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)

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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)

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Abstract
In the Northern Apennines of Italy, mud-rich olistostromes (sedimentary mélanges) occur at different stratigraphic levels within late Oligocene – early Miocene sedimentary record of episutural/wedge-top basins. They are widely distributed along the exhumed outer part of the Ligurian accretionary complex, atop of the outer Apenninic prowedge, over an area of about 300 km long and 10-15 km wide. Olistostromes represent excellent examples of ancient submarine mass-transport complexes (MTCs), consisting of stacked cohesive debris flows that can be directly compared with some of those observed in modern accretionary wedges. We describe the internal arrangement of olistostrome occurrences in the sector between Voghera and the Monferrato, analyzing their relationships with mesoscale liquefaction features, which are commonly difficult to observe in modern MTCs. Slope failures occurred in isolated sectors along the wedge front, where out-of-sequence thrusting, seismicity and different pulses of overpressured tectonically-induced fluid flows acted concomitantly. Referring to the Northern Apennines regional geology, we also point out a gradual lateral rejuvenation (from late Oligocene to early Miocene) toward the SE and an increasing in size and thickness of the olistostromes along the strike of the frontal Apenninic prowedge. This suggests that morphological reshaping of the outer prowedge via mass transport processes balanced with different pulses in a short time span the SE-ward migration and segmentation of the accretionary processes. The latter have been probably favored by the occurrence in the northwestern part of the Northern Apennines of major, inherited paleogeographic features controlling the northward propagation of the prowedge. The detailed knowledge of olistostromes, as ancient examples of MTCs related to syn-sedimentary tectonics and shale diapirism, and of their lateral variations in term of age and size, provides useful information for better understanding both the tectono-stratigraphic evolution of the Apenninic prowedge and the submarine slope failures in modern accretionary wedges.

Key words: Olistostromes, Sedimentary mélanges, Mass transport complexes, ancient and modern accretionary wedges, Northern Apennines.

1. Introduction

Observations on modern accretionary complexes in convergent plate boundaries show that the outer wedge is highly sensitive to changes of the dynamic equilibrium (e.g., Davis *et al.* 1983; Platt, 1986; Del Castello *et al.* 2004, 2005; von Huene *et al.* 2004; Sage *et al.* 2006; Vannucchi *et al.* 2012). In this framework, mass-transport processes are leading agents in maintaining the dynamic equilibrium by reshaping the accretionary wedge topography and producing high concentration of small-to medium-scale submarine landslide accumulations (McAdoo *et al.* 2004; Mosher *et al.* 2008; Camerlenghi *et al.* 2009; Moore *et al.* 2009; Harders *et al.* 2011; Strasser *et al.* 2011) and megaslides (Moore *et al.* 1976; Golfinger *et al.* 2000; Cochonat *et al.* 2002; von Huene *et al.* 2004; Hühnerbach *et al.* 2005; von Huene, 2008; Yamada *et al.* 2010). Earthquake shaking, as well as long-term causal factors (i.e., sea level variations, rate of sedimentation, gas-hydrates instability, tectonic oversteepening), may exert a primary role in triggering slope failures (e.g., Keefer 1984; Hampton *et al.* 1996; Cochonat *et al.* 2002). The latter may have devastating consequences in terms of natural hazards (i.e., earthquakes plus landslide-induced tsunamis; e.g., Kawamura *et al.* 2012 and reference therein) and potential socio-economic loss (e.g., failure of submarine cable network; see, e.g., Hsu *et al.* 2008). Thus, improving our understanding of mechanisms and processes able to promote and propagate submarine slope failure, and of related mass-transport deposit (MTD) emplacement, is one of the most urgent and challenging task faced in the Earth Sciences.

Although recent studies in modern accretionary wedges provided excellent results on the comprehension of the complex interplay between tectonic and submarine mass-transport processes (e.g., Moore *et al.* 2009; Kawamura *et al.* 2009, 2011; Strasser *et al.* 2011), some complexities still exist in defining entirely the conditions, structures and processes leading to stratal disruption and mélange and chaotic rock formation, as well as the triggering factors and mechanisms for slope failure. In particular, the internal structure of the deposits from mass transport (hereafter defined as mass-transport deposits, or MTDs, and mass-transport complexes, or MTCs when they consist of different superposed MTDs, see, e.g., Ogata *et al.* 2012b) is commonly difficult to be deciphered in detail mainly because of the acoustic transparency and the small-scale of the related features (meters to tens of meters) that is below the standard seismic resolution. Detailed studies on exhumed analogues can than provide useful information on the small-scale internal geometry and on deformation mechanisms, which are complementary to those obtained through off-shore geophysical investigations and drilling (e.g., Lucente and Pini, 2003; Mienert 2004; Codegone *et al.* 2012a; Ogata *et al.* 2012a, 2014; Pini *et al.* 2012).

In this paper we investigate and review different mud-rich sedimentary mélanges (classically defined as olistostromes, following Flores 1955), which represent excellent examples of ancient submarine MTDs and MTCs emplaced during late Oligocene – early Miocene(?) along the slope of the Ligurian accretionary complex in the Italian Northern Apennines, from Monferrato to Voghera sector (Fig. 1). Those olistostromes, part of which was described in previous published papers focused on mélange forming processes (see Codegone *et al.* 2012b, and Festa *et al.* 2013), are here correlated and compared to others well-known examples (e.g., Bettelli and Panini, 1985; Bettelli *et al.* 1985; Pini 1993, 1999; Remitti *et al.* 2011) cropping out to the SE of the studied sector (i.e., southern part of the Northern Apennines between Reggio Emilia and Bologna; Fig. 1A). This correlation allows a regional-scale interpretation of the mass-transport processes during the post-collisional evolution of the Ligurian accretionary wedge as a part of the outer Apenninic prowedge (*sensu* Koons 1994), and particularly of its northwestern part. We interpret the emplacement of such olistostromes is the result of a complex interplay between regional tectonics related to out-of-sequence thrusting, and earthquake-related rise of overpressured fluids along the faults. These interrelated processes are crucial in causing slope failure, favoring en-mass translation (e.g., basal and internal shear zones in MTD/MTCs), as well as providing further source material from the upward rise of intrusive chaotic bodies (i.e., mud diapirs/volcanoes). These lines of evidence testify that the morphological reshaping and structural reconstruction of the exhumed Ligurian accretionary complex was highly dynamic all along its frontal wedge and migrated, from NW (late Oligocene) to SE (early Miocene), as a result of the occurrence of inherited (i.e., paleogeographic and structural) major obstacles to the North-verging propagation of the Apenninic prowedge.

2. Regional setting

The Northern Apennines (Fig. 1) record the complex evolution from Late Cretaceous subduction to Cenozoic continental collision between European plate and Adria microplate (i.e., Africa plate) and subsequent intra-continental deformation (e.g., Coward and Dietrich, 1985; Castellarin *et al.* 1992; Elter *et al.* 2003; Dilek 2006; Marroni *et al.* 2010; Festa *et al.* 2013). Late Cretaceous – early Eocene accretionary stage has been recorded in the complex evolution of the Ligurian accretionary complex that consists of different units (i.e., Internal, External and Subligurian units) containing tectono-sedimentary assemblages that were originally deposited in an ocean basin (i.e., Jurassic ophiolites and sedimentary cover), ocean-continental transition zone (OCT), and thinned continental crust of the Adria margin, respectively.

Since the middle Eocene (Fig. 2), the thinned continental margin of Adria was involved in the west-dipping Apennine subduction (e.g.; Castellarin 1994; Marroni *et al.* 2010; 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 (Figs. 1A, 1D and 2), which, in turn, overthrust the deformed Adria continental margin causing the Apenninic prowedge (*sensu* Koons 1994) to develop. During the progressive incorporation into the accretionary wedge, a consistent part of the External Ligurian Units (i.e., Lower-to Upper Cretaceous “Basal Complex”) was strongly deformed by tectonic processes forming broken formations and tectonic mélanges (e.g., Pini 1999; Bettelli and Vannucchi, 2003; Cerrina Feroni *et al.* 2004; Festa *et al.* 2010b, 2013; Marroni *et al.* 2010; Remitti *et al.* 2011; Codegone *et al.* 2012b; Festa and Codegone 2013). Since middle-late Eocene, different episutural and wedge-top basins (i.e., Tertiary Piedmont Basin and Epiligurian Units, respectively) unconformably covered the Ligurian accretionary complex (Fig. 1) and the N to NE-verging thrust related structures (e.g., Mutti *et al.* 1995; Ricci Lucchi 1986; Rossi *et al.* 2009).

Different types of MTD (Fig. 2), including olistostromes, occur at different stratigraphic levels, within the episutural/wedge-top basin succession (e.g., Bettelli *et al.* 1989a, 1989b; Castellarin and Pini, 1999; Mutti *et al.* 1995; Martelli *et al.* 1998; Pini, 1999; Panini *et al.* 2002b, 2013; Papani *et al.* 2002; Pini *et al.* 2004; Festa *et al.* 2010a, 2010b; Festa 2011; Remitti *et al.* 2011; Ogata *et al.* 2012a; Festa *et al.* 2013). Particularly, the occurrence of olistostromes in the late Oligocene – early Miocene time interval (i.e., Val Tiepido – Canossa argillaceous breccias of Panini *et al.* 2002b; Canossa Olistostrome of Fazzini and Tacoli 1963, Papani 1963, 1971, Bettelli *et al.* 1987; Val Tiepido-Canossa sedimentary mélange of Bettelli and Panini, 1985, 1989, Bettelli *et al.* 1989a, 1989b; see also Castellarin and Pini, 1987; Pini, 1999; Balatri *et al.* 2002; Benini *et al.* 2002; Bettelli *et al.* 2002; Papani *et al.* 2002; Gasperi *et al.* 2005a, 2005b; Martelli *et al.* 2009; Remitti *et al.* 2011) show a significant regional scale distribution (about more than 300 km long by 10-15 km wide) in almost all the outer part of the present-day Northern Apennines (Fig. 1A).

In the southeastern part of the Northern Apennines, between Reggio Emilia and Bologna (Fig. 1A), those olistostromes consist of different superposed debris flow events, which form a single chaotic complex (i.e., mass-transport complex – MTC), made up by different amalgamated bodies in turn interfingered within slope marls of the Antognola Formation (Bettelli and Panini, 1985; Bettelli *et al.* 1985; Pini 1993, 1999; Panini *et al.* 2002a, Pini *et al.* 2012) with a total maximum thickness of about 300 meters (Remitti *et al.* 2011). Those olistostromes record an important regional scale episode of reorganization of the Ligurian accretionary complex and, in general, of the Apenninic prowedge, during late Oligocene - Aquitanian post-collisional stage and related flexural deformation of the Adria continental crust. This regional scale episode was recorded by positive tectonic inversion in the wedge-top basin succession, accompanied by thrusting (e.g., Pini 1999; Cerrina Feroni *et al.* 2004; Marroni *et al.* 2010; Remitti *et al.* 2011; Codegone *et al.* 2012b). Switching from tectonic accretion to tectonic erosion has been recently proposed (see Vannucchi *et al.* 2008; Remitti *et al.* 2011) to explain the instability of the leading slope and frontal part of the Ligurian accretionary complex, as a result of the underthrusting of external Subligurian Units.

In the northwestern part of the Northern Apennines (between Voghera and the Monferrato area; Fig. 1A), the comparable and coeval olistostrome occurrences, that are discontinuously exposed and poorly described in detail (see, *"Complesso caotico pluriformazionale"* of Gelati *et al.* 1974; Val Tiepido - Canossa argillaceous breccias of Panini *et al.* 2002b, and Polygenetic argillaceous breccias of Festa *et al.* 2013) have not been correlated with one another, or evaluated for their regional significance. We focus the present study on these type units.

