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Multiscale structural analysis of an Epiligurian wedge-top basin: insights into the syn- to post-orogenic evolution of the Northern Apennines accretionary wedge (Italy)

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Abstract

Wedge-top basins represent useful tectonic elements for the characterisation of the evolution of their underlying accretionary wedge in space and time, as their final state of deformation sums up the bulk shortening and structural instability conditions of the wedge. Here, we present the geometric and kinematic patterns of deformation structures deforming the wedge-top Epiligurian basins of the Northern Apennines (Italy). Our main goals are to generate an evolutionary model to account for the syn- to post-orogenic evolution of the Epiligurian basins and to infer the building style of the Northern Apennines wedge during continental collision. Mesoscale structural analysis shows that common and widely distributed thrust and normal fault arrays deform the entire Epiligurian stratigraphic succession infilling the broadly E-vergent wedge-top basins. Thrusts are invariably cut by later NW–SE and NE-SW-striking normal and oblique fault systems characterised by fault planes that mutually intersect at all scales to form polygonal patterns. Remote sensing analysis of the tectonic structures affecting the Epiligurian formations confirms the variable orientation of both thrusts and normal faults within the different studied stratigraphic successions. As a whole, results suggest a polyphase tectonic evolution of the Epiligurian wedge-top basins during the widening of the Northern Apennines accretionary wedge towards the foreland by frontal accretion. The recognised main phases are: (i) syn-orogenic compression accommodating overall tectonic transport towards the eastern quadrants; (ii) post-orogenic extension genetically related to the extension of the inner zone of the Northern Apennines; (iii) more recent extension forming collapse-induced normal faults spatially arranged in polygonal patterns.

Keywords Wedge-top basins · Normal faulting · Accretionary wedge · Epiligurian formations · Northern Apennines

Introduction

Wedge-top basins are dynamic stratigraphic and structural features located atop thrust sheet stacks imbricated during the contractional structuring of the underlying accretionary wedge (e.g., DeCelles and Giles 1996). They are filled by deposits deriving from the progressive dismantling of the growing wedge itself and may be involved in the build-up, uplift and evolution of actively shortening fold-and-thrust belts (e.g., Ori and Friend 1984; Ford 2004).

The architecture of the underlying accretionary wedge and its kinematic evolution exert a significant influence upon the geometry and the stratigraphic evolution of wedge-top basins. From a structural point of view, their final state of deformation expresses and accommodates the (i) bulk shortening and thickening of the wedge, at all scales, (ii) propagation of in-sequence and out-of-sequence thrusts, (iii) uplift and subsidence, (iv) creation of accommodation space and potentially variable sedimentation rates and, finally, (v) reworking of the thickened wedge under overall extension in post-orogenic conditions (Beaumont 1981; Jordan 1981; Ori and Friend 1984; Bally et al. 1985; De Celles and Giles 1996; Mutti et al. 2003; Ford 2004).

Wedge-top clastic deposits generally reflecting only limited transport and are characterised by immature textures controlled by different types of growth structures depending on the increasing proximity to the basin edges and according to the geometry of the thrust ramps upon which they

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develop (Beaumont 1981; Ori and Friend 1984; Peper and Boer 1995). Previous studies have mostly focused on the sedimentological and stratigraphic features of wedge-top basins, aiming at defining the depositional environment of the involved stratigraphic units and their mutual relationships in terms of stratigraphic gaps, lateral continuity, interdigitation and angular unconformities (e.g., DeCelles and Giles 1996; Ricci Lucchi 1986, 1990; Amorosi 1995; Ambrosi et al. 1996; Amorosi et al. 1996; Horton 1998; Sempere 2000; Chiang et al. 2004; Ciarcia and Vitale 2013). On the other hand, only little attention has instead been paid to the structural record of wedge-top basins, although a multidisciplinary structural perspective including the study of meso- to regional-scale structural features may indeed provide useful insights into the regional and local paleo-stress regime evolution, burial and thermal history and other far-field factors (shortening, exhumation and erosion rate, among others) influencing the space–time evolution of this type of basins (e.g., Hippolyte et al. 1994; Ferrière et al. 2004; Carrapa and DeCelles 2008; Vera et al. 2015). Wedge-top basins have been only seldomly used as structural-stratigraphic gauges to track down the tectonic style and orogenic evolution of accretionary wedges worldwide (e.g., Apennines and Calabrian Arc: Weltje 1992; Hippolyte et al. 1994; Catanzariti et al. 1999; Piazza et al. 2016; Wyoming-Idaho-Utah thrust belt: Coogan et al. 1992; Mesohellenic Basin: Ferrière et al. 2004).

The Epiligurian Basins of the Northern Apennines of Italy represent an iconic example of wedge-top basins formed atop an accretionary wedge progressively evolving into a fold-and-thrust belt (e.g., Conti et al. 2020). These middle Eocene-upper Miocene basins are characterised by a complex stratigraphic and sedimentological record (including highly variable lithological infill, composition and thickness, lateral interdigitation and occurrence of regional and second-order unconformities) that was governed and modulated by the dynamic and continuously evolving tectonic regime and state of stress of the underlying Apennines wedge (e.g., Amorosi 1995; Cibin et al. 2001). Therefore, the Epiligurian basins and their sedimentary successions can be used as powerful structural/stratigraphic markers to unravel the deformation history of the Northern Apennines wedge, with noteworthy implications upon its tectonic evolution since the middle Eocene.

In this paper, we describe the structural setting of the Marzabotto wedge-top basin of the Northern Apennines, which is an Epiligurian basin located immediately to the south of the city of Bologna (Fig. 1). This basin is of particular interest because (i) it exposes the entire Epiligurian sedimentary succession, (ii) its contact to the underlying wedge units is easily accessible and is thus suitable for in-depth analysis, and (iii) its internal stratigraphic architecture is affected and deformed by multiple generations of

deformation structures (e.g., Panini et al. 2002; see below), the study of which can reveal many insights into the local and regional deformation history. Through a multiscalar and multitechnique approach including geological mapping, mesoscopic structural analysis, and remote sensing analysis of lineaments, we characterised different structural elements by defining their orientation, kinematics, mutual cross-cutting, and their genetic relationships with the deformed sedimentary succession. Results are used to support an evolutionary structural model that reflects the interaction between regional far-field and local tectonic stress conditions. We propose a polyphase tectonic evolution for the Marzabotto Basin that is representative for other wedge-top Epiligurian basins recording syn-orogenic compression and post-orogenic extension, with the latter accompanied by local instabilities during overall thinning of the transiently supercritical wedge.

Terminology used

In this work, we consider an accretionary wedge as the product of the first stage of orogen build-up, wherein sedimentary rocks belonging to passive margin sequences are involved in the trench dynamics, are reworked, accreted and imbricated and, eventually, displaced from the orogenic core towards the foreland (e.g., Dewey and Bird 1970; Twiss and Moores 1992; Cloos and Shreve 1988a, b; Cawood et al. 2009). Accretionary wedges are effectively conceptualised as a wedge-shaped geodynamic object (e.g., Davis et al. 1983; Dahlen 1984; Platt 1986), the evolution of which, in space and time, also depends on the combination of the flexure of the underthrusting lower plate and the mode of deformation of the wedge material itself (e.g., Mitra 1997; Ford 2004). Wedge-top basin depozones may form on top of the frontal part of the accretionary wedge, which tapers towards the foreland (Davis et al. 1983; Dahlen 1990; Ruh 2020). On the other hand, fold-and-thrust belts represent the result of the more advanced evolutionary stages of an accretionary wedge (Morley et al. 2011). They tend to form in response to wedge uplift and the progressive involvement of foreland basin systems during progressive shortening (Davis et al. 1983). Folding and thrusting accommodate crustal short-ening at shallow crustal levels and may variably affect the early stratigraphic setting of the wedge-top basins (Boyer and Elliot 1982).

Geological setting

The Northern Apennines

The Northern Apennines (NA) are a fold-and-thrust belt that belongs to a retreating collisional foreland basin system
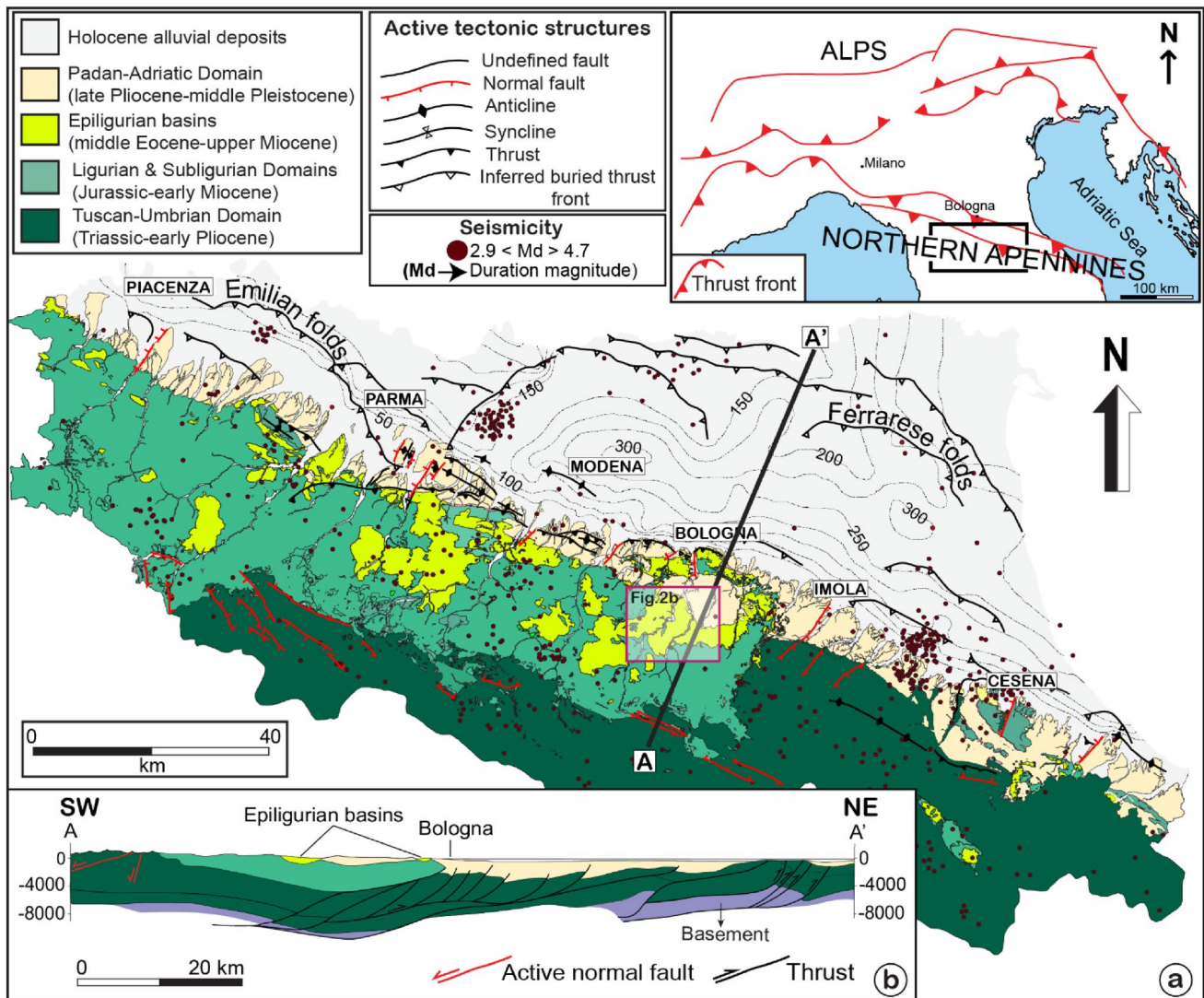
Fig. 1 **a** Geological-structural map of the Northern Apennines (modified and redrawn after Conti et al. 2020). Seismicity data were taken from the Italian Seismological Instrumental and Parametric Database (ISIDe) at: http://terremoti.ingv.it/en/iside. **b** Geological cross-section of the external Northern Apennines (modified and redrawn after Boccaletti et al. 2011)

(De Celles and Giles 1996; Ford 2004). The NA initially formed as part of an accretionary wedge in response to the Late Cretaceous-Eocene closure of the Ligurian-Piedmont Ocean, before later evolving into a NE-verging fold-and-thrust belt related to the W-vergent subduction of the Adria plate beneath Europe and their Oligo-Miocene collision (Carmignani and Kligfield 1990; Carmignani et al. 1995; Bettelli and Vannucchi 2003; Elter et al. 2003; Rosembaum and Lister 2004; Doglioni et al. 2006; Boccaletti et al. 2011; Carminati and Doglioni 2012; Papeschi et al. 2022). The progressive development of the NA stems from the summation of both contractional and extensional deformation during syn- and post-orogenic tectonic phases (e.g., Malinverno and Ryan 1986; Carmignani and Kligfield 1990; Cavinato and DeCelles 1999), with the former linked to the

orogenic wedge structuring and the latter to the opening of the Tyrrhenian back-arc domain inducing the formation of extensional basins (e.g., Faccenna et al. 2001).

