Geology of the Curone and Staffora Valleys (NW Italy): field constraints for the Late Cretaceous – Pliocene tectono-stratigraphic evolution of Northern Apennines

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\textbf{ABSTRACT}

In the northwestern part of Northern Apennines, between Curone and Staffora Valleys, the tectonic superposition between the External Ligurian Units (i.e. the ophiolitic-bearing chaotic complex of the Groppallo Unit and the non-ophiolitic Cassio Unit), the Middle Eocene – Miocene wedge-top basin Epliligurian Units succession, and the Late Messinian – Pliocene Po Plain succession, records the multistage tectono-stratigraphic evolution from subduction to continental collision. Our geological map, at the 1:20,000 scale, allows us to define 6 main tectonic stages on the basis of (i) the crosscutting relationships between main faults and local to regional stratigraphic unconformities and (ii) the differentiation among different types of chaotic rock unit (olistostromes and broken formations) deposited since Late Cretaceous to late Messinian. This approach provides a new understanding on the tectono-stratigraphic evolution of this sector, and its meaning in the evolution of the northwestern part of Northern Apennines.

\textbf{1. Introduction}

In the hanging wall of the Apenninic thrust front, the northwestern part of Northern Apennines belt (between Voghera and Piacenza) is characterized by complex structural relationships among discontinuous remnants of ophiolite-bearing chaotic units (e.g. Boccaletti & Coli, 1982) of Late Cretaceous age (i.e. Western External Ligurian Unit, see Marroni & Pandolfi, 2007), non-ophiolitic External Ligurian Units (e.g. Eastern External Ligurian Unit, see Marroni & Pandolfi, 2007), and the overlying wedge-top basin Epliligurian Units (Figure 1). Although this sector is covered by different editions of the Geological Map of Italy (e.g. Bellinzone, Boni, Braga, & Marchetti, 1971; Boni, 1969; Vercesi et al., 2005, 2015), the understanding of the tectono-stratigraphic relationships between these different units is complicated by poor rock exposures and lack of continuous outcrops. A new detailed geological mapping, focused on (i) the crosscutting relationships between main faults and local to regional stratigraphic unconformities and (ii) the differentiation among different types of chaotic rock unit (i.e. olistostromes and broken formations) of various age, provides further specific data covering the partial lack of geological information, allowing a new understanding on the tectono-stratigraphic evolution of this sector and its meaning in the evolution of the northwestern part of Northern Apennines.

On the basis of a new geological mapping at the 1:5000 scale, detailed structural and stratigraphic observations, and targeted collection of biostratigraphic data, we present the ‘Geological map of the Curone and Staffora Valleys (Northern Apennines, Italy)’ (see Main Map) at the 1:20,000 scale. This Geological Map represents the northern prolongation of the ‘Geological Map of the Villalvernia – Varzi Line between Scrivia and Curone valleys (NW Italy)’ by Festa, Fioraso, Bissacca, and Petrizzo (2015).

\textbf{2. Methods}

The geological map was produced from about four years (2014–2017) of fieldwork at the 1:5000 scale and accompanying detailed structural analyses and stratigraphic observations. The definition of the structural setting of the sector was defined through the mapping of the crosscutting relationships between main faults and local to regional stratigraphic unconformities that are documented in the attached geological map at the 1:20,000 scale (see Main Map), using the topographic maps ‘CTR – Carta Tecnica Regionale’ of Regione Piemonte and Regione Lombardia. The dis-
tinction among different types of chaotic rock units (i.e. olistostromes and broken formations) followed specific criteria defined in literature (e.g. Bettelli & Panini, 1989; Bettelli, Conti, Panini, & Vannucchi, 2006; Dilek, Festa, Ogawa, & Pini, 2012; Festa, Dilek, Codgone, Cavagna, & Pini, 2013; Festa, Ogata, Pini, Dilek, & Alonso, 2016; Festa, Pini, Dilek, & Codgone, 2010; Pini, 1999). The geological map was edited using the methodological cartographic and representative criteria from the CARG Project (Project of Geological Cartography) of Italy, at the 1:50,000 scale (see Pasquaré, Abbate, Bosi, et al., 1992; Pasquaré, Abbate, Castiglioni, et al., 1992).