3. Olistostromes in the northwestern part of the Northern Apennines

In the northwestern part of the Northern Apennines, late Oligocene – early Miocene (?) olistostromes occurrences crop-out limitedly to three different sectors (i.e., Voghera, Tortona and Monferrato hereafter), separated each other by mainly a thick cover of Pliocene-Pleistocene sediments (Fig. 1A). We here describe, for the first time, their internal structure, main characteristics and differences, and relationships with regional scale tectonic features. They share a chaotic block-in-matrix fabric resulting from submarine cohesive debris flows that involve heterogeneous material sourced from exhumed Ligurian Units (i.e., mainly mélange and broken formation units) and disrupted portions of middle Eocene – Oligocene Epiligurian or Tertiary Piedmont Basin successions. The slide blocks and clasts, from centimeters to meters in size, show irregular to subangular shape and are randomly distributed in a grayish shaly/clayey matrix with reddish to purple internal banding. In turn, the matrix has a typical brecciated (i.e., clastic) fabric (see Ogniben 1953; Rigo de Righi 1956; Abbate *et al.* 1981; Bettelli and Panini, 1985) with prevailingly clayey microclasts (less than one cm in dimension, see Swarbick and Naylor, 1980) dispersed and sustained by open honeycomb texture clays (e.g., Pini 1999).

3.1. The Voghera sector

In this sector (Fig. 3), different olistostromes (Val Tiepido – Canossa argillaceous breccias of Panini *et al.* 2002b; Remitti *et al.* 2011) are merged into a single mass-transport complex (MTC). The latter unconformably overlaps out-of-sequence thrusts (Fig. 3), which superpose the Late Cretaceous External Ligurian Units onto the Eocene – Oligocene Epiligurian Units (Monte Piano marls and Ranzano Formation) and some remnants of the lower part (late Oligocene) of the Antognola Formation (e.g., Panini *et al.* 2002b; Remitti *et al.* 2011; Codegone *et al.* 2012b). The younger sediments below and lateral to the MTC are late Oligocene (late Chattian) in age (Planktonic foraminiferal zone IFP22 (P22) of Mancin *et al.* 2003) and, younger soft clasts embedded within it consist of disrupted fragments of the late Oligocene portion of the Antognola Formation. The MTC rests below the unconformably superposition of the Langhian - Serravallian deposits of the Bismantova Group (Figs. 3). These data agree with a main late Oligocene stage of emplacement of the MTC. Because of the occurrences of embedded soft clasts of late Oligocene age within the olistostromes, we cannot exclude, however, that slope failure progressively continued up to early Miocene (see also Panini *et al.* 2002b).

The MTC, up to 180-200 m in thickness (Figs. 3, and 4B), is bounded at the base by an erosional surface that is concave upward at kilometers scale as shown by lateral pinching out. If we exclude later tectonic deformation and faulting, the MTC covers an area of tens of square kilometers (Fig. 3). The base of the whole MTC (Figs. 4D, 4E and 4F) is characterized by a horizon of sheared argillaceous breccia up to 50 cm thick with the maximum of shearing concentrated in the basal 5-

10 cm. Here, sub-millimeters to 1 cm-sized hard clasts, with elongated shapes, are aligned parallel to the pervasive scaly fabric which consists of millimeters to centimeters-scale lenticular mudchips (Figs. 4F and 4H). Surfaces of the clay mudchips locally show striation. Poorly consolidated clasts (i.e., marl and fine-grained sandstone) display extreme elongation (short/long axis ratio up to 1:8) in the direction of emplacement with asymmetries related to simple shear (Fig. 4H). The matrix within the shear zone is brecciated at sub-millimeter- to millimeter scale. Shearing gradually decreases upward (Figs. 4G and 4I).

Above the basal shear zone, the MTC consists of a stacking of different single olistostromes, each of which ranging from meters to about tens of meter in thickness (Figs. 4C and 4D). The single olistostromes are characterized by inverse grading of the largest blocks (Figs. 4C and 4D), which are decimeters to one meter in size, and are bounded at the base by decimeter thick shear zones, similar to that above described for the base of the whole MTC but with a minor intensity of deformation. Tabular blocks, that correspond to bed and bedset fragments of mudstone and sandstone reworked from further disrupted and disaggregated Cretaceous External Ligurian Units (i.e., Palombini Shale, pelagic limestone, Scabiazza Sandstone, Helmintoid Flysch) are aligned parallel to a millimeter-to centimeter-spaced sub-planar foliation mainly related to burial compaction which resulted in the flattening of clay particles and decrease of porosity (Figs. 4D and 4G). The matrix is brecciated with irregularly shaped hard clasts randomly distributed in the host matrix (Fig. 4I).

Below the base of the MTC, the stratigraphic succession corresponds to the hanging wall of a main out-of-sequence thrust and it is characterized by different types of soft-sediment deformation and fluidal features (Figs. 4 and 5). Sub-vertical flame-shaped shaly dikes, decimeters- to few meters wide and up to some meters high, occur few meters to tens of meters above the main out-of-sequence thrust (Codegone *et al.* 2012b; Fig. 5A). The dike injections propagate from: (i) the original bedding surfaces of the Monte Piano marls, and (ii) the pervasive scaly fabric horizons and extensional boudinaged levels deforming the Upper Cretaceous broken formations of the External Ligurian Units (i.e., *Argille varicolori*) (Codegone *et al.* 2012b). They also occur at the margins of two main shale diapirs, up to 100-150 meters wide, which remobilized the *Argille varicolori* and protrude the MTC (see Codegone *et al.* 2012b for major details; Fig. 3)

Liquefaction features, interpreted as seismites (Figs. 5B, 5C, 5D and 5E), up to 1-2 meters high and up to 20-30 cm wide, occur in the alternating sandstone and marl of the Oligocene Ranzano Formation (Epiligurian units), few meters to tens of meters below the basal erosional surface of the MTC (Fig. 3). They consist of injections of homogeneous coarse-grained sandstone (Figs. 5B and 5C), that devoid of sedimentary structures with respect to the bedded hosting sediments, and/or whitish shale that irregularly disrupt and envelop centimeters-to decimeters bed fragments (Fig. 5D). The whitish shale show sub-vertical and anastomosing fluidal features according with the upward migration of the fluid flow. In plan view, they show sharp boundaries (Fig. 5D) and, in some cases a bowl-shaped structure, up to decimeters wide, internally deformed by irregular cracks filled by whitish shale (Fig. 5E). Sandstone injections commonly show rounded shapes in plan view (Figs. 5D and 5E).

3.2. The Tortona sector

Three main olistostromes (i.e., *"Complesso caotico pluriformazionale"* of Gelati *et al.* 1974; see Fig. 6) are interfingered (with local partial superposition of the two uppermost ones) at different stratigraphic levels within early Oligocene – early Miocene slope marls (Antognola Formation, Gelati *et al.* 1974; Varano de' Melegari member of the Ranzano Formation of Martelli *et al.* 1998). The age of the normal sedimentation above and laterally to the thicker and uppermost olistostromes is late Oligocene (late Chattian; plaktonic foraminiferal zone IFP22 (P22) of Mancin e al., 2003). A lower olistostrome is followed by early Oligocene (Rupelian) sediments (Panini *et al.* 2013). Differently from the Voghera sector, these data suggest a relatively wider time interval (early – late Oligocene) for the emplacement of the different olistostromes but they agree with a main slope failure episode of late Oligocene age.

The block-in-matrix fabric and composition of the olistostromes are the same of those of the Voghera sector (i.e., material sourced by from Ligurian Units, such as blocks of Palombini Shale, pelagic limestone, Scabiazza Sandstone, Helmintoid Flysch, and Epiligurian Units represented by blocks of Ranzano Formation). The thicker olistostrome represents the main slope failure event in term of size and areal extension and it is also the better exposed (Figs. 7A and 7B), showing a wedge-like geometry (maximum thickness of about 80 m) that gradually pinches out laterally. It is bounded at the base by an erosional surface (Figs. 7A, 7B and 7D) with concave-up lenticular geometry that can be traced in outcrop for more than 1 km (Fig. 6D). Locally, the basal surface overlies a decimeters- to meters thick horizon of brecciated marl (Fig. 7D) bounded at the base by a sharp contact with the underlying slope marl succession. This sharp contact consists of a layer of black shale (Fig. 7E), millimeters to centimeters thick, characterized by highly sheared fluidal structures with millimeters to centimeters sub-vertical flame injections intruding the overlying brecciated marl. The upper surface of the thicker olistostrome is a roughly planar depositional surface (Figs. 7A and 7B). Internally, the olistostrome consists of different single cohesive mud/debris flows (Figs. 7A, 7B, 7F and 7G), ranging in thickness from 8 to 20 meters, that are bounded at the base by irregular sub-planar surface pinching-out toward west (Figs. 7A, 7B and 7C). Each single mud/debris flow is characterized by inverse grading (Figs. 7F and 7G) from matrix-supported, centimeters to decimeters irregular to equidimensional blocks at the base, to subangular and tabular blocks, up to meters wide, at the top (Figs. 7C and 7G).

As for the Voghera example, the basal part of the olistostromes and of each single debris flow is characterized by a decimeter thick sheared horizon consisting of block-in-matrix fabric deformed by stretching and simple shear (Figs. 7H, 7G and 7I). The long axis of millimeters to centimeters-sized hard clasts, with elongated shape, are aligned to the pervasive scaly fabric (Figs. 7H, 7G and 7I). The latter is pervasive and wraps around equidimensional to angular hard blocks that rotate within the shear flow. The matrix is brecciated at the millimeter scale. Shearing gradually decreases upward, while blocks size increases as well as their random distribution (Fig. 7I). Tabular blocks and weak foliation, probably related to subsequent burial, define a sub-parallel layering. The intensity of shear deformation reaches the maximum at the base of the thicker olistostromes and decreases upward.

Soft-sediment deformation structures (e.g., fluidal banding and sedimentary injectites) are observed to occur inside the succession below the basal surface of the olistostromes (Fig. 6B) with notable examples of sandy and muddy injections in the alternating sandstones and marls of the uppermost part of the Ranzano Formation, Oligocene in age (Figs. 7L and 7M). These examples consist of massive sandstone intrusions wrapping around isolated fragments of the disrupted original bedding of the host sediments (Fig. 7L). In the marly portions of the Ranzano Formaton, they are represented by irregular sub-vertical injections, filled of whitish shale that isolate centimeters- to decimeters-sized disrupted bed fragments of the host sediments (Fig. 7M). In section view, these features show irregular sharp fluidal contacts (Fig. 7M) that are roughly rounded to ellipsoidal in plain view. Although crosscutting relationships between soft-sediment deformation structures and olistostomes are not preserved in outcrop, the geological mapping and stratigraphic correlation show that they occur in the same stratigraphic position (i.e., few to tens meters below the base of the olistostromes) of those observed in the Voghera sector.

3.3. The Monferrato sector

The olistostromes of Monferrato (i.e., Polygenetic argillaceous breccias of Festa *et al.* 2013), that are characterized by the same nature and composition of those described for the other two sectors, show an area extension of up to thousands of square meters each and a maximum thickness of less than 50 m (Fig. 8). These olistostromes, late Chattian in age (Planktonic foraminiferal zone IFP22, P22 of Mancin *et al.* 2003), overlap the high-angle out-of-sequence thrust superposing the External Ligurian Units (Upper Cretaceous *Argille varicolori*) onto the middle Eocene - Oligocene Tertiary Piedmont Basin succession (Monte Piano marls and Cardona Formation; Figs. 8A and 8C). Internally they consist of different superposed cohesive debris flows, about few meters-thick, bounded by concave upward surface at the base. The basal part of the mud/debris flows closely resembles that described for both the Voghera and Tortona sectors, being characterized by a decimeters thick, highly sheared horizon (Figs. 9A, 9B, 9C and 9D). Simple shear is prevalent as evidenced by the asymmetric boudinage and C'-type shears cutting both hard clasts and the brecciated matrix (see also Festa *et al.* 2013). Above to the basal shear zone, a disordered block-in-matrix fabric characterizes the single debris flows with blocks of decimeters and up to one meter in size, randomly distributed into a brecciated matrix (Fig. 9E). Shearing surfaces at the base of both the whole olistostromes and single debris flows indicate directions of emplacement that are radially distributed with respect to the occurrences of two main diapirs, which crop out in the hanging wall of the main out-of-sequence thrust (Fig. 8). Festa et al. (2013) demonstrated that the material that formed the olistostromes was sourced by the gravitational collapse of the flanks of shale diapirs, which formed topographic highs on the sea floor in the hanging wall of main out-of-sequence thrusts. Extruded material derived from the diapiric remobilization and reworking of the chaotic rock units of the External Ligurian Units. The blocks inside the olistostromes are smaller (mainly centimeters-to decimeters, rarely up to one meter wide), rarely tabular, and irregular to equidimensional in shape with respect to those embedded within the diapirs (from decimeters to meters in size) that are mainly elongated to tabular in shape and aligned parallel to the margins of the diapirs.