The syn-orogenic tectonic phase led to the stacking of tectonic units belonging to different paleogeographic domains along NW–SE-striking and NE-verging thrusts (Boccaletti et al. 1985; Carmignani et al. 1995; Pauselli et al. 2006). From the innermost to the outermost and from top to bottom, these domains are (e.g., Conti et al. 2020 and references therein): (i) the Ligurian Domain, formed by Jurassic ophiolites and their Cretaceous-to-Paleocene sedimentary cover; (ii) the Sub-Ligurian Domain, formed by Paleocene-to-lower Miocene deep marine sediments and turbidites deposited on the Adria thinned continental crust; (iii) the Tuscan-Umbria-Marche Domain, mostly including

Triassic-to-Oligocene platform and basinal carbonate successions, overlain by Miocene-Pliocene turbidites.

Atop those domains occur the Epiligurian Basins, the focus of this study, which unconformably overly the Ligurian Domain and consist of middle Eocene-upper Miocene siliciclastic successions deposited in an environmental domain that evolved in time from bathyal to shallow water conditions (e.g., Ricci Lucchi 1986; 1990; Nirta et al. 2007).

During the tectonic evolution of the NA accretionary wedge, shortening culminated with the Ligurian Domain being thrusted over the Tuscan Domain during the Oligo-Miocene collision (e.g., Boccaletti et al. 1990; Mantovani et al. 2019). Starting in the late Burdigalian, contemporaneous to compression in the most external wedge, an extensional tectonic regime started to affect the most internal portion of the NA (Tyrrhenian side) and began to migrate eastwards in the wake of the NA advancing thrust front (e.g., Martini and Sagri 1993; Barchi et al. 2006; Fig. 1b). This post-orogenic phase led to the development of NW–SE basin-bounding faults that invariably reworked and cut through the earlier contractional features (e.g., Lavecchia et al. 1984; Pialli and Alvarez. 1995; Barchi et al. 2006; Pauselli et al. 2006). The extensional tectonic regime affected the northernmost exposed margin of the NA since the middle Pleistocene causing uplift of the southwestern sector of the belt and subsidence in the north-eastern area (Bertotti et al. 1997).

The present-day thrust front of the NA mainly formed in the Pliocene-lower Pleistocene. It is defined by concentric arcuate thrusts that are associated with the WNW-ESE-striking Emilian and Ferrarese fold systems, buried beneath the middle Pleistocene-Holocene Padan-Adriatic foredeep deposits (Boccaletti et al. 1985; 2011; Fig. 1a).

The NA complex orogenic architecture fits well the seismotectonic framework of the belt (Fig. 1a). Seismicity linked to the compressional tectonic regime is presently distributed both along the thrust front of the exposed belt and the frontal arcs (Emilian and Ferrarese fold systems) buried below the Holocene alluvial deposits (Pieri and Groppi 1981; Massoli et al. 2006; Pauselli et al. 2006; Picotti and Pazzaglia 2008; Mantovani et al. 2014; 2019). The latter are genetically associated with blind thrusts (e.g., Bartolini et al. 1982; Boccaletti et al. 1985; 2011), which are the seismogenic source of the 2012 Emilia seismic sequence and accommodate a maximum compressive stress oriented approximately N-S (e.g., Scisciani and Pizzi 2012; Pondrelli et al. 2012). The recent to current activity of these contractional structures is also documented by the differential uplift of the Padan foredeep deposits and river terraces (Boccaletti et al. 2011), with the NE side systematically affected by higher uplift that the SW side. Seismicity linked to the extensional tectonic regime, on the other hand, is attributed to the NW–SE-striking, SW-dipping basin-boundary normal faults cited above that affect the most internal (southwestern) part of the belt (Mantovani et al. 2014).

The Epiligurian formations

Stratigraphic setting

The internal succession of the Epiligurian Basins (Fig. 2a) reflects a complex geological evolution and is characterised by regional unconformities that directly track the evolution of the underlying wedge (Ricci Lucchi 1986; Amorosi 1995; Amorosi et al. 1996; Cibin et al. 2001).

As an example, a major Burdigalian unconformity represents a key regional element marking an abrupt shift from a deep marine (pre-Burdigalian) to platform (post-Burdigalian) depositional environment during the progressive uplift of the wedge. Furthermore, the deposits of the pre- and post-Burdigalian sequences are characterised (even internally) by remarkable lateral thickness variations and local interdigitations and are in contact with each other along second-order angular erosive unconformities at the basin margins that tend to progressively disappear moving towards the depocenter (e.g., Amorosi 1995). The Epiligurian sedimentary succession is also characterised by basal erosive unconformities (Fig. 2a) marking the beginning of mass-transport processes during the uplift of the underlying wedge (Barbero et al. 2017).

The base of the Epiligurian succession (Fig. 2a) is represented by the Baiso Fm (upper Lutetian-Bathonian), which consists of mudflow and debris flow deposits. The Baiso Fm is overlain by the Loiano Fm (upper Lutetian), a turbiditic sequence of resedimented course- to fine-grained arkosic sandstone with channel-fill facies. Upwards, the Marne di Monte Piano Fm (Bathonian-Priabonian), consists of greenish-reddish clayey marl and marly clay commonly poorly or not stratified. Above, the Ranzano Fm (middle-upper Rupelian) is characterised by sandstone interlayered with shale related to a slope-basin depositional environment. Moving up, the Antognola Fm (Chattian-Aquitanian) consists of hemipelagic marl and pelite, intercalated with turbiditic arenaceous beds deposited in a slope depositional environment. Higher up, the Contignaco Fm (lower Burdigalian) consists of dark grey marl mixed with turbiditic terrigenous currents deposited in a slope depositional environment transitional to hemipelagic conditions.

Above the major Burdigalian unconformity (Fig. 2a), the Pantano Fm (upper Burdigalian-lower Langhian) is characterised by very fine calcarenite and greyish siltstone, with poorly developed or even locally absent bedding, intercalated by coarse arenaceous resedimented beds typical of a slope depositional facies.

The upward transition to the Cigarello Fm (lower Langhian-Serravallian) is the expression of a complex
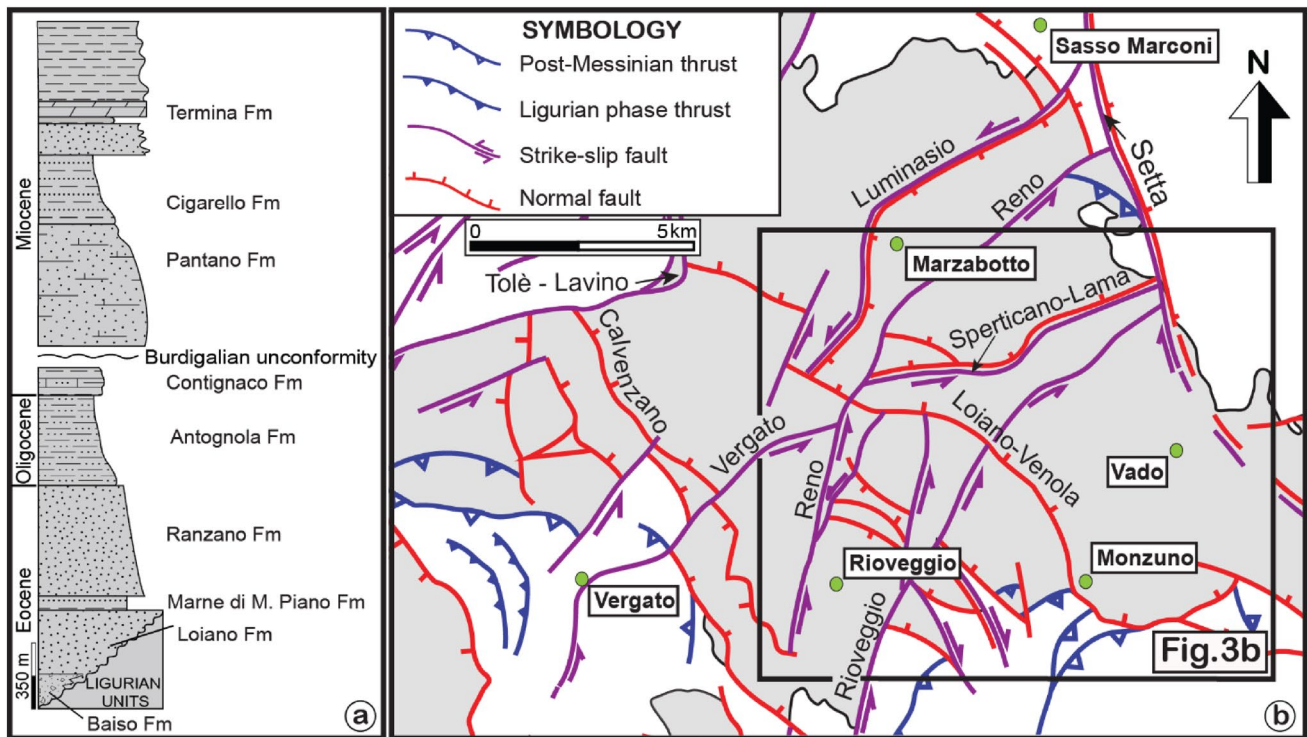
Fig. 2 **a** Schematic Epiligurian sedimentary succession; **b** Structural-tectonic scheme of the Marzabotto Basin and surroundings, which illustrates the main fault systems affecting the Marzabotto Basin in the study area (modified after Panini et al. 2002). Faults marked by double red and purple lines represent earlier strike-slip faults that were later reactivated as normal faults

paleogeographical evolution with the drowning of the Burdigalian platform and the sedimentation of a pelitic marly-sandy and poorly sorted, locally cemented, arenaceous sequence.

The top of the Epiligurian sedimentary succession is formed by the Termina Fm (upper Serravallian-lower Messinian), which consists of poorly stratified clayey marl interspersed with fine arenaceous intercalations typical of a transitional-to-outer shelf depositional environment.

The Epiligurian formations are overlain by deposits of the Intra-Apenninic Pliocene basinal sequence, which is composed of conglomeratic-arenaceous deposits related to a distal coastal plain- to deltaic plain depositional environment (e.g., Amorosi et al. 2002).

Structural setting

Different deformation structures, styles and stress regimes have been documented for the Epiligurian formations of the NA (e.g., Capitani and Sasso 1994; Ottria 2000; Antonellini and Mollema 2002; Panini et al. 2002; Artoni et al 2006; Balocchi 2014; Piazza et al. 2016; Balocchi and Santagata 2018; Del Sole et al. 2020; Fig. 2b).

Two main compressional phases affected the Marzabotto Epiligurian Basin during the early Oligocene and the early Aquitanian to produce N-S and NW–SE-striking and NE- and SW-dipping thrusts (e.g., Catanzariti et al 1999; Panini et al. 2002). Ottria (2000) even documented SW-vergent thrusts and associated km-scale recumbent folds deforming the Epiligurian formations during the late Eocene–Oligocene. During the Rupelian to Serravallian, sedimentation in the area was strongly controlled by the development of a major NE-SW left-lateral transpressive deformation zone that exerted a long-term control on the local syn-shortening Epiligurian sedimentation (Piazza et al. 2016). Subsequently, a stress field dominated by N-S compression ensued, leading to the formation of major left- and right-lateral conjugated fault systems oriented NNE-SSW and NNW-SSE, respectively (Panini et al. 2002; Balocchi 2014). The NNE-SSW-striking left-lateral faults controlled the lateral juxtaposition of the Ligurian Units against the Epiligurian formations (Reno, Rioveggio and Vergato Faults in Fig. 2b). Some of these strike-slip structures (e.g., Grizzana Morandi and Loiano-Venola Faults in Fig. 2b) were later reactivated as normal faults in response to N-S extension during the Pleistocene (Balocchi 2014). Meso-to-micro-scale subsidiary structures, such as deformation bands within the highly porous sandstone of the Loiano Fm, have been reported to occur in proximity to the main normal faults dissecting the area, thus providing evidence of structural control on fluid

flow atop the wedge units (Antonellini and Mollema 2002; Del Sole and Antonellini 2019; Del Sole et al. 2020).