3. Regional setting

The Northern Apennines (Figure 1) record the complex evolution from Late Cretaceous subduction to Cenozoic continental collision between the European plate and Adria microplate and subsequent intra-continental deformation (e.g. Coward & Dietrich, 1989; Elter, Grasso, Parotto, & Vezzani, 2003; Festa, Pini, Dilek, Codgone, Vezzani, et al., 2010; Handy, Schmid, Bousquet, Kissling, & Bernoulli, 2010; Marroni, Mencighini, & Pandolfi, 2010; Molli, Crispini, Mosca, Piana, & Federico, 2010). The Late Cretaceous – Early Eocene accretionary stage has been recorded in the complex evolution of the Ligurian accretionary complex, which consists of different units containing tectono-sedimentary assemblages originally deposited in an ocean basin (i.e. Jurassic ophiolites and sedimentary cover of the Internal Ligurian Units), ocean-continental transition zone (External Ligurian Units), and thinned continental crust of the Adria margin (Subligurian Units), respectively. During the Late Cretaceous through Middle Eocene, these different units were deformed and incorporated into the Alpine accretionary wedge, formed as consequence of the east-dipping ‘Alpine’ subduction (i.e. Elter, 1975; Marroni et al., 2010; Marroni, Molli, Ottria, & Pandolfi, 2001; Principi & Treves, 1984). Since the Middle Eocene, the thinned continental margin of Adria was involved in the W-dipping Apennine subduction (e.g. Castellarin, 1994; Handy et al., 2010; Marroni et al., 2010; Molli et al., 2010; Schmid, Kissling, Diehl, van Hinsbergen, & Molli, 2017; Vezzani et al., 2010). The External Ligurian Units underthrust below the Internal Ligurian Units and together overlie the Subligurian Units, ultimately forming the frontal part of the advancing Ligurian accretionary complex, which, in turn, overthrust the deformed Adria continental margin. During the progressive incorporation into the accretionary
wedge, a consistent part of the External Ligurian Units (i.e. the Lower to Upper Cretaceous ‘Basal Complex’) was strongly deformed by tectonic processes forming broken formations and tectonic mélanges (e.g. Bettelli & Panini, 1989; Codegone, Festa, Dilek, & Pini, 2012; Festa et al., 2013; Festa, Pini, Dilek, Codegone, Vezzani, et al., 2010; Pini, 1999; Remitti et al., 2011). Since the Middle – Late Eocene, different episutural and wedge-top basins (i.e. Tertiary Piedmont Basin and Epiligurian Units, respectively) unconformably covered the Ligurian accretionary complex (Figure 1) and the N- to NE-verging thrust-related structures (e.g. Mosca, Polino, Rogledi, & Rossi, 2010; Mutti et al., 1995; Ricci Lucchi, 1986).

Different mass-transport deposits, including olistostromes (i.e. sedimentary mélanges), occur at different stratigraphic levels within both the External Ligurian Units and Epiligurian Units, representing excellent markers of tectonic events (e.g. Festa et al., 2016; see also Bettelli & Panini, 1989; Codegone et al., 2012; Festa et al., 2013; Festa, Fioraso, et al., 2015; Ogata, Mountjoy, Pini, Festa, & Tinterri, 2014; Piazza, Artoni, & Ogata, 2016; Pini, 1999; Remitti et al., 2011).

4. Data

The study sector (Figure 1), which is located between Curone and Staffora Valleys, is characterized by complex tectono-stratigraphic relationships between two different units of the External Ligurian Succession, represented by the Groppallo Unit (e.g. Vercesi et al., 2015) and the Cassio Unit (e.g. Elter, Elter, Sturani, & Weidmann, 1966; Vescovi, Fornaciari, Rio, & Valloni, 1999). These units are unconformably overlain by the Middle Eocene – Miocene Epiligurian Succession. To the north, this complex tectono-stratigraphic setting is sealed by the late Messinian – Early Pliocene succession.

4.1. Stratigraphy

4.1.1. External Ligurian Units

The stratigraphic succession (Chronostratigraphic Scheme in Main Map) of the Cassio Unit shows a complete transition from the ‘Basal Complex’ (Scabiazza Sandstone and Argille Varicolori) to the late Maastrichtian – Late Palaeocene Viano Clays. The Scabiazza Sandstone (SCB in the Main Map, late Albanian– Santonian) consists of a strongly disrupted chaotic succession (broken formation sensu Hsü, 1968) with bed fragments of whitish micaceous sandstones, embedded into a pelitic- to argillaceous matrix (Figure 2(a,b)). The analysis of calcareous nannofossils shows mixing of Late Albanian, Aptian-Albian, Early Cretaceous and Early Jurassic taxa, and few taxa younger than Coniacian. The Argille Varicolori (AVV in the Main Map, Varicolored scaly clays; Santonian – Campanian; Figure 2(c)) also represent a highly disrupted broken formation with blocks (limestones, sandstones, and manganiferous siltstones), deriving from stratal disruption of the primary lithostratigraphic unit, embedded in a varicolored (gray, red, and purple) clays and shales matrix. Tens of meters thick body of Salti del Diavolo Conglomerate (AVV1 in the Main Map, Figure 2(d)), with clasts consisting of prevailing carbonate rocks and minor micaschist, gneiss, quartzite, granulite, pinkish granite and diorite, are interbedded within the Argille Varicolori. The latter are overlain by the late Campanian Monte Cassio Flysch (MCS in the Main Map, Figure 2(e)), which consists of alternating beds of clayey marls and carbonate-rich calcareous-marly turbidites, dm to m thick. The Viano Clay (AVI in the Main Map, late Maastrichtian – Late Palaeocene), consisting of alternating layers of claystones and less abundant limestones in dm thick beds, closes upward the stratigraphic succession of the Cassio Unit.

