Swiss J Geosci (2016) 109:17–36
DOI 10.1007/s00015-016-0211-x

The Epiligurian wedge-top succession in the Enza Valley (Northern Apennines): evidence of a syn-depositional transpressive system

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Received: 30 January 2015 / Accepted: 16 February 2016 / Published online: 18 March 2016

Abstract We here discuss the Early Oligocene–Middle Miocene evolution of the Epiligurian wedge-top basin system cropping out in the middle Enza Valley (Northern Apennines, Italy). Newly acquired stratigraphic and structural data, backed up by literature review, highlight that during the Rupelian to Serravallian time span, sedimentation was controlled by a left-lateral transpressive system. This system, here named as the Enza Valley Deformation Zone (EVDZ), is SW–NE directed and trends obliquely to the main regional NW–SE-directed structural axis characterizing this part of the Northern Apennines nowadays. The syn-sedimentary activity is testified by: (1) local to regional stratigraphic unconformities, (2) lateral variations of sedimentary facies associations, (3) thickness changes of the stratigraphic units and (4) the occurrence of mass transport deposits. This study suggests that structural lineaments like the EVDZ, transversal to the main regional tectonic trends, may have played a long-term control on the syn-orogenic sedimentation atop the evolving Apennine orogen.

Keywords Northern Apennines · Strike-slip faulting · Syn-sedimentary transpression · Transversal structural lineaments · Wedge-top basin

1 Introduction

Orogenic wedges and associated foreland basins system (Decelles and Giles 1996) are commonly crossed by major tectonic structures, transversal to the principal axial orientation of fold-and-thrust belts (Allen and Allen 2005; Kearey et al. 2009). These counter-regional structures create along-axis segmentation of the orogenic wedge with consequent variations of the mountain-building processes, ultimately controlling the tectono-sedimentary evolution of the syn-orogenic basins in convergent margins (Christie-Blick and Biddle 1985).

In this framework, in the Northern Apennines of Italy many regional, transverse deformational systems occur, historically known as “anti-apenninic” lineaments in the inherent literature due to their marked obliquity to the main NW–SE axial structures. Such structures are well constrained in the Quaternary evolution but still questioned (or not well constrained) in the older collisional phases (Ghelardoni 1965; Fazzini and Gelmini 1982; Gunther and Reutter 1985; Castellarin and Vai 1986; Gasperi et al. 1986; Ricci Lucchi 1986a, b; Vescovi 1988; Bernini et al. 1997; Bernini and Papani 1987; Sorgi et al. 1998; Cibin et al. 2001; Vescovi 2005; Elter et al. 2011), even though they are interpreted to have strongly controlled the Eocene–Miocene sedimentation in the Epiligurian basins on top of the evolving Northern Apennines orogenic wedge (Castellarin and Vai 1986; Gasperi et al. 1986; Cibin et al. 2001).

The Vetto-Carpineti Epiligurian succession is one of the best exposed and it has been studied since long time (Roveri 1966; Papani et al. 1987, 2002; Cerrina Feroni et al. 2002a, b; and reference therein). Within the SW-portion of the Vetto-Carpineti outlier, located in the middle Enza Valley (Fig. 1), new detailed geological field

Editorial handling: W. Winkler.

Electronic supplementary material The online version of this article (doi:10.1007/s00015-016-0211-x) contains supplementary material, which is available to authorized users.

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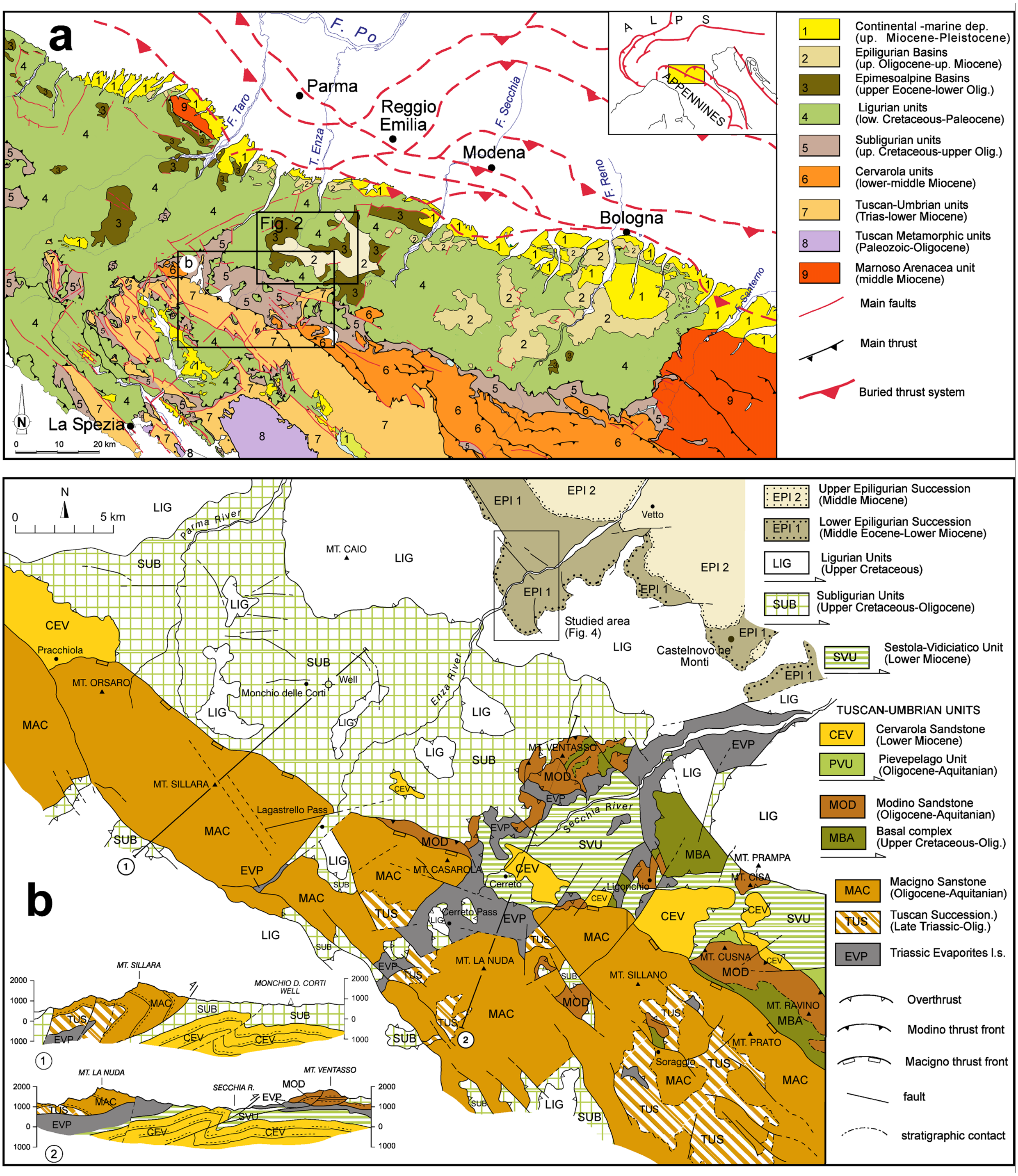


Fig. 1 **a** Schematic geological map of the Northern Apennines and location of the Vetto-Carpineti syncline (Fig. 2). Modified after Bernini, Vescovi, Artoni (unpublished), already modified from Bernini et al. (1997), Boccaletti and Coli (1982) and Bigi and Scandone (1991). **b** Geological map of the Emilian Apennines between the Parma Valley and Monte Prado with the location of the studied area (Fig. 4). Modified after Vescovi (2005)

mapping, structural analysis, sedimentary facies description and accurate revision of the inherent literature have been carried out. The results document new evidence in support of a SW–NE trending transpressive structure previously overlooked in the concerning studies, here named as Enza Valley Deformation Zone (EVDZ). This major structure is here interpreted to have controlled the syntectonic deposition of marine clastics within this part of the Epiligurian basin system, from Rupelian to Serravallian, giving new insights on the importance of transversal tectonic structures in controlling the evolution of syn-orogenic wedge-top basins.

2 Geological setting

2.1 Northern Apennines outline

The regional structural architecture of the Northern Apennines orogen is characterized by the tectonic stacking of tectono-stratigraphic units deriving from the Tuscan–Umbrian, Subligurian, and the Ligurian paleogeographic domains, from base to top (Elter et al. 2003).

The Epiligurian stratigraphic succession was unconformably deposited upon this tectonic pile, directly above the uppermost allochthonous Ligurian units, represented by the Cassio, Groppallo and Caio tectonic units (Figs. 2, 3; Online Resources 1 and 2). The Ligurian units are the remnants of a submarine accretionary prism developed by the subduction of the Western Tethys oceanic crust and its sedimentary cover (Reutter and Groscurth 1978; Marroni et al. 2002; Stampfli and Borel 2002), the so-called Ligure-Piemontese Ocean, from the Late Cretaceous to the Early-Middle Eocene (“Ligurian phase”; Elter 1975; Treves 1984; Abbate et al. 1994; Carmignani and Kligfield 1990; Principi 1994; Bortolotti et al. 2001; Carmignani et al. 2001). The underlying Subligurian units (Late Cretaceous to Late Oligocene), widely outcropping southwest of the studied area (Fig. 1), were deposited in a palaeogeographic domain bounded by the continental Tuscan–Umbrian domain (i.e. Adria margin) to the East and the oceanic Ligurian domain to the West (Remitti et al. 2010 and references therein). The Tuscan–Umbrian units, representing the sedimentary cover of the Adria continental margin (i.e. eastern African margin of Ligure-Piemontese Ocean), are characterized by Triassic evaporites, pelagic carbonate sequences (Trias–Oligocene) and foredeep siliciclastic turbidites (Chattian–Aquitanian) (Barchi et al. 2001; Elter et al. 2003).

Since the Oligocene, the collision between Africa and Europe caused overthrusting of the frontal part of the Ligurian accretionary prism onto the Adria foreland. The consequent flexural loading generated an eastward—migrating foredeep system progressively filled by siliciclastic turbidites, which are represented, from innermost to the outermost, by the Macigno–Modino, Cervarola and Marnoso-arenacea formations (Argnani and Ricci Lucchi 2001; Ricci Lucchi 1986a).