As for the Voghera example, shale dikes and/or injections (decimeters-to about one meter high and up to decimeters wide) occur in the hanging wall of the out-of-sequence thrust (Figs. 8 and 9F), piercing the basal part of the olistostromes (Fig. 9F).

4. Discussion

The characteristics of the above described olistostromes in the northern part of the Northern Apennines and their relationships with different types of soft-sediment features, sedimentary injections and shale diapirs observed in the hanging wall of the main out-of-sequence thrusts, allow regional-scale consideration on the overall geodynamic context in which slope failures occurred. Triggering factors (see Section 4.1.) at both regional and local-scale, and mechanisms of emplacement of the olistostromes (see Section 4.2.) are discussed in the following in the evolutionary framework of the Ligurian accretionary complex as a part of the outer Apenninic prowedge during late Oligocene – Early Miocene post-collisional stage (see Section 4.3.).

4.1. Triggering factors for slope failure

The distribution of late Oligocene – early Miocene (?) olistostromes and of soft-sediment deformation features (i.e., liquefaction features and injectites) and shale diapirs over a large portion of the northern part of Northern Apennines (i.e., about 150 km long and up to 15 km wide) on top of the exhumed Apenninic prowedge, suggest that regional tectonics played a significant role as triggering mechanism for slope failures. Particularly, two main triggering factors worked concomitantly over a wide area:

(i) slope oversteepening related to out-of-sequence thrusting and the consequent structural reorganization of the outer Apenninic prowedge;

(ii) overpressured fluid discharge related to earthquake shaking associated to coseismic out-of-sequence thrusting.

In all the studied sectors (i.e., Monferrato, Tortona and Voghera), the occurrence of liquefaction structures at the same stratigraphic and/or structural level suggests that underthrusting processes related to out-of-sequence thrust propagation within the outer Apenninic prowedge, favored shale dike injections by fast compaction and dewatering of the highly permeable Oligocene sandstones of the footwall succession (Fig. 10). Expelled fluids and their vertical migration throughout the tectonic pile were controlled and favored by the occurrence of both low permeability shale horizons and marked anisotropy surfaces (i.e., scaly fabric and meso-scale faults) in the hanging wall of the out-of-sequence thrusts (Codegone *et al.* 2012b; see Fig. 10B). In addition, the clayey beds of the Argille varicolori of the Cassio Unit (i.e., External Ligurian Units) commonly show high content of smectite and mixed layers illite-smectite (e.g., Loschi Ghittoni and Minopulos, 1976; Loschi Ghittoni, 1977; Dondi, 1999). These minerals may have undergone low-temperature illitization processes in the fault zones by fluid diffusion and tectonic shear strain (Dellisanti et al. 2010), with a further significant water release. These minerals may have undergone low-temperature illitization processes in the fault zones by fluid diffusion and tectonic shear strain with a further significant water release. These processes have been described by Dellisanti *et al.* (2008) in fault zones at relative low burial (i.e., less than 2 km), which is comparable with that of the studied areas. The combined effects of fluid expulsion by both dewatering of sandstones and mineral transformation and its migration along fault surfaces may have induced significant fluid flow with consequent overpressure likely causing dike injection (Codegone *et al.* 2012b).

The distribution of sediments deformed by and containing liquefaction features, interpreted as seismites, over a large area (i.e., all the three sectors) and in the same stratigraphic-structural position (i.e., hanging wall of the out-of-sequence thrusts, meters to tens of meters below the erosional surface of the olistostromes; Fig. 10B, see also Figs. 3, 6B and 8A), suggests coseismic earthquake shaking related to out-of-sequence thrusting. Amplification of seismic ground shaking can occur in the hanging wall of a splay fault ("hanging-wall effect" of Abrahamson and Somerville 1996; Fig. 10A), if the fault rupture coseismically acts (e.g., the Nankai out-of-sequence megasplay and other fault systems; see Planfker 1972; Tanioka and Satake 2001; Baba *et al.* 2006; Kawamura *et al.* 2009; Strasser *et al.* 2009, 2011). Seismites are generally related to close seismic source areas subjected to a minimum magnitude of earthquake >5 (e.g., Atkinson 1984; see also Allen 1975, 1986; Youd 1978; Seed, 1979; Seed *et al.* 1983; Obermeier *et al.* 1993). Hence, the widespread occurrence of such structures over a broad area (hundreds to about thousands of kilometer square), characterized by the same geological setting, may suggest earthquake shaking of greater magnitude (e.g., Seed, 1968; Obermeier *et al.* 1993; Moretti *et al.* 1995; Perucca and Moreiras 2006), which worked in conjunction and cumulatively with generalized fluid flows, creating different weakness zones within the hanging wall of the out-of-sequence thrust (Fig. 10B) that potentially represented triggering factor for slope failure (Fig. 11).

Particularly, Festa et al. (2013) demonstrated that in the Monferrato area the out-of-sequence thrusting caused slope oversteepening (see also Piana 2000; Festa *et al.* 2005, 2009) and the extrusion of overpressured fluids and remolded material concentrated along the thrust surface. This resulted in shale diapirism (Fig. 11A; see also Fig. 8) concentrated in the core zones of hanging wall positive structures mainly consisting of mélanges and broken formations (i.e., Upper Cretaceous *Argille varicolori* of the External Ligurian Units). The outward radial spreading of the olistostromes with respect to the diapirs emergences, the same lithological composition and their limited areal extension (i.e., hundreds of meters square), allowed us to interpret the mass-transport events as directly sourced by the extrusion of diapiric bodies on the seafloor (Fig. 11A).

In contrast, in the Voghera sector (and locally in the Monferrato), the combination (Fig. 11C) of rapid sedimentary loading provided by the emplacement of the olistostromes may have favored a later discharge of overpressured fluid flows able to drive the extrusion of fluid-saturated shaly sediments (i.e., *Argille varicolori* of the External Ligurian Units) as decimeters to meters-scale injectites and tens to hundreds of meters-scale diapirs, which, in fact, intrude into the lower part of the main olistostrome (Codegone *et al.* 2012b). A later pulse of overpressured fluids also occurred in the Monferrato sector as shown by mesoscale injectites piercing the basal part of the olistostromes (Fig. 11A).

In the Tortona sector, where direct relationships between thrusts and olistostromes are not exposed, slope instability occurred with different pulses during a wider time interval (early to late Oligocene), recording different and repeated slope failure episodes along the frontal leading slope of the outer Apenninic prowedge. According to the above described framework, the main episode of slope failure was triggered by the combination of faulting and seismic-induced overpressured fluid-discharge (Fig. 11B).

4.2. Mechanisms of emplacement: a paradox in translation and emplacement?

The olistostromes described in this paper pertain to the Type 1 MTD of Pini et al. (2012). They are classically characterized by (i) blocks dispersed in a muddy, brecciated matrix, (ii) a high content of clays of the matrix, (iii) a crude negative gradation of blocks, (iv) a faint iso-orientation of the blocks parallel to the basal surface, (v) a marked erosive base, and (vi) well defined shear zones at the base and inside the bodies.

The mechanism of translation and emplacement of these bodies is basically related to the rheological behavior of a viscous matrix, as pointed out for typical cohesive debris flow (Middleton and Hampton 1973; Lowe 1982; Mulder and Alexander 2001). The basal and internal shear zones show a “mylonite-like” style, with enhanced reorientation of rigid clasts and microclasts, strong deformation of “soft” clasts and microclasts, matrix banding and a crude foliation, as described before (Figs. 4A and 9D). These structures suggest a constriction- plus flattening-type (i.e. prolate plus oblate) strain ellipsoid, with a prevailing stretching along the direction of flow and a minor component of planar flattening (see Pini et al. 2012). Simple and sub-simple shear structures are also present, with sigma-type deformation of elongated “soft” clasts, a scaly fabric, and S/C type structures (Fig. 4A). The latter structures, not systematically classified in the literature, have been only recently observed in other examples of exhumed MTDs (Ogata *et al.* 2010, 2012b), reinforcing the importance of simple shearing mechanism in the basal shear zones.

The mechanism of movement is likely related to the "viscous" shear zones in a clay-dominated matrix. Hence, these olistostromes, and generally the Type 1 MTDs, should represent relatively slow moving bodies. With this kind of mechanics, thick olistostromes are expected to do not widely expand into the basins. It is difficult to explain, therefore, the presence of bodies thicker than 200-300 meters and covering large areas of hundreds of square kilometers.

Moreover, the base of the MTC is always lens-shaped, with erosional surfaces and scars (see also Pini 1999; Pini *et al.* 2012), suggesting a strong erosion of the substratum. The latter should not be compatible with a viscous laminar flow, as typical of cohesive debris flows.

Two lines of speculation emerge from our study that can help in explaining this paradox.

First, the elevated thickness of this kind of MTC and/or olistostromes may represent the stack of subsequent depositional events (Remitti *et al.* 2011; Pini *et al.* 2012). As we documented before, the presence of an amalgamated pile of olistostromes and/or debris flows is evidenced by the presence of different (basal) shear zones inside the entire MTC, as also supported by the observed repetition of the inverse grading above each individual shear zone (Figs. 4C and 7C).

Notably, the lowermost basal shear zone appears to be the most important one. At the present, we can suggest as an operational hypothesis that repeated events of en-mass movement occurred in a very short time, probably related to retrogressive slope failure, or more clustered collapses of material sourced by shale diapirs. After the definitive emplacement, during the post-depositional accommodation (e.g., downslope creeping), the MTCs may have acted as a single body achieving the largest deformation at its very base. The observed negative gradation of each individual sub-body (Figs. 4C and 7C) reinforces this interpretation, ruling out consideration of the internal shear zones as internal structures partitioning the deformation in a single mass transport event (see Pini *et al.* 2012).

The second line of observation takes into account the presence of pervasive deformation in the marls of the substratum, just below the basal shear zone. We document decimeter- to meter-thick intervals of brecciated substratum with soft clasts (Figs. 7D and 7E), suggesting a non-indurated state of the underlying (overridden) sediments at the deformation. These intervals are bounded at the base by thin layers (mm- to cm-thick) of blackish shales showing highly sheared fluidal structures (Fig. 7E), and mm- to cm-thick, sub-vertical, flame-shaped sedimentary injections intruding the overlying brecciated marls. We interpret these structures as products of a fluid overpressure-related deformation of the substratum due to the undrained dynamic loading exerted by the moving slide mass.

Accordingly to the working hypothesis formulated by Pini *et al.* 2012, these bodies could be interpreted as products of relatively fast-rated processes, able to carry material for longer distances if sustained by a basal "carpet" comprising a liquefied/fluidized mixture of water and loose sediment (hydroplaning, Mohrig *et al*. 1998; Ogata *et al.* 2014).

In this framework, the possible product of this overpressured horizon could be found in the localized and concentrated deformation of the substratum just below the basal shear zone. This being also the responsible for the concave-upward shape of the bases of olistostromes, and the erosional surfaces and scars. According to this, the "mylonite-like" shear zones at the base, and inside the bodies, can represent zones of concentrated viscous deformation, which could have either acted in combination with the overpressured basal carpet, or singularly, after the dissipation of the basal fluid overpressuring, during the final stages of the slide mass emplacement.