The Groppallo Unit consists of a chaotic complex with a block-in-matrix fabric (the Pietra Parcellara Complex – CPP in the Main Map), up to 150 m (or more) in thickness, in which heterogeneous blocks, up to hundreds of m in size (Figure 2(f)), are randomly distributed in a matrix of coarse-grained ophiolitic sandstones (Figure 2(g,h)) and polymictic argillaceous breccias. Huge blocks (olistoliths) are represented by mantle ultramafic rocks (i.e. spinel-lherzolites) locally intruded by small gabbro bodies, while clasts consist of lherzolites, gabbros, bed fragments of Calpionella Limestone and Palombini Shale, minor basalt/s, cherts (i.e. Radiolarites) and granitoids. It is worth noting that, although the nature of blocks and clasts of this Unit closely resemble that one of the Casanova Complex Auct. (sensu Bertotti, Elter, Marroni, Mecccheri, & Santi, 1986; Elter, Marroni, Molli, & Pandolfi, 1991; Marroni et al., 2001) rather than the classical one described for the Pietra Parcellara Complex (see, e.g. Marroni et al., 2010; Vercesi et al., 2015), we prefer to maintain this last formational name because its structural position is well consistent with that of the Gropallo Unit described in the Northern Apennines (e.g. Vercesi et al., 2005; 2015). Analyses of calcareous nannofossils show an early Campanian age (CC18 zone of Sissingh, 1977) for the uppermost part of this chaotic complex.