2.2 The Enza Valley case study: stratigraphic and structural outline

The studied area is located in the middle portion of the Enza Valley (Northern Apennines, Italy), between Parma and Reggio Emilia provinces, where the Epiligurian formations are well exposed (Figs. 1, 2). Since the Middle Eocene, the Epiligurian Succession was deposited onto the deforming Ligurian units, in a complex system of separated but interconnected wedge-top basins, classically used to trace the geological history of the underlying Apenninic orogenic wedge (Ricci Lucchi and Ori 1985; Ricci Lucchi 1986a; Mutti et al. 1995; Amorosi et al. 1996; Argnani and Ricci Lucchi 2001; Carrapa et al. 2004). As the Epiligurian deposits are the uppermost elements of the Apenninic structural architecture, they are usually deeply eroded, forming isolated, often synclinalic, outliers surrounded by the underlying Ligurian units (Figs. 1, 2).

In the Enza Valley, the Epiligurian stratigraphic succession starts with the sedimentary *mélanges* of the Baiso Formation and the overlaying hemipelagic marl of the Monte Piano Formation (BAI and MMP in Fig. 3, respectively), Bartonian–Priabonian in age (Bettelli and Panini 1987). An important, regional erosive unconformity marks the base of the overlaying Ranzano Formation (Tagliavini 1968; Ottria et al. 2001; Cerrina Feroni et al. 2002a), here represented (see below) by two formal Members (Cerrina Feroni et al. 2002a; Martelli et al. 1998): the Val Pessola Member, subdivided into arenaceous–conglomeratic (Ran 2a), arenaceous–pelitic (Ran 2b) and “chaotic” (Ran 2c) lithofacies; and the Varano Melegari Member, represented by a basal pelitic arenaceous lithofacies (Ran 3a) and an upper “chaotic” lithofacies (Ran 3b).

The succession continues with the clastic deposits of the Lagrimone Sandstone, passing upward into the Antognola Marls (Early Oligocene–Early Miocene) with an overall fining upward trend (see Fig. 3) (Cerrina Feroni et al. 2002a, b). Up-section, the Contignaco Formation (Burdigalian) is characterized by silica-rich marlstones (Amorosi et al. 1995) and by the turbiditic sandstones of the Villaprara Member, interpreted as submarine channels infills (De Nardo et al. 1991). A regional Burdigalian–Langhian erosive unconformity marks the base of the Bismantova Group (Amorosi 1996; Papani et al. 2002) (base of EPI 2 in Fig. 1b), which is subdivided into shelfal (Pantano Formation) and slope-basin facies (Cigarello Formation), characterized by complex vertical and lateral relationships in the studied area (Papani et al. 1987, 2002; De Nardo et al. 1991). Locally the entire succession is extremely thinned or missing, with the Bismantova Group lying directly above the Ligurian units (Figs. 2, 3).

From a tectonic point of view, the study area is located in the southwestern part of the Epiligurian outlier, known

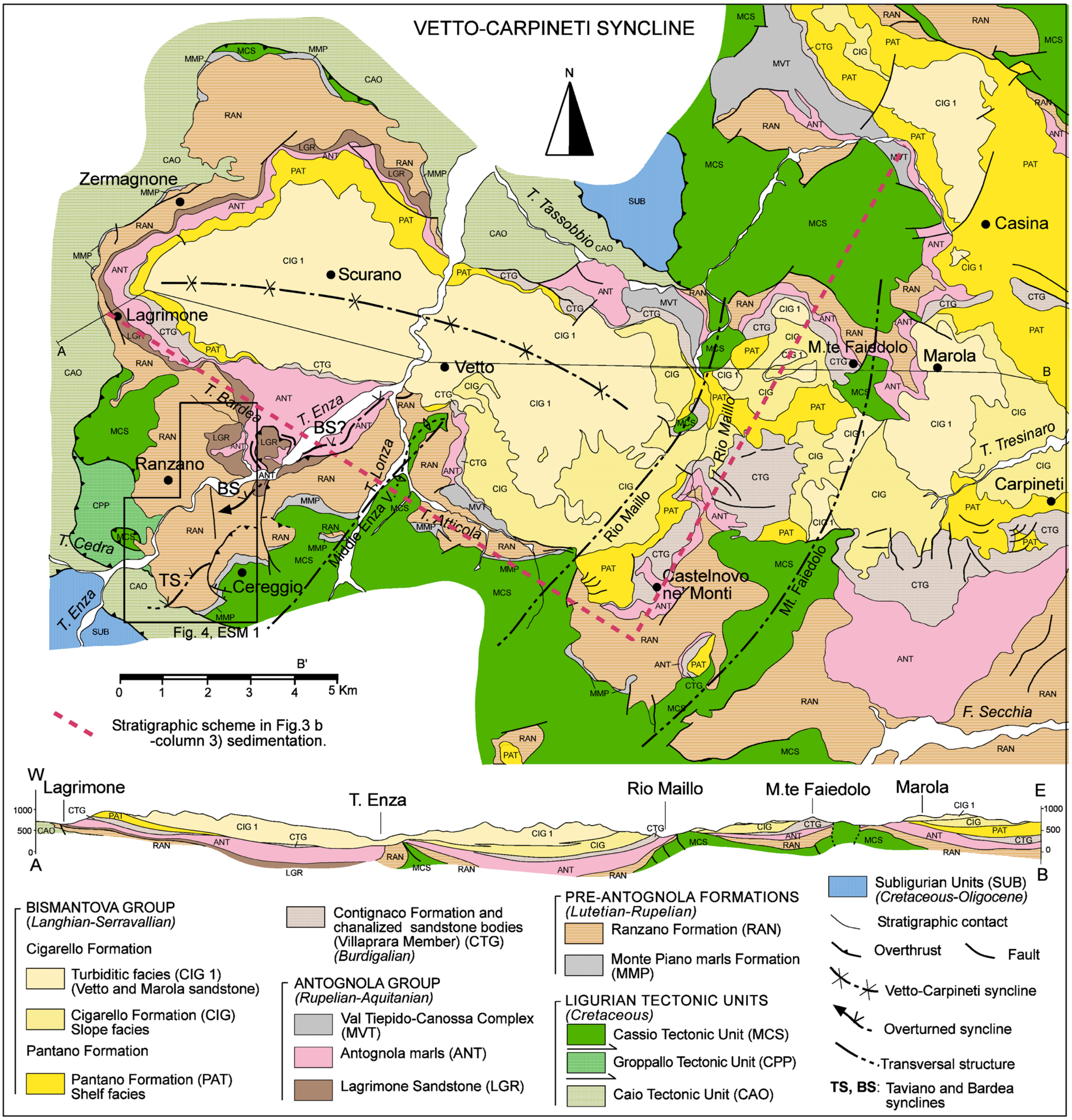


Fig. 2 Simplified geological map and geological cross section of Epiligurian Vetto-Carpineti syncline outlier. In the geological cross sections and in the map the middle Enza Valley, the Rio Maillo and the Monte Faiedolo transversal tectonic structures, striking NE–SW, are evidenced. Modified after Papani et al. (1987) and De Nardo et al. (1991)

in the literature as Vetto-Carpineti syncline (Roveri 1966; Boccaletti and Coli 1982; Papani et al. 1987), a post-Serravallian, WNW–ESE trending, open syncline that preserves the Lutetian–Serravallian interval of the Epiligurian succession as introduced above (Figs. 2, 3). Close to the study area, the overall structural framework comprises a complex N-verging, overturned syncline (Enza Valley syncline in Ottria et al. 2001 and Bertelli et al. 1984; Middle Enza Valley Structure in Papani et al. 1987 and De Nardo et al. 1991) and a related low-angle thrust (Rupelian Poggio della Torre thrust in Ottria 2000). Other two main tectonic lineaments NE–SW oriented, called Rio Maillo and Monte Faiedolo, occur to the East of the Enza Valley (see Fig. 2) and they are interpreted as positive strike-slip "flower" structures (Papani et al. 1987; De Nardo et al. 1991). All these structures appear unconformably sealed by

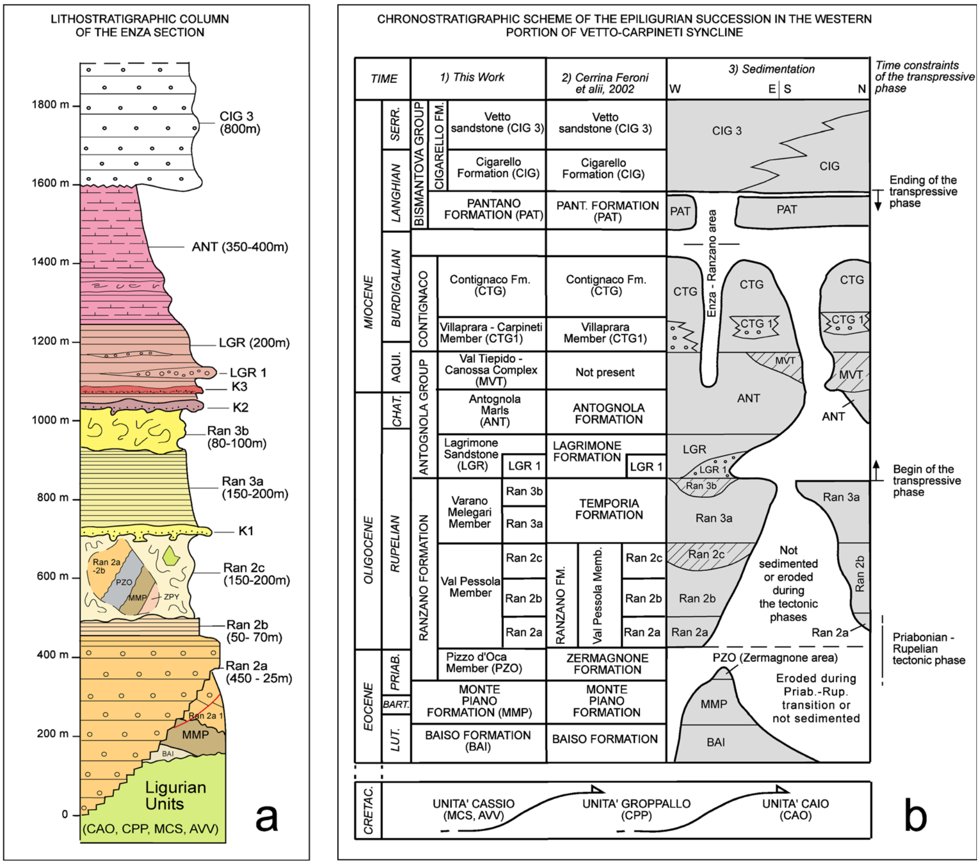


Fig. 3 **a** Lithostratigraphic column of the Epiligurian Succession located along the Enza Valley in the study area. **b** Chronostratigraphic scheme of the Vetto-Carpineti syncline and study area: *1* stratigraphic scheme for this work, *2* stratigraphic scheme in Cerrina Feroni et al. (2002a, b), *3* schematic and simplified distribution of stratigraphic units within the western portion of the Vetto-Carpineti syncline showing the depositional, erosional or non-depositional area, see Fig. 2 for the distribution of units

the Serravallian deposits of the Cigarello Formation (Papani et al. 1987; De Nardo et al. 1991).

