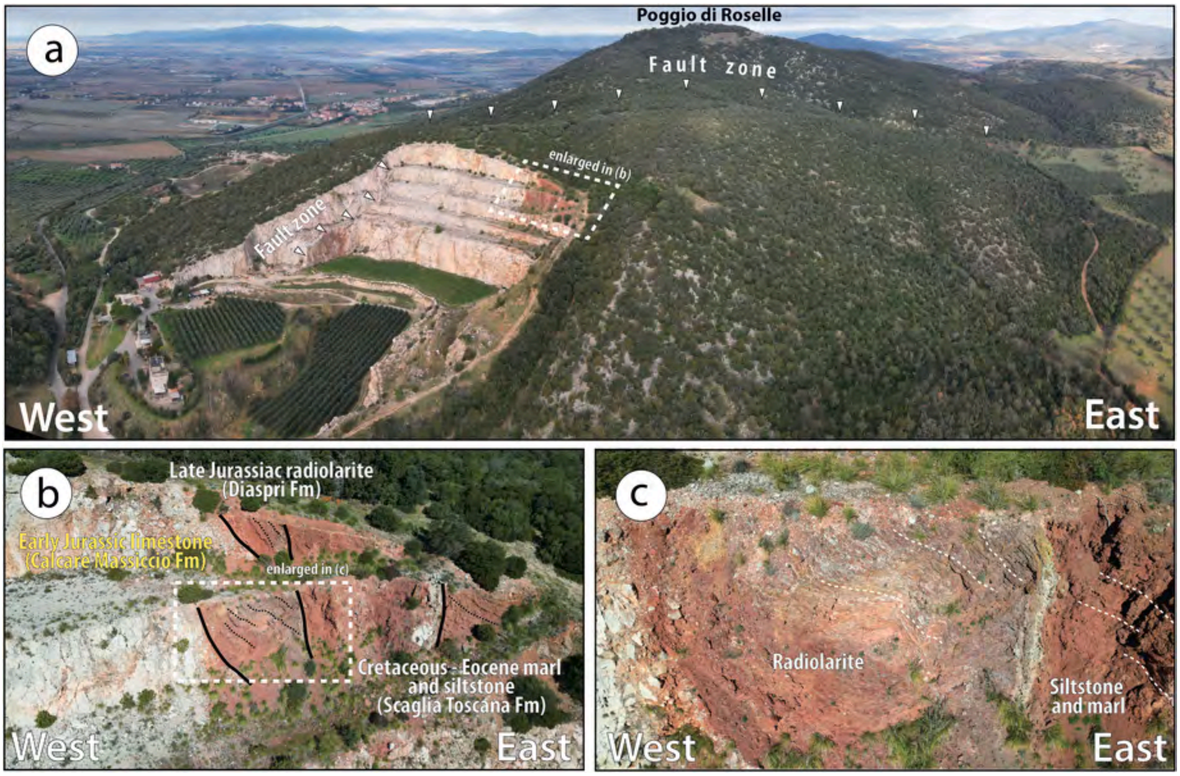

Fig. 10. – Panoramic view of the southern slope of Poggio di Roselle and the main quarry, where the contact between the Jurassic limestones (Calcare Massiccio Formation) and the overlying radiolarite–Scaglia Toscana succession is well exposed. The stratigraphic contact is shown in detail in (b) and (c).

composed of carbonate breccia, but also containing fragments from TU1 through TU7. The breccia can be several meters to tens of meters thick. Adjacent to this zone, within TU1, a suite of shear structures with well-developed kinematic indicators has been recognized. These include conjugate fault systems with slickensides and associated brittle shear planes (Fig. 14).

Kinematic data collected from structural stations along the eastern slope of Monte Leoni indicate that this main shear zone dips eastward