Methods

A cartographic review of the study area was first carried out by consulting the geological maps available at the 1:50,000 and 1:25,000 scales that are freely available from the link https://datacatalog.regione.emilia-romagna.it/catalogCTA/. We then performed detailed structural mapping at the 1:10,000 and 1:5,000 scale in the Marzabotto Basin, to the south of the Bologna foothills, where the complete Epiligurian succession is well exposed over an area of about 200 km². We collected more than 500 orientations for bedding and tectonic structures (faults and associated structures) at 27 representative structural sites from the pre- and post-Burdigalian formations, with the aim to constrain the local structural framework. The kinematics of the studied fault segments were determined by classical field criteria such as fault offset, growth fibres and secondary structures associated with faults (e.g., Petit 1987; Doblas 1998). The results of our structural investigations are synthesised in geological-structural maps and representative geological cross-sections (Figs. 3 and 4).

Finally, a remote sensing analysis of lineaments was carried out with the aim to define their geometry at the scale of the entire NA belt where the Epiligurian formations are exposed. We used the geo-referenced vectorial database of linear structural elements (WMS, WFS and WCS layers) provided by the Progetto CARG (CARtografia Geologica) and made available at the *minERva* portal (https://datacatalog.regione.emiliaromagna.it/(PortaleminERVA); last access March 2022). The remote sensing analysis was carried out for structures affecting both the pre- and post-Burdigalian formations through the Structural Data Integrated System Analyser provided within the DAISY 3 (v5.40) software (Salvini 2002).

Structural data

General structural setting

The Marzabotto Basin (Fig. 3a) is a geographically isolated basin that well preserves the entire Epiligurian succession between the underlying Ligurian Units and the overlying Intra-Apenninic Pliocene Domain (Fig. 3b). The Epiligurian formations are evenly distributed in the Marzabotto Basin, although they exhibit clear lateral variations of thickness across it.

The entire stratigraphy in the Marzabotto Basin dips between 20° and 40° monoclinally towards the NE, although the bedding locally dips to the WSW at low-to-very low angle (Fig. 3a). To the south of the basin, the pre-Burdigalian Epiligurian formations (e.g., the Baiso Fm and Loiano Fm) rest above the Ligurian Units through an erosional angular unconformity or through tectonic contacts. To the north, the post-Burdigalian formations (e.g., Pantano Fm, Cigarello Fm and Termina Fm) dip below the Pliocene Domain. In the central portion of the basin, the Ligurian Domain crops out as inliers between the Epiligurian formations, the boundaries between them being commonly controlled by high-angle faults showing variable orientations.

Tectonic structures directly influence the distribution of the Ligurian and Epiligurian sedimentary successions across the entire Marzabotto Basin. In particular, the stratigraphic-structural architecture of the basin suggests the presence of a transfer zone at basin scale with a general transport towards the NNE. This is also reflected in the lateral continuity of the lithological units, which commonly crop out as relics and isolated bodies (e.g., Baiso Fm, Marne di Monte Piano Fm and Ranzano Fm in Fig. 3), especially in the south and northeastern sectors of the area. In particular, the pre-Burdigalian Epiligurian formations exhibit a greater stratigraphic complexity and poor outcropping lateral continuity than the post-Burdigalian Fms. In addition, also the contact to the upper Pliocene Domain, which crops out only in the north-eastern portion of the Marzabotto Basin, reflects both a stratigraphic and tectonic component, with the former represented by an erosive angular unconformity and the latter connected with faulting along a right-lateral transfer zone, which caused the displacement of the Monte Rumici Fm to the SE (Fig. 3a).

The tectono-stratigraphic relationships between the pre- and post-Burdigalian Epiligurian formations within the Marzabotto Basin are analysed in detail in two representative areas both in plain and cross-section view (Fig. 4).

The Epiligurian formations contain the mutual intersection between variably oriented faults (striking from NNE-SSW to NNW-SSE, to WNW-ESE) to form a polygonal geometry in plain view. For example, a low angle NW–SE-striking and SW-dipping thrust juxtaposes the Baiso Fm against the Cigarello Fm in the western part of the investigated area (Fig. 4b). Moving to the E, the Epiligurian formations are affected by NNW-SSE and N-S-striking normal faults that dip either to the E or W, which cut and variably downthrow the basin infill with throws from a few decametres up to several hundred metres. The most significant extensional structure analysed in that area is a N-S-striking, W-dipping normal fault that juxtaposes the Pantano Fm against the Loiano Fm along the southeastern slope of Monte Pezza (Fig. 4a).

The eastern part of the geological section of Fig. 4b illustrates the hybrid nature of the contact between the Epiligurian formations and the Ligurian Domain below,
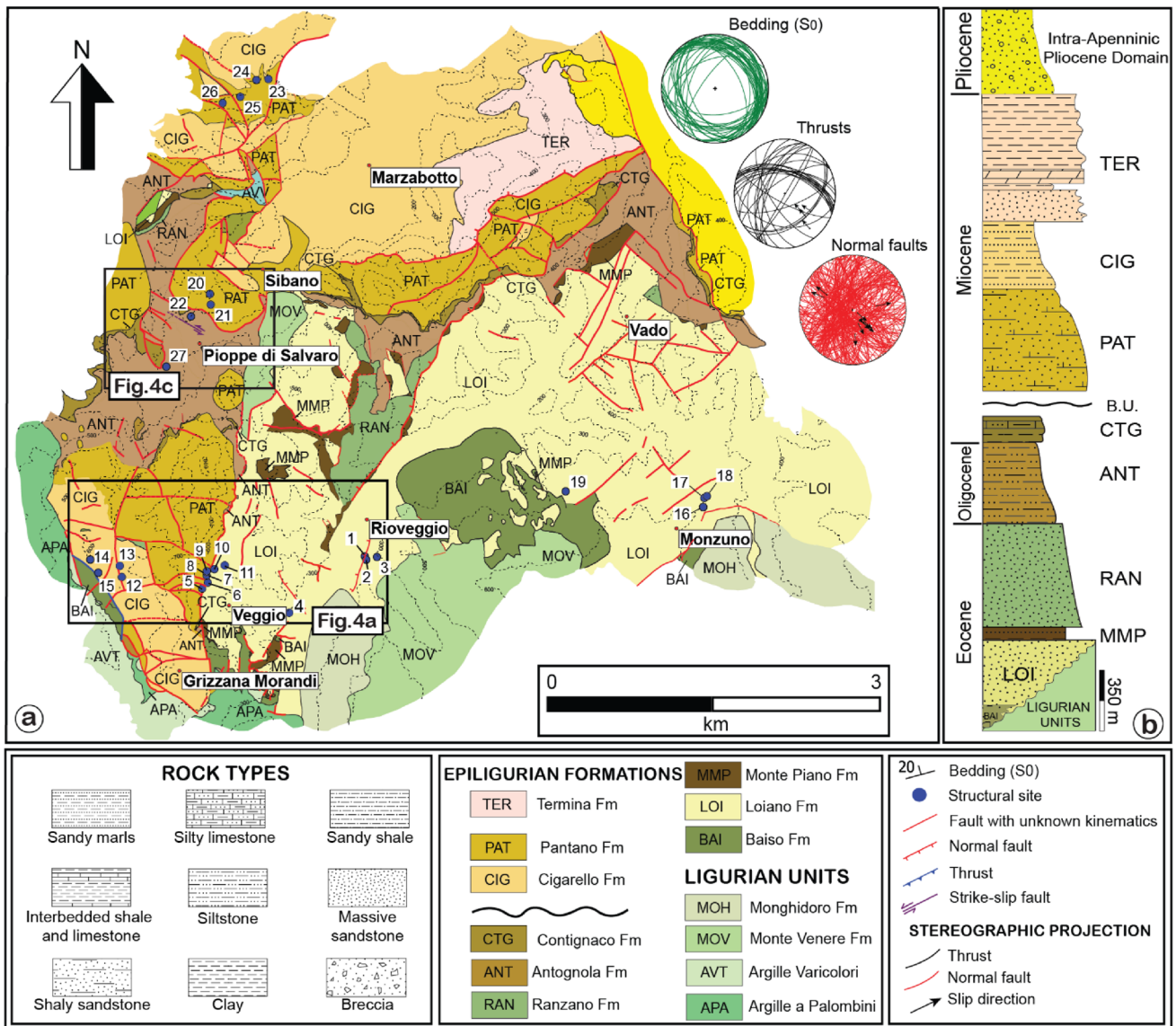
Fig. 3 **a** Structural map of the study area based on the geological map of the Emilia-Romagna Region website (https://datacatalog.regione.emilia-romagna.it/(PortaleminERva)). The inserts report the cumulative stereographic projections (Schmidt net, lower hemisphere pro-jection) of the main structural features (bedding, thrusts and normal faults). The area covered by the figure is shown in Fig. 2; **b** Stratigraphic column illustrating the Epiligurian formations defining the sedimentary succession in the Marzabotto Basin

which stems from both a stratigraphic and tectonic origin. In particular, the stratigraphic component is represented by an erosional unconformity between the Loiano Fm and the Monghidoro and Monte Venere Fm, while the structural aspect thereof relates to the contact between the Ranzano and Antognola Fms and the underlying Monte Venere Fm through a normal fault (Fig. 4b).

Figure 4c illustrates how high-angle faults control the lateral juxtaposition of pre-Burdigalian (Antognola and Contignaco Fms) and post-Burdigalian (Pantano and Cigarello Fms) formations. In particular, from the SW to the NE, the Antognola Fm is affected by NW–SE-striking

and NE-dipping high angle normal faults while, moving to the NE, it is cut by a NW-SE-striking left-lateral fault that displaces the pre-Burdigalian Epiligurian formations towards the north-western sectors of the basin (Fig. 4d). In the north-eastern part of the basin, the Epiligurian succession is affected by a NW–SE and NE-dipping normal fault, which puts in contact the Cigarello Fm in the hanging wall with the Pantano Fm in the footwall (Fig. 4d), thus downthrowing the succession towards the NE (Fig. 4c).