To the South, the Cenozoic siliciclastic foredeep turbidites comprising the Macigno Formation, which constitutes the main Apenninic watershed, and the Modino Formation, crop out between Mt. Casarola and Mt. Ventasso, whereas the Cervarola Formation, is exposed in a tectonic windows located in the high Enza Valley (Fig. 1) (Chicchi and Plesi 1988, 1991). According to Vescovi (2005), the Modino Formation is locally involved in an arcuate structure, developed during Early-Middle Miocene, and terminating to the West against the Mt. Ventasso structure, represented by a NW-verging, thrust-related fold involving the Subligurian units (Fig. 1b).

3 Methods and data

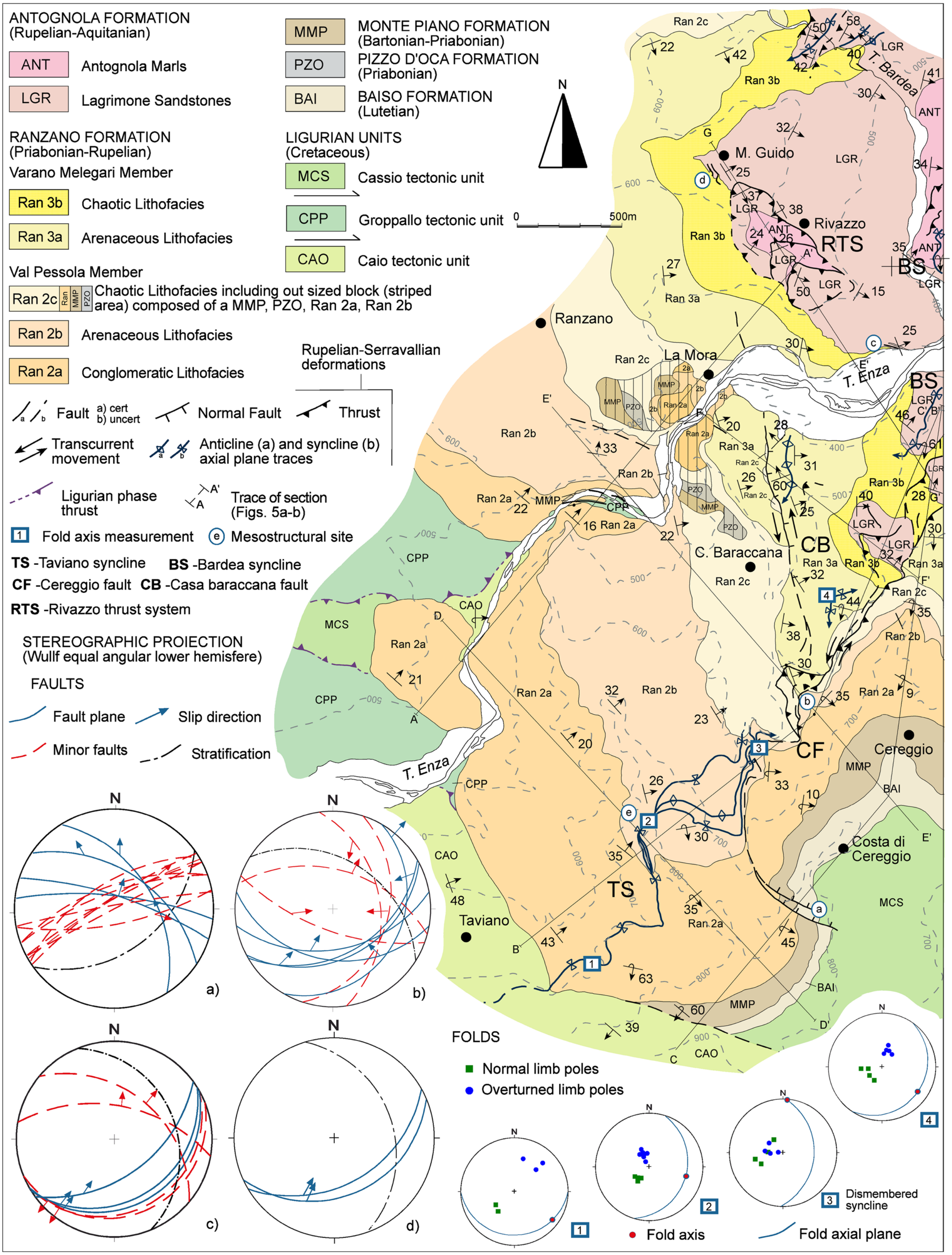
A detailed (1:5000 scale) geological survey has been carried out to develop a new 1:10,000 geological map of the study area (Online Resource 1, Fig. 4) and seven geological cross-sections (Fig. 5a, b).

The lithostratigraphic units have been described in detail in order to characterize both the meso-scale sedimentary features and large-scale geometries, which are used as markers to trace the basinal arrangement (Online Resource 2). The turbidite beds have been described according to the well-known facies schemes proposed by Mutti et al. (1999). Meso-scale sedimentary features indicative of flow confinement (Mutti et al. 1999; Muzzi Magalhaes and Tinterri 2010) were used to complement the definition of the overall depocentral physiography (Online Resource 2).

The collected structural dataset comprises spatial information on: (1) meso-scale fold axes, (2) deformation structures on fold limbs, (3) fault planes and (4) kinematic indicators on fault surfaces. The axial trend of the main Enza Valley syncline has been reconstructed by calculating the intersection line of the different bedding attitudes, and represented on four ß and π diagrams (Rowland et al. 2007). Structural data have been collected in eight different sites and have been plotted on lower hemisphere equiangular Wulff stereonets (Fig. 4).

4 Stratigraphic and sedimentological results

The stratigraphic scheme used in this work is in agreement with that proposed by previous authors (Martelli et al. 1998; Cibin et al. 2001; Mancin et al. 2006), but the


ANTOGNOLA FORMATION (Rupelian-Aquitanian)
ANT Antognola Marls
LGR Lagrimone Sandstones
RANZANO FORMATION (Priabonian-Rupelian)
Varano Melegari Member
Ran 3b Chaotic Lithofacies
Ran 3a Arenaceous Lithofacies
Val Pessola Member
Ran 2c Ran MMP PZO Chaotic Lithofacies including out sized block (striped area) composed of a MMP, PZO, Ran 2a, Ran 2b
Ran 2b Arenaceous Lithofacies
Ran 2a Conglomeratic Lithofacies
MMP MONTE PIANO FORMATION (Bartonian-Priabonian)
PZO PIZZO D'OCA FORMATION (Priabonian)
BAI BAISO FORMATION (Lutetian)
LIGURIAN UNITS (Cretaceous)
MCS Cassio tectonic unit
CPP Groppallo tectonic unit
CAO Caio tectonic unit
N
0 500m
Rupelian-Serravallian deformations
a b Fault a) cert b) uncert
Normal Fault
Thrust
Transcurrent movement
a b Anticline (a) and syncline (b) axial plane traces
Ligurian phase thrust
A A' Trace of section (Figs. 5a-b)
1 Fold axis measurement
e Mesostructural site
TS -Taviano syncline
BS -Bardea syncline
CF -Cereggio fault
CB -Casa baraccana fault
RTS -Rivazzo thrust system
STEREOGRAPHIC PROIECTION (Wulff equal angular lower hemisfere)
FAULTS
Fault plane
Slip direction
Minor faults
Stratification
N
a)
N
b)
N
c)
N
d)
FOLDS
Normal limb poles
Overturned limb poles
Fold axis
Fold axial plane
Dismembered syncline
1
2
3
4
M. Guido
Rivazzo
RTS
BS
Ranzano
La Mora
T. Enza
T. Bardea
C. Baraccana
CB
CF
Cereggio
Costa di Cereggio
Taviano
TS
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◀**Fig. 4** Structural map of the studied area based on the geological map in Online Resource 1; the study area is located in the south western margin of the Vetto-Carpineti syncline (see Fig. 2). The stereonets projections (Wulff lower hemisphere) *a*, *b*, *c*, *d* show the orientation and the kinematics of the studied faults; the stereonets projections (Wulff lower hemisphere) *1*, *2*, *3*, *4* show the bedding poles and the fold axial trend in the Taviano syncline

terminology and, in few cases, ranking of stratigraphic units is slightly different from that used in Cerrina Feroni et al. (2002a, b) and Ottria et al. (2001). Such discrepancies are due to the lateral variations of lithology within the same units, remarkable facies heteropy, lithology interfingering and depocentral compartmentalization, which further testify and help to unravel the complex basin arrangement. For comparison among the different stratigraphic schemes see Fig. 3 and Online Resource 2, along with detailed descriptions of all the investigated units. Our data allow new interpretations for the stratigraphic contacts and depositional mechanisms of the Oligocene Epiligurian deposits, providing an updated, alternative reconstruction of the basinal evolution, as discussed in the following sections.