4.1.2. Epiligurian Succession

The Epiligurian Succession starts with the Bajo Argillaceous Breccias (BAI in the Main Map, Lutetian – Bartonian) (Figure 3(a)), which consist of a lenticular and laterally discontinuous mass-transport chaotic deposit (olistostrome) sourced from the downslope dismemberment of the ‘Basal Complex’ and Monte Cassio Flysch. They pass upward (and local laterally) to hemipelagic clays and marls of the Monte Piano Marls (MMP in the Main Map, Lutetian – Priabonian) (Figure 3(b,c)), which are overlain through an erosive
unconformity surface (Figure 3(b)) by turbidites of the Ranzano Formation. The latter, which is locally deposited directly above the External Ligurian Succession, is subdivided in three superimposed members (Pizzo d’Oca Member – RAN1 in the Main Map – of late Pria-bonian age, Val Pessola Member – RAN2 – of late Pria-bonian – early Rupelian age, and Varano de’ Melegari Member – RAN3 – of middle – late Rupelian age; Figure 3(b), (d), and (e)), which differ for the stratigraphic position and petrographic composition of lithic fragments (see, e.g. Cibin, Di Giulio, & Martelli, 2003; Martelli, Cibin, Di Giulio, & Catanzariti, 1998; Mutti et al., 1995). The succession continued, through an unconformity surface, with the slope fine-grained hemipelagic deposits of the Antognola Formation (ANT and ANT1a in the Main Map, late Rupelian – Aquitanian), which includes olistostromal lenticular bodies, up to 60 m thick, of the Val
Tiepido–Canossa Argillaceous Breccias (ANT1b in the Main Map, i.e. ‘Complesso caotico pluriformazionale’ of Gelati, Bruzzi, Catasta, & Cattaneo, 1974; Figure 3 (f)) of Late Chattian age (planktonic foraminiferal zone IFP22 (P22) of Mancin, Pirini, Bicchi, Ferrero, & Valleri, 2003; see Festa, Ogata, Pini, Dilek, & Codegone, 2015). Blocks embedded within the olistostrome are sourced from both the External Ligurian Succession and Epiligurian Succession (Monte Piano Marls and Ranzano Formation). The siliceous marls of
Contignaco Formation (CTG in the Main Map, late Aquitanian – Burdigalian; see Figure 3(g)) drape both the Ranzano Formation and Antognola Formation. The stratigraphic contact with Ranzano Formation (Colletta sector) corresponds to an angular unconformity, which passes laterally to a correlative conformity (Case Cucchi sector) where the Contignaco Formation overlies the Antognola Formation. In the latter sector, locally, the lower part of the Contignaco Formation is characterized by slumping structures. The Monte Lisone Chaotic Complex (CML in the Main Map, Late Burdigalian – Langhian?), which represents another mass-transport chaotic deposit (olistostrome), rests unconformably on both the uppermost part of the External Ligurian Succession and the Antognola Formation. It differs from the above described olistostromes on the basis of the nature of blocks, consisting of only disrupted bed fragments of Helminthoides Flysch, and to the South of the studied sector it is overlain by the Monte Vallassa Sandstone (see Festa, Fioraso, et al., 2015 for major details). The Epi- 
ligurian Succession continues through a regional unconformity with the shallow and coarse shelf deposits of the Monte Vallassa Sandstone (AMV in the Main Map, Gelati & Vercesi, 1994) of the Bismantova Group, its members of the Monte Piano Marls and the Ranzano Formation; see cross sections 2, 3 and 4 in Main Map. This deformation zone juxtaposes the Scabiazza Sandstone (northeastern side), the Monte Cassio Flysch and the Scabiazza Sandstone (southwestern side) onto the Pietra Parcellara Complex (see cross section 2 in Main Map). Along the northeastern side of the tectonic window, the Scabiazza Sandstone is locally involved by thrust splays and imbricated with the Pietra Parcellara Complex, forming lenticular tectonic slices, hundreds of m in length. To ENE, the footwall of the BST is characterized by a hundreds of meters wide and 5 km long deformation zone (San Desiderio Deformation Zone – SDDZ hereafter), which is about WNW- ESE oriented to the West and East sectors of the Staffora Valley, respectively (Figure 4(c)). Mesoscale structural associations (S-C shears; Figure 4(d)) and fault striations (slickenlines) show transpressive right-lateral movements, according to the cartographic displacement of stratigraphic contacts observed in the Map. This deformation zone juxtaposes the Monte Cassio Flysch and the Argille Varicolori to different terms of the Epiiligurian Succession (i.e. Baiso Argillaceous Breccias, Monte Piano Marls and Ranzano Formation; see cross sections 2, 3 and 4 in Main Map; Figure 4(c)). Far from faults bounding the SDDZ, the Argille Varicolori preserve an earlier
layer-parallel extensional block-in-matrix fabric, which is deformed by rootless and transposed folds (Figure 4(e,f)). The latters are characterized by curviplanar axial surfaces, with fold axes displaying a broad girdle with WNW- and ESE-oriented maxima (Figure 4(a,e)), and asymmetrical boudinaged limbs by R and C' shears along NE-SW cross sections, commonly displaced by localized shear zones.

The tectonic setting above described is cut by two main fault systems, NW- and N-striking. The former
corresponds to pluri-km long faults, which cut with left-lateral movements, reactivated by right-lateral ones as shown by fault striations (slickenlines) on fault surfaces (Figure 4(a)) and S-C shears, both the BST and the SDDZ (see Main Map). From East to West of the NW-striking fault of the Curone Valley, the main fold axes, bedding surfaces, and stratigraphic boundaries are gradually rotated from ENE-WSW to WNW-ESE directions and cut by NE-striking faults to the West of that Valley (see Main Map).

The N-striking fault system shows best exposures only in the northeaster sector of the studied area (East of Mt. Treno), representing the southern prolongation of the Pliocene Schizzola Valley Fault of Perotti and Vercesi (1991) and Vercesi et al. (2015). The latter defines a hundreds of meters wide deformation zone, with left-lateral kinematics (e.g. Vercesi et al., 2015), bounded by interlaced subvertical faults with anastomosed geometry.

5. Conclusions

The crosscutting relationships between mapped faults and stratigraphic unconformities, and the distinction of different types of chaotic rock unit, allow describing a detailed tectono-stratigraphic evolution of this sector of the Northern Apennines. Six main tectonic stages have been defined from Late Cretaceous to Pliocene (Figure 5(a,b)).