4.3. Regional-scale correlation and tectonic significance of the olistostromes

Two main findings need to be regarded and discussed in the spatial and temporal tectonic evolution of the Ligurian accretionary complex as a part of the Apenninic prowedge (Fig. 12A): (i) in the studied sector (i.e., northern part of the Northern Apennines) a main episode of gravitational instability and slope failure occurred in late Oligocene time (Planktonic foraminiferal zone IFP22, P22 of Mancin *et al.* 2003), sealing out-of-sequence thrusts in the Monferrato and Voghera sectors; (ii) at regional scale, if compared with the southern sector of the Northern Apennines, this episode shows a SE-ward gradual rejuvenation (up to early Miocene), along with an increase in thickness of the studied olistostromes.

In the studied area a younger early Miocene age for slope failure may be pointed out only for the Voghera sector (see also Panini *et al.* 2002b), thus a potential SE-ward rejuvenation (from the Monferrato to the Voghera sector; Fig. 12A) of gravitational instability along the Ligurian accretionary complex can be only supposed. On the contrary, this SE-ward temporal and spatial migration of gravitational instability is better constrained and documented if we compare the studied sector with the southern part of Northern Apennines (between Reggio Emilia and Bologna; Fig. 12A). In fact, for the southern sectors, different authors documented that the emplacement of those olistostromes occurred from late Oligocene up to early Miocene (see Pini, 1999; Balatri *et al.* 2002; Benini *et al.* 2002; Panini *et al.* 2002a; Gasperi *et al.* 2005a, 2005b). Particularly, Remitti et al. (2011) proposed that slope oversteepening occurred as consequence of the early Miocene (Aquitanian) underthrusting and "shallow underplating" of external Subligurian Units (i.e., part of Adria Units; Fig. 12A), causing the uplift and the consequent slope collapse of the frontal wedge with the emplacement of olistostromal accumulations at its toe (i.e., Val Tiepido-Canossa argillaceous breccias; see Papani, 1971; Fregni and Panini 1988; Papani *et al.* 2002; Martelli *et al.* 2009; Remitti *et al.* 2011). At the regional scale, it is thus evident that the relatively younger age of very similar olistostromes (i.e., Aquitanian, see Remitti *et al.* 2011; late Oligocene – Aquitanian, see Pini, 1999; Balatri *et al.* 2002; Benini *et al.* 2002; Panini *et al.* 2002a; Gasperi *et al.* 2005a, 2005b) to the SE of the studied sector (Fig. 12A), records a lateral temporal variation and migration of tectonic deformation and related gravitational instability along the outer wedge of the Apenninic prowedge (i.e., part of the Ligurian accretionary complex; Figs. 12A and 12B), spanning about 3-5 million years (i.e., late Chattian – Aquitanian), as expected along hundreds of kilometers long convergent plate margins. In addition, the progressive increasing in volume of olistostromes (Fig. 12A), from Monferrato (hundreds of meters square and less to 50 m thick) to Voghera sector (tens of kilometers square and up to 200 m thick) down to the southeastern of the studied sector (tens of kilometers square and up to 300 m thick, see Fazzini and Tacoli 1963; Papani 1963; Bettelli *et al.* 1989a, 1989b; Remitti *et al.* 2011), also suggest that the instability of outer prowedge increased toward the SE, accordingly with the above-proposed lateral differential dynamic re-equilibration of the Ligurian wedge front.

In a broader framework, the SE-ward migration of the gravitational instability along the advancing Appenninic prowedge fits with timing and deformation style of the early stages of the Western Alps – Northern Apennines junction as occurred in the northern part of the studied sector (Fig. 12B). This tectonic junction (i.e., the “Ligurian knot” of Laubscher *et al.* 1992; Schumacher and Laubscher, 1996) results in a complex tectonic jigsaw (Figs. 1A, 2 and 12B) including the buried metamorphic Western Alpine units, the SE-verging front of the South Alpine thrust system (i.e., Adria Units), and the northeast-verging External Ligurian Units of the Northern Apennines (i.e., the outer part of the Apenninic prowedge) (see, e.g. Biella *et al.* 1988, 1997; Laubscher *et al.* 1992; Castellarin 1994; Mutti *et al.* 1995; Roure *et al.* 1996; Schumacher and Laubscher, 1996; Piana 2000; Mosca *et al.* 2010). In the northwestern sector of the studied area (Monferrato and Torino Hill), the SE-ward migration of the South Alpine thrust system is recorded within the upper Eocene – Oligocene succession (Festa *et al.* 2005, 2009; Mosca *et al.* 2010). Here, the occurrence at shallow structural levels of the Mesozoic Adriatic Units as positive relief of the foreland (see, e.g., Festa *et al.* 2009; Mosca *et al.* 2010; see also Miletto and Polino 1992; Piana 2000) and the SE-ward propagation of structures associated with the South Alpine thrust system (Fig. 12B), represented a major obstacle for the northward migration of the Apenninic prowedge (see, e.g., Festa *et al.* 2005, 2009; Mosca *et al.* 2010). This created, since late Oligocene, a kinematic impasse to the North-verging migration of the outer Apenninic prowedge (Fig. 12B), promoting: (i) out-sequence thrusting inside the frontal wedge and related slope oversteepening; (ii) slope instability and consequent rapid reshape and disequilibrium of the accretionary wedge; and (iii) the lateral SE-ward shifting, in agreement with the occurrence of a major accommodation space in the same direction (Fig. 12B), of the contractional deformation associated with the North-verging migration of the prowedge. Hence, in a broader regional view, the main pulse of slope failure shows rejuvenation toward SE. Since late Oligocene (Fig. 12A), slope failures affected northwestern part of the present-days Northern Apennines (between Monferrato and Tortona), sealing the out-of-sequence thrusts, and progressively rejuvenated toward SE (Oligocene – early Miocene? in the Voghera sector) up to Aquitanian times (between Reggio Emilia and Bologna, see, e.g., Remitti *et al.* 2011).

5. Conclusions

Comparable olistostromes (or sedimentary mélanges *sensu* Festa *et al.* 2012) with block-in-matrix fabric have been described in different sectors in the Northern Apennines, from Monferrato to the Voghera sector. They represent excellent examples of ancient submarine MTDs and MTCs resulting from cohesive debris flow accumulations that record an important period of instability, morphological reshaping and structural reconstruction through out-of-sequence thrusting of the frontal part of the Ligurian accretionary complex as part of the outer Apenninic prowedge during late Oligocene – early Miocene post- collisional stages.

Although tectonics affected the slope geometry over a large area, our example documents that slope failures occurred in specific regions along the wedge of the Ligurian accretionary complex where the interplay and superposition of tectonic oversteepening, earthquake shaking, and fluid overpressure occurred concomitantly. The scale, style and distribution of those ancient olistostromes can be directly compared with those observed in modern accretionary wedge (i.e., Nankai accretionary wedge, Middle America Trench, Peru margin, Hikurangi margin in New Zealand, etc.) for some of which a direct link with earthquake—related tsunamis has been demonstrated (e.g., Kawamura *et al.* 2012 for Nankai accretionary wedge). Further significant slope failure processes forming sedimentary mélanges and triggered by the concomitant activity of faulting and overpressured fluids occurred also in the late Miocene (late Messinan) time a top of the Tertiary Piedmont Basin episutural basin (Dela Pierre *et al.* 2007; Festa 2011).

The coexistence, at the scale of each single olistostrome, of different mutual causative links between slope failure and overpressured fluid and diapirism, suggests that the reshaping and reconstruction of the accretionary wedge was highly dynamic all along its front. Local variation in the different tectonically-related physical and mechanical properties of sediments, the gradual SE-ward increasing in size and volume of olistostromes (Figs. 12A and 12B), from Monferrato to the Reggio Emilia-Bologna sector, and their apparently gradual rejuvenation to the SE of the studied sector (i.e., from late Chattian to Aquitanian), document a lateral variation and segmentation of tectonic processes along the strike of the frontal wedge during the frontal migration of the Ligurian accretionary complex. This is likely due to the occurrence of major obstacles on the overridden Adria Units (e.g., South-Alpine thrust system), hampering the North-verging migration of the Ligurian accretionary complex.

Understanding the progressive lateral (and temporal) variation of slope instability along the wedge front, and the different causative links between mechanisms and processes triggering slope failure in ancient submarine accretionary wedge, represent an important baseline task to quantify the influence over frequency and magnitude of submarine failure in modern accretionary wedges characterized by comparable structural setting (i.e., out-of-sequence thrusting or megasplay faulting as in Nankai accretionary wedge, see Strasser *et al.* 2009, 2011; Moore *et al.* 2011 and reference therein). Our examples also show that exhumation of heterogeneous material such as mélanges and broken formations, which commonly occur in modern accretionary wedges, represent an additional factor promoting the chances of submarine slope failures. After the slope failure related to out-of-sequence thrusting, and consequent re-equilibration of the frontal accretionary wedge, the covering heterogeneous material may become easily unstable and prone to be remobilized downslope if external triggers occur.

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Figure captions

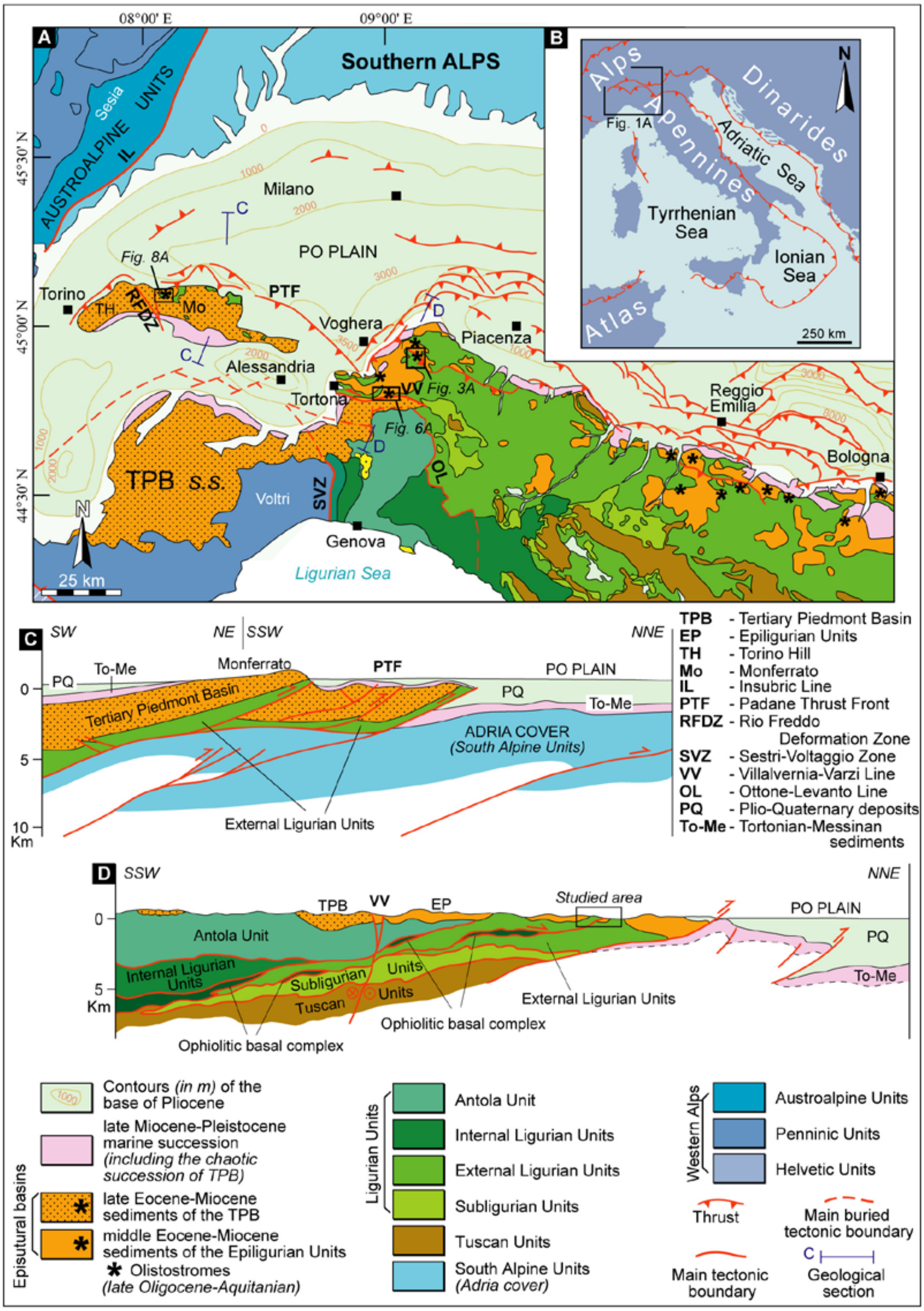

Figure 1 - (**A**) Structural sketch map of the Northern Apennines (modified from Bigi *et al.* 1983; Marroni *et al.* 2010; Mosca et al., 2010; Vezzani *et al.* 2010), showing the location of the study area of Figs. 3A, 6A and 8A). (**B**) Location of Fig. 1A. (**C**) Geological cross sections across the northern sector of the Tertiary Piedmont Basin (modified from Bello and Fantoni, 2002), and (**D**) the Northern Apennines (modified from Boccaletti and Coli, 1982). The trace of the geological cross sections is shown in Figure 1A.