4.1 The basal unconformity of the Val Pessola Member (Ranzano Formation) and the geometry of the arenaceous–conglomeratic lithofacies (Ran 2a)

The basal contact of the Ranzano Formation has been classically recognized as a regional unconformity surface (Tagliavini 1968), marking the Priabonian–Rupelian boundary (Ottria et al. 2001), above which the Ran 2a seems to maintain a thickness of ca. 300 m (Cerrina Feroni et al. 2002a). Based on sedimentological analysis, Bonazzi (1971) interpreted the coarse grained deposits of the Ran 2a lithofacies (see Fig. 3) as the infill of a submarine valley. In the following we provide new observations and updated interpretations on the geometric relationships between the units beneath the unconformity and the stratigraphic arrangement of the overlying Ran 2a lithofacies.

Along the Enza river bed, the erosive contact and the meso-scale on-lap geometries of the arenaceous–conglomeratic lithofacies of Val Pessola member (Ran 2a) upon the overturned Monte Caio Flysch are well exposed (cross section A–A′ in Fig. 5a and Fig. 6). It is worth to underline that in this location, on the normal limb of the Enza Valley syncline, the Ran 2a lithofacies sits unconformably on the deepest Ligurian tectonic unit (i.e. Monte Caio Flysch) (see Figs. 4, 6). Whereas, on the overturned limb (Cereggio area in Fig. 4; Online Resource 1 and 2), the Ran 2a unconformably lies upon (i.e. geometrically beneath) the Epiligurian Monte Piano (MMP) and Baiso (BAI) formations, deposited on top of the Monte Cassio tectonic unit, which is the highest in the Ligurian tectonic stack (Online Resource 2). Such geometries and stratigraphic contacts indicate that the Enza Valley syncline involves an unconformity extending over a structurally and lithologically variable substrate, which is locally deeply incised and the lower Epiligurian succession is consequently missing.

The Ran 2a lithofacies is the first depositional unit encountered above the unconformity and it is characterized by laterally wedging and meso-scale onlapping relationships, interpreted to be related to the very narrow geometry of the basin. It comprises massive, poorly-sorted sandstones and conglomerates (Facies F2, F3, F5 of Mutti et al. 1999), typically deposited by low-efficiency turbidity currents (efficiency being the capability to redistribute the different grain-size populations across the basin, *sensu* Mutti et al. 1999; Tinterri and Muzzi Magalhaes 2011). These beds progressively fill large-scale erosional features generating sharp lateral on-lap relationships with the substratum (see section A–A′ in Fig. 5a and Fig. 6). The thickness of Ran 2a unit ranges from a maximum of ca. 450 m in the Taviano area to a minimum of ca. 30 m about 3 km to the North (section A–A′ in Fig. 5a). These values, and the restoration of the Ran2a beds to horizontal, allow to estimate an on lap surface inclined at 16°–20° (i.e. ratio between thicknesses difference/distance), which approximates the original slope of the depocentral margin. Moreover, the same trend is evident in the overturned limb of the Enza Valley syncline where, toward N–NE, the Ran 2a unit tapers out and disappears, as also testified by its areal distribution in the map of Cerrina Feroni et al. (2002a).

4.2 The “chaotic” lithofacies of the Val Pessola Member (Ran 2c)

Within the fine-grained material characterizing the “chaotic” lithofacies of Val Pessola Member, isolated bodies, hundreds of meters in size, comprising detached, folded bedded fragments of the Monte Piano (MMP)-Pizzo d’Oca (PZO)-Ran 2a succession have been documented (Fig. 4; section A-A’ in Fig. 5a; Online Resource 1, 2 and 3). In Catanzariti et al. (1999) and Cerrina Feroni et al. (2002a, b), these bodies and their geometric relationships have been interpreted as the result of a shallow crustal level, syn-sedimentary thrust system, sealed by the Varano Melegari Member, and recording an Early Oligocene compressive tectonic phase.

However our data make this interpretation unlikely. As matter of fact, it has been detected that the bodies made up by MMP, PZO and Ran 2a sediments (see Fig. 4, and Online Resource 1, 2 and 3) have a lateral continuity not exceeding 800 m, and appear completely embedded within a fine-grained, unsorted matrix with dispersed

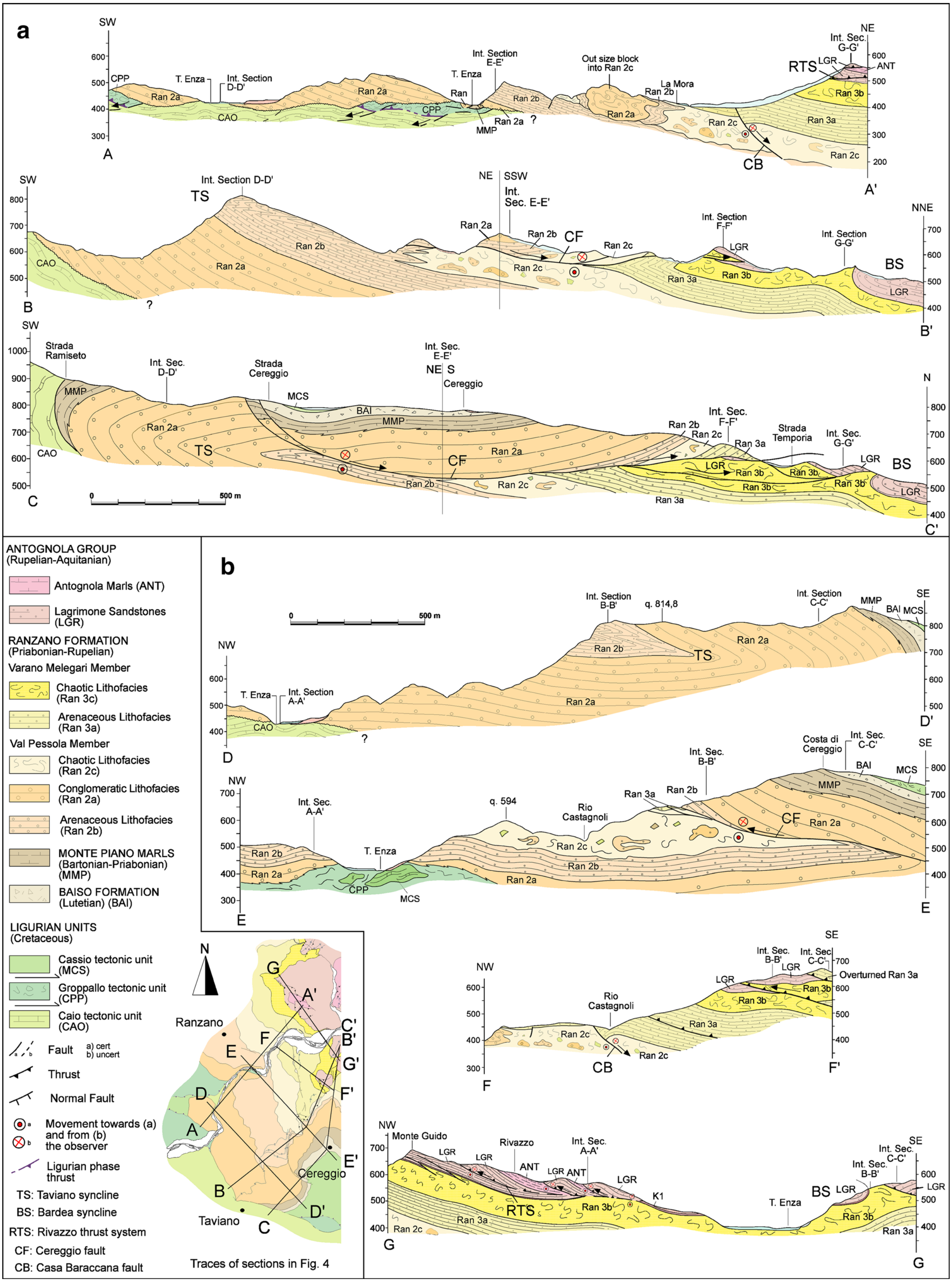

Fig. 5 **a**, **b** Cross sections of the studied area. The traces of sections are shown in Fig. 4

Fig. 6 **a** The outcrop of the arenaceous-conglomeratic lithofacies of Ranzano Formation (*Ran2a*) located on the hydrographic right bank of Enza River, between Ranzano and Taviano villages. The *dashed lines* mark the bases of the beds that show lenticular geometries. Approximately along the Enza riverbed, the main erosional unconformity at the base of Ran 2a lithofacies (see Sect. 4.1) is well exposed in tiny outcrops (e.g. **b**) where the on-lap relationship between Ran 2a lithofacies (Rupelian) and the Ligurian Flysch (uppermost Cretaceous) is clearly shown

disarticulated/disaggregated lithologies (Online Resource 3), which is typical of the classic sedimentary *mélanges* (i.e. mass transport deposits; Ogata 2010; Ogata et al. 2012b, 2014) to form a regional lithological unit. Moreover the peculiar K1 key bed (see Fig. 3, Online Resource 1 and 3), interpreted as the seal of the tectonic stack in Catanzariti et al. (1999), covers without distinction the rock bodies of MMP-PZO-Ran 2a as well as the background disrupted lithologies of the mass transport complex (Online Resource 3). The K1 bed is characterized by basal, mudstone clasts-rich, "impact breccias" (*sensu* Tinterri and Muzzi Magalhaes 2011), and an upper arenaceous portion that shows plane-parallel, undulated and convolute lamination (see "f" in Online Resource 3). This bed shows great lateral variability in thickness, from a maximum of 13 m to few decimeters, smoothing the rough top surface of the remolded lithologies of the Ran 2c unit. The basal breccia comprises a (micro)conglomeratic-arenaceous muddy matrix that incorporates a great number of marly, pelitic and arenaceous clasts, ripped up from the local substratum.

This particular K1 bed can be interpreted as deposited by a large-volume turbidity current (*sensu* Mohrig and

Marr 2003) associated to the underlying mass transport complex (Muzzi Magalhaes and Tinterri 2010; Ogata 2010; Ogata et al. 2012b) (Fig. 3; Online Resource 3). In this context, the above mentioned rock bodies of MMP-PZO-Ran 2a are interpreted as out-sized slide blocks (*sensu* Ogata et al. 2012b) or slabs (*sensu* Blair and McPherson 1999) embedded within a mass transport complex (i.e. the "chaotic" Ran 2c lithofacies of Val Pessola Member) as previously proposed by Tagliavini (1968) and Cerrina Feroni and Plesi (1986).