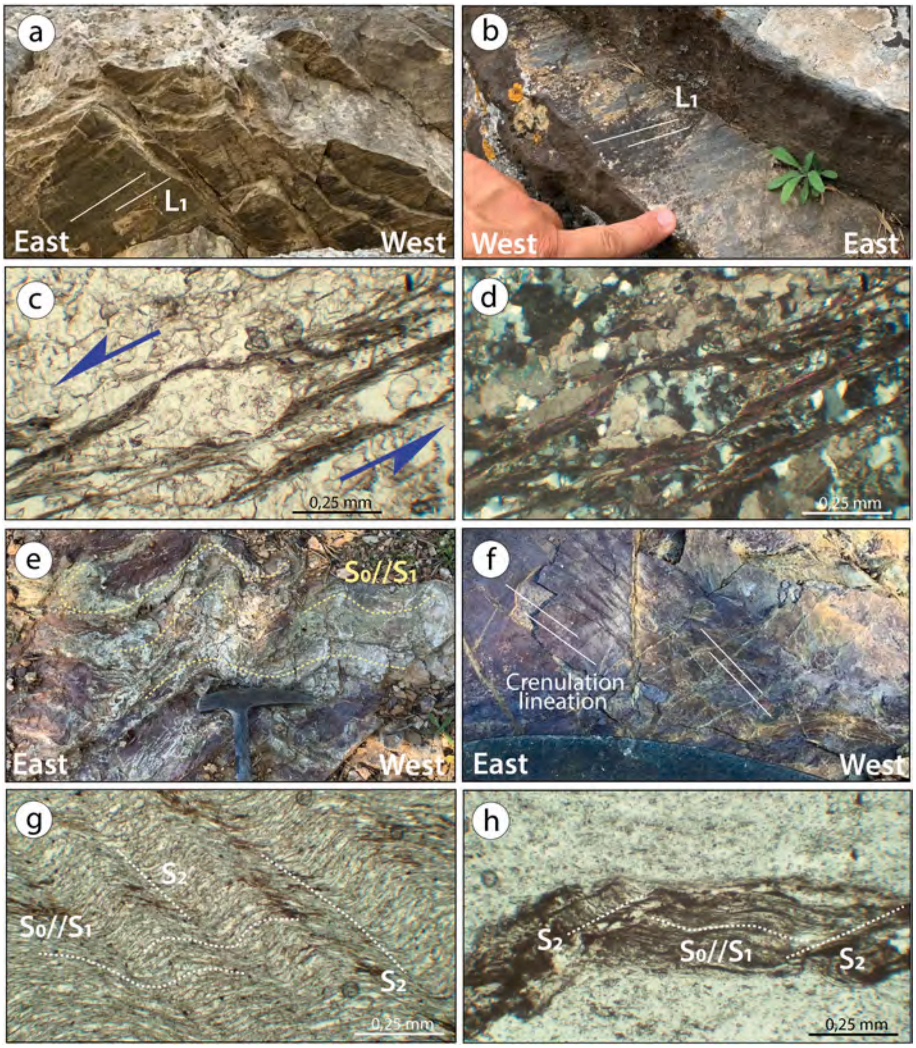

Fig. 11. – Micro- and mesoscale structural features recorded in the marble and metapelites. a-b) Mineral lineation (L_1) developed on marble S_1 foliation surfaces, visible at outcrop scale; c-d) Photomicrographs (plane-polarized and crossed polars, respectively) showing the S_1 foliation, marked by intense flattening and asymmetric crystal fabrics indicating a top-to-the-left (east) shear sense and sigma-type structures; e-f) outcrop-scale F_2 folds deforming the earlier transpositional S_1 foliation; g-h) Photomicrograph (plane-polarized light) showing a crenulation cleavage overprinting S_1 and defining a secondary foliation (S_2) in metapelite and calcschist.

and accommodated top-to-ENE displacement. Structural station locations and related stereoplots are presented in Fig. 12c.

This shear zone facilitated eastward translation of the upper tectonic units over the deeper metamorphic core, effectively breaching the intervening thrust contacts. The resulting structural configuration is a gentle antiform, with its western limb forming a monoclinal structure dipping W–SW (Fig. 14). Kinematic indicators, such as slickensides and fracture patterns in the surrounding damage zones (Fig. 14), systematically record a tectonic transport direction toward the ESE (see stereoplots in Fig. 12c).

6. Discussion

This discussion is structured into four subsections. The first addresses the main issues concerning the evolution of the inner Northern Apennines orogenic belt. The second examines the dataset within the current regional and local geodynamic framework. The third integrates these findings, and the final subsection synthesizes the main points and proposes a new interpretative model, which serves as the foundation for the conclusions. Beyond its regional significance, the discussion also provides insights that may help improve the understanding of structural architectures and tectonic processes in other orogenic belts worldwide, particularly those affected by polyphase deformation and post-collisional extension.

6.1. Certainties and ambiguities for the inner northern apennines and the middle Tuscan ridge

The Neogene tectonic evolution of the inner Northern Apennines, now exposed in the Tyrrhenian offshore and southern Tuscany (e.g., Carmignani et al., 2001), has long been debated, with previous studies yielding a combination of well-established observations and conflicting interpretations. These concern the stacking pattern of tectonic units, the nature of tectonic contacts, and the development of Miocene–Pliocene sedimentary basins (Martini and Sagri, 1993). Additional issues concern the relationships between crustal structures and anatectic and sub-crustal magmatism (Serri et al., 1993; Peccerillo, 2003) but this topic lie beyond the scope of this study.

In the study area (Fig. 1), there are many points that have been discussed and accepted by the scientific community over the past decades: certain fixed points (i.e. certainties) are broadly accepted and undisputed: (i) the significant “jump” in metamorphic grade between