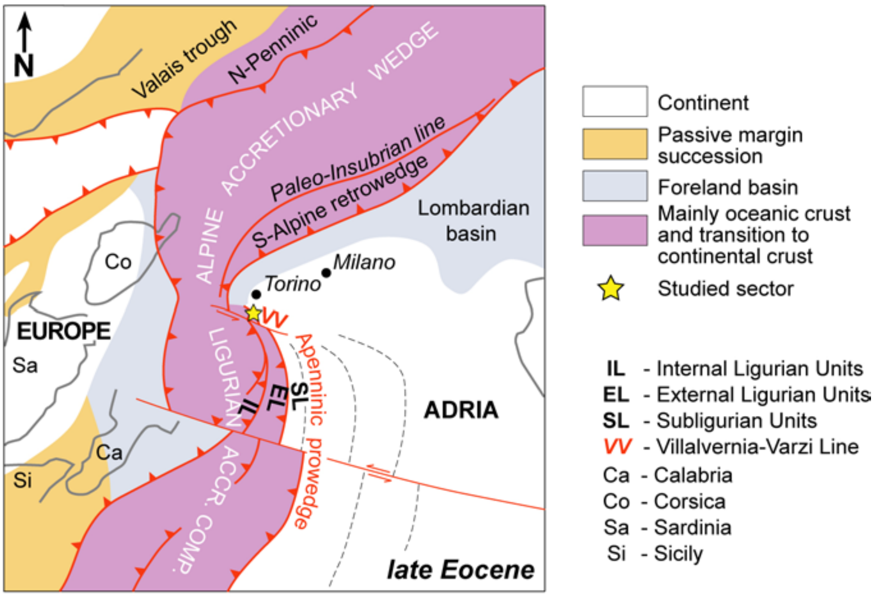

Figure 2 - Paleogeographic reconstruction of the Alpine accretionary wedge and Ligurian accretionary complex as part of the outer Apenninic prowedge (*sensu* Koons, 1994) in late Eocene times (modified after Castellarin, 1994; Festa *et al.* 2010b, 2013; Mosca *et al.* 2010).

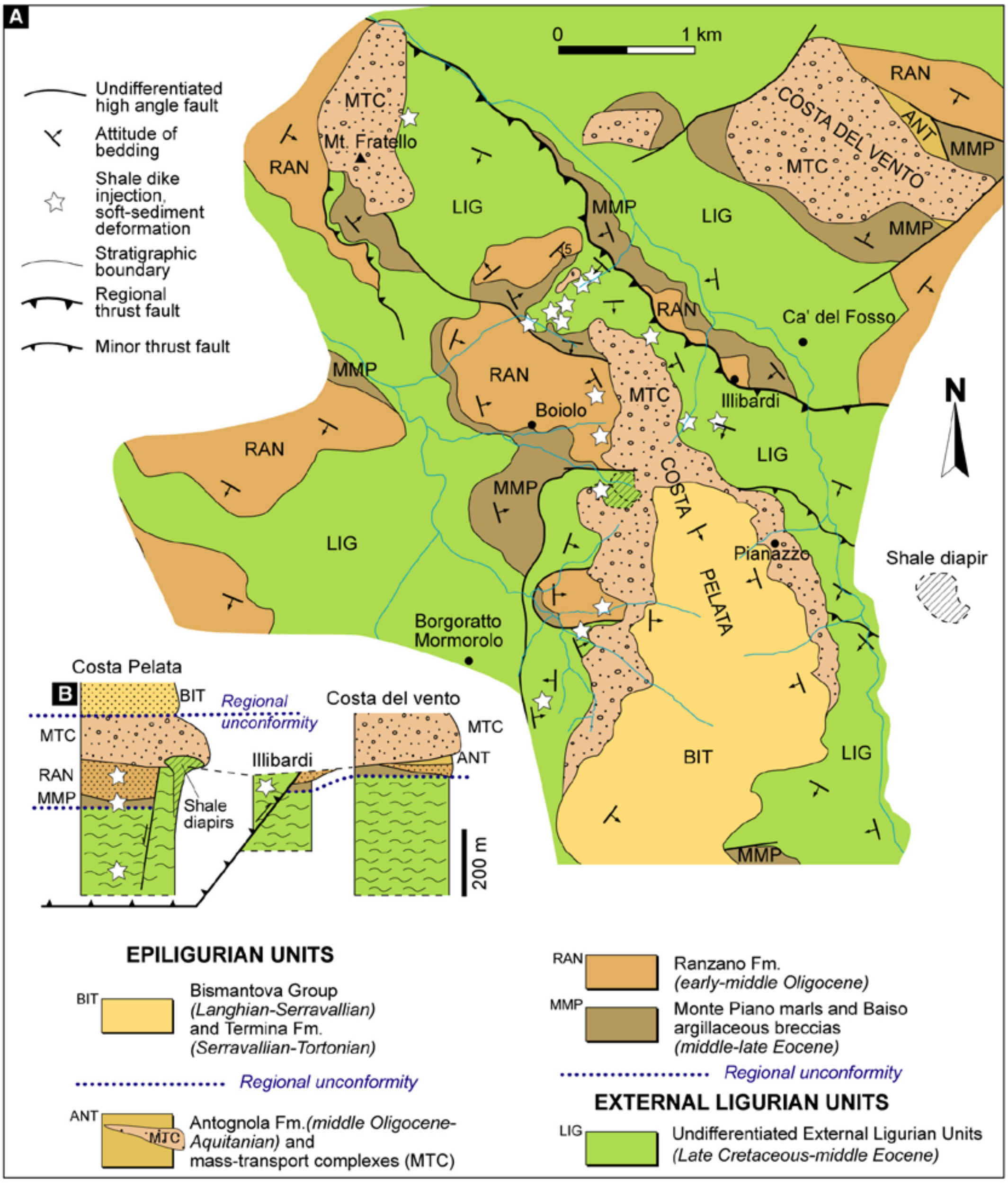

Figure 3 – (**A**) Simplified geological-structural map of the Voghera sector (location in Fig. 1A), showing the distribution of the mass-transport complexes (MTCs) (modified from Codegone *et al.* 2012b). (**B**) Stratigraphic and structural relationships between the MTCs and hanging wall and footwall units of main thrust.

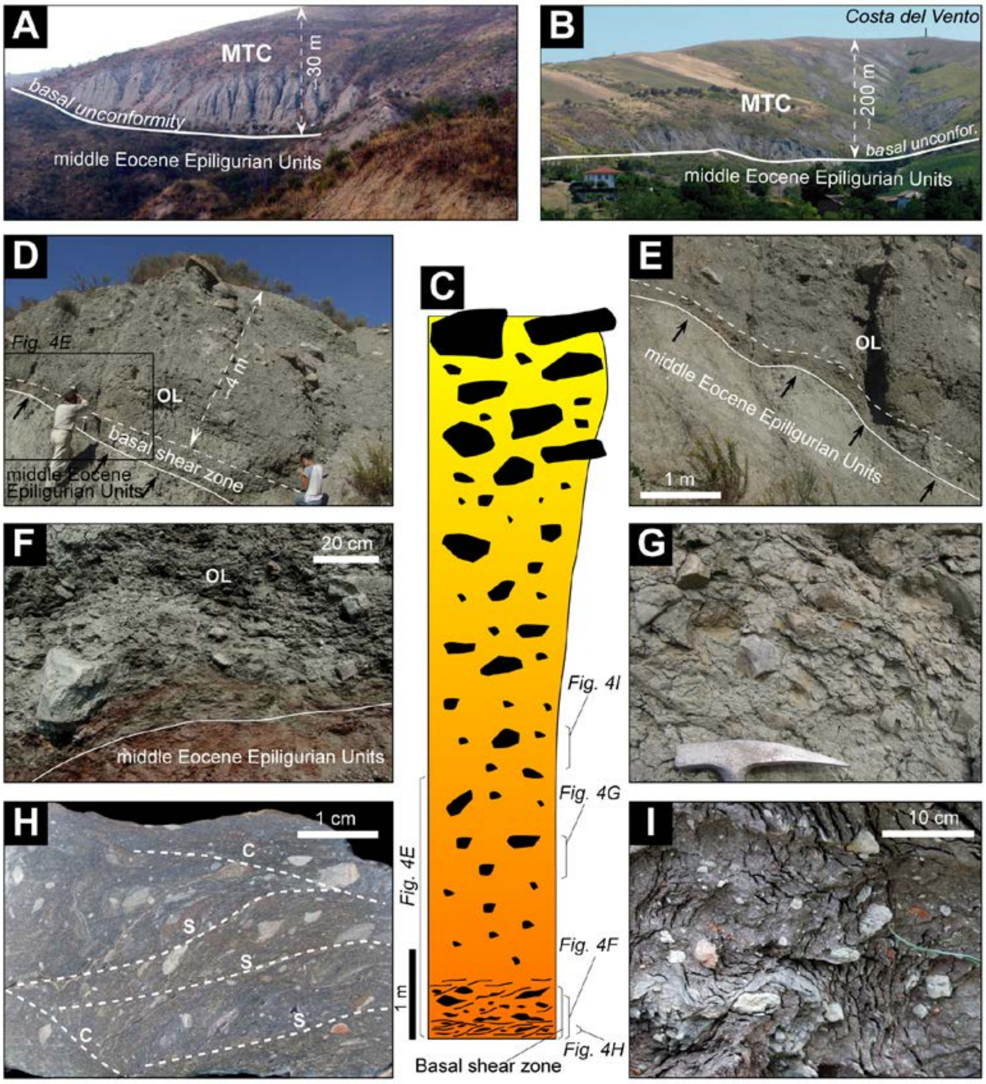

Figure 4 – Olistostromes in the Voghera sector. (**A**) Panoramic view of the main mass-transport complex (MTC) at Monte Fratello and (**B**) Costa del Vento. (**C**) Conceptual stratigraphic column of a single olistostrome, showing the decimeters thick basal shear zone and the inverse grading of the largest blocks. (**D**) Basal part of the olistostromes (OL) at Costa del Vento. The white line and the dashed white line bound the basal shear zone, superposing the olistostrome onto middle Eocene marls of the Epiligurian Units. Note the inverse grading of largest blocks above the basal shear zone (G.A. Pini and G. Codegone as scale). (**E**) Close-up of the basal shear zone shown in Fig. 4D. (**F**) Close-up of the basal shear zone of the olistostromes (OL) at Monte Fratello, showing the pervasive scaly fabric that wraps around equidimensional blocks. Smaller elongated blocks are aligned parallel to the scaly fabric. Note the upward decrease of shearing deformation. The white line indicates the contact with the underlying middle Eocene deposits of the Epiligurian Units (i.e., Monte Piano marls). (**G**) Close-up of the block-in-matrix about one meter above the basal shear zone, showing equidimensional and irregular hard blocks (limestone, mudstone and sandstone) randomly floating in the foliated shaly matrix. (**H**) Polished surface of hand sample of the basal MTC shear zone, showing the reorientation of elongated hard clasts to S-C fabric (white dashed lines). (**I**) Hard clasts with irregular shape, randomly distributed in the brecciated matrix.