4.3 Thickness and facies changes within the Rupelian–Chattian deposits (Antognola Group)

In the Vetto-Carpineti syncline, the Rupelian–Chattian sedimentary units are represented by the Lagrimone Sandstone Member, locally expressed by the Poggio della Torre conglomerates, and the Antognola Marls (see Figs. 2, 3) (Ottria 2000; Cerrina Feroni et al. 2002a, b). Across the investigated area, the Rupelian–Chattian units show marked thickness and facies changes, fundamental to understand the geological evolution of the studied area as it will be shown in the following paragraphs.

4.3.1 The Lagrimone Sandstone

Arenaceous and conglomeratic turbidite deposits characterize the Lagrimone Sandstone Member (LGR). It starts with a local key bed (K2), a turbidite bed characterized by a basal mudstone breccia, appearing very similar to the K1 bed described above (see Fig. 3). Accordingly, the K2 bed is interpreted as a large-volume turbidity current associated to the emplacement of the underlying Ran 3b unit, which is interpreted as another regional, basin-wide mass transport complex in the Epiligurian stratigraphic succession, basically showing the same characteristics of the above-described Ran 2c lithofacies (see Fig. 3, Online Resource 2 for further details).

The LGR unit is composed of an alternation of bedsets with a A/P ratio >1 and other with an A/P ratio <1, characterized by complex vertical and lateral facies distribution. Single beds generally comprise a basal massive arenaceous (coarse- to medium-grained) interval that passes to a fine-grained and laminated interval at the top. Locally, beds with conglomerate-sized clasts encased in the massive basal sandstone are also present (facies F5 of Mutti et al. 1999).

Between Bardea and Enza Valleys, the LGR unit also shows a localized conglomeratic facies (LGR 1 in Fig. 3), termed as Poggio della Torre conglomerates in Ottria (2000) and Cerrina Feroni et al. (2002a, b). Generally, these deposits show grain-size populations increasing from the NW (Lagrimone area) to the SW (Enza River, where the bulk of the conglomeratic facies crops out). The LGR unit has a maximum thickness, documented in Bardea Valley, of about 200 m and wedges out laterally to the E (Figs. 2, 3), as also evident in map view (Cerrina Feroni et al. 2002a, b; Papani et al. 2002).

In the LGR unit, we also document a key bed K3 (Fig. 3) consisting of a basal para-conglomerate interval with a muddy sandstone matrix and an upper interval (20–50 cm thick) comprising a graded sandstone (medium- to fine-grained) with convolute lamination and load casts (e.g. "ball-and-pillow" structures) at the base (see Online resource 2 for details). The LGR unit passes gradually upward into the Antognola Marls with a fining upward trend.

4.3.2 The Antognola Marls

The Antognola Marls, as classically known in the literature, crop out in northern part of the studied area (Bardea Valley; see Fig. 4), locally represented by a turbiditic succession with a fining upward trend. The lower part of the succession is characterized by thick-bedded (maximum thickness of 4 m), fine-grained sandstones at the base, and thinner pelitic–marly bedsets toward the top. In the upper part, a clayey–marly interval predominates and sandstone beds occasionally occur with a thickness of 1–10 cm (Fig. 7a). Inside the turbiditic sequence, few m-thick, slump/debris flow-type deposits and growth-stratal geometries are observed, and interpreted as symptomatic of an active syn-tectonic control.

In the southwestern sector of the Vetto-Carpineti syncline, the Antognola Marls vary in thickness from about 100 m (Lagrimone area) to a maximum of 400 m along the Enza River (see Fig. 3) (Cerrina Feroni et al. 2002a, b). The sedimentary facies associations and the thickness variations within these Oligocene stratigraphic units (Lagrimone Sandstone and Antognola Marls) could be explained as related to the deposition within a confined depocenter, roughly located along the course of the present-day Enza River.

5 Structural results

5.1 The Enza Valley syncline

The Enza Valley syncline is a first order structure affecting the entire studied succession (from Ligurian units to Antognola Formation) characterized by an extensive overturned SE limb, partially detached, and a main NE–SW-trending axial plane trace (see Figs. 2, 4).

Our data suggest a very complex structure characterized, at least, by two overturned polyphased synclines whose

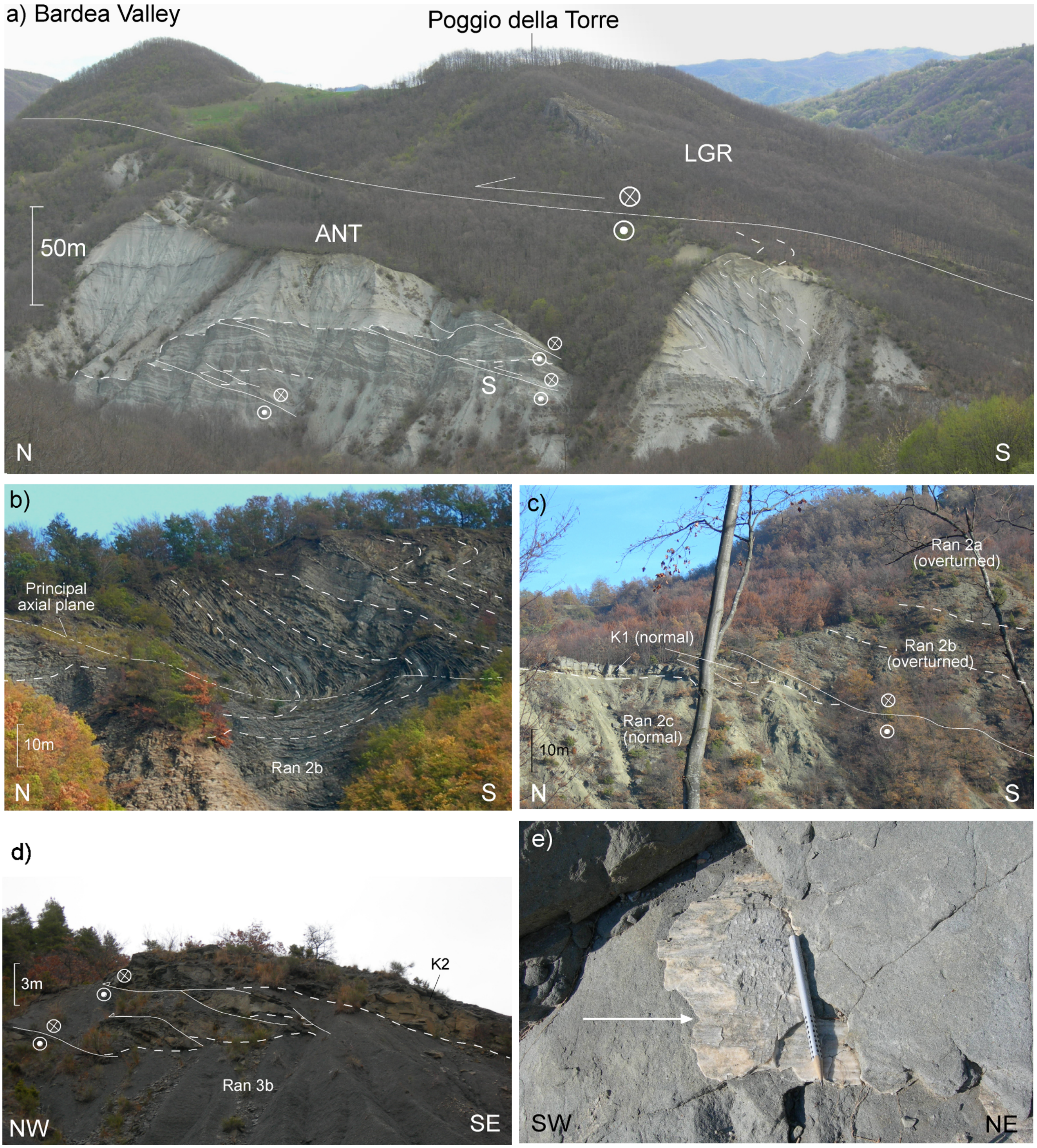

Fig. 7 View of some tectonic structures present in the studied area. **a** Panoramic view on the Antognola Marls cropping out in the left bank of the lower Bardea Valley at the north eastern border of the studied area (Fig. 4). They show: (1) a main left lateral transpressive fault system with low angle thrusts; (2) an overturned syncline with second order folds forming a Z geometry; (3) the low angle left lateral transpressive fault in the normal limb of the syncline (LGR—Lagrimone Sandstone, ANT—Antognola Marls). **b** Panoramic view of the Taviano syncline that involves the arenaceous–pelitic lithofacies of Val Pessola Member. **c** Panoramic view of the Cereggio fault that brings the overturned Epiligurian Succession on top of the normal limb of the Taviano syncline (site b in Fig. 4), the Key bed 1 (K1) gives the polarity of the chaotic lithofacies. **d** The Monte Guido-Rivazzo low angle imbricate and transpressive thrusts (site d in Fig. 4) that displace the Key bed two (K2) at the top of the Varano Melegari chaotic lithofacies (*Ran 3b*). *Dashed lines* represent bedding planes, continuous lines are fault planes. **e** An example of kinematic indicators (stepped calcite slip fibres) on the low angle faults that displace the Key bed two (*K2*) outcropping near T. Enza (site c in Fig. 4)