- **Late Cretaceous – Early Eocene:** this tectonic stage preserves the record of both gravitational (i.e.olistostrome) and tectonic-induced (i.e. broken formation) deformation related to the evolution at shallow structural levels of the External Ligurian wedge during the subduction stage. The random distribution of polymictic blocks within the matrix of the Pietra Parcellara Complex (Groppallo Unit) is consistent with mass-transport processes occurred at the wedge front during Campanian time (Figure 5(b), Eoalpine Phase of Elter et al., 1966; see also, Bertotti et al., 1986; Elter et al., 1991). On the contrary, far from the main faults of the SDDZ, the orientation and distribution of fold axes (with WNW- and ESE-oriented maxima) within the Argille Varicolori is consistent with the tectonic deformation related to NE-SW to NNE-SSW shortening directions, which are commonly attributed (e.g. Cerrina Feroni, Ottria, Martinelli, & Martelli, 2002; Elter & Marroni, 1991; Levi, Ellero, Ottria, & Pandolfi, 2006) to the Paleocene – Early Eocene European verging overthrust (Figure 5(b)) of the Helminthoides Flysch nappe onto the ‘Basal Complex’. The characteristics of mesoscale deformation within the Argille Varicolori (see ‘Tectonic setting’) well agree with deformation occurred in the frontal and shallower levels of the External Ligurian wedge, affecting unconsolidated sediments in the latest stages of accretion (e.g. Bettelli & Vannucchi, 2003; Festa et al., 2013; Festa & Codegone, 2013; Pini, 1999). Although the time for tectonic superposition of the Cassio Unit onto the Groppallo Unit is difficult to constrain because of the lack of a detailed stratigraphic marker, the lack of involvement of Epiligurian Succession suggests it occurred earlier than Middle Eocene time (Figure 5(a,b)). Regarding the Cassio Unit, it is worth noting that the age of the Scabiazzia Sandstone (late Albain – Santonian) is similar to that one observed in the Media Val Taro Unit (see, Vescovi et al., 2002; see also Ostia Sandstone of Vescovi et al., 1999) and in the Cabella Ligure sector (see, Marroni, Ottria, & Pandolfi, 2015), and younger than that one commonly described for the classical Cassio Unit (i.e. Cenomanian – Turonian). Although additional investigations are needed, these data suggest the deposition of this Formation in an outer sector of the Cassio basin (with respect to the West-verging ‘Alpine’ accretionary wedge), providing new constraints for a more detailed reconstruction of the internal physiography of the depositional environment of the External Ligurian Succession.

- **Middle Eocene (Lutetian – Bartonian):** the wide occurrence of the Baiso Argillaceous Breccias along the SDDZ, ENE- to WNW-oriented, and their increase in thickness away from it, suggest that this deformation zone was active at least since Middle Eocene (Figure 5(a,b)), favoring mass-transport processes triggered by the tectonic uplift of the ‘Basal Complex’ and Monte Cassio Flysch. Unfortunately, a detailed description of Middle Eocene kinematics of the SDDZ is hampered by late Messinian – Early Pliocene right-lateral reactivations of main faults (see below ‘Late Messinian – Early Pliocene’ stage). This mass-transport event marks an important stage of the regional scale instability of the External Ligurian wedge (e.g. Bettelli & Panini, 1989), which can be related to the early stage of continental collision (Mesoalpine stage or Ligurian Phase, e.g. Cerrina Feroni, Ottria, & Ellero, 2004; Elter, 1975; Marroni et al., 2010; Mutti et al., 1995). The uppermost temporal constrain to this tectonic stage is represented by the unconformable deposition of the Ranzano Formation (Late Eocene – Early Oligocene) onto both the Baiso Argillaceous Breccias and External Ligurian Succession (Figure 5(a,b)).