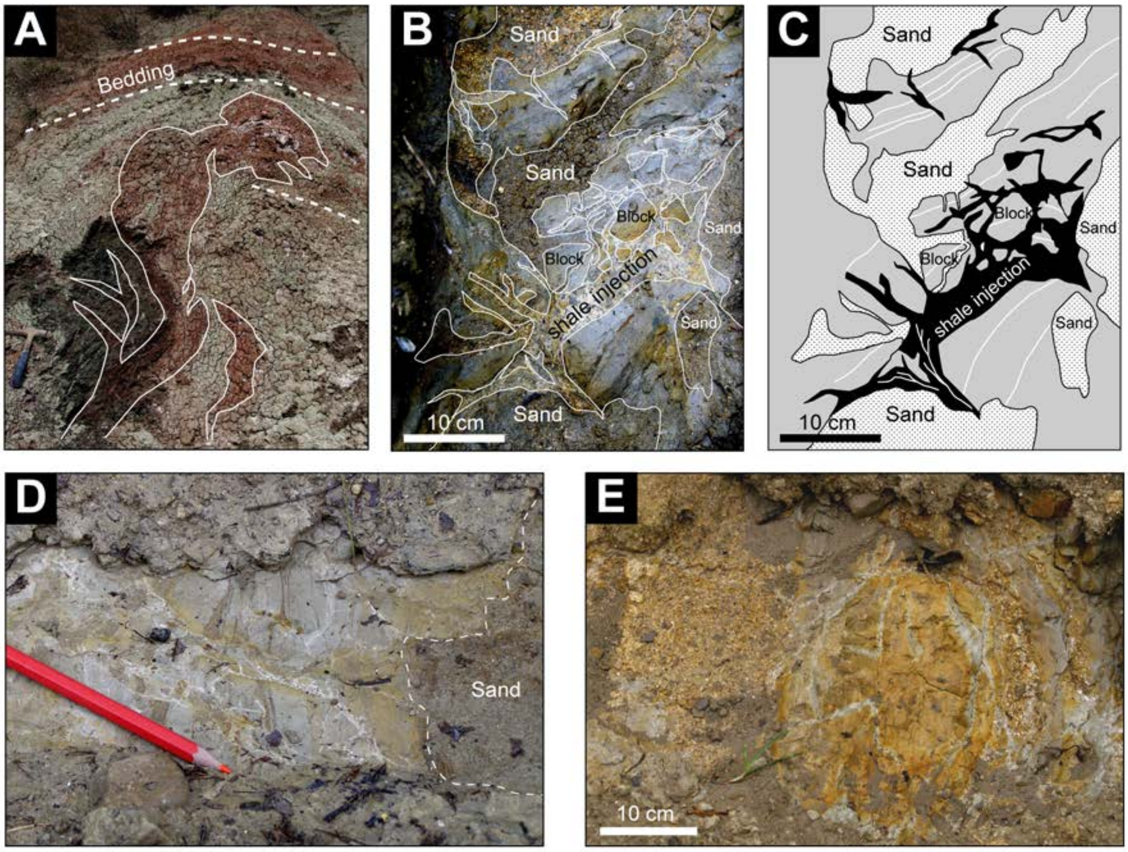

Figure 5 – (**A**) Shale injection, with irregular flame-shape, piercing the Upper Cretaceous *Argille varicolori* (External Ligurian Units) in the hanging wall of the main thrust. Dashed white lines indicate the original bedding. (**B**) Plan view of shale and coarse-grained sand injections in the marly horizons of the Ranzano Formation (Epiligurian Units). (**C**) Drawing of Fig. 5B showing the irregular distribution of both shale and sand injections. Isolated blocks of marl are enveloped within shale injections. (**D**) Plan view of shale injection (seismite), bounded by sharp contacts, enveloping highly disrupted fragments of marl. On the right side of the photograph, coarse-grained sand that devoid of any sedimentary feature (liquefaction feature) intrudes the marly beds of the Ranzano Formation. Pencil as scale. (**E**) Plan view of bowl-shaped structures comprising muddy and sanding patches. Note the partially concentric shape of both whitish shale and sand around the bowl-shaped extrusion feature.

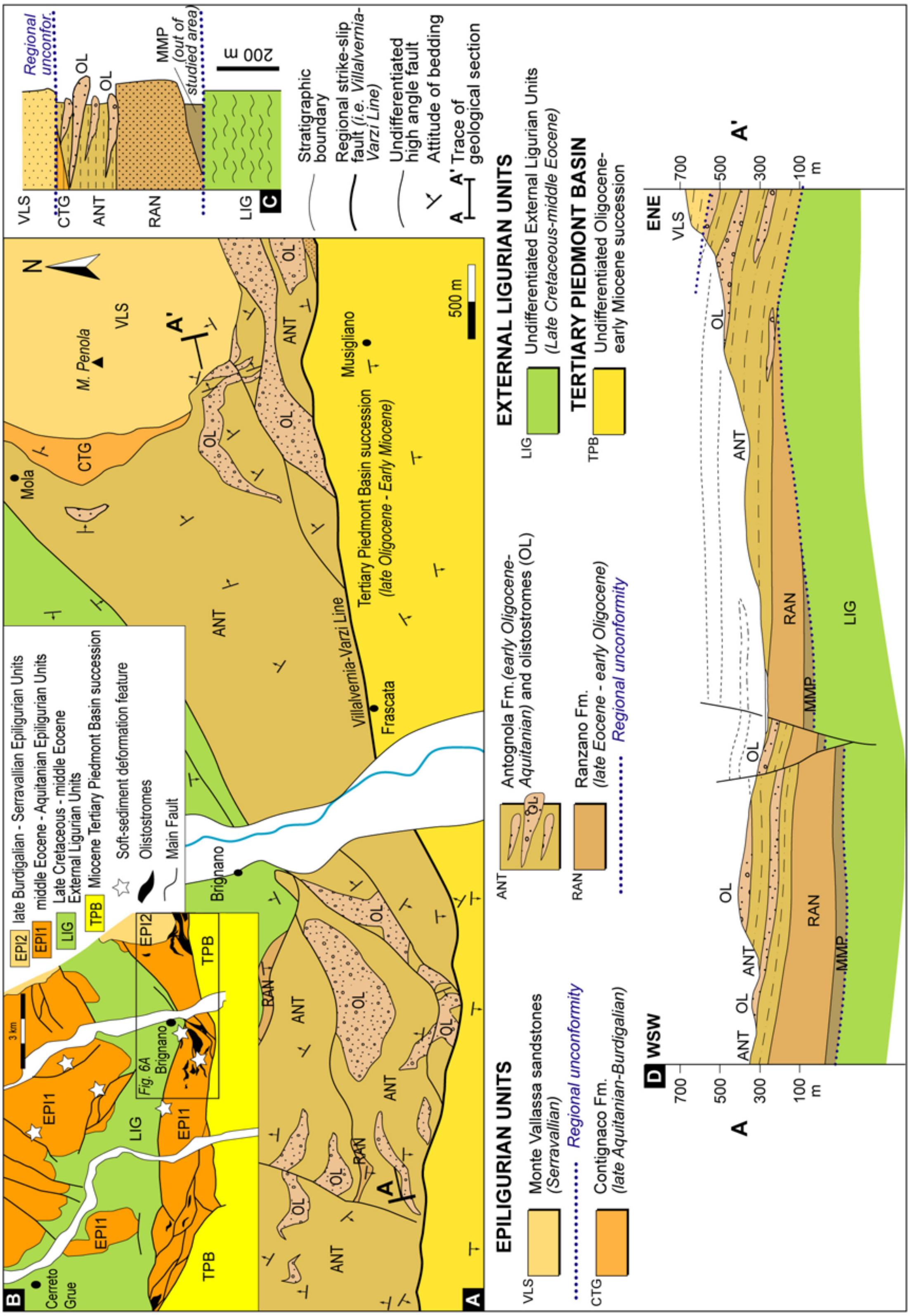

Figure 6 – (**A**) Simplified geological-structural map of the Tortona sector (location in Figs. 1A and 6B), showing the distribution of the olistostromes. (**B**) Simplified regional geological

map, showing the distribution of soft-sediment deformation features indicated by white stars. (**C**) Stratigraphic column. (**D**) Simplified geological section, showing the distribution of the olistostromes at different stratigraphic levels.

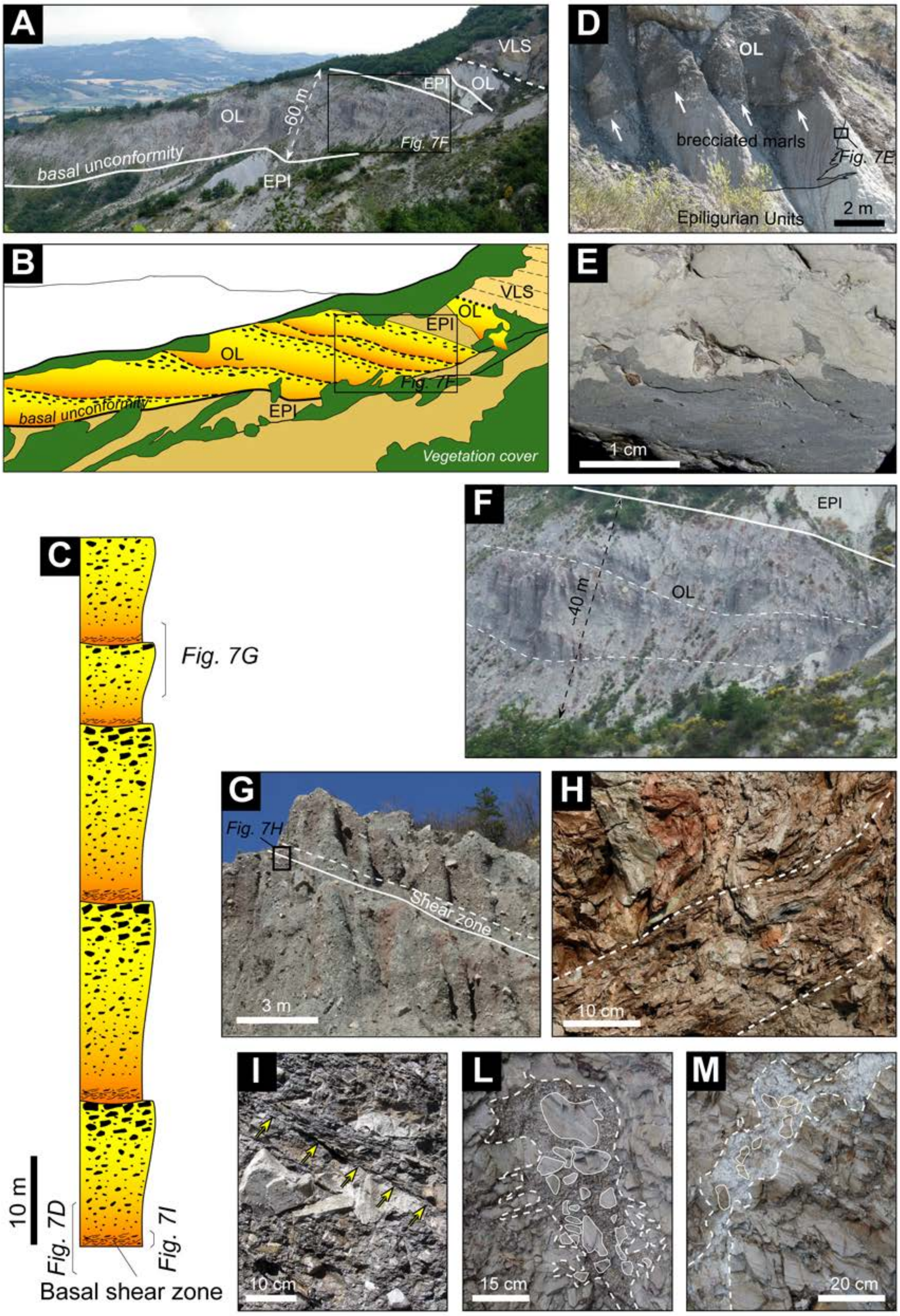

Figure 7 – Olistostromes at Monte Penola in the Tortona sector. (**A**) Panoramic view of the two uppermost olistostromes at Monte Penola. VLS: Monte Vallassa sandstones (Serravallian), EPI: Epiligurian Units (middle-late Oligocene), OL: olistostrome (**B**)