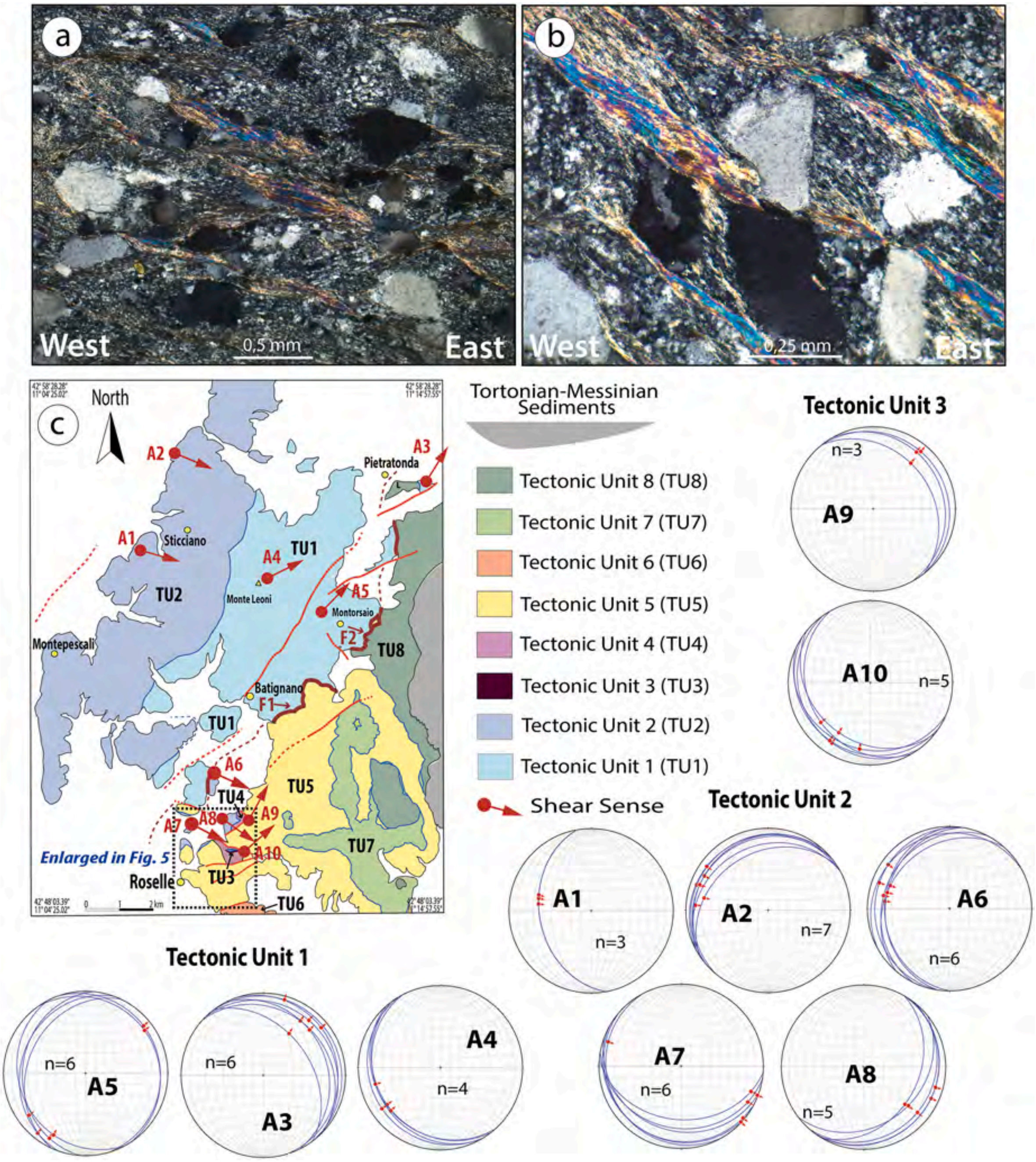

Fig. 12. (a–b) Cross-polarized photomicrographs of Palaeozoic metasandstones showing a penetrative S_1 foliation defined by a flattening fabric and east-verging asymmetric shear sense. (c) Tectonic sketch map of the area shown in Fig. 4, illustrating the distribution of tectonic units and the shear sense, inferred from the combination of L_1 orientation and shear sense indicators observed in mesoscopic structures and thin-section analysis. Stereographic diagrams (lower hemisphere, equal-area projection) show L_1 lineation data for each structural analysis station displayed in Figs. 4 and 5.

some stacked units (e.g., Carmignani and Kligfield, 1990); (ii) the omission of entire tectonic units within the orogenic stack, as well as within individual units (e.g., Trevisan, 1950; Lazzarotto and Mazzanti, 1976; Bertini et al., 1991; Decandia et al., 1993); (iii) the progressive deformation of tectonic units from ductile through semi-ductile to brittle regimes, indicative of deformation during exhumation (e.g., Carmignani et al., 1994; Liotta et al., 1998); (iv) the presence of Miocene basins with characteristic bowl-shaped geometries (e.g., Lazzarotto and Sandrelli, 1977; Bonini and Moratti, 1995; Pascucci et al., 1999) on top of the highest tectonic units of the orogenic stack and where these directly lie on the Late Triassic evaporite (e.g., Brogi, 2004, 2006; Brogi et al., 2025); (v) the occurrence of tectonic units and/or laterally discontinuous metabasite bodies intercalated between units related to the Adria continental margin (e.g., Ardigò, 1961; Gianniello et al., 1964; Lazzarotto et al., 1964; Marinelli, 1964; Keller and Pialli, 1990; Rossetti et al., 1999; Bortolotti et al., 2001).

Despite these established facts, ambiguities and unresolved questions persist, especially regarding the westernmost sector of the chain (i.e. inner zone), including the Middle Tuscan Ridge. The metamorphic gap among units, for instance, has been attributed either to out-of-sequence thrusting (Finetti et al., 2001) or to extensional detachments related to lithospheric thinning (Carmignani et al., 1994; Liotta et al., 1998; Jolivet et al., 1998; Di Stefano et al., 2011; Moeller et al., 2013; Le Breton et al., 2017). Similarly, the omission of entire tectonic units has been

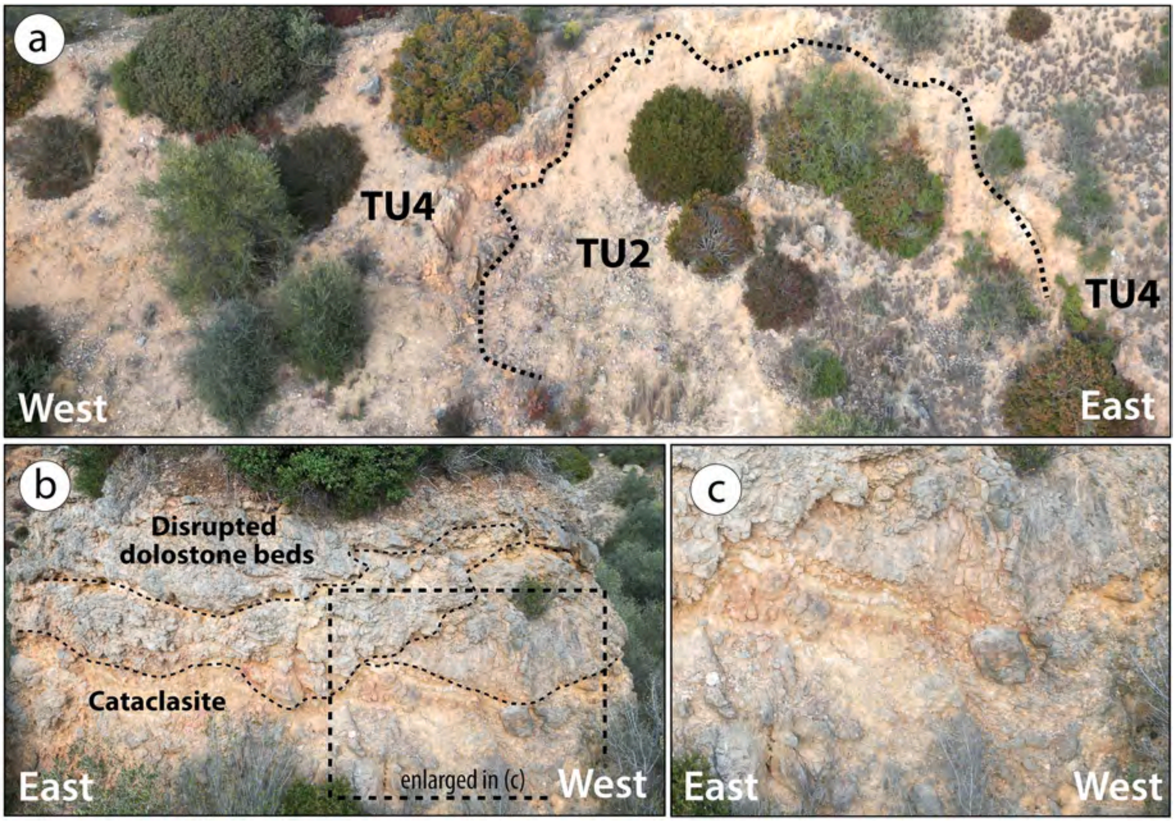

Fig. 13. – a) Panoramic view of the tectonic contact separating the metamorphic Scaglia Toscana Formation of TU2 from the Late Triassic dolostone of TU4. **b–c)** Close-up views of the tectonic contact, which is characterized by anastomosing shear planes along which cataclasite has developed.