axial plane traces and terminations cannot be directly linked to a single axial plane on the field (see Figs. 2, 4, 5, Online Resource 1): the Taviano syncline (TS in Figs. 2, 4, 5, 7b), to the south, and the Bardea syncline (BS in Figs. 2, 4, 7a), to the north. The overturned limb of the Taviano syncline (cropping out in Taviano–Cereggio area; see Figs. 4, 5) can be divided in southern and northeastern zones, respectively un-breached and breached; the latter zone moved northwards along the Cereggio fault (CF, see cross sections B–B′ and C–C′ in Fig. 5a and Sect. 5.2). This overturned limb shows peculiar changes in dip-domain directions: from N200° to N90° in the southern un-breached zone, and from 90 to N 200° in the northeastern one (see Fig. 4; Online Resource 1). In this framework, the stratigraphic boundaries as mapped in the overturned limb of the Taviano syncline mark two arcuate structures in plan view: a southwestern one with northward concavity, and a northeastern one with a southward concavity (Fig. 4). The Taviano syncline axial planes have been reconstructed by calculating the intersection line of the different bedding attitudes of the normal and overturned flank. The inferred axial plane generally dips 10°–30° toward E–SE with NW–SE axial trends (see folds in stereplots 1, 2 and 4 in Fig. 4). We also calculated the axial trend in the central sector of the fold (site 3 in Fig. 4) where the hinge zone is not preserved due to the low-angle, oblique thrust breaching the overturned limb, resulting in N–S axial trend (see fold axis in stereoplots 3 in Fig. 4). The hinge zone of the Taviano syncline shows second order, parasitic folds affecting the arenaceous–pelitic lithofacies (Ran 2b) close to the main axial plane; these folds show a down-plunge, “z” symmetry indicating a north-northwestward vergence (Ramsay and Huber 1987; Park 2013). This pattern is likely due to disharmonic folding related to the different rheological behavior of the arenaceous–pelitic Ran 2b and the arenaceous–conglomeratic lithofacies Ran 2a multilayers (see cross section D–D′ in Fig. 5b). These meter-scale, disharmonic folds (site “e” in Fig. 4) show axes oriented from NW–SE to W–E, and axial planes dipping 8°–36° to the E–SE (Fig. 8a). Unfortunately, further NE along the Taviano syncline axial trace, the worse outcrop conditions and the interference with the breaching Cereggio fault (see Sect. 5.2) hampered to collect a significant number of meso-structural data. To better understand the folding mechanism, the Taviano syncline could be better studied because of favorable outcrop conditions. The limbs and the hinge zone of the second order folds have been analyzed (Figs. 7b, 8). These folds are characterized by thickening of the hinge zones (Fig. 8a, b) and by well-developed slickensides (Fig. 8c). The folds limbs are also affected by a well-developed syn-kinematic extensional features mainly represented by high-angle, low-displacement normal faults, contained within single beds or within thin-bedded packages (Fig. 8d, e). These small-scale normal faults can be interpreted as synthetic and antithetic Riedel shears (R–R′), which can be used as kinematic indicators to unravel the sense of movement within shear zones (see e.g. Mercier and Vergely 1995; Ogata et al. 2012a and reference therein). The small-scale normal faults strike 20°–30° oblique to the direction of the strata (Fig. 8d, e). These Riedel structures (Fig. 8d, e) along with the bedding-parallel shear veins (see Fig. 8c) record a shear with sense of movement directed toward the hinge zone and thus suggesting flexural slip as the main deformation mechanism. Furthermore, the measured sense of shear movement results 15°–30° oblique both to the fold hinge’s axis and to the dip direction of the small-scale faults, supporting the interpretation of a non-cylindrical folding.

The linkage between the Taviano and Bardea synclines appears complex. Although their axial plane traces cannot be directly linked on the field, the cross section B–B′ and C–C′ at the intersection with cross section G–G′ (Fig. 5a) suggest the occurrence, between the two synclines, of an anticline which is completely dismembered and breached by splays of the Cereggio fault (see Sect. 5.2 for details). This intervening anticline, link between Taviano and Bardea synclines, should prosecute to the E of the studied area, near the Lonza stream, where a core of argillaceous Ligurian units is emplaced between the overturned limbs of the two synclines (see Fig. 2 and Cerrina Feroni et al. 2002a). Nonetheless, further detailed field surveys are needed in this area to the E to better described the complex situation.

5.2 Faults and related folding

The above-described Taviano and Bardea synclines appear deeply affected by the development of the Cereggio fault (CF in Fig. 4), which causes the detachment and the northward movement of northeastern zone of the overturned limb of the Taviano syncline (i.e. hangingwall block of the Cereggio fault; see cross sections B–B′, C–C′, E–E′, F–F′ in Fig. 5a, b). The Cereggio fault can be interpreted as a complex low-angle thrust system generally dipping to SE, with some different features moving from S to N. In the southern sector the termination of this fault cuts the overturned limb of the Taviano syncline separating the two arcuate segments as described above (see Fig. 4; cross section C–C′ in Fig. 5a). In this area the Cereggio fault is made of a transtensional fault array oriented NW–SE (site “a” in Fig. 4), which is inferred to accommodate the northward movement of the breached overturned limb. Toward the N the Cereggio fault becomes transpressive (cross sections B–B′, C–C′, E–E′ in Fig. 5a, b) and it juxtaposes, through a left-lateral, low-angle strike-slip fault with a southeastward dipping plane (10°–20°), the breached overturned limb against the normal limb of the

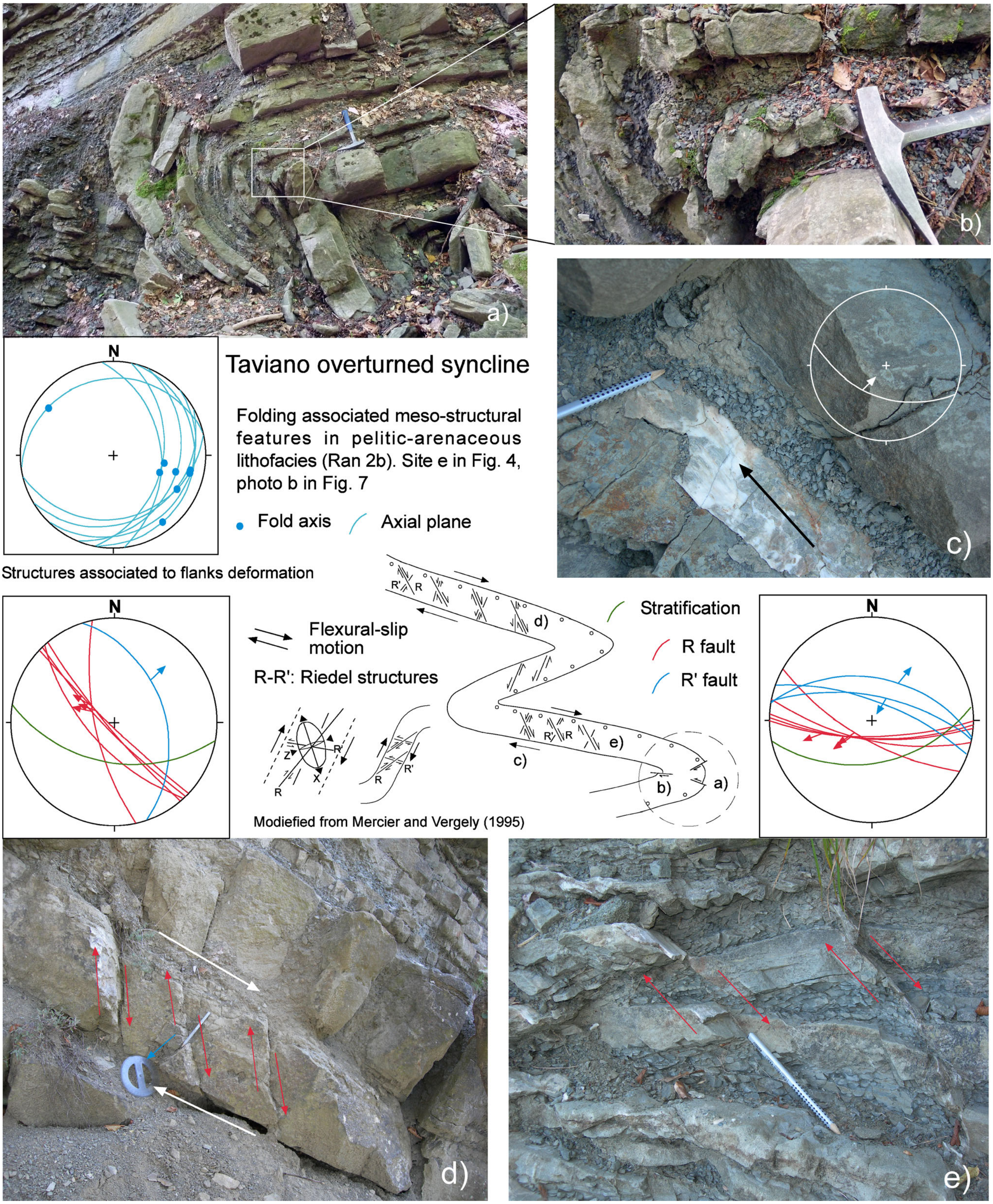

Fig. 8 Folding and associated meso-structural features of the Taviano syncline. Mesostructural site "e" in Fig. 4. **a** Hinge zone of the parasitic z shaped folds with axial trend NW–SE and E–W directed as shown in the stereonet. **b** Detail on the hinge zone with evidence of sediment accretion and related hinge thickening. **c** Flexural slip developed on the flanks of the fold. **d**, **e** Small-scale normal faults interpreted as Riedel shears (*R*) associated to flexural slip. The slip direction on the faults collected along the fold limbs is oblique to the fold axis suggesting that the folds are non-cylindrical

Taviano syncline. Such faults are basically low-angle thrusts with pronounced strike-slip movement (site “b” in Fig. 4), carrying the overturned Ran 2b lithofacies on its hangingwall block (see Fig. 7c). Our results outline a north–northeastward movement of the hanging wall block (i.e. SE block) with an overall left-lateral kinematics (Fig. 4) for the Cereggio fault.

In the normal limb of the Bardea syncline, other transpressive, low-angle faults, similar to the above-described ones, form the imbricate thrusts stack of Monte Guido-Rivazzo (RTS in Fig. 4; cross sections F–F′ and G–G′ in Fig. 5b). These structures are well exposed on the western slope of the Enza River and in the Antognola Marls on the eastern slope of Bardea River (Fig. 7a, d). The faults belonging to this system are generally 40°–13° SE dipping, sometimes layer-parallel (see sites “c” and “d” in Fig. 4). These low-angle faults root down into the Ran 3b lithofacies, which represents a preferential detachment level due to its meso-scale characteristics (see above and cross section G–G′ in Fig. 5b). The hanging wall block of these imbricate low-angle faults is characterized by a complex meso-scale fold system that can be observed in the Rivazzo area (cross section G–G′ in Fig. 5b).