Drawing of Fig. 7A, showing the different superposed olistostromes. They consist of mud/debris flows each one up to tens of meters thick (see Fig. 7C). The green pattern indicates the vegetation cover (**C**) Simplified stratigraphic column of the internal arrangement of the thicker olistostrome of Fig. 7A. Each single mud/debris flow is characterized by inverse grading of largest blocks and a decimeters-thick basal shear zone. (**D**) Basal sharp contact of the thicker olistostrome of Fig. 7A (white arrows), overlying a lenticular horizon of brecciated marl interfingered (black line) with slope marl of the Epiligurian succession. (**E**) Close-up of a polished surface of hand sample of the brecciated marl underlying the olistostromes of Fig. 7D. The brecciated horizon is bounded at the base by a centimeters-thick interval of blackish fluidal shale and silt with sub-vertical flame features intruding the breccias. (**F**) Zoomed in view of Fig. 7A, showing the stack of debris flow deposits (white dashed lines), each one shows the inverse grading of largest blocks. OL: olistostrome, EPI: Epiligurian Units (middle - late Oligocene). (**G**) Internal arrangement of the olistostrome, showing the superposition (and amalgamation) of two single mud/debris flows characterized by inverse grading of blocks. A decimeters thick shear zone bounds at the base the upper mud/debris flow. (**H**) Close-up of the sheared basal contact of the olistostromes of Fig. 7D. Dashed white lines bound a decimeter horizon, accommodating the bulk of the extensional shearing as shown by a pervasive centimeters-spaced scaly fabric and the preferential alignment of elongated clasts to the shear zone walls. (**I**) Close-up of Fig. 7G, showing the sharp superposition of the two single mud/debris flows. Above the basal contact (arrows), the upper mud/debris flow show a decimeters thick shear zone characterized by elongated hard blocks aligned to a pervasive extensional scaly fabric. Below the basal contact, equidimensional and irregular blocks, that are larger than those above, are randomly distributed in a brecciated matrix. (**L**) Liquefaction feature, consisting of coarse-sand that intrudes regular bedded marl horizons in the Ranzano Formation. Note that the sand devoid of any sedimentary feature. (**M**) Shale injection intruding marly horizon of the Ranzano Formation.

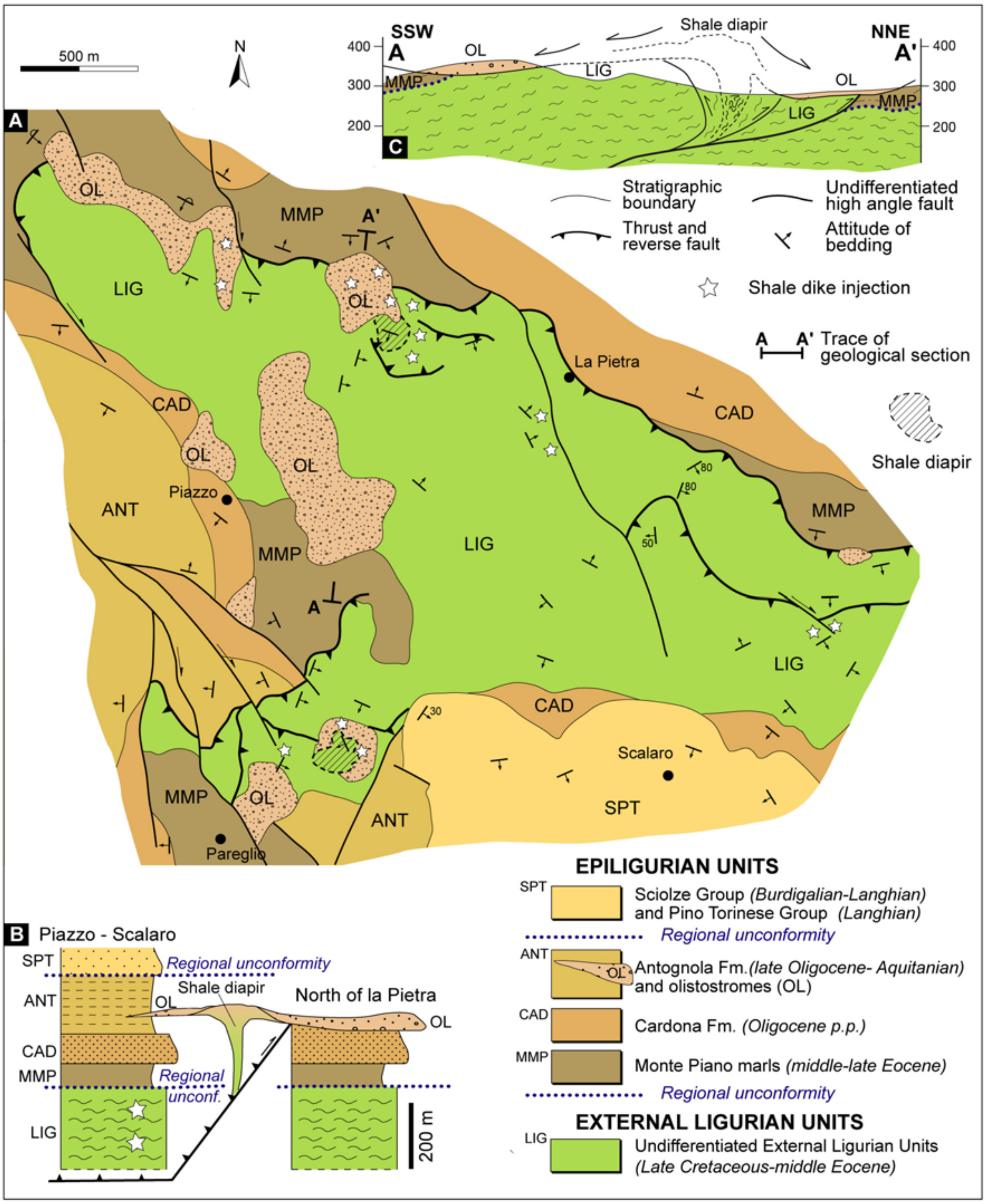

Figure 8 – (**A**) Simplified geological-structural map of the Monferrato sector (location in Fig. 1A), showing the distribution of the olistostromes (OL) (modified from Festa and Codegone 2013). (**B**) Stratigraphic and structural relationships between olistostromes (OL) and hanging wall and footwall units of main thrust. (**C**) Simplified geological section, showing the stratigraphic and structural relationships between the olistostromes and the shale diapir.

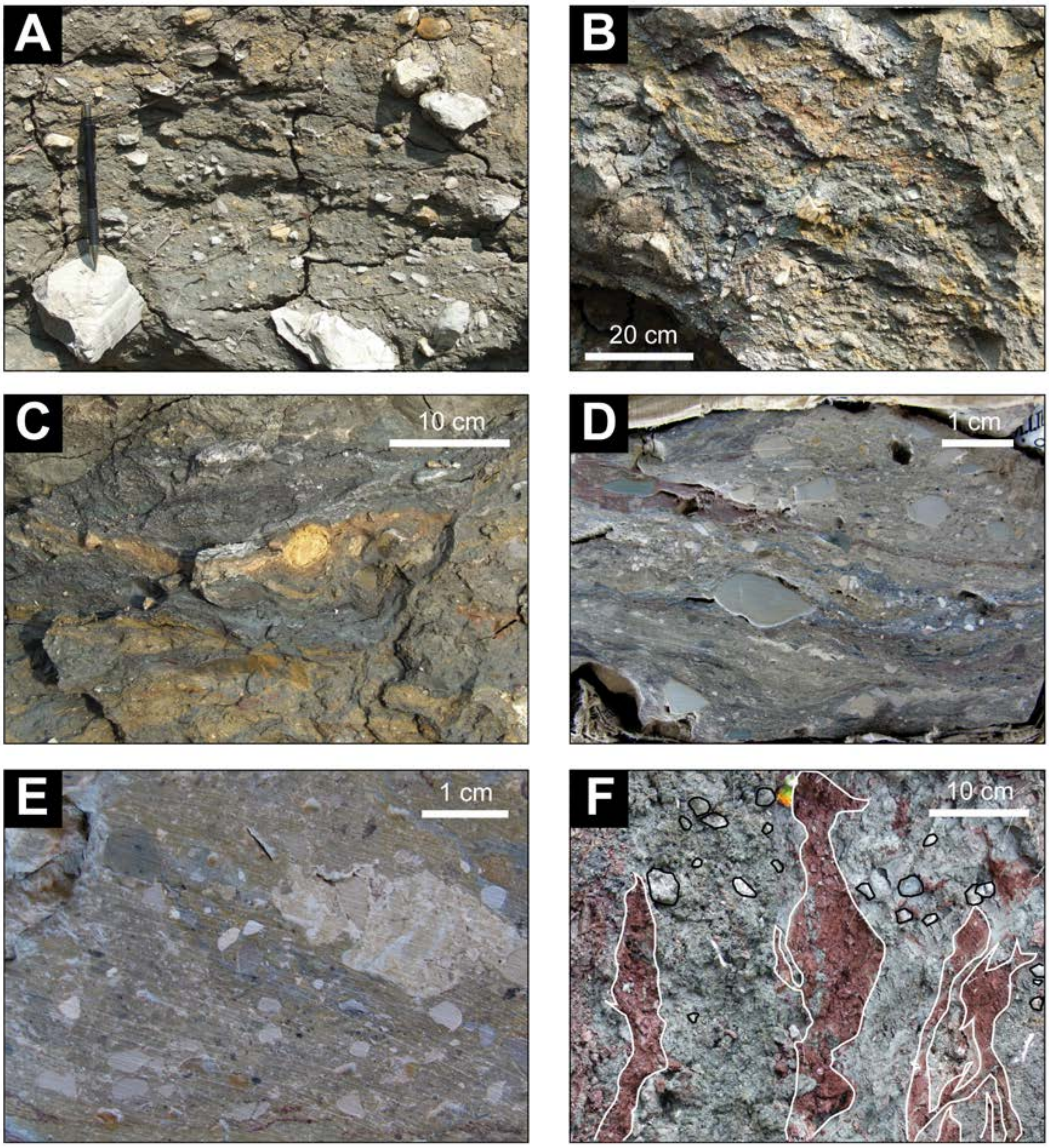

Figure 9 – Olistostromes in the Monferrato sector. (**A**) and (**B**) Different images of the basal portion of an olistostrome, showing the alignment of elongated and tabular blocks to the flow-related deformation. Note in (B) that the brecciated matrix is deformed by a pervasive foliation. (**C**) Close-up of the extensional shearing deformation of the basal shear zone characterized by high stretching values of unconsolidated horizon. (**D**) Close-up of a polished hand sample of the basal shear zone, showing highly stretched flow-related deformation features deforming the brecciated matrix. (**E**) Close-up of a polished hand sample of the brecciated matrix some meters above the basal shear zone, showing the random distribution of hard clasts in the matrix. (**F**) Shale dike injections, flame-shaped, intruding the block-in-matrix fabric of the olistostrome.