attributed to out-of-sequence thrusting (Finetti et al., 2001; Bonini and Sani, 2002) or to extensional low-angle fault systems capable of generating megaboudinage, particularly within carbonate units of the Tuscan succession (Decandia et al., 1993; Carmignani et al., 1994; Brogi et al., 2005; Brogi and Liotta, 2008).

The transition from ductile to brittle deformation has been broadly associated with continuous tectonic activity related to the subduction of the Adriatic margin beneath Europe (e.g., Molli, 2008), leading to HP–LT metamorphism (Brunet et al., 2000) and subsequent exhumation (Liotta et al., 1998). However, the mechanisms driving exhumation remain debated, with proposed models including channel flow (Ryan et al., 2021; Papeschi et al., 2022), out-of-sequence thrusting (Finetti et al., 2001), extensional detachment faulting (Carmignani et al., 1994; Liotta et al., 1998), or hybrid mechanisms (Brogi et al., 2025).

Bowl-shaped basins have been interpreted as thrust-top basins, often associated with retrovergent thrusts (back-thrusts; Bonini, 1999; Bonini and Sani, 2002; Bonini et al., 2014), but alternatively as supradetachment or synclinal basins linked to extensional detachments (Brogi, 2004, 2011, 2020; Brogi and Liotta, 2008; Barchi, 2010; Martini et al., 2021).

Discontinuous metabasite bodies intercalated between tectonic units related to the Adria margin have been interpreted as remnants of Ligurian Domain oceanic crust (Lazzarotto et al., 1964; Ricci, 1968; Keller and Pialli, 1990; Bortolotti et al., 2001). Their presence has favoured debate on the palaeogeographic origin of the overlying units, some of which are attributed to the European margin, with implications for the belt's structural architecture. Alternatively, assuming all tectonic units originated from the Adria margin, an out-of-sequence thrusting mechanism has been proposed to explain the duplication of Tuscan Domain units above Ligurian Domain units (Keller and Pialli, 1990; Pertusati et al., 1993; Bortolotti et al., 2001; Brogi et al., 2025).

We contribute to this ongoing discussion by refining the structural interpretation of the southern Middle Tuscan Ridge, with particular focus on the tectonic context of the metabasite bodies and the nature of the contacts between stacked units, thereby providing new constraints on the stacking order and kinematics of the nappe pile. These findings allow for a more robust reconstruction of the tectonic evolution of this segment of the Northern Apennines, which we detail in the following sections.

6.2. *Interpretation of the position of the metabasite bodies*

The metabasite bodies, discontinuously exposed along the western slope of Roselle Hill (Fig. 5), were first investigated for mining purposes (Ardigò, 1961). Their nature and significance have been the subject of a long-standing debate. Based on mineralogical composition, Ardigò (1963) tentatively interpreted these rocks as products of Neogene Tuscan magmatism, an interpretation later categorically rejected by Marinelli (1964). In contrast, Ricci (1968) proposed that these metabasites represent slices of ophiolitic basement derived from the Ligurian Domain, drawing comparisons with similar mafic bodies intercalated within tectonic units of the Tuscan Domain at Monte Argentario, Giglio Island, and Elba Island (Lazzarotto et al., 1964; Bortolotti et al., 2001). According to this interpretation, the Roselle metabasites would constitute an ophiolitic slice (Ricci, 1968) tectonically interposed between units of the Tuscan Domain (Moretti, 1991; Gelmini and Mantovani, 1970).

New field mapping, however, has led to the identification of additional, previously undocumented metabasite outcrops in the same area (Fig. 5). These new data, partially consistent with the earlier observations by Gelmini (1969), provide inputs that leads us to consider the metabasites as intrusive bodies associated with the tectonic Unit TU3. In this view, they were likely emplaced within the Permian–Triassic metasandstone–metaconglomerate and metacarbonate succession that constitutes TU3 (Figs. 5 and 6), rather than representing a discrete

