UNIVERSITÀ DEGLI STUDI DI TORINO

Small-scale polygenetic mélanges in the Ligurian accretionary complex, Northern Apennines, Italy, and the role of shale diapirism in superposed mélange evolution in orogenic belts

Giulia Codegone[1,*], Andrea Festa[1], Yildirim Dilek[1, 2], and Gian Andrea Pini[3]

[1] Dipartimento di Scienze della Terra, Università di Torino, 10125 Torino, Italy;
[2] Department of Geology and Environmental Earth Science, Miami University, Oxford, OH 45056, USA;
[3] Dipartimento di Scienze della Terra e Geologico-Ambientali, Università di Bologna, 40127 Bologna, Italy.

*Corresponding author:
Giulia Codegone
E-mail: giulia.codegone@unito.it

Submitted to:
Tectonophysics
Special Issue: *Chaos and Geodynamics: Mélanges, Mélange Forming Processes and Their Significance in the Geological Record*

Abstract

The *Argille varicolori* (Varicolored scaly clays) of the External Ligurian Units of the Northern Apennines have been widely described as a typical unmetamorphosed broken formation (i.e., a chaotic unit without exotic blocks), produced by offscraping and tectonic imbrication during the evolution of the Ligurian accretionary wedge. Geological mapping and integrated structural and stratigraphic observations show that the *Argille varicolori* consist of diverse types of small-scale mélanges (non-mappable at a 1:25,000 scale) forming a composite chaotic unit, in which the superposition of tectonic, sedimentary and diapiric processes resulted in the occurrence of polygenetic chaotic bodies at different scales. These mélange units record the evolution of the Ligurian accretionary wedge from subduction to collision and intracontinental deformation. Tectonically Disrupted Body 1 (TDB1) comprises boudinage and pinch-and-swell structures formed by layer-parallel extension/contraction at the wedge front of the Ligurian accretionary complex during the late Cretaceous–middle Eocene. It is interleaved with non-mappable Gravity-driven Chaotic Bodies (GCB) developed during alternating episodes of accretion and removal of material at the wedge front. The late Oligocene–early Miocene out-of-sequence thrusting related to the collisional episodes in the Apennines overprinted the previously formed chaotic bodies and formed a polygenetic tectonic mélange (Tectonically Disrupted Body 2, TDB2). This unit is characterized by a structurally ordered block-in-matrix fabric and by the gradual decrease of stratal disruption away from the regional thrust. Overpressurized fluids concentrated along the shear surfaces, and the scaly cleavage planes facilitated the diapiric upward movement of unconsolidated sediments in the early Miocene. This process produced non-mappable shale dike injections (DDB1) and mappable Diapirically Disrupted Bodies (DDB2), which show an internal zonation of deformation. This deformation reworked the previously formed chaotic bodies. Although some of these polygenetic mélanges cannot be mapped at a 1:25,000 scale, their careful documentation provides a better understanding of time-progressive, scale-independent mélange-forming processes.

Key words: Polygenetic mélanges; broken formation; tectonic and sedimentary mélanges; accretionary wedge; shale diapirism; Northern Apennines.

1. Introduction

Accretionary complexes in convergent margins constitute a primary tectonic setting for the formation of chaotic bodies of mixed rocks and mélanges. Comparative studies of modern and ancient accretionary complexes are, therefore, a natural laboratory to investigate the mode and nature of all geological processes involved in mélange formation and their mechanisms and interplay (Ogawa et al., 2011).

Tectonic, sedimentary and diapiric processes that play the most important role in the formation of chaotic bodies and mélanges occur at all scales in convergent margin settings. While it is possible to decipher the internal architecture and large-scale structures in modern accretionary complexes by indirect methods of observations (i.e., seismic imaging), it is difficult to do so when the scale of observation is smaller (mesoscale to outcrop scale). Submersible investigations and drill cores provide *in situ* samples and measurements from accretionary complexes (Kawamura et al., 2009; Anma et al., 2010, 2011; Ogawa et al., 2011), but these methods are usually highly expensive and limited in coverage. The well-preserved on-land examples of ancient accretionary complexes are, therefore, highly important to conduct three-dimensional studies of chaotic bodies of mixed rocks and mélanges at various scales, and to better document different processes and their superposition during progressive evolution of accretionary complexes (Hsü, 1968; Aalto, 1981; Raymond, 1984; Cowan, 1985; Sample and Moore, 1987; Orange, 1990; Ogawa, 1998; Tankut et al., 1998; Hashimoto and Kimura, 1999; Pini, 1999; Cowan and Pini, 2001; Ujiie, 2002; Vannucchi and Bettelli, 2002; Yamamoto et al., 2005, 2009; Festa et al., 2010a, 2010b; Ghikas et al., 2010).

The results of comparative studies of active and ancient accretionary complexes demonstrate that their complex evolution in time and space also affects the mode of tectonic, sedimentary and diapiric processes and how they interact during mélange formation. Therefore, the structural architecture preserved in a mélange record may be an artifact of the latest and/or more pervasive process(es) involved (e.g., Raymond, 1984; Yamamoto et al., 2005; Dela Pierre et al., 2007; Festa et al., 2010a, 2010b; Festa, 2011). This is particularly the case for "polygenetic mélanges" whose evolution may have transcended several different tectonic settings with complex spatial and temporal interrelationships and superposition (e.g., Raymond, 1984; Orange, 1990; Pini, 1999; Cowan and Pini, 2001; Bettelli et al., 2002; Dilek et al., 2005; Dela Pierre et al., 2007; Camerlenghi and Pini, 2009; Yamamoto et al., 2009; Festa et al., 2010a, 2010b; Festa, 2011). Clear understanding of the geological processes and their interplay in modern and young accretionary complexes is also highly important in better documenting the structural architecture and evolution of more ancient examples in the Precambrian record (Dilek and Ahmed, 2003; Dilek and Polat, 2008).