A similar complex fold system has been found in the northern sector of the studied area (Val Bardea, Fig. 4) in the same stratigraphic-structural position, where anticlines and synclines with NE–SW axial trend and low-angle faults striking NE–SW are documented.

Immediately to the W of the Ceregggio fault, the Casa Baraccana fault (CB in Fig. 4) is a roughly N–S-directed normal fault with a subordinate strike-slip component, which downthrows the eastern block (cross section F–F′ in Fig. 5b). The strike-slip displacement of this fault is outlined by a small-scale anticline with a NE–SW axial direction, which develops within the hanging wall block, in agreement with a left-lateral kinematics of the main fault (see Fig. 4 and Online Resource 1).

6 Discussion

6.1 The Enza Valley Deformation Zone: evidence of a left-lateral transpressive zone

The structural features analyzed in the previous chapter (see Sect. 5) have been described in the simplified model of Fig. 9. A way to explain this complex structural association is to refer to the classical strike-slip tectonic model within a shear zone of variable width (Cunningham and Mann 2007; Legg et al. 2007; Waldron et al. 2007; Blick and Biddle 1985; Sylvester and Smith 1976). In this frame, the Taviano and Bardea synclines could be interpreted as “left stepping” distributed folds that tend to align parallel to the boundary of a left-lateral shear zone. As consequence, they should be characterized by a progressive rotation and a strongly non-cylindrical growth; evidence of non-cylindrical folding of Taviano syncline are shown in Sect. 5.1. The left-lateral kinematic of the Cereggio fault and Rivazzo thrust system and the changes from transtensional to transpressional fault array along its length is also in agreement with the development of a left lateral shear zone. The N–S-directed, high-angle left-lateral, transtensive Casa Baraccana fault can be also framed within a transcurrent shear zone; high-angle normal fault being commonly aligned to the direction of the maximum stress. Thus, the association of structures mapped in the study area might belong to a left-lateral transpressive shear zone, at least 2–3 km width, striking NE–SW and responding to a maximum stress directed N–S (Fig. 9).

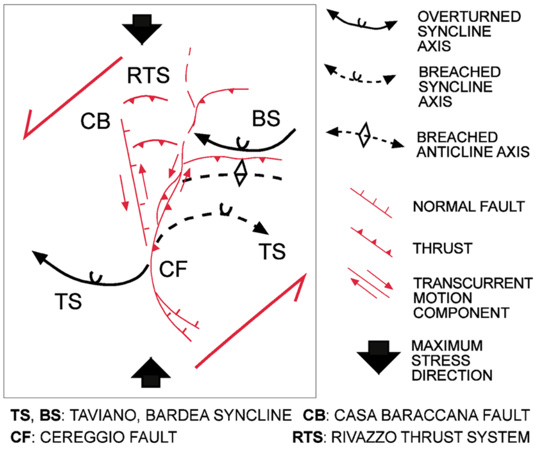

Fig. 9 Schematic model illustrating the association of deformation structures belonging to the EVDZ in the study area (Fig. 4). The tectonic features can be framed in a left-lateral transpressive shear zone

Extending the observations to a wider area (see Fig. 2), the overturned limb of the Bardea syncline can be traced northeastward from the studied area for at least 6 km to the Lonza stream (Bertelli et al. 1984; Cerrina Feroni et al. 2002a, b) where it disappears below the Serravallian deposits of the Cigarello Formation (De Nardo et al. 1991). De Nardo et al. (1991) called this NE–SW trending structure as the Middle Enza Valley Structure. In this case, the shear zone should be even wider than the portion mapped in this study. In the Vetto-Carpineti syncline, other NE–SW trending lineaments are highlighted by morphological highs cored by argillaceous and dismembered Ligurian units (see Fig. 2); they are called Rio Maillo and Mt. Faiedolo (Fig. 2). Papani et al. (1987) interpreted such structures as positive “flower” structures related to a regional transpression. In this context, the transpressive deformation recorded in the Epiligurian units of the study area may represent the shallowest expression of strike-slip-related structures developed in the underling Ligurian units and subparallel to those evidenced by Papani et al. (1987).

It is also useful to remind that the association of structures described in this work cannot be explained with a pure SW–NE (Apenninic) oriented maximum stress; unless, it coincides with a lateral ramp of a main Apenninic thrust. But even in this case, the study area has to represent a transcurrent shear zone. Thus, the mapped structures are part of a "local" NE–SW trending left-lateral shear zone developed in an overall N–S-directed compressive regime and here named Enza Valley Deformation Zone (EVDZ). Assuming that in the Vetto Carpineti syncline, the other NE–SW transpressive lineaments (Rio Maillo, Mt. Faiedolo above cited) behave as the EVDZ, the width of the shear zone could be even 15 km and it should affect the Epiligurian and Ligurian units between Enza and Secchia Valleys (Fig. 2).

6.2 The evidence of syn-sedimentary activity of the EVDZ

In the Sect. 4.3 we have presented clues about the syn-tectonic deposition of the Lagrimone and Antognola units. As testified by the representative facies associations and as suggested by De Nardo et al. (1991), these formations are characterized by narrow depocenters, aligned NE–SW, located in between the major positive structures trending as the EVDZ. This basin system configuration is due to the development of NE–SW-oriented intrabasinal highs, growing to the SE of the main depocentral areas. Consequently the resulting basin evolution scenario is interpreted to be characterized by depocentral zones migrating north–northwestward and progressively involved within the transpressive zones. This situation is schematically reconstructed in the conceptual model of Fig. 10, which shows the evolution of the depocenter near the EVDZ after the deposition of the Ranzano Formation (Early Rupelian stage 1 of Fig. 10). The inception of the EVDZ uplift is evidenced by a major basin-margin reorganization and consequent destabilization, as recorded by the emplacement of MTDs such as the Ran 3b lithofacies at the top of Varano Melegari Member (Ran 3a) (stage 2 in Fig. 10). Thus, it is suggested that the EDVZ started during Rupelian. At this stage, variations in the basin geometry are expressed by the areal (re)distribution of the main depocenters: in particular, the Lagrimone Sandstones deposited only to the NW, and close to the EDVZ (see Fig. 2 and Sect. 4.3), while the older deposits, the Ranzano Formation, are present over all the Vetto-Carpineti syncline (see Figs. 2, 3b). A syn-depositional activity of the EVDZ appears also evident in the Aquitanian–Burdigalian time, with the deposition of Antognola Marls (see Sect. 4.3.2) and the highly-confined turbidite deposits (Villaprara Member; Cerrina Feroni et al. 2002a, b) within a depocenter shifted to the NW (stages 3 and 4 in Fig. 10). The younger evolutionary stages of the EVDZ activity (stage 5–6 in Fig. 10), are deduced by the Langhian–Serravallian sedimentary record of the Bismantova Group (see Fig. 2) which has been controlled by the development of NE–SW trending morphological highs (Papani et al. 1987; Campioli 1989; De Nardo et al. 1991) sub-parallel to the EVDZ (see Sect. 6.1). Shelfal and destabilized shelfal deposits (Pantano formation), on top of the structural highs, rapidly pass to slope and basinal turbidite (Cigarello formation with Vetto member) deposited within the depocenter; these rapid lateral facies changes are the evidence of the submarine morphologies created by the NE–SW trending syn-tectonic lineaments. The isolated and/or interconnected sub-basins were unconformably sealed by the Serravallian deposits of Cigarello Formation (see stage 6 in Fig. 10) marking the last phase of the EVDZ activity. The NW–SE axial direction of the Vetto-Carpineti syncline, well recorded in the Serravallian deposits (see Fig. 2), is related to a post-Serravallian compressional phase (Apenninic), reworking but not completely overprinting the earlier Rupelian-Serravalian EVDZ structures.

This evidence of syn-depositional control of the EVDZ from Rupelian to Serravallian fits with the subsidence rates calculated by Mancin et al. (2006) for this part of the Enza Valley Epiligurian basin. Their reconstruction indicates a general subsidence phase (Late Rupelian–Serravallian) likely due to the progressive inception of the depocentral area along the flanks of the EVDZ. Finally, also the petrographic study by Cibin (1993) and Cibin et al. (2001) highlights the importance of transversal structures in controlling the sediment supply and redistribution: notably, one of such transversal structures, informally called Secchia Line by the authors, may partly coincide with or be parallel to the EVDZ described in this work.

6.3 Was the EVDZ active before the Oligocene? The role of the Late Priabonian–Early Rupelian tectonic phase

In order to investigate the role of EVDZ before Rupelian, the discussion needs to be focused on the complex relationships among the formations underlying the basal unconformity of Ran2a lithofacies (see Sect. 4.1). In the overturned limb of the Taviano syncline this lithofacies lays above the oldest Eocene Epiligurian formations (BAI and MMP; see Fig. 4), which in turn drape the Ligurian stack (from the base to the top CAO, CPP, MCS). On the other hand, over short distance (ca. 2 km) on the normal limb of the Taviano syncline, the same lithofacies onlaps directly upon the Caio Formation (CAO), which is the