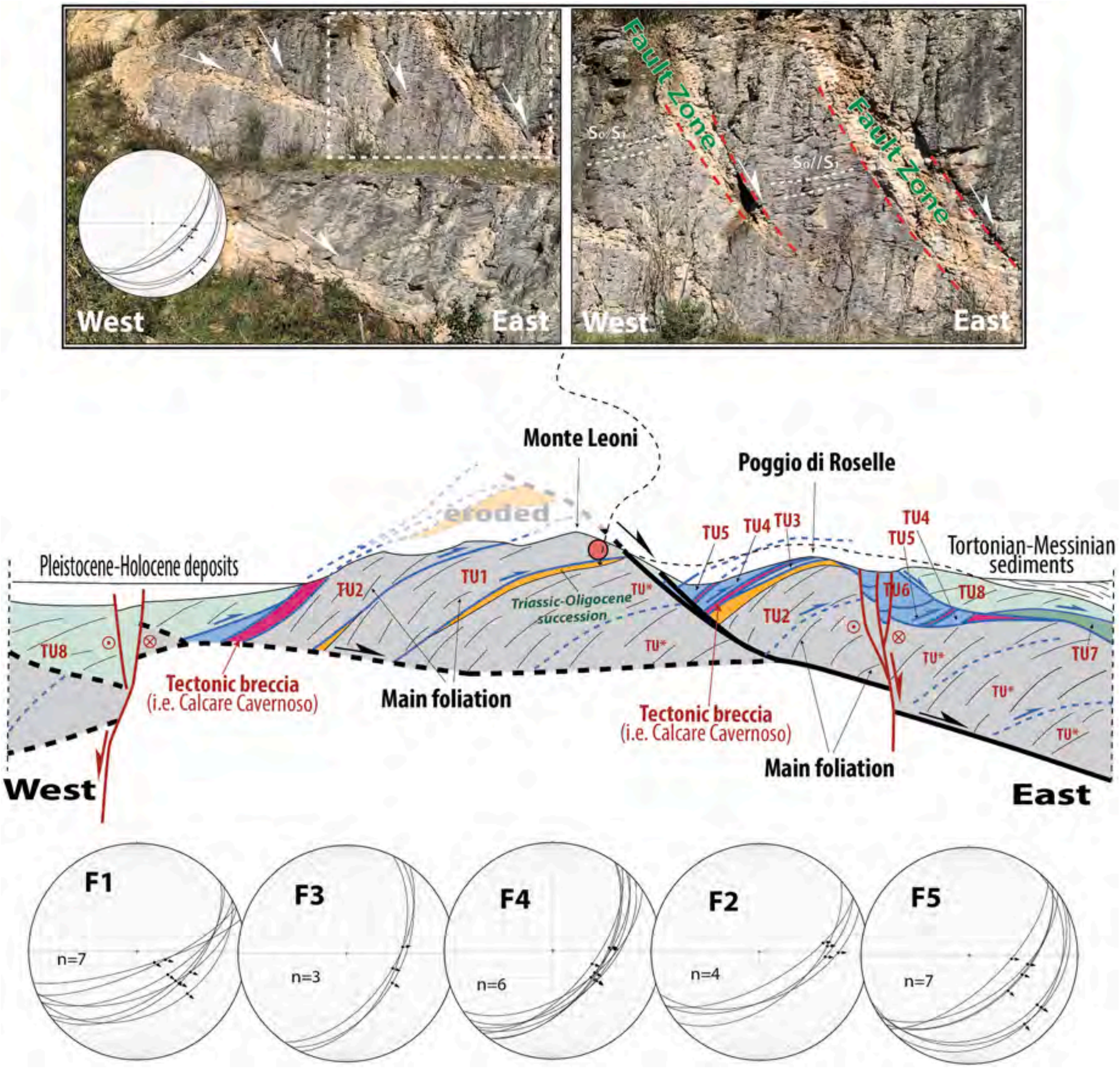

Fig. 14. – Conceptual geological cross-section (not to vertical or horizontal scale) illustrating the structural setting of the tectonic units exposed in the study area and the medium-angle shear zone that bounds the Monte Leoni. Field photographs show outcrop-scale details of minor structures associated with the main shear zone, exposed within the Triassic Verrucano succession, which constitutes the damage zone of the footwall block. At the bottom of the figure, lower-hemisphere stereonets display fault and striae data from minor faults related to the main shear zone, measured in several kinematic structural stations of analysis shown in Fig. 3.

tectonic slice of oceanic affinity. In particular, the metabasite exposures northwest of Poggio Moscona (Fig. 5), initially described by Ardigò (1961, 1963) as rock fragments within debris or colluvial/alluvial deposits, are more likely (at least in part) to be part of a cataclastic shear zone a few meters thick. This interpretation is supported by a restricted outcrop at the same site and by observations in the Roselle archaeological area, where mafic rocks are embedded within a clay-rich matrix derived predominantly from black and grey quartz-phyllites, with minor quartz-metaconglomerate fragments. A similar structural setting was also noted by Gelmini and Mantovani (1970), who emphasized the tectonized nature of the host rocks.

The basal (exposed) succession of TU3 consists of phyllites and metasandstones with high organic matter content, from which palynological assemblages yield a Middle to Late Permian (Guadalupian–Lopingian) age (Fig. 1 SM and Table 1 SM). This palynoflora shows strong affinities with coeval lithostratigraphic units of the Tuscan Domain exposed in other sector of the Middle Tuscan Ridge and surroundings, and on Elba Island, such as the Arenarie del Monte Argentario Formation (Cirilli et al., 2002), Arenarie di Poggio al Carpino Formation (Lazzarotto et al., 2003), Farma Formation (Aldinucci et al., 2008), Rio Marina Formation (Spina et al., 2019), Gavorrano Monzogranite-host rocks (Brogi et al., 2021), Falsacqua Formation (Spina et al., 2022), Rosia Creek (Brogi et al., 2023). A comparable assemblage is also reported from coeval units of the Alpi Apuane tectonic domain (Pieruccioni et al., 2023).

In summary, although exposures of metabasites in the Roselle area are limited and largely discontinuous, available field and stratigraphic evidence suggests that these bodies are most likely intrusive into the Late Permian - Triassic sedimentary succession (i.e., *Phyllitic-quartzitic Group* and *Verrucano* Auctt. and its carbonate cover) at the base of TU3. However, the TU3 unit is now almost entirely absent due to tectonic omission and erosion, precluding further direct observations.

6.3. *Stacking pattern and tectonic unit relationships*

The nature of the tectonic contacts separating the different tectonic units previously described (TU1–TU8) is relatively well established. However, the timing and geodynamic context of their development remain the subject of ongoing incertenties and debates. In most official geological maps, including those covering areas adjacent to the study site (e.g., CARG Project 1:50,000: https://www.isprambiente.gov.it/Media/carg/toscana.html; CARG Project Regione Toscana 1:10,000: https://www502.regione.toscana.it/geoscopio/cartoteca.html), these boundaries are interpreted as regional-scale reverse faults (i.e., thrusts), because they juxtapose tectonic units derived from distinct palaeogeographic domains involved in the Apennine orogenic process. Nonetheless, field and structural data suggest that this interpretation is only partially valid. Indeed, the superposition of the different units resulted from compressional tectonics that built the nappe stack, whereas the present geometric configuration is the consequence of an extensional tectonic process that post-dates the main thrust-stacking phase. However, this interpretation should not be understood as implying that the original thrust faults were reactivated as normal faults during later extension. Rather, the current contacts between the tectonic units are to be considered newly formed normal faults that dissect a pre-existing nappe stack. This stack preserves the structural architecture acquired during the earlier compressional phase, when the units were originally emplaced through thrusting. The subsequent extensional deformation overprinted this architecture, generating normal faults that now separate units previously juxtaposed by reverse faulting. A key piece of evidence supporting this interpretation is the tectonic juxtaposition observed at Monti Leoni, where non-metamorphic units of the Tuscan Succession (i.e., Tuscan Nappe) lie directly above high-pressure metamorphic units (TU1 and TU2; see Giorgetti et al., 1998). This configuration implies the omission of several tectonic units that would originally have been interposed between them. This sharp metamorphic discontinuity is difficult to reconcile with a thrust or even an out-of-sequence thrust system, based on the geometric and structural relationships observed in the field (Fig. 4). Moreover, the L_1 mineralogical lineation, interpreted as having developed during peak metamorphic conditions in TU1–TU3, shows significant variation in orientation between different units (Fig. 4). This further supports the interpretation that the contacts separting these tectonic units post-date peak metamorphism and initial stacking, to which the L_1 lineation is attributed.