- **Late Priabonian – Rupelian:** the NE- and N-striking normal faults, which displace the lower portion of the Epiligurian Succession, controlled the physiography of Late Eocene – Early Oligocene depositional basin as suggested by both the E-W change in thickness of the Val Pessola Mb. and Varano de’ Melegari Mb. of the Ranzano Formation (see
cross section 1 in Main Map, Figure 5(a)). At the regional scale, this stage is close associated with faulting along the Villalvernia – Varzi Line, which controlled the depositional settings of both the Tertiary Piedmont Basin and Epiligurian Succession (e.g. Di Biase, Marroni, & Pandolfi, 1997; Di Giulio & Galbiati, 1995; Felletti, 2002; Festa, Fioraso, et al., 2015; Marroni et al., 2002; Mutti et al., 1995), and corresponds to the Ligurian phase II of Mutti et al. (1995) and Faulting stage A of Piana (2000) and Festa et al. (2005, 2013), Festa, Fioraso, et al. (2015), which are related to the opening of the Balearic Sea. The deposition of the Antognola Formation (late Rupelian – Aquitanian), which unconformably overlains different terms of the Ranzano Formation and External Ligurian Succession, provides the temporal constrain for this tectonic stage (Figure 5(a,b)).
Late Serravallian – Chattian: the former extensional regime was inverted to a compressional one that accompanied the deposition of the Antognola Formation. This stage is mostly recorded along the MVDZ, developed by the interlacing of ENE-striking transpressive right-lateral faults and E-striking transpressive left-lateral ones, and the widespread occurrence of olistostromes of the Val Tiepido – Canossa Argillaceous Breccias, which sourced from denudation of uplifted External Ligurian Succession and the lower part of Epiligurian Succession. In the southwestern sector of the study area, submarine structural highs formed during the Middle Eocene – Rupelian stage were sealed by the unconformable deposition of the Contignaco Formation (Colletta sector; see cross section 3, Figure 5(a,b)). Toward east (e.g. Case Cucchi sector), the occurrence of slumping in the lower part of the Contignaco Formation marks the paleo-scarp connecting the structural highs with a seafloor basinal low, where the unconformity surface at the base of the Contignaco Formation passes gradually to a correlative conformity. A second pulse of gravitational instability occurred in the Burdigalian – Langhian(?) as suggested by the mass-transport emplacement of the Monte Lisone Chaotic Complex. This tectonic stage was definitively sealed by the Monte Vallassa Sandstone, which unconformably overlain faults associated with the MVDZ (Figure 5(a,b)). At the regional scale, this stage is related to the migration toward NE of the Apenninic thrust front (Ligurian Phase III of Mutti et al., 1995; Faulting Stage B of Festa et al., 2005, 2013; Piana, 2000; see also Piazza et al., 2016).

Late Serravallian – Tortonian(?): The NNW-verging migration of BST, ENE-striking, and the deformation of the Epiligurian Succession with ENE-directed fold axis, well agree with this tectonic stage. The left-lateral NW-striking faults, which displace the lateral continuity of the BST, probably worked as transfer faults (Figure 5(a,b)) as documented to the south of the study area for the left-lateral Sarizzola Fault Zone, NW-striking, which cuts the Villalvernia – Varzi Fault Zone (see Festa, Fioraso, et al., 2015). At the regional scale, this tectonic stage is related to the north-westward propagation of Apenninic thrust system (e.g. Festa et al., 2005; Mosca et al., 2010; Piana, 2000), during which left-lateral NW-faults represented transfer faults (Costa, 2003). Although only minor evidences are preserved in the mapped area, the uppermost temporal constrain to this tectonic stage is represented by the unconformity at the base of the late Messinian Valle Versa Chaotic Complex immediately to the south (Figure 5(b); e.g. Festa, Fioraso, et al., 2015 and reference therein.

Late Messinian – Early Pliocene: tectonic deformation triggered the mass-transport emplacement of the Valle Versa Chaotic Complex. NW-striking transtensional faults cut both the SDDZ and the BST (Figure 5(a,b)). At the northern boundary of the SDDZ, this caused the juxtaposition of the Argille Varicolori to the late Messinian – Early Pliocene succession, while across the Curone Valley it separates sectors characterized by a gradual reorientation of both the late Priabonian – Rupelian faults (from N- to NE-striking; Figure 5(a)) and the main fold axes (from ENE- to NW-striking; Figure 5(a)). This reorientation suggests a refolding of earliest main tectonic features, during which the NW-striking fault of the Curone Valley acted as transfer fault, accommodating part of this deformation (Figure 5(a)). To the West of the Curone Valley, the displacement of fold axial plane along NE-striking faults also suggests the reactivation of those faults, which controlled the deposition of the Ranzano Formation during the late Priabonian – Rupelian stage. At the regional scale, this stage is related to the N-S shortening that caused a further northward migration of the Apenninic frontal thrust (Faulting Stage D of Festa et al., 2005; see also Artoni et al., 2010; Festa, 2011; Mosca et al., 2010). Finally, the N-striking Schizzola valley fault, which cuts the SDDZ, probably represents a fault system younger than Early Pliocene as suggested by Perotti and Vercesi (1991) and Vercesi et al. (2015).

Software

The geological map and map inclusions were digitized and edited with Adobe Illustrator CC.