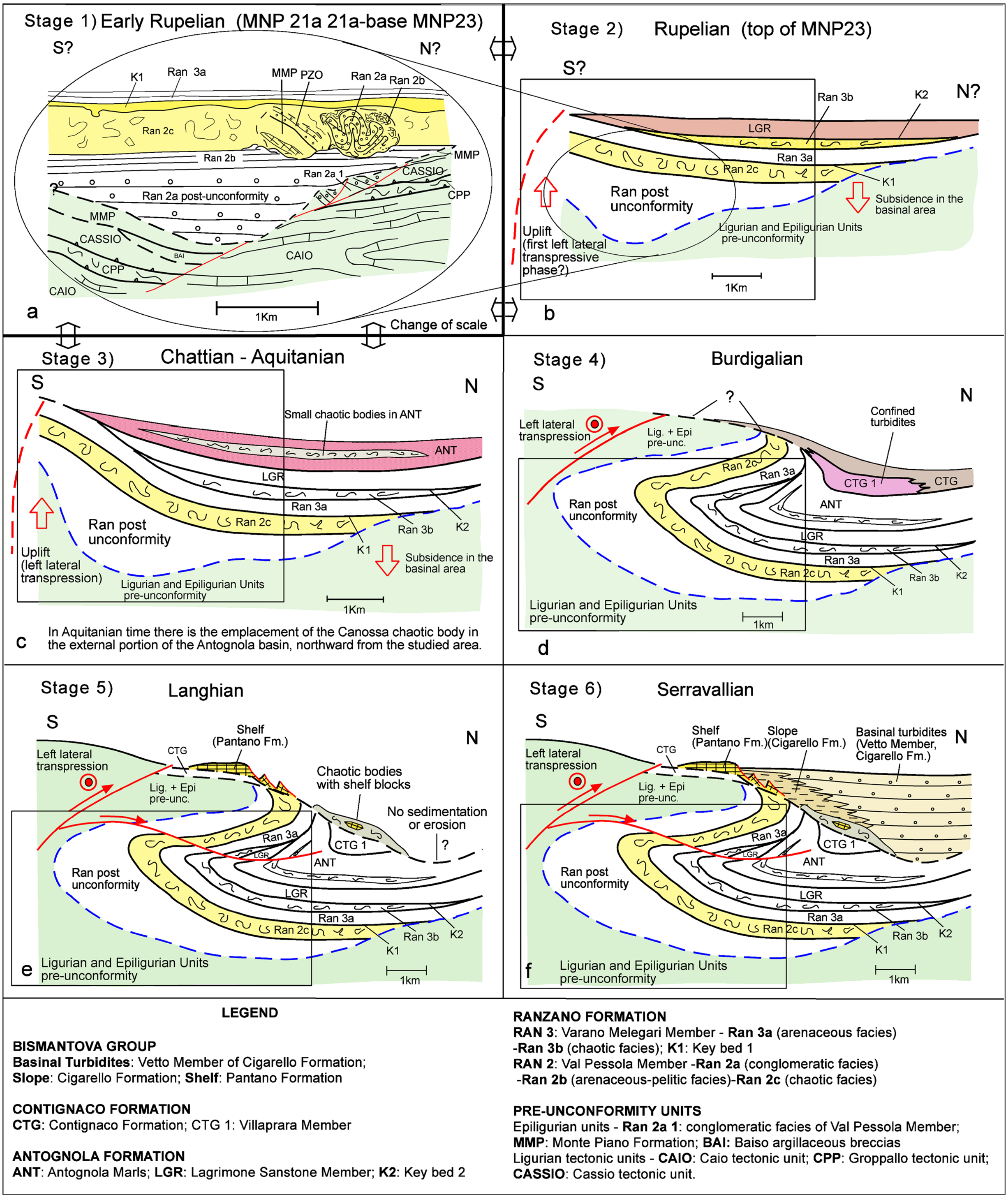

Fig. 10 Conceptual model illustrating a possible stratigraphic and tectonic evolution of the Epiligurian wedge-top basin from Rupelian to Serravallian as derived from present study and from literature (Papani et al. 1987, 2002; De Nardo et al. 1991; Cerrina Feroni et al. 2002a, b). The *scales* indicate order of magnitude and *vertical scale* is exaggerated. Note the change of scale between stages 1 (focusing on the study area of Fig. 4) and stages 2–6 (focusing on the Epiligurian wedge-top basin preserved in the Vetto-Carpineti syncline in Fig. 2); in stages 2–6, the area analyzed in this study is marked by the *rectangle*

deepest Ligurian tectonic units. A way to explain the "exhumation" of the deeper tectonic units and the coeval development of a deep and narrow depocenter hosting the Ran 2a lithofacies, is to assume that the Priabonian–Rupelian basin was tectonically controlled by the development of a major low-angle extensional fault (see stage 1 in Fig. 10). This hypothesis, although still speculative, is supported by analogies with the extensional structures documented in other coeval episutural basins of the Apennines, such as Tertiary Piedimont Basin (Epimesoalpine basins of Mutti et al. 1995; Maino et al. 2013) and exhumation of HP/UHP units in the Alps (Malusà et al. 2011, 2015). This extensional phase occurs when, during the collision between Adria and Europe, the Ligurian (or Mesoalpine) tectonic phase ended (~Lutetian) and the "Apenninic" phase (Mutti et al. 1995) started to create northeast-verging/Apenninic tectonic structures. Within this regional framework the deposition of the oldest Epiligurian units (i.e. Ran 2a lithofacies of the Ranzano Formation) appear to record the development of extensional faults due to significant changes in rates, types and magnitudes of the collisional processes (Argnani 2002). The extension affected the uppermost Ligurian allochthonous prism, before it over thrust on top of the Oligocene foredeep deposits of the Adria plate (see Sect. 2). The available data do not allow to constrain precisely the relationships between this pre-Rupelian extensional event and the transversal fault system of the EVDZ. The Epiligurian succession of the Vetto-Carpineti outlier provides evidence of syn-depositional activity of the EVDZ transpressive tectonics only from (late) Rupelian to Serravallian.

6.4 The EVDZ and the other transversal lineaments of the Northern Apennines

Several transversal structures have been reported in the Northern Apennines through the years (Ghelardoni 1965; Fazzini and Gelmini 1982; Ghunther and Reutter 1985; Castellarin and Vai 1986; Gasperi et al. 1986; Ricci Lucchi 1986a; Vescovi 1988; Bernini et al. 1997; Bernini and Papani 1987; Cibin et al. 2001; Vescovi 2005; Elter et al. 2011). The EVDZ is of particular interest because represents a displaced structure, generated during the Late Oligocene–Middle Miocene, when the Epiligurian basin system on top of the uppermost allochthonous Ligurian units was located more to the SW with respect to the present-day configuration. Nonetheless, between the Enza and Secchia Valleys, transversal structures that might share a genetic relationship with the EVDZ are recognized, possibly extending downward into the deeper tectonic units of the Tuscan–Umbrian domain. Such deep-rooted structures are evidenced by:

1. Kilometric-scale, SW–NE trending and NW-verging folds (M.te Ventasso structure; see Fig. 1b), recognizable in the Chattian–Aquitanian Modino Sandstone and within the Subligurian units (Plesi et al. 2000; Vescovi 2005);
2. The watershed between Enza and Secchia Valleys represents a structural-stratigraphic divide for the Subligurian units (Late Cretaceous–Late Oligocene; Elter et al. 2003; Vescovi 2005; Remitti et al. 2010). The classic Subligurian units stratigraphy to the NW of this watershed (Montanari and Rossi 1982; Vescovi 1998) is distinguished from the Sestola-Vidiciatico tectonic unit (see Fig. 1b), which is tectonically located beneath the Ligurian, as the Subligurian, but it is formed by a 500 m-thick tectonic *mélange* containing mixed gravitationally and tectonically reworked material derived from the frontal part of the Palaeogene Ligurian accretionary prism (Remitti et al. 2010).
3. The Triassic evaporites of the Tuscan Unit largely crop out along the high Secchia Valley, with a NE–SW trend (Fig. 1), tectonically lying on top of the Cervarola unit (Chicchi and Plesi 1991; Andreozzi et al. 1989). The final emplacement of these evaporites might be related to the dragging action of the allochthonous units (i.e. Ligurian and Subligurian; Plesi et al. 2000) in their northeastward movement, and to the development of the arc-shaped Modino structure during the Early-Middle Miocene as suggested by Vescovi (2005).

These observations support the interpretation of one or more major transversal structures crossing the Northern Apennine, active since Palaeogene (Late Rupelian?), which roughly intercept the high Enza and Secchia Valleys. This structure, or these structures, could represent the so-called "Val Secchia line" as introduced by Ghelardoni (1965): a tectonic lineament with a SW–NE trend that borders the Apuane metamorphic complex and it prosecutes northeastward in the Emilian foothills of the Apennines (see Fig. 1). A discussion on the genetic relationship between these transversal structures and their development at different structural levels during time is challenging. Further studies in this direction are needed to better define these transversal tectonic lineaments at a scale of the entire Apennine chain during Palaeogene and Neogene.

7 Conclusions

Detailed geological field mapping, stratigraphic and structural analyses have been carried out in the middle Enza Valley (Parma–Reggio Emilia Provinces, Northern

Italy), within the SW portion of a siliciclastic wedge-top basin (i.e. Epiligurian Vetto-Carpineti syncline) developed on top the evolving Palaeogene–Neogene Apennine orogen. The newly acquired geological data, backed up by review of the available literature, highlight a polyphasic, syn-depositional tectonic evolution of this part of the basin system, which lasted from the Early Oligocene to the Middle Miocene.

Here we present an alternative, updated conceptual evolutionary model, subdivided in transitional stages within a time frame of about 22 Myrs (from Rupelian to Serravallian), defined on the basis of specific basinal morphologies and depositional characters of stratigraphic units, in turn related to the progressive migration and narrowing of the depocentral zone.

This basin system is strictly controlled by the development and evolution of a syn-depositional, left-lateral transpressive system, trending NE–SW, herein named as Enza Valley Deformation Zone (EVDZ). This system trends obliquely to the major NE verging folds and thrusts of this part of the Northern Apennines. This study shows that transversal lineaments such as the EVDZ had an important role in the superficial reshaping, structural rearrangement, accommodation and redistribution of the sedimentary basins and related flow pathways on top of the Apenninic orogenic wedge during its early stages of development (Oligocene–Middle Miocene), remarking the importance of such elements in the tectonic-stratigraphic evolution of orogenic wedges.

Acknowledgments The present study is part of the project on the evolution of post-collisional Apenninic orogenic wedge (FIL0757788-CR07597518 Università degli Studi di Parma—Coord. Andrea Artoni). We wish to thank Paolo Vescovi for his continuous and fruitful helps during the survey and reading a preliminary version of the paper; Giovanni Papani, Giuseppe Ottria and Vincenzo Picotti for their helpful suggestions after reading a preliminary version of the paper; Roberto Tinterri for the suggestions on turbiditic facies. Finally we wish to thank Klaus-Joachim Reutter and Andrea Zanchi for very constructive reviews which largely improved the manuscript. We also thank Wilfrid Winkler for the careful editorial support.

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