Additional evidence comes from the widespread presence of stratigraphic discontinuities within all the metamorphic units (Figs. 4 and 6), suggesting the occurrence of tectonically subtractive contacts. It is worth noting that the subtractive character of these contacts further supports an extensional interpretation of the tectonic boundaries, likely low-angle normal faults. For instance, TU3, which includes the metabasite bodies, is highly discontinuous and severely elided, preserving only the Permian-Triassic succession. TU3 forms isolated remnants, often only a few meters thick, at the contact between TU2 and TU4. In localities where TU3 is entirely absent, TU2 and TU4 are in direct tectonic contact (Fig. 5).

This geometry contrasts with the interpretation proposed by Moretti (1991), who suggested that units containing the Pseudoverrucano succession (TU5) overlie the Ligurian Units. Our observations show instead that TU5 consistently occupies the uppermost position within the Tuscan Domain stack, as documented also in the Monti dell'Uccellina (Salto del Cervo Unit; Campetti et al., 1996), the Collecchio Mountains (Costantini et al., 1980a), and the Punta delle Rocchette area (Costantini et al., 1980b; Aldinucci et al., 2008).

Taken together, these structural relationships imply that the major tectonic contacts separating the mapped units formed after ~19 Ma—i.e., later than the youngest peak metamorphic ages reported for adjacent sectors such as Elba Island (Bianco et al., 2019) and Punta Bianca (Montomoli et al., 2024).

Furthermore, our data (Fig. 3) indicate that these tectonic contacts are cut by a major shear zone that defines the eastern margin of the Middle Tuscan Ridge, thereby constraining the maximum age of their development. This shear zone extends northward along the margin of the ridge (Brogi, 2008, 2011), accommodating the juxtaposition of Ligurian Units against metamorphic units, and promoting the development of bowl-shaped basins filled by continental sediments during the Late Tortonian–Messinian. Deposition within these basins occurred syn-tectonically with the activity of the shear zone, as indicated by soft-sediment deformation structures in Miocene deposits (Lazzarotto and Sandrelli, 1977; Brogi and Liotta, 2008; Brogi, 2011), consistent with evidence from other Miocene basins in southern Tuscany (e.g., Bonini et al., 1994; Bonini and Moratti, 1995). Although exposure conditions limit detailed analysis, the Miocene deposits in the study area show significant similarities with those described above. These deposits rest on Ligurian Units and are not fault-bounded (Fig. 4), mirroring other Miocene basins. In particular, they show strong structural similarities to those documented in adjacent basins: notably, these deposits rest directly on Ligurian Units and are not fault-bounded (Fig. 4), in agreement with the geometry of other Miocene extensional basins in the region (Brogi et al., 2005).

Based on this evidence, we interpret the shear zone bounding the eastern margin of the Monte Leoni ridge (southern Middle Tuscan Ridge) as an extensional detachment fault active during the Tortonian–Messinian. This structure was subsequently dissected by high-angle normal faults that remained active into the Pliocene, as indicated by offsets affecting Early Pliocene deposits (Brogi, 2011), thus providing a minimum age constraint for the activity of the detachment (Fig. 4).

6.4. *Summary and general consideration on the tectonic process*

The definitive structural configuration of the study area reflects a polyphase extensional evolution that significantly overprinted the original thrust belt architecture of the Northern Apennines. At least three generations of superimposed normal faults have been recognized (Fig. 14), each contributing to the progressive dismantling and reorganization of the nappe stack: i) Low-angle normal faults, active after ~19 Ma, decoupled previously stacked tectonic units, locally leading to the omission of entire units or parts of their successions (Figs. 3–6). ii) An east-dipping extensional shear zone, active during the Tortonian–Messinian and possibly extending into the early Zanclean, cut across pre-existing thrust contacts. This shear zone generated a rollover structure, with associated earlier shear zones dipping to the west–southwest (Fig. 14). iii) Post-Zanclean high-angle normal faults that displaced all previous structures, further fragmenting the nappe stack (Fig. 14).

This structural evolution is consistent with that documented in adjacent sectors such as the Elba Island area (Brogi et al., 2025) and the geothermal regions of Tuscany (Larderello and Monte Amiata; Bertini et al., 1991; Baldi et al., 1994; Carmignani et al., 1994; Dallmeyer and Liotta, 1998; Batini et al., 2003; Brogi, 2008), where a comparable polyphase extensional setting has been interpreted as a post-orogenic reworking of the Northern Apennines belt (Fig. 15).

Within this tectonic framework, we interpret the metabasite bodies of the study area as consistently associated with the Adria continental margin. Based on their geological context, these bodies are interpreted as mafic intrusions emplaced during crustal thinning and rifting phases predating the development of the Adria passive margin, following the opening of the Alpine Tethys (Vai and Martini, 2001; Lucci et al., 2025). As such, there is no compelling evidence to support their reinterpretation as oceanic ophiolites from the Ligurian Domain (cf. Ricci, 1968), such as the mafic bodies of the Monte Argentario and Elba Island (Bortolotti et al., 2001), nor is it necessary to invoke out-of-sequence thrusting to explain their position within the nappe stack.