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Festa, A., Dilek, Y., Codegone, G., Cavagna, S., & Pini, G. A. (2013). Structural anatomy of the Ligurian accretionary wedge (Monferrato, NW Italy), and evolution of superposed mélanges. *Geological Society of America Bulletin*, 125(9–10), 1580–1598. doi:10.1130/B30847.1

Festa, A., Dilek, Y., Codegone, G., Cavagna, S., Pini, G. A., & Valleri, G. (2015). Late Oligocene – early Miocene olistostromes (sedimentary mélanges) as tectono-stratigraphic constraints to the geodynamic evolution of the exhumed Ligurian accretionary complex (Northern Apennines, NW Italy). *International Geology Review*, 57, 540–562. doi:10.1080/00206814.2014.931260

Festa, A., Piana, F., Dela Pierre, F., Malusà, M. G., Mosca, P., & Polino, R. (2005). Oligocene-Neogene kinematic constraints in the retroforeland basin of the Northwestern Apls. *Rendiconti della Società Geologica Italiana (nuova serie)*, 1, 107–108.

Festa, A., Pini, G. A., Dilek, Y., & Codegone, G. (2010). Mélanges and melange-forming processes: A historical overview and new concepts. In Y. Dilek (Ed.), *Alpine Concept in Geology*. *International Geology Review*, 52 (10–12), 1040–1105. doi:10.2113/GSRGEO20100355704

Festa, A., Pini, G. A., Dilek, Y., Codegone, G., Vezzani, L., Ghisetti, F., Lucente, C. C., & Ogata, K. (2010). Adriatic mélanges and their evolution in the Thetyan realm. In Y. Dilek (Ed.), *Eastern Mediterranean geodynamics (Part II)*. *International Geology Review*, 52(4–6), 369–406.

Fornaciari, E., & Rio, D. (1996). Latest Oligocene to early middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean area. *Micropaleontology*, 42, 1–36.

Gelati, R., Buzzi, D., Catasta, G., & Cattaneo, P. C. (1974). Evoluzione stratigráfico – structurale nell’Appennino vogherese a nord-est della Val Staffora. *Rivista Italiana di Paleontologia e Stratigrafia*, 40, 479–514.

Gelati, R., & Vercesi, P. L. (1994). Itinerario N8 3. Da Voghera a Tortona (Km 120). Geologia delle Valli Staffora, Curone, Grue: le Successioni Epiliguri a nord della Linea Villalvernia – Varzi. *Guida Geologiche Regionali S.G.I.*, N° 6, BE-MA Editrice, 157–174.

Handy, M. R., Schmid, S. M., Bousquet, R., Kissling, E., & Bernoulli, D. (2010). Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. *Earth-Science Reviews*, 102, 121–158.

Hsu, K. J. (1968). Principles of mélanges and their bearing on the Franciscan-Knoxville paradox. *Geological Society of America Bulletin*, 79, 1063–1074.

Levi, N., Ellero, A., Ottria, G., & Pandolfi, L. (2006). Polyorogenic deformation history recognized at very shallow structural levels: The case of the Antola Unit (Northern Apennines, Italy). *Journal of Structural Geology*, 28, 1694–1709.

Mancin, N., Pirini, C., Bicchi, E., Ferrero, E., & Vallieri, G. (2003). Middle Eocene to Early Miocene planktonic foraminiferal biostratigraphy for internal basins (Monferrato and Northern Apennines, Italy). *Micropaleontology*, 49(4), 341–358.

Marroni, M., Feroni, A. C., Di Biase, D., Ottria, G., Pandolfi, L., & Taini, A. (2002). Polyphase folding at upper structural levels in the Borbera Valley (Northern Apennines, Italy): Implications for the tectonic evolution of the link-age area between Alps and Apennines. *Comptes Rendus Geoscience*, 334, 565–572.

Marroni, M., Meneghini, F., & Pandolfi, L. (2010). Anatomy of the Ligure-Piemontese subduction system: evidence from Late Cretaceous-middle Eocene convergent margin deposits in the Northern Apennines, Italy. *International Geology Review*, 52, 1169–1192.

Marroni, M., Molli, G., Ottria, G., & Pandolfi, L. (2001). Tectono-sedimentary evolution of the External Liguride units (Northern Apennines, Italy): Insights in the pre-collisional history of a fossil ocean-continent transition zone. *Geodinamica Acta*, 14, 307–320.

Marroni, M., Ottria, G., & Pandolfi, L. (2015). Carta Geologica d’Italia alla scala 1:50.000. Foglio 196 ‘Cabella Liure’. ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale, 1 sheet at 1:50,000 scale and illustrative notes.

Marroni, M., & Pandolfi, L. (2007). The architecture of the Jurassic Ligure-Piemontese oceanic basin: Tentative reconstruction along the Northern Apennine-Alpine Corsica transect. *International Journal of Earth Science*, 96, 1059–1078.

Martelli, L., Cibin, U., Di Giulio, A., & Catanzariti, R. (1998). Litostratigrafia della Formazione di Ranzano (Priaonianu-Rupeliano, Appennino Settentrionale e Bacino Terziario Piemontese). *Bollettino Della Società Geologica Italiana*, 117, 151–185.