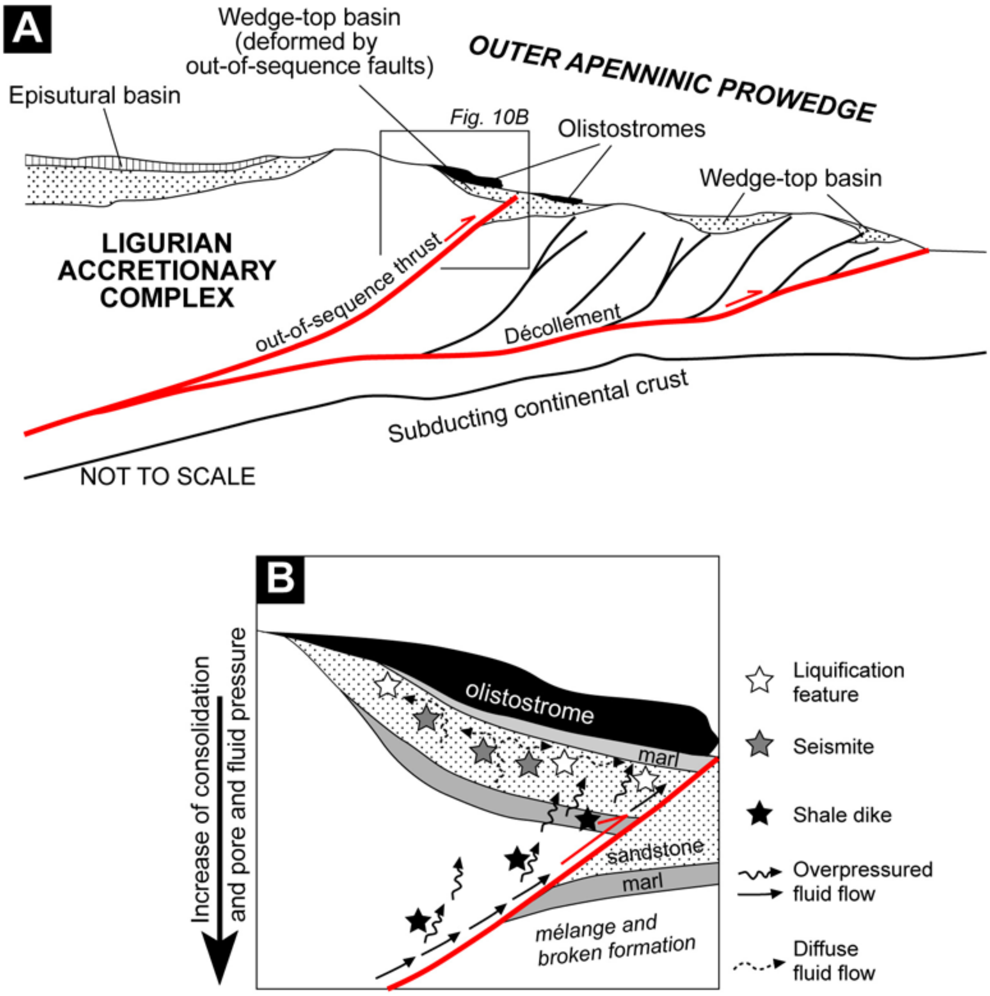

Figure 10 – (**A**) Conceptual cross-section of the Ligurian accretionary complex (i.e.,part of the outer Apenninic prowedge; not to scale) during late Oligocene collisional stage, showing the stratigraphic and structural setting of the studied sectors which is characterized by episutural/wedge-top basins displaced by out-of-sequence thrusts. (**B**) Schematic section (not to scale), showing the vertical piling of the different types of soft-sediment deformation and shale dike injections, and the lateral and vertical migration pathways of fluid flows in the hanging wall of main out-of-sequence thrust (see text for a detailed explanation).

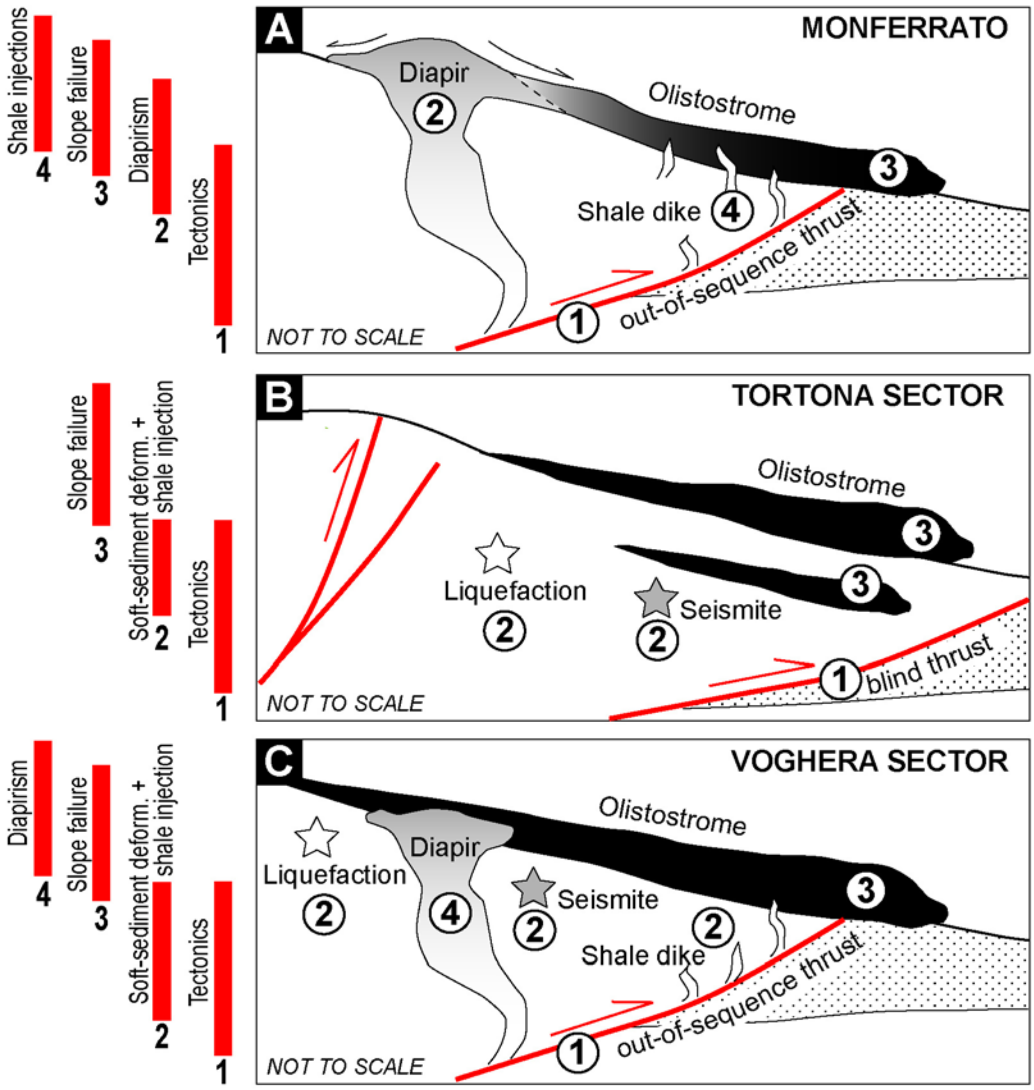

Figure 11 – Cartoons showing the different causative links between tectonics, diapirism, shale dike injection, soft-sediment deformation and slope failure in (**A**) Monferrato, (**B**) Tortona sector and (**C**) Voghera sector. Vertical bars on the left of the figures indicate the temporal interplay and superposition of the different processes (see text for a detailed explanation).

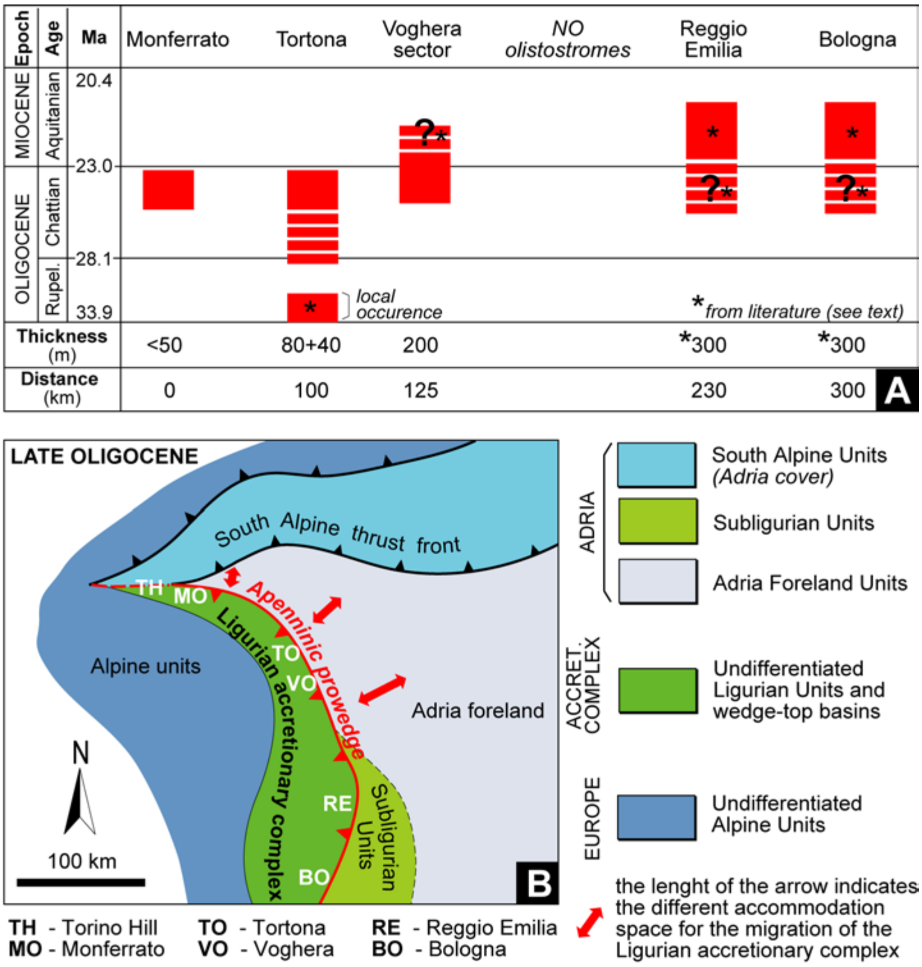

Figure 12 – (**A**) Diagram showing the variation in age of the studied olistostromes (from Monferrato to Voghera sector; see Fig. 12B) and comparable olistostromes to the southeast of the studied sector (i.e., from Reggio Emilia to Bologna sectors, see Fig. 12B). For the sector between Reggio Emilia and Bologna, literature data are from Papani (1971), Pini (1999), Balatri et al. (2002), Benini et al. (2002), Bettelli et al. (2002), Panini et al. (2002a), Papani et al. (2002), Gasperi et al. (2005a, 2005b), Martelli et al. (2009), and Remitti et al. (2011). The early Rupelian age of the "local occurrence" of the olistostromes in the Tortona sector is from Panini et al. (2013). (**B**) Schematic paleogeographic reconstruction at late Oligocene of the sector of the Alps-Apennines junction (modified from Castellarin, 1994; Mosca *et al.* 2010; Festa *et al.* 2013), showing the tectonic and kinematic interference between the SE-verging South Alpine thrust system and the N-verging Ligurian accretionary wedge (i.e., outer Apenninc prowedge) (see text for a detailed explanation). This interference created a major obstacle for the northward migration of the Apenninic prowedge in the Monferrato and Torino Hill sectors that shifted laterally to SE where a major accommodation space was present (red arrows). As a consequence, also the slope oversteepening of the wedge front and related slope instability and failure migrated toward SE from late Oligocene (Monferrato and Tortona sectors), to late Oligocene – early Miocene? (Voghera sector), up to early Miocene (between Reggio Emilia and Bologna) as shown in Fig. 12A.