The Contignaco Fm crops out as lensoidal bodies, with a significant lateral variation of thickness below the Pantano Fm due to the presence of the erosional Burdigalian
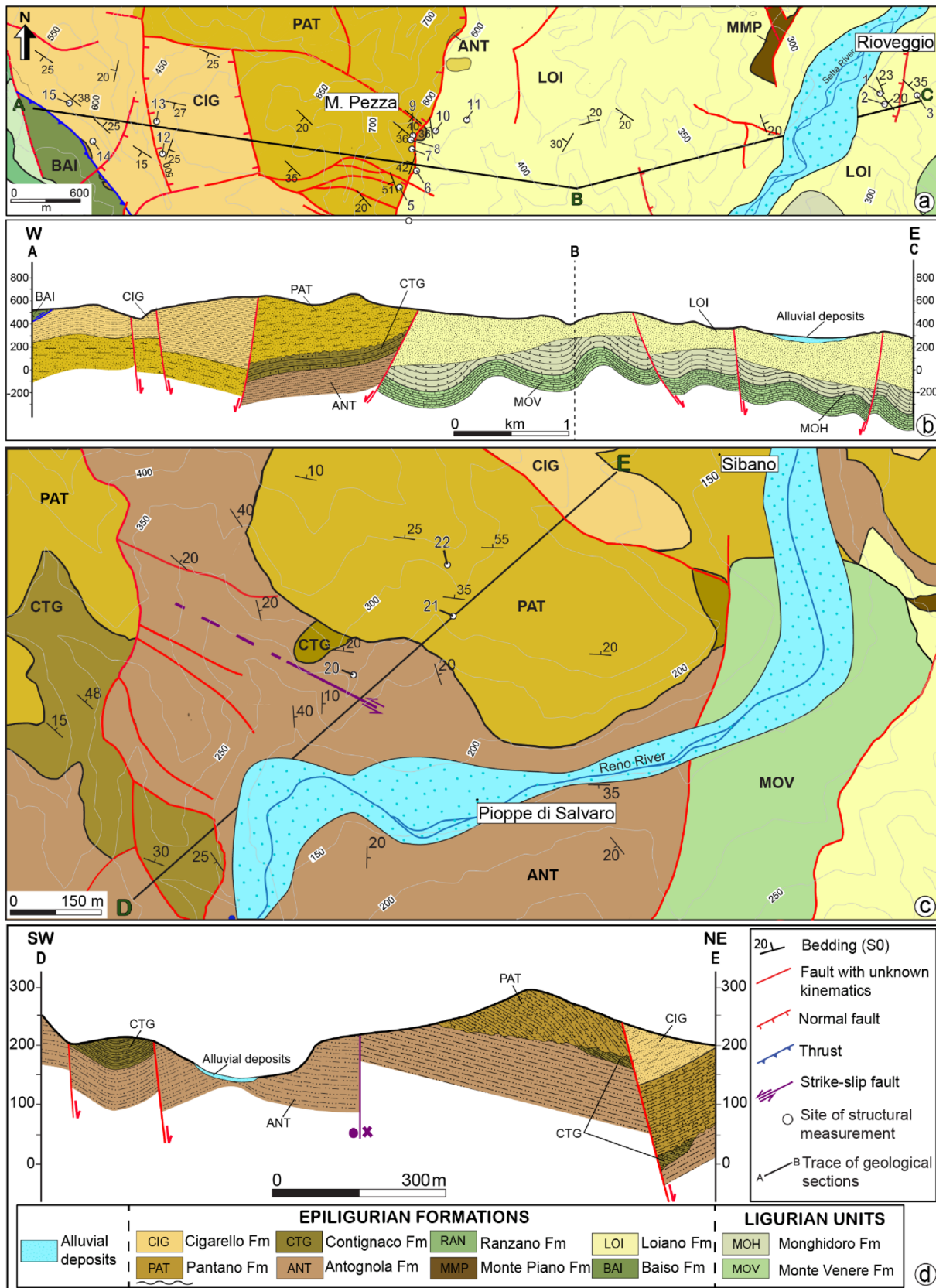
Fig. 4 **a**, **c** Zoom onto the central/southern and northwestern areas of the Marzabotto Basin; **b**, **d** Geological cross-sections representing the main structural relationships between pre-and post-Burdigalian Epiligurian formations

unconformity as shown in the geological section of Fig. 4d.

Between Pioppe di Salvaro to the south and Sibano to the north (Fig. 4c), the tectonic contact between the pre-Burdigalian Antognola Fm and the Ligurian Monte Venere Fm (Figs. 3a and 4c) reflects the NNE-SSW-striking Reno Line, which is ascribable to the left-lateral transcurrent tectonic event mentioned above.

All the mentioned different tectonic structures have been studied and characterised according to their position with the Epiligurian stratigraphy and are reported accordingly (Fig. 5). They have been sorted in homogeneous and presumably coeval kinematic/faulting classes and are described below.

Tectonic structures analysed in pre-Burdigalian Epiligurian formations

Within the pre-Burdigalian formations (e.g., Loiano and Antognola Fm; structural stops $n°$ 1–3, 16–18, 20–23 in Fig. 3a) we observed: (i) reverse, (ii) normal and (iii) strike-slip faults (Figs. 5, 6, 7). Due to the granular and porous character of the deformed rock types, deformation bands (DBs) are very common and, as such, have also been systematically investigated (Fig. 7).

It is not uncommon to find both reverse and normal faults at the same outcrop, which makes it possible to study in detail their cross-cutting relationships (Fig. 6a). Thrusts consist of NNE-SSW-striking and moderately WNW-dipping single slip surfaces associated with cataclastic layers and fractured damage zones (Fig. 6b). Fault surfaces have a general planar morphology and decametre persistence at the outcrop. They locally contain preserved slickensided surfaces, mostly with abrasion striae (Fig. 6c). Slickenlines exhibit pitch values of c. 30°, indicating an oblique component of slip (Fig. 5 and 6a). The analysis of kinematic indicators such as stratigraphic offset, dragging of bedding into fault surfaces and Riedel shears, indicate top-to-the NE thrusting (Fig. 6b–c).

Normal faults strike either NE-SW or NW–SE and dip to the SW, NE or NW at a relatively high angle (average dip: 73°) or even vertically (Figs. 5 and 6a). They consist
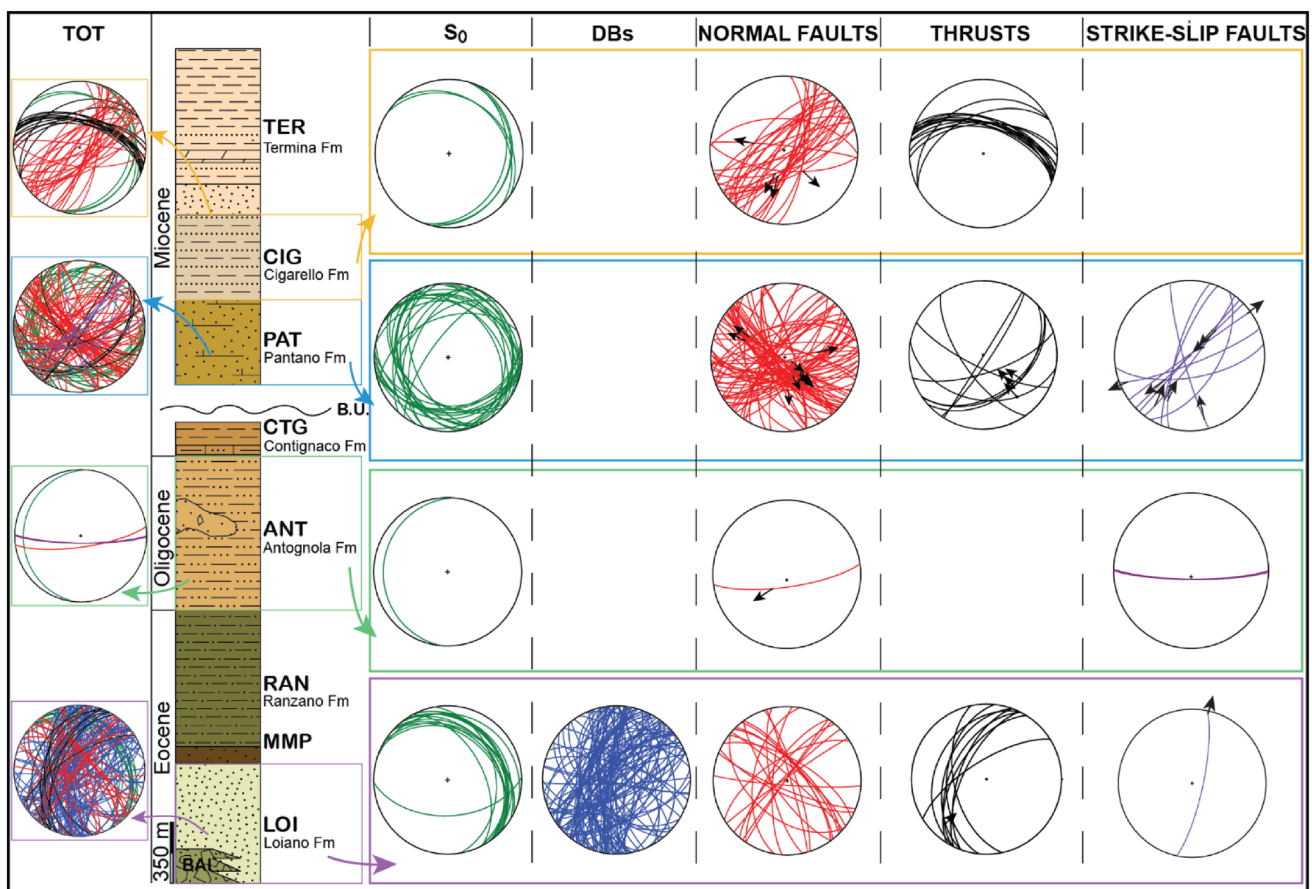

Fig. 5 Stereographic projections (Schmidt net, lower hemisphere projection) of bedding and faults sorted according to their kinematics and stratigraphic position
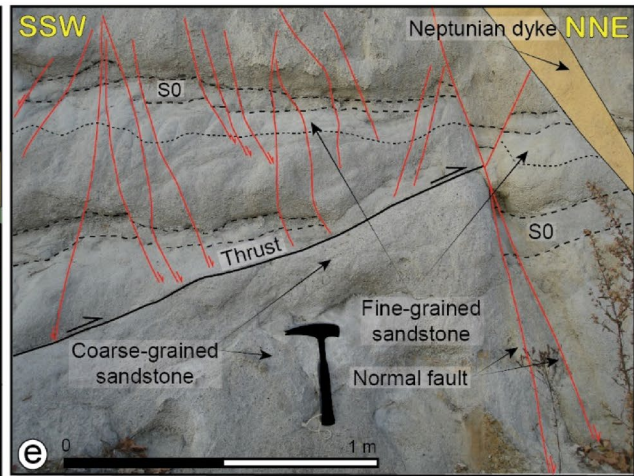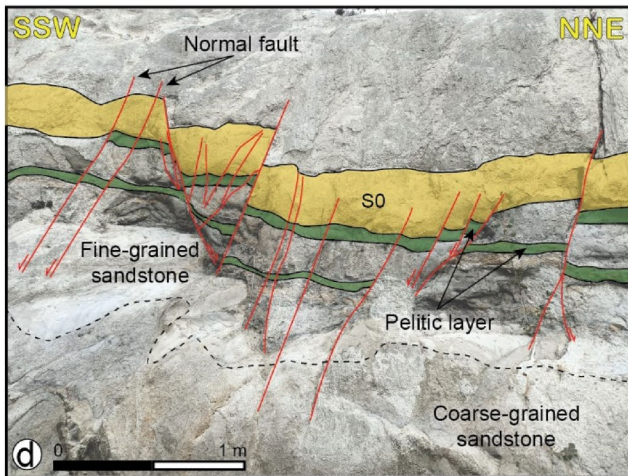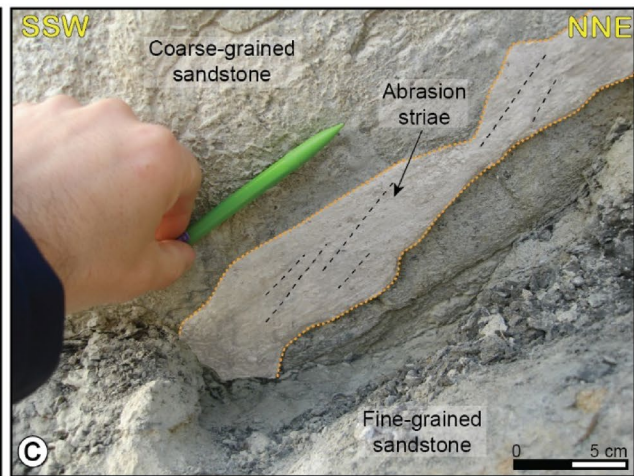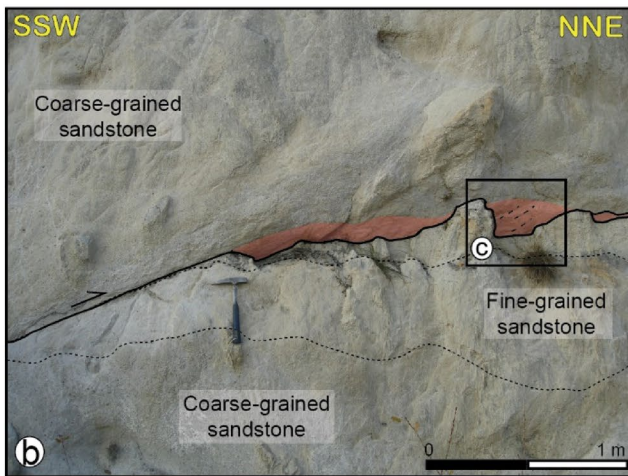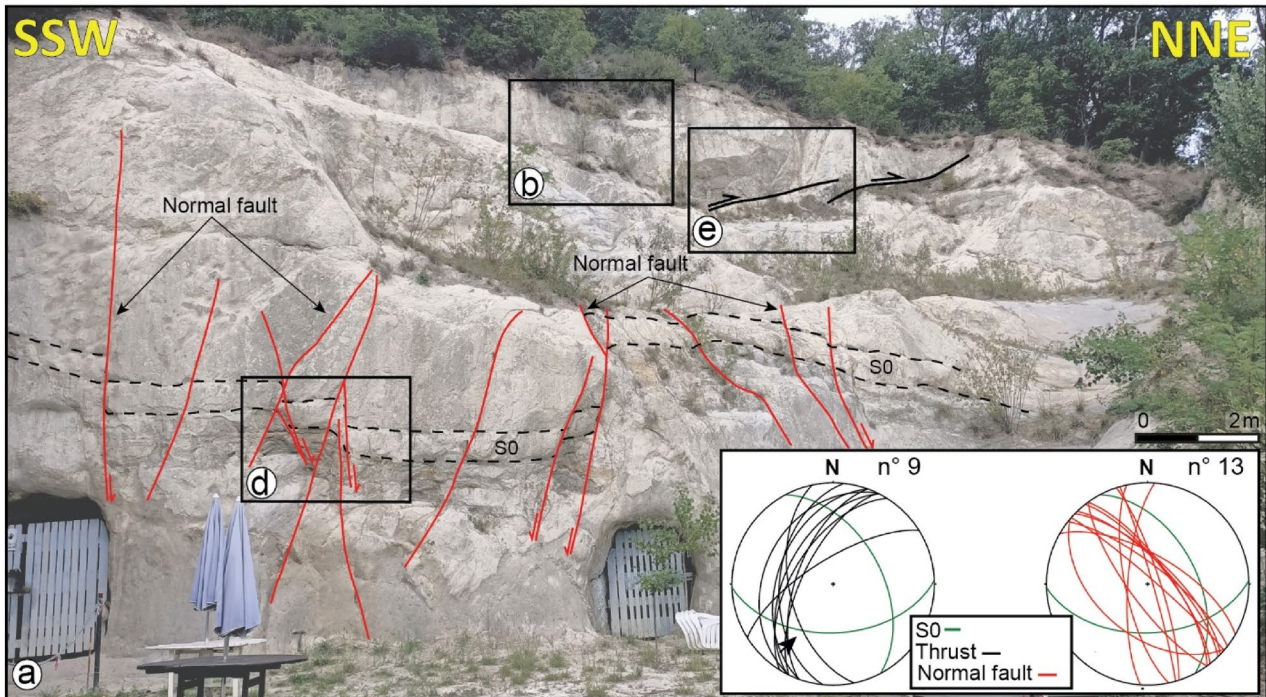
◄**Fig. 6 a** Loiano Fm outcrop located in the central/southern part of the study area. **b** SSW-dipping reverse fault plane with a gently dipping planar morphology decorated by abrasion striae **c**, indicating top-to-the NNE tectonic transport; **d** Normal faults cut across coarse-grained sandstone beds (S0) with a centimetric to decametric offset; **e** SSW-dipping reverse fault with an oblique component (black solid line) cut by a NNE-dipping normal fault