We therefore propose an integrated tectonic model, in which an early orogenic stacking phase (pre-19 Ma) was followed by a progressive extensional dismantling and reconfiguration of the nappe architecture (Fig. 15). This framework not only reconciles field-based structural and stratigraphic evidence but also aligns with the broader regional evolution of the inner Northern Apennines. It provides a more coherent and parsimonious interpretation than alternative models invoking alternating compressional and extensional pulses or uninterrupted compressional tectonics from the Cretaceous onwards (e.g., Finetti et al.,

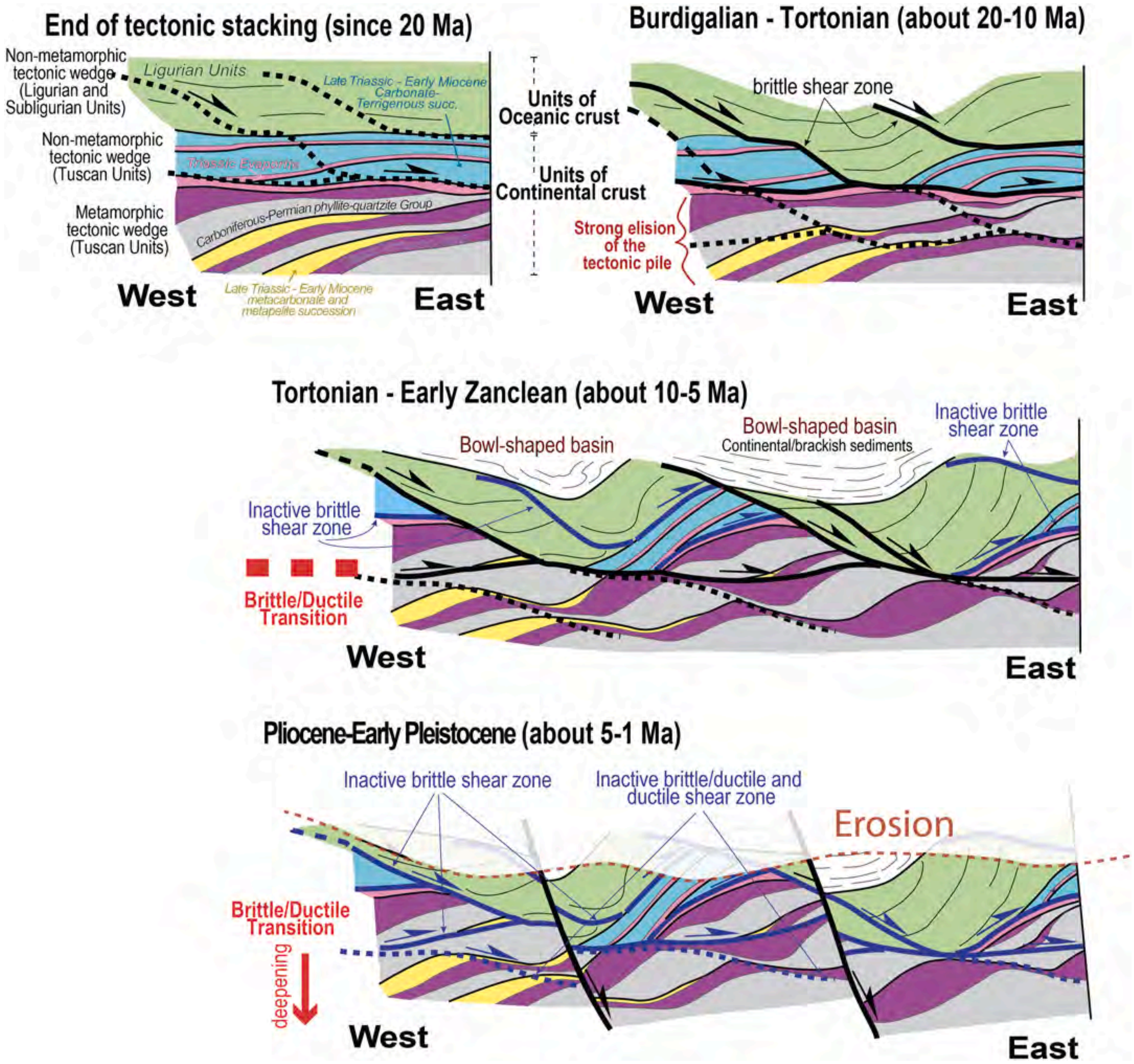

Fig. 15. – Conceptual model illustrating the polyphase extensional evolution of normal faulting responsible for the lateral segmentation of geological units (i.e. crustal boudinage) over time. Extension is associated with progressive uplift and exhumation, leading to successive generations of normal faults and a gradual deepening of the brittle–ductile transition zone.

2001; Finetti, 2006; Bonini and Sani, 2002; Bonini et al., 2014).

7. Conclusions

This study contributes to a more integrated interpretation of the tectonic evolution of the inner Northern Apennines and provides broader insights into orogenic systems that have experienced extensional tectonics superimposed on a pre-existing compressional framework. It may also serve as a reference model for interpreting post-collisional extensional systems in other orogenic belts, regardless of their geological age.

The proposed conceptual model (Fig. 15) strengthens previous interpretations that the orogenic belt underwent a polyphase extensional overprint following its initial construction, likely beginning after the Burdigalian (~19–20 Ma). During this extensional phase, early-formed low-angle normal faults, originally active at depth, were progressively reactivated or dissected by younger fault systems. This evolution reflects a transition toward a progressively shallower brittle–ductile (B–D) boundary. The superposition of these deformation events led to the back-tilting of older extensional systems, coeval with rollover geometries generated by boudinage-related stretching.

These processes resulted in the development of isolated structural domains (extensional duplexes) that locally preserve elements of the original nappe stack. These domains are bounded by the earliest extensional detachments, which initiated the dismantling of the orogenic edifice and contributed to crustal thinning.

Early fault systems, typically with listric or staircase geometries, were overprinted by younger structures during progressive exhumation.

This structural overprinting was influenced by isostatic adjustment, crustal thinning, and increased heat flow, all of which drove the upward migration of the B–D transition. The overall evolution is schematically illustrated in Fig. 16.

The geological process leading to the development of the polyphase extensional tectonics described in this study is schematically illustrated in Fig. 16. It shows how, in a rifting process involving a heterogeneous lithosphere, lithospheric thinning results in the superposition of multiple generations of normal faults, potentially producing highly complex geometric configurations.