Martini, E. (1971). Standard Tertiary and Quaternary calcareous nannoplankton zonation. In A. Farinacci (Ed.), Proceedings of the second planktonic conference, Roma 1970: Edizioni Tecnoscienza, 2, 739–785.

Molli, G., Crispini, L., Mosca, P., Piana, P., & Federico, L. (2010). Geology of the Western Alps-Northern Apennine junction area: A regional review. *Journal of the Virtual Explorer*, 36, paper 10 of the electronic edition ISSN 1441-8142.

Mosca, P., Polino, R., Rogledi, S., & Rossi, M. (2010). New data for the kinematic interpretation of the Alp-Appennine junction (northernwestern Italy). *International Journal of Earth Sciences*, 99, 833–849.

Mutti, E., Papani, L., Di Biase, D., Davoli, G., Mora, S., Segadelli, S., & Tinterri, R. (1995). Il Bacino Terziario Epimesoalpino e le sue implicazioni sui rapporti tra Alpi ed Appennini. *Memorie della Società Geologica di Padova*, 47, 217–244.

Ogata, K., Montjoyt, J.J., Pini, G.A., Festa, A., & Tinterri, E. (2014). Shear zone liquefaction in mass transport deposit emplacement: A multi-scale integration of seismic reflection and outcrop data. *Marine Geology*, 356(Special Issue), 50–64.

Paspasár, G., Abbate, E., Bosi, C., Castiglioni, G. B., Merenda, L., Mutti, E.,...Sassi, F. P. (1992). *Carta Geologica d’Italia – 1:50.000. Guida al Rilevamento. Servizio Geologico Nazionale*. Quaderni serie III. Vol. 1, 203 pp.

Pasquaré, G., Abbate, E., Castiglioni, G. B., Merenda, L., Mutti, E.,...Sassi, F. P. (1992). *Guida al rilevamento e all’informatizzazione della Carta Geologica d’Italia alla scala 1:50,000. Quaderni del Servizio Geologico Nazionale*. Serie III, 1, 203.
Perotti, C., & Vercesi, P. L. (1991). Assetto tettonico ed evolu-zione strutturale recente della porzione nord-occidentale dell’Appennino emiliano. Memorie Descrittive della Carta Geologica d’Italia, 46, 313–326.
Piana, F. (2000). Structural features of Western Monferrato (Alps-Apennines junction zone, NW Italy). Tectonics, 19, 943–960.
Piazza, A., Artoni, A., & Ogata, K. (2016). The Epiligurian wedge-top succession in the Enza Valley (Northern Apennines): Evidence of a syn-depositional transpressive system. Swiss Journal of Geosciences, 110, 581–612.
Sissingh, W. (1977). Biostratigraphy of Cretaceous calcareous nanoplankton. Geologie en Mijnbouw, 56, 37–65.
Vercesi, P. L., Falletti, P., Pasquini, C., Papani, L., Perotti, C., & Tucci, G. (2015). Carta Geologica d’Italia alla scala 1:50.000. Foglio 178 ‘Voghera’. ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale, 1 sheet at 1:50,000 scale and illustrative notes.
Vercesi, P. L., Piccin, A., Di Dio, G., Rio, D., Catanzariti, R., Cobianchi, M., … Valloni, R. (2005). Carta Geologica d’Italia alla scala 1:50.000. Foglio 179 ‘Ponte dell’Olio’. ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale, 1 sheet at 1:50,000 scale and illustrative notes.
Vescovi, P., Andreozzi, M., Lasagna, S., Martelli, L., Truffelli, G., Rio, D., … Cibin, U. (2002). Carta Geologica d’Italia alla scala 1:50.000. Foglio 216 ‘Borgo Val di Taro’. ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale, 1 sheet at 1:50,000 scale and illustrative notes.
Vescovi, P., Fornaciari, E., Rio, D., & Valloni, R. (1999). The Basal Complex stratigraphy of the Helmintoid Monte Cassio Flysch: A key to the eo-alpine tectonics of the Northern Apennines. Rivista Italiana di Paleontologia e Stratigrafia, 105, 101–128.
Vezzani, L., Festa, A., & Ghisetti, F. (2010). Geology and Tectonic evolution of the Central-Southern Apennines. Italy. Geological Society of America Special Paper 469, pp. 58, accompanying by a CD-ROM including the “Geological-Structural Map of the Central-Southern Apennines (Italy)” at 1:250.000 scale, Sheets 1 and 2. doi.org/10.1130/2010.2469