of decametric isolated slip segments without appreciable damage zones. At the outcrop, NW–SE normal faults have a general planar to gently curvilinear geometry, cross-cut bedding at high angle and accommodate centimetric to decametric offsets (Fig. 6d). The analysis of the stratigraphic offset, together with the occurrence of synthetic shear fractures, attests to a normal-sense kinematics (Fig. 6d and e). Cross-cutting relationships document that normal faults systematically cut and displace the aforementioned thrusts (Fig. 6a, e), thus providing evidence for a relative chronology of faulting.

In the southern part of the Marzabotto Basin, the resedimented course- to fine-grained arkosic sandstone of the Loiano Fm is affected by normal faults with a complex structural architecture represented by the occurrence of deformation bands (see also Antonellini and Mollema 2002; Del Sole et al. 2020; Fig. 7a, b). Deformation bands occur as either single structures or in clusters. They mainly strike NNE-SSW (average attitude: 225°), and, subordinately, WNW-ESE (average attitude: 334°; see stereographic projection in Fig. 5). The dip angle of the deformation bands is generally medium–high (average 70°). They deform and cut across the bedding accommodating offsets between a few mm to 1 m (Fig. 7c, d). When approaching the main fault surfaces from an undeformed block, one can appreciate how deformation bands (i) tend to group into metre-thick deformation zones, (ii) systematically have their spacing decreasing from 1 m to 1–5 cm, and (iii) accommodate increasing cumulative offset from a few millimetres to half a metre (Fig. 7a–e).

Strike-slip faults consist of single structures having generally a planar geometry and decametric persistence. They mostly strike NNE-SSW (strike attitude: 026°) and dip at high angle (average dip: 77°) to the ESE (Fig. 5). Kinematic criteria were defined based on the persistence of associated second-order fractures (pitch: 010°) and shears (R, R' and T fractures) and they indicate dominant right-lateral kinematics for the WNW-ESE-striking segments.

Tectonic structures analysed in post-Burdigalian Epiligurian formations

Reverse, normal and strike-slip faults cut across the post-Burdigalian formations (e.g., Pantano and Cigarello Fms; structural sites *n*° 5–15, 20–27 in Fig. 3a).

Thrusts (Figs. 8a, b and 9a) include both WNW-ESE and NE-SW-striking slip surfaces dipping either to the NE or SE, respectively, at a relatively high angle (average dip: 64°).

Those dipping to the NE consist of a main slip surface, with a gently curvilinear morphology associated with a well-developed damage zone, with a thickness of 20–30 cm (Fig. 8c) that is instead missing along fault planes dipping to the SE. Within the damage zones, there occur sigmoidal lithons of dismembered finer arenaceous beds, the asymmetry of which has been used to constrain an overall top-to-the NW sense of shear (Fig. 8c). Reverse fault planes are commonly associated with slickensides and slickenlines (Fig. 9b) with pitch values between 48° and 82° (see stereographic projections in Fig. 5). Within the damage zones, there locally occur white, altered sandy injections parallel to and along the slip surfaces, side by side with cm-thick fault breccia (Fig. 8c).

Normal faults dip steeply (average dip ~ 68°) to vertical and strike from NW–SE to NE-SW (average attitude: 284° and 42° see stereographic projections in Fig. 5). At the outcrop, fault surfaces are generally several meter long, have a smooth to planar morphology and bear slickenlines with pitch between 70° and 85° (Fig. 5). These normal faults cut across and displace with decametric to metric offset the thrusts described above (Fig. 8b, e). These faults are locally characterised by decimetre-thick damage zones filled by altered white sandy injections and lenses of fault breccia (Fig. 8d). Normal faults are locally associated with vertical, NE-SW-striking calcite veins formed during extension (Fig. 8f).

Finally, NNE-SSW-striking (average attitude: 202°) strike-slip fault planes, dipping either to WNW or ESE, are associated with WNW-ESE-striking normal faults (Fig. 9c).

These minor structures are characterised by planar slip surfaces bearing slickenlines and slickensides (Fig. 9d) with pitch values between 15° and 35° (see stereographic projection in Fig. 5). Criteria kinematic analysis based on R-shears and T fractures suggests a dominant left-lateral kinematics for the NNE-SSW-striking strike-slip faults.

Lineament analysis

Lineaments affecting all the Epiligurian Basins in the area between Bologna and Parma (Figs. 1a and 10) have been remotely sensed and classified in terms of pre- or post-Burdigalian age in relation to the mapped stratigraphic units. We acknowledge that the lineaments mapped within the either pre- or post-Burdigalian Epiligurian formations do not necessarily have an age corresponding to these periods of time. However, we use them to discriminate the structural patterns that affect only part of the whole Epiligurian sedimentary succession. Structures affecting the oldest formations
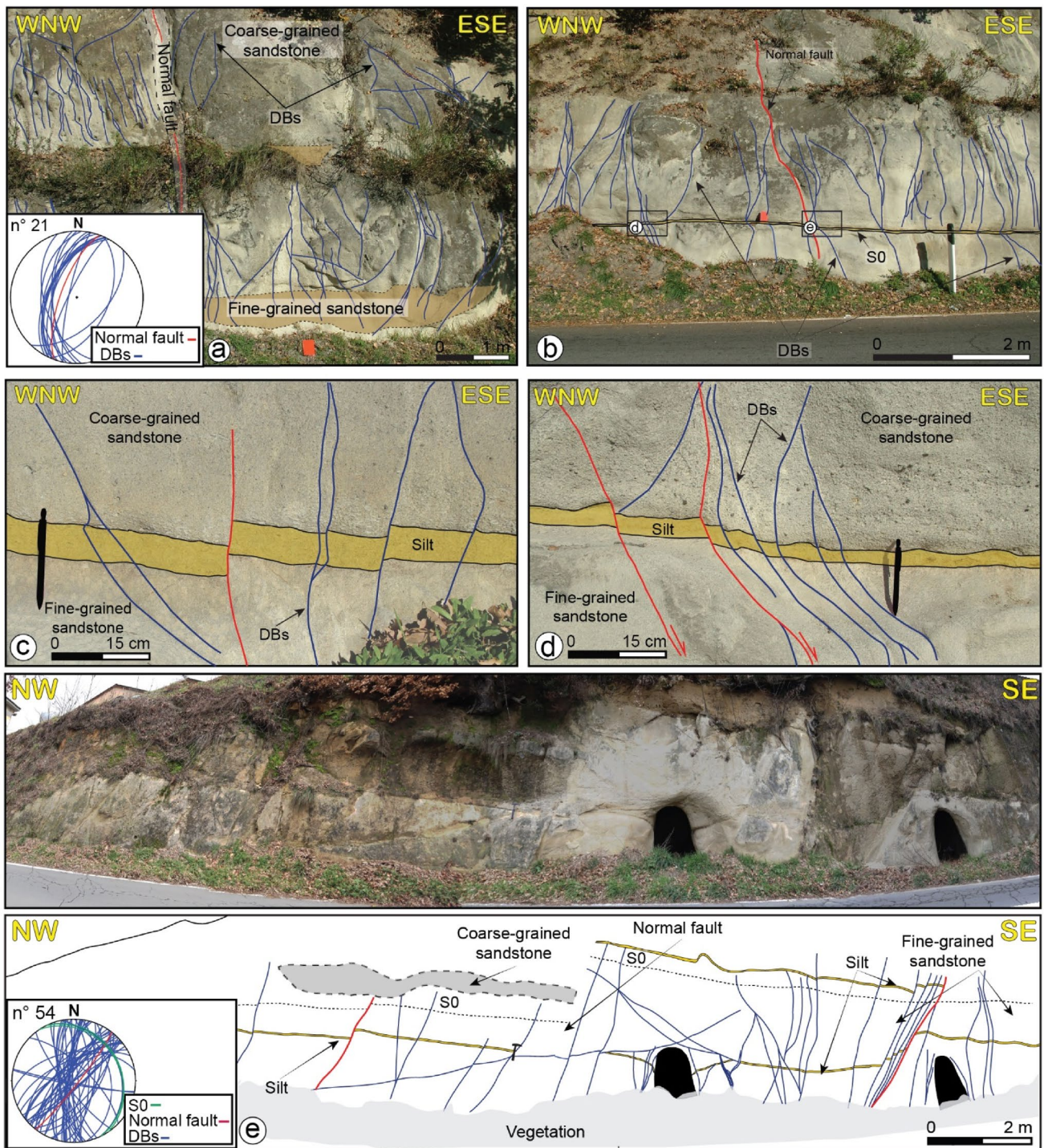
Fig. 7 **a**, **b**, **e** Loiano Fm outcrops located in the central part of the study area where WNW and ESE-dipping DBs (blue solid lines) occur as both single bands and clusters. The coalescence of DBs develops fault zones with a well-defined main slip surface (red solid lines); **c**, **d** DBs deform and cut the bedding represented by a silty-sandy level of about 3–5 cm thick, accommodating variable offsets (from a few mm to 1 m)