While this study represents a significant step forward in understanding the extensional evolution of the inner Northern Apennines, it

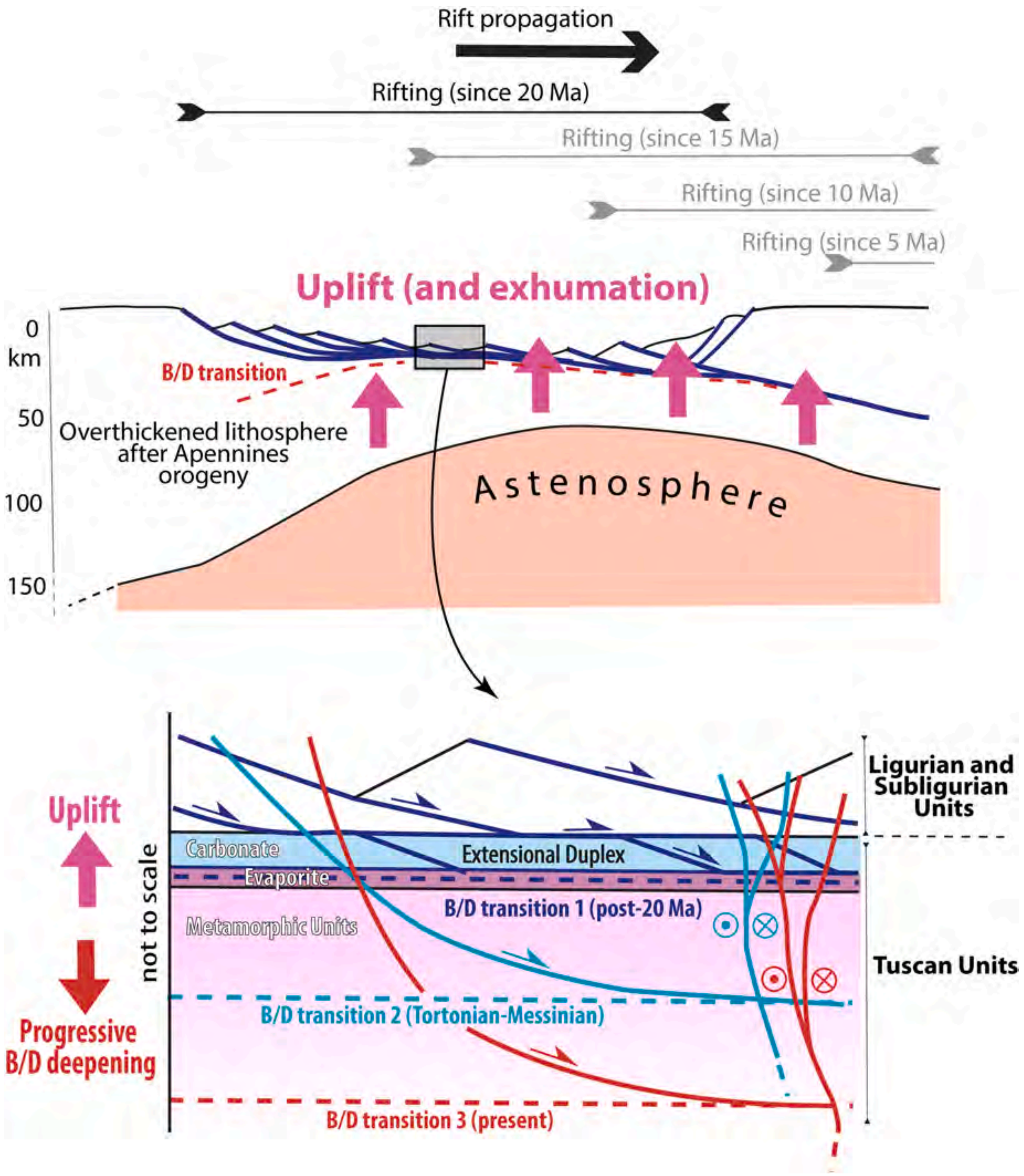

Fig. 16. – Conceptual model showing the post-collisional rifting process affecting a overthickened lithosphere (which led to the opening of the Northern Tyrrhenian Sea starting from 20 Ma) and its development through eastward asymmetric shearing. The thinning of the lithosphere, previously thickened by the Apennine orogeny (Bianco et al., 2015), reached values of less than 50 km (Moeller et al., 2013). Asthenospheric upwelling in response to lithospheric thinning caused overheating of the thinned sector, uplifting the brittle–ductile transition (B/D transition), along which normal faults flattened. These faults also developed staircase geometries because the Tuscan Units contained horizons with strong competence contrasts (e.g., evaporites and carbonates). The staircase geometry led to crustal boudinage through the formation of extensional horses (Brogi, 2004; Brogi et al., 2005; Brogi and Liotta, 2008). Overheating of the lithosphere also caused uplift of the thinned area, triggering exhumation of deeper tectonic units, as well as a relative downward shift of the brittle–ductile transition. Over time, this process resulted in the development of normal faults with a deeper detachment level than those formed earlier, cutting across and offsetting them. This evolution, illustrated in the figure through three steps for clarity, occurred uninterruptedly, producing polyphase normal faults, the youngest of which dissected the older ones. Transfer faults associated with these structures bounded crustal sectors subjected to different amounts of extension.

also lays the groundwork for future research, particularly aimed at:

(i) determining the age, origin, and tectonic significance of the mafic igneous protoliths within the metabasite bodies; and
(ii) reconstructing the pressure-temperature-time (P–T–t) evolution of both the metabasites and their metasedimentary host rocks derived from the Adria continental margin.

CRediT authorship contribution statement

Andrea Brogi: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Enrico Capezzuoli:** Writing – review & editing, Supervision, Investigation, Formal analysis. **Amalia Spina:** Supervision, Formal analysis. **Martina Zucchi:** Writing – review & editing, Visualization, Supervision, Software, Investigation. **Chiara Montemagni:** Writing – review & editing, Visualization, Supervision, Investigation. **Federico Lucci:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsg.2025.105541.

Data availability

Data will be made available on request.

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