(e.g., pre-Burdigalian) and not occurring in the youngest ones (e.g., post-Burdigalian) can be considered a threshold for constraining the variation of orientation and density of tectonic lineaments as a function of the affected Epiligurian

sedimentary succession. This allows us to individuate temporal constraints on changes in faulting regime at the scale of the distribution of the Epiligurian basins along the Northern Apennines.
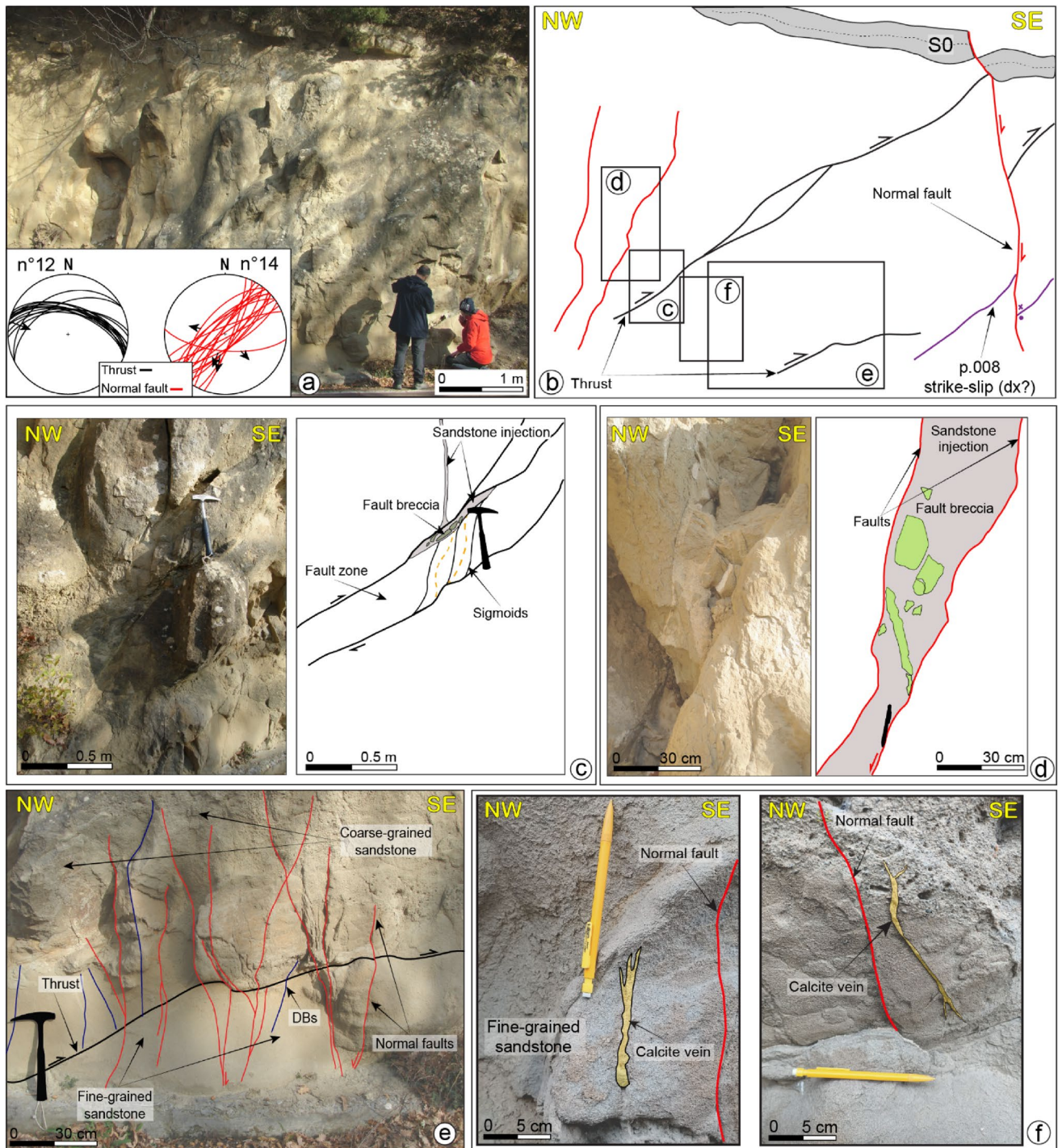
Fig. 8 **a** Cigarello Fm outcrop located in the south-eastern part of the study area. **b** NW-dipping thrusts cut by a SE-dipping normal fault, characterised by a sigmoidal lens shape damage zone; **c** Zoom of the NW-dipping reverse fault with a white-coloured sandstone injection; **d** Fault breccia and sandstone injection in the damage zone of a NW-dipping normal fault; **e** Cross-cutting relationship between reverse and normal faults viewed at a smaller scale; **f** Calcite veins associated with extension
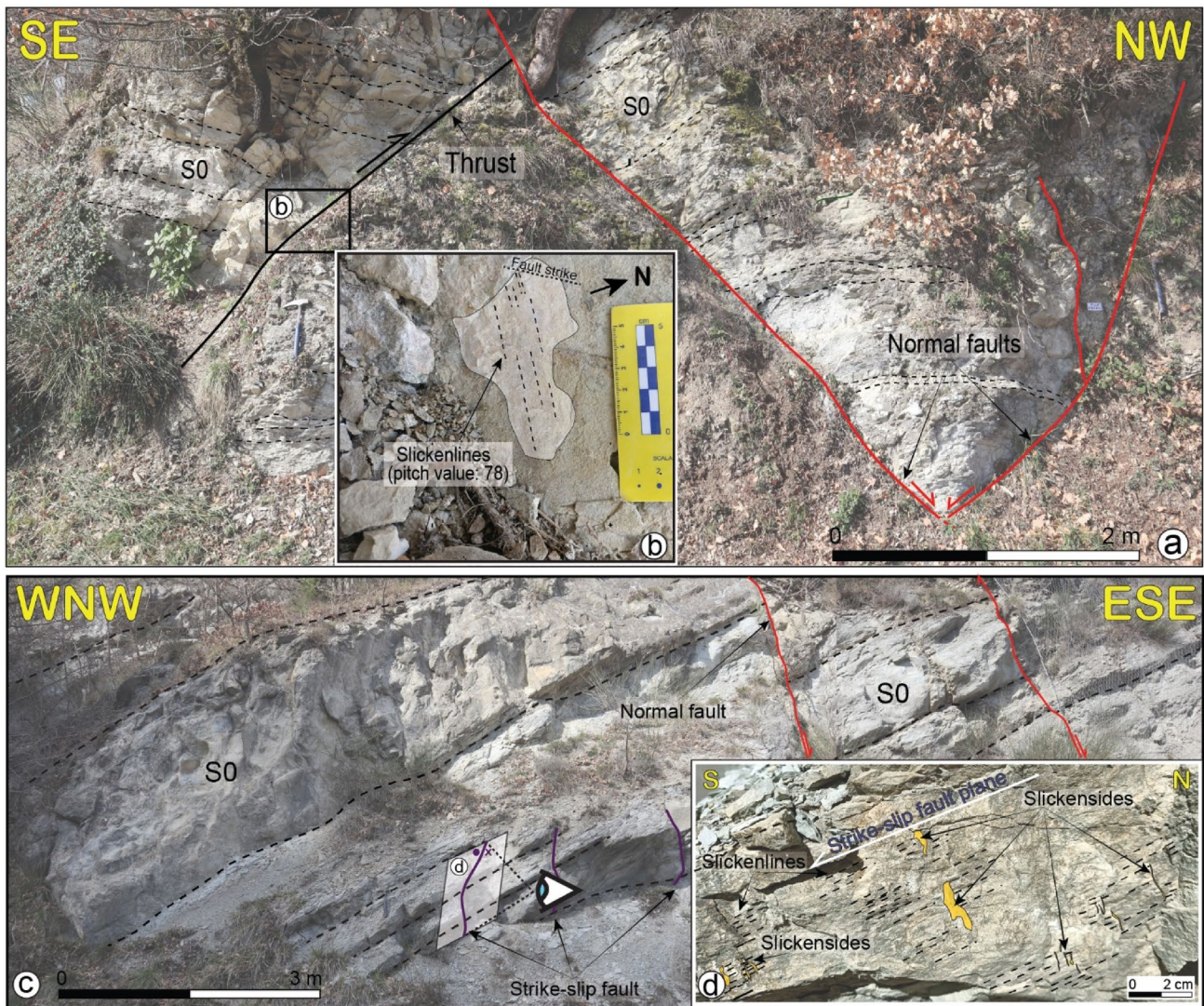
Fig. 9 **a** Pantano Fm in the central part of the study area deformed by a SE-dipping, top-to-the NW reverse fault and by NW and SE-dipping normal faults; **b** The reverse fault plane hosts clear slickenlines; **c** Pantano Fm cut and deformed by an ESE-dipping normal fault that cuts the bedding with a metric offset, associated with NNE-SSW-striking and WNW and ESE-dipping strike-slip fault planes characterised by almost planar slip surfaces bearing slickenlines and slickensides (**d**)

Our database was then additionally sorted according to the kinematics of the lineaments into (i) normal faults, (ii) thrusts, (iii) strike-slip faults (without a defined sense of movement) and (iv) undefined faults, i.e., faults without a clear kinematics (Table 1).

To better understand the implications of the analysis of those lineaments, results are reported in here by describing separately lineaments occurring in pre- or post-Burdigalian units belonging to: (i) the Marzabotto Basin; (ii) other Epiligurian basins (remote and fieldwork data). For the comparison between structural elements, only normal faults and thrusts have been considered. A comparison is also made between lineaments mapped remotely in all Epiligurian Basins and fieldwork data from the Marzabotto Basin (Fig. 11).

Lineaments mapped in pre-Burdigalian Epiligurian formations

Normal faults are characterised by a preferred NE-SW strike for both the field data and remote sensing data, while thrusts strike NE-SW when constrained in the field and NW–SE when remotely sensed (Fig. 11).
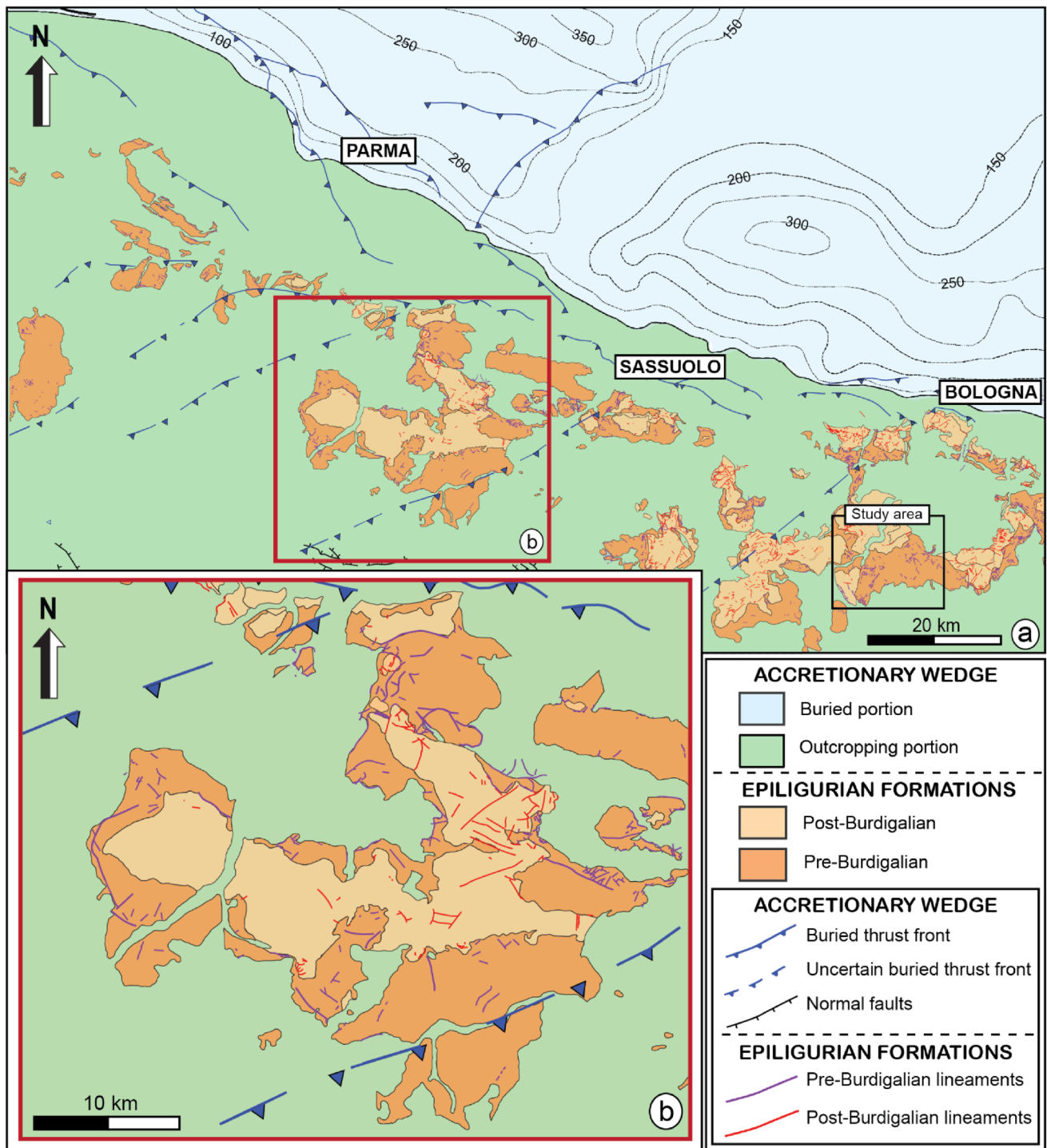
Fig. 10 **a** Simplified geological map cantered on the structural lineaments cropping out in either pre- or post- Burdigalian Epiligurian Basins located in the area between Bologna to the SE and Parma to the NW. The study area is represented by the black square in the south-eastern portion of the map; **b** Zoom of an example of an Epiligurian Basin located in the NW sector respect to the study area

The analysis of strike-slip faults is not complete because of the lack of field data in the pre-Burdigalian succession. However, these tectonic structures are characterised by a dominant NW–SE direction in the remote sensing dataset.

Lineaments mapped in post-Burdigalian Epiligurian formations

Normal faults are characterised by a different orientation

Table 1 Summary of the tectonic structures considered by the remote sensing analysis subdivided according to their kinematics and their occurrence in either pre- or post-Burdigalian Epiligurian formations (see Fig. 10)

Occurrence	Kinematics	n°
Pre-Burdigalian formations	Normal faults	21
	Thrusts	358
	Strike-slip faults	30
	Undefined faults	3989
Post-Burdigalian formations	Normal faults	81
	Thrusts	121
	Strike-slip faults	18
	Undefined faults	2735

for the different analysed datasets (NE-SW for the field-work data and NW–SE for the remote sensing data), while thrusts show a preferred NW–SE orientation for both datasets (Fig. 11).

Remotely mapped sinistral strike-slip faults strike NE-SW, in agreement with what has been mapped in the field but in contrast with the same faults mapped in the pre-Burdigalian units.

Discussion

Structural synthesis

The structural constraints derived from the Marzabotto Basin, integrated with other published data from field studies (Ottria 2000; Antonellini and Mollema 2002; Balocchi and Santagata 2018), a re-interpretation of the available geological maps (Panini et al. 2002; Balocchi 2014; Piazza et al. 2016), and results from our remote lineaments analysis, are used here to propose a model accounting for the local tectonic history as recorded by the Epiligurian basins during the syn- to post-orogenic evolution of the Northern Apennines (e.g., Boccaletti et al. 1985; Carmignani et al. 1995; Conti et al. 2020; Mantovani et al. 2019). Both the pre- and post-Burdigalian Epiligurian successions exhibit a tectonic history characterised by similar structural features and structural style, despite an important change of structure orientation that will be discussed farther down in this chapter.

Thrusts strike heterogeneously in the mapped area and they indicate both NE-SW and NW–SE shortening of the entire Epiligurian succession, as we could conclude also by lineament remote sensing analysis. This combined approach shows that the NW–SE-striking set is well recognisable for both the pre- and the post-Burdigalian succession. When discriminating the thrusts on the basis of their development with respect to the Burdigalian unconformity, we can say that the tectonic structures affecting the upper Lutetian

Loiano Fm may probably be ascribed to the lower Oligocene to lower Miocene tectonic phase documented in two other Epiligurian basins located in the axial and in the frontal portion of the outcropping NA belt, where contractional deformation structures have been recognised within the sediments of Bartonian-Aquitanian age (Ottria 2000; Balocchi and Santagata 2018). However, lineament analysis shows that there is no correspondence between the orientations from the remote sensing analysis and those measured in the field. This is probably due to the different number of faults measured in the field compared to those in the regional dataset, the latter stemming from all the Epiligurian Basins and not only to the Marzabotto Basin. On the other hand, the NE-SW and WNW-ESE thrusts mapped within the post-Burdigalian units can be tentatively correlated with the post-Messinian compressional tectonic phase that controlled the juxtaposition of tectonic slices of Ligurian Units on top of Epiligurian formations (Panini et al. 2002; Figs. 3a and 4a, b).

A strike-slip tectonic phase affected the Epiligurian formations after the shortening phase. The associated structures consist of NE-SW-striking, left-lateral faults that run through the entire sedimentary succession, leading to the lateral juxtaposition of Ligurian and Epiligurian formations along the Rioveggio, Reno and Luminasio Faults (Panini et al. 2002; Fig. 2b). A comparison between the lineaments mapped remotely and field data is not possible because we do not have sufficient structural data to generate a statistically meaningful picture.

Extensional structures are rather pervasive in the entire Epiligurian succession, cutting and displacing the thrusts described above. We recognised three main sets of extensional structures as a function of their main strike and geometrical-structural properties (length, offset, thickness of damage zone, associated features):

(a) Longitudinal (i.e., Apennines-oriented) normal faults consisting of high angle structures characterised by small (intraformational or intra-Epiligurian) stratigraphic offset. At the outcrop, they exhibit a curvilinear geometry, metre-to-decametre persistence and whitish alteration surfaces. They are barren of mineralised shear planes or thick damage zones. At the Marzabotto Basin scale, these mapped normal faults resemble the orientation and the kinematics of the Loiano-Venola and Calvenzano Faults that systematically determine the lowering of the succession towards the north-eastern sectors of the outcropping belt (Panini et al. 2002; Figs. 2b and 3a). Concerning their relationship with the remote sensing analysis of lineaments, these longitudinal normal faults correspond to the second-order class of structures reported on the rose diagrams shown in Fig. 11, showing a strike orientation of about NNW-SSE and WNW-ESE.

(b) Transverse normal faults oriented approximately NNE-SSW (i.e., Antiapennines) and that can be mapped both at the outcrop (metric persistence) and basin-scale (length greater than 1 km). These are tectonic structures recognised in the entire Marzabotto Basin that cause significant offsets within the Epiligurian formations of up to several kilometres and rework the early juxtaposition between the Ligurian and the Epiligurian formations. The structures consist of architecturally complex faults, with fairly planar morphologies and mineralised shear planes characterised by calcite veins from a few millimetres to a few centimetres thick. Within pre-Burdigalian formations (i.e., the Loiano Fm), normal fault planes are commonly associated with deformation bands that developed either as single, isolated planes or resulted from the progressive localisation of slip after clustering of these brittle structures. This set of normal faults corresponds to the structures that reactivated the Rioveggio, Reno, Vergato Faults (Fig. 2b) in the Marzabotto Basin and, at the scale of the other Epiligurian basins, the Rupelian-Serravallian left-lateral faults. At the regional scale, these extensional tectonic structures might be correlated with the NNE-SSW-striking normal faults that affect the frontal part of the outcropping belt (i.e., at the southern edge of the Po Plain) deformed by fold systems with WNW-ESE axis (Martelli et al. 2017). Lineament remote analysis indicates that these tectonic structures are characterised by strike values compatible with the main and most statistically significant class shown in the rose diagrams in Fig. 11.

Moreover, the membership classes of the tectonic structures mapped in the field described above and the lineaments extracted from the remote sensing analysis are confirmed by the cross-cutting relationship between them, which can be compared to the existing intersection between the Rioveggio, Reno and Vergato Faults with the Loiano-Venola and Grizzana Morandi Faults.

c) The third group of normal faults is characterised by a wide range of strike values and mutual intersection relationships. These normal faults are common along the eastern and western edges of the Marzabotto Basin (Fig. 3a and 4). They show a greater spacing than the NE-SW-striking faults with deformation bands but are also more closely spaced with respect to faults with antiapenninic trends. Faults of this third group are also characterised by a planar geometry, short trace lengths and, at times, negligible offsets (they are mostly intraformational). In map view, these normal faults define a non-systematic, polygonal architecture (e.g., Cartwright et al. 2003; Petracchini et al. 2015), suggesting a shallow, gravity-driven tectonic origin. We tentatively connect the formation of these structures with a stress field variation through time that would have occurred in response to a local change in slope gradient, faulting along active tectonic structures or the influence of local tectonic stresses (e.g., Cartwright et al. 2003) triggering gravity-driven deformation mostly within the shallower portions of the Marzabotto Basin. The relationships between these faults and the lineaments mapped by remote sensing analysis remain rather uncertain. This could be due to the different scale of data acquisition, which is smaller for field structural analysis. However, this group of normal faults could be related to the less representative classes of the rose diagram reported in Fig. 11, which are arranged orthogonally to each other, confirming the highly variable trend distribution of these structures.

The significance of the Epiligurian formations within the evolution of the Northern Apennines accretionary wedge

Previous tectonic models relate the formation of wedge-top basins, the accommodation of sediments therein, and the development of unconformities to the interplay between subsidence (as due to the regional load) and the regional-to-local uplift of the accretionary wedge due to underplating and crustal thickening in the framework of its dynamic evolution (e.g., Beaumont 1981; Jordan 1981; Ori and Friend 1984; Bally et al. 1985; De Celles and Giles 1996; Mutti et al. 2003). In this perspective, the Epiligurian wedge-top basins are key geological elements to refine conceptual models that account for the syn- to post-orogenic history of the Northern Apennines accretionary wedge since the middle-late Eocene. Our structural dataset documents the structuring of the Epiligurian formations during the evolution of the entire foreland basin system framed within the dynamics of a critically tapered orogenic wedge, where the activation, geometry, and cross-cutting relationships of both thrusts and extensional faults, concomitant with sedimentation and erosion, are key to the unravelling of the internal architecture of the growing wedge (e.g., Dahlen 1990; Willet 1992; Zoetemeijer et al. 1993).

The starting configuration is represented by the Late Cretaceous-Paleocene growth of the NA accretionary wedge by bulk shortening, thickening and piling of tectonic slices scraped off from the subducting Ligurian-Piedmont Ocean plate and underplated at the bottom of the wedge (e.g., Marroni et al. 2002; Remitti et al. 2011; Vannucchi et al. 2012; Papeschi et al. 2022). The nappe stack of the Ligurian Domain represents the most internal (i.e., westernmost) paleoenvironment of the entire foreland basin system accommodating heterogeneous subsidence and sedimentation. Since the late Eocene (stage I in Fig. 12a), the depozones atop the Ligurian Domain were filled by sediments accumulated on top of inactive thrusts, leading to the formation of
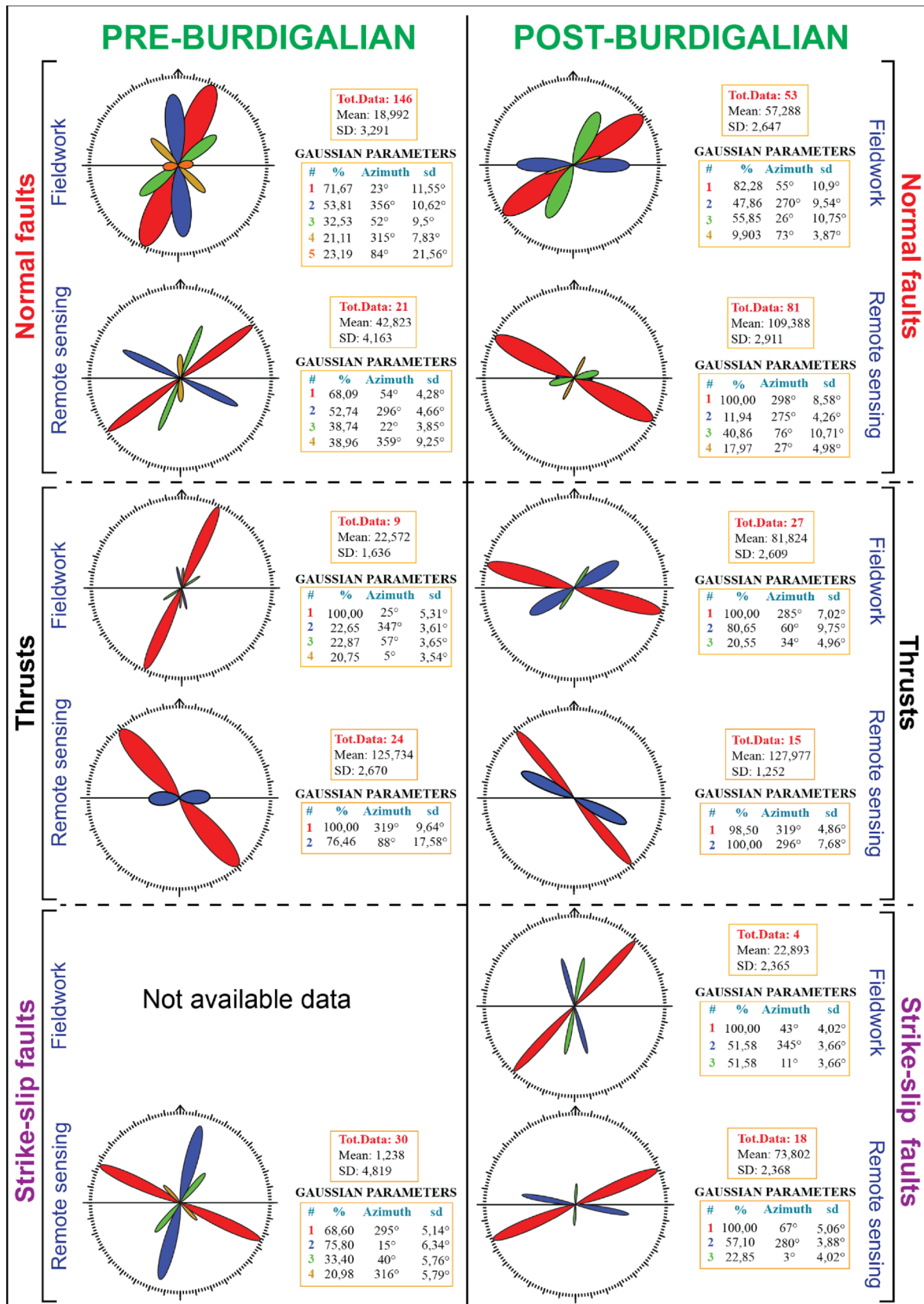
the Epiligurian wedge-top basins. At this stage, lateral thickness variations and local interdigitations within the Epiligurian basins occurred in response to alternating phases of turbiditic deposition and cessation of sedimentation, marked by the occurrence of second-order angular unconformities within the basal stratigraphic succession (e.g., Cibin et al. 2001; Barbero et al. 2017).

During the pre-Burdigalian Epiligurian deposition (stage II in Fig. 12a), the accretionary wedge and the wedge top basins became progressively involved in the build-up and uplift of the evolving fold-and-thrust belt. We attribute this evolutionary stage of shortening from accretionary wedge to fold-and-thrust belt in NA to the progression of the Europe-Adria continental collision (e.g., Faccenna et al. 2001; Doglioni et al. 2006). At this stage, active compressional deformation induced both foreland-ward propagation of thrust fronts and reactivation of internal (and deeper) thrusts at the wedge toe to produce a stable wedge configuration. The development of syn-orogenic thrusts since the upper Lutetian affected the base of the sedimentary succession. This tectonic phase was interrupted by a marine regression documented by the presence of the regional Burdigalian angular unconformity, which developed in response to the uplift of the wedge concomitant with an abrupt change in the sedimentation pattern (e.g., Amorosi 1995).

After the Burdigalian (stage III in Fig. 12a), the evolving fold-and-thrust belt was being deformed by folding and general tilting toward the hinterland and was affected by in-sequence and out-of-sequence thrusting. Wedge-top basins were thus deformed by active thrust sheets and were eroded and/or uplifted in response to thrusting. Our structural data, coupled with insights from published works (Catanzariti et al. 1999; Ottria 2000; Panini et al. 2002; Balocchi and Santagata 2018) document that the shortening direction fluctuated from NE-SW to NW–SE in the entire Epiligurian succession. Since the upper Burdigalian, the former syn-orogenic thrusts activated with different trend distribution, probably reflecting the concomitant activity of in-sequence and out-of-sequence thrusts. We thus propose that the post-Burdigalian Epiligurian formations probably started to form under supercritical taper conditions before thrusts nucleated and propagated toward the foreland to restore a critical taper (e.g., DeCelles and Mitra 1995; Mitra 1997).

The post-orogenic extensional phase that started to affect the Tyrrhenian side of the NA and then migrated to its northernmost uplifted margin (e.g., Martini and Sagri 1993; Bertotti et al. 1997; Barchi et al. 2006), led to the normal-sense reactivation of inherited (mostly strike-slip) structures and the activation of newly formed normal faults. These post-orogenic normal faults cut and down-throw the earlier thrusts, affecting the whole sedimentary succession. The activation of normal fault systems adjusted the structural architecture of the upper portion of the belt and operated to reduce the taper angle to finally achieve the critical configuration. This tectonic phase included widespread gravity-driven deformation, which is documented by short, non-systematic, polygonal faults developed within the uppermost sequence of the Epiligurian formations and probably reflecting structural adjustments to local taper instability conditions (Fig. 12b).

In conclusion, our results suggest that a polyphase tectonic evolution has affected the Epiligurian formations during the progressive growth of the NA accretionary wedge by frontal accretion, its progressive involvement in the fold-and-thrust belt and the successive switch from a syn- to a post-orogenic phase. Within this evolutionary scenario, three distinct types of tectonic structures have been recognised in the Marzabotto Basin as being characterised by different kinematic and geometric properties and timing (Fig. 12b): (i) syn-orogenic, NNE-SSW and WNW-ESE-striking thrusts with a transport direction towards the north-eastern quadrants; (ii) post-orogenic, NW–SE-striking normal faults connected with an extensional tectonic regime affecting the inner and the axial zone of the NA and partly reactivating earlier left-lateral strike-slip structures connected with the thrust zones; (iii) post-orogenic, collapse-induced faults that are related to the local variation of the wedge configuration and that connect, and partly cut, the early normal faults to form a polygonal architecture.

Conclusions

The wedge-top Epiligurian basins of the Apennines in northern Italy allow us to document the progressive deformation that steered the evolution of the shallowest structural levels of the Northern Apennines accretionary wedge during its syn- to post-orogenic evolution. The Epiligurian formations record a polyphasic tectonic history accommodating significant changes in stress field orientation and faulting regime in the pre- and post-Burdigalian period. The kinematics, geometry and cross-cutting relationships of the main tectonic structures reflect the interaction between regional and local tectonic stress conditions that steered the stratigraphic configuration of the Epiligurian formations through time and space. In particular, the mesostructural characteristics of these wedge-top basins suggest that the axial domain of the Northern Apennines
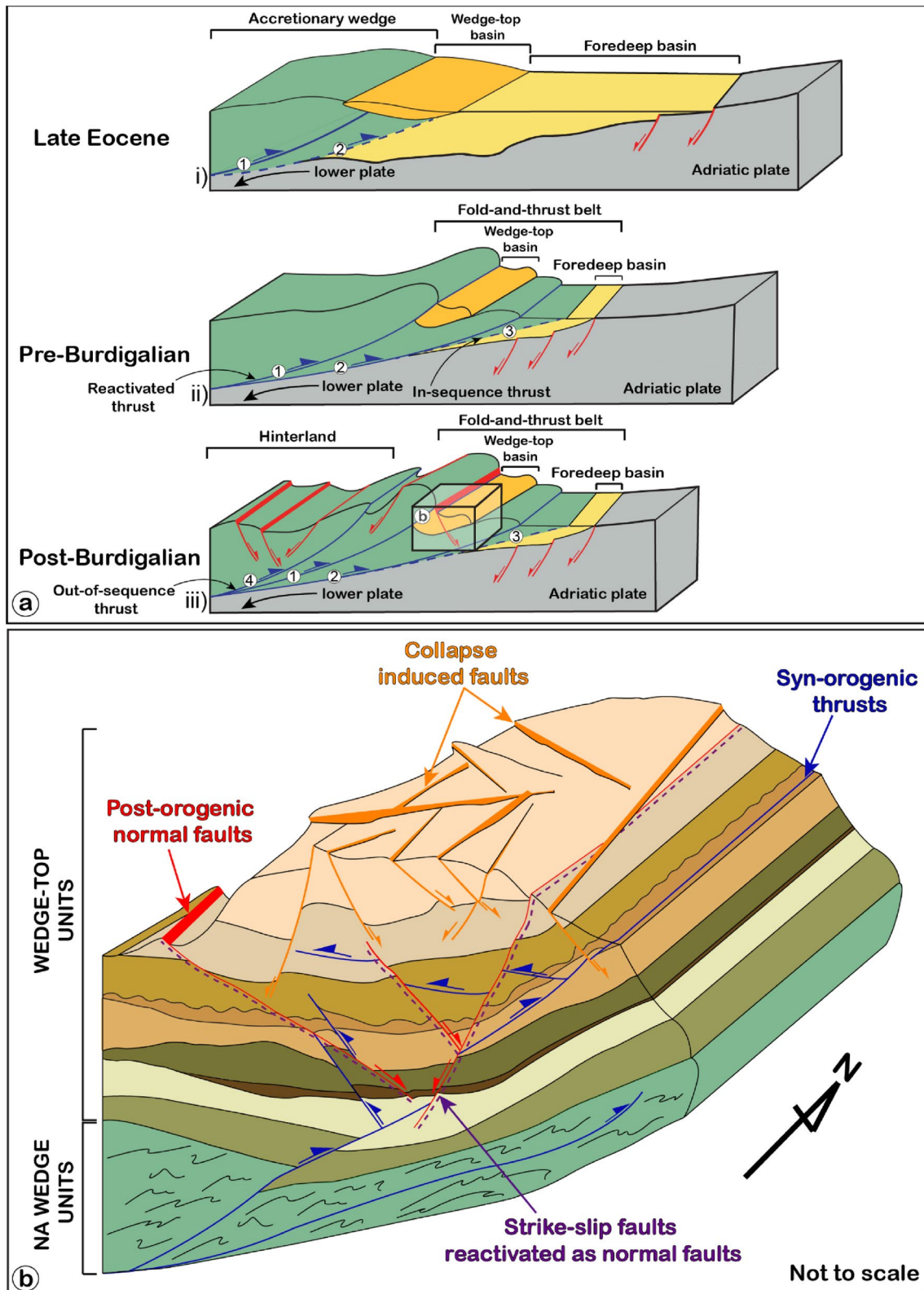
Fig. 12 a Schematic evolution of wedge-top basins through time and space in relation to the propagation of the underlying Northern Apennines accretionary wedge (modified and redrawn from Mutti et al. 2003); **b** representative conceptual deformation model illustrating the tectonic structures affecting both the Ligurian and Epiligurian formations and their cross-cutting relationships

belt started to experience an extensional tectonic phase within the complex configuration of an orogenic wedge, here driven by the NE propagation of the thrust fronts.

Software

The map was digitalised and georeferenced with the open-source software Qgis (version 3.16.3. https://www.qgis.org/it/site/). The final editing of the map and the geological cross-sections was realised with Adobe Illustrator (version CC).

Stereographic projections were realised using the software Stereonet 11 (version 11.0.7, http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html). Rose diagrams were realised with the software DAISY 3 (version 5.40) http://host.uniroma3.it/progetti/fralab/Downloads/.

Data availability The data that support the findings of this study are available from the corresponding author, F. S., upon reasonable request.

Declarations

Conflict of interest All the authors declare that they have no conflict of interest.

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