In this paper, we report on the occurrence of small-scale mélanges *s.l.* (non-mappable at 1:25,000 or smaller scale according to the definition of mélange of Silver and Beutner, 1980) in the Ligurian accretionary wedge in Italy, and discuss the various processes (particularly shale diapirisim) involved in their formation during subduction-accretion, continental collision, and post-collisional periods of the tectonic evolution of the Northern Apennines. These small-scale mélange occurrences recorded in the "*Argille varicolori*" (Varicolored scaly clays) or *"Argille scagliose"* (Scaly clays) *Auct.* of the Northern Apennines provide an excellent case study to demonstrate the significance of their structures to better understand the time-progressive and scale-independent development of chaotic bodies in evolving orogens with superimposed processes and non-coaxial strain patterns.

In the following, we refer to mélange (*sensu* Silver and Beutner, 1980) in describing chaotic rock bodies, mappable at 1:25,000 or smaller scale, of mixed blocks composed of exotic (with respect to the lithostratigraphic unit of the matrix and/or its depositional environment) and native rocks in a pervasively deformed matrix. We refer, on the contrary, to broken formation (*sensu* Hsü, 1968; see also "broken" and "dismembered units" *sensu* Raymond, 1984) in describing, chaotic rock units in which blocks are only of native nature with respect to the matrix (i.e. not-exotic but of the same original lithostratigraphic unit or depositional environment). The term mélange *s.l.* (*sensu lato*) is used to describe in the wider sense chaotic rock units independently of the nature (exotic or not) of the blocks. Moreover, we define "small-scale" mélanges as the chaotic rock units that, according to the definition of Silver and Beutner (1980), are not mappable at 1:25,000 or smaller scale.

2. Regional geology of the Northern Apennines

The Northern Apennines (Figs. 1A and 2) comprise an E to NE-verging accretionary wedge composed of imbricate thrust sheets and nappes developed as a result of the late Cretaceous – early Cenozoic convergence between the European continental margin and the Adria microplate (e.g., Boccaletti et al., 1980; Bally et al., 1986; Dewey et al., 1989; Castellarin, 1994; Marroni et al., 1998, 2001, 2002; Elter et al., 2003; Cavazza et al., 2004; Dilek, 2006; Lucente and Pini, 2008; Festa et al., 2010b; Vezzani et al., 2010). The Ligurian Units in this thrust package represent the remnants of the Jurassic oceanic crust and its Jurassic – Eocene sedimentary cover, and include the eastward transition to the thinned Adria continental margin (e.g., Abbate et al., 1986; Vai and Castellarin, 1993; Castellarin, 1994; Marroni et al., 1998, 2001; Pini, 1999; Lucente and Pini, 2003).

During the pre-collisonal (eo-to meso-Alpine) episodes of continental convergence, the Ligurian Units were deformed and progressively incorporated into the late Cretaceous – middle Eocene accretionary wedge (e.g., Marroni et al., 2001; Bortolotti et al., 2005). These units currently occupy the highest structural position in the wedge, representing the farthest traveled thrust sheets in the Apennines. They are composed mainly of the Internal and External Ligurian Units, respectively (Fig. 1A). The Internal Ligurian Units include an "incomplete" ophiolite sequence (Fig. 2) composed of upper mantle lherzolites and gabbros intruded by dikes and overlain by pillows lavas, chert and hemipelagic sedimentary rocks (e.g., Elter, 1975; Abbate et al., 1980; Marroni and Pandolfi, 2001; Marroni et al., 1998; 2001, 2010; Dilek and Furnes, 2011). The External Ligurian

Units consist of non-metamorphosed succession deposited on the ocean-continent transition zone (OCT) of the rifted Adria continental margin. The rock assemblages in the External Ligurides include Lower-to Upper Cretaceous, highly disrupted pelagic and hemipelagic succession (Fig. 2) composed of the Palombini Shale, Ostia and/or Scabiazza Sandstone, and *Argille varicolori Auct.* including "Salti del Diavolo" Conglomerate (collectively known as the "basal complexes"). The *Argille varicolori Auct.* (or *Argille Scagliose, Varicolored scaly clays*) represents a non-metamorphosed chaotic complex formed by active tectonics at the front of the Ligurian accretionary wedge (e.g., Elter, 1975; Abbate et al., 1980; Marroni et al., 1998, 2001; Pini, 1999; Cowan and Pini, 2001; Bettelli and Vannucchi, 2003; Camerlenghi and Pini, 2009; Festa et al., 2010b). The "basal complexes" stratigraphically pass upward into the Upper Cretaceous – lower Paleocene succession of calcareous turbidites (known as the Helmintoid Flysch) that are, in turn, overlain by the Paleocene – middle Eocene clay-rich flysch deposits.

Both the Internal and External Ligurian Units overlie the Subligurian Units (Fig. 1C), which were originally deposited on the western margin of Adria (e.g., Bortolotti et al., 2001). All three units are unconformably overlain (Fig. 2) by the middle Eocene – late Miocene wedge-top basins (piggy-back basin *sensu* Ori and Friend, 1984). These basinal strata constitute the Epiligurian Units of the Northern Apennines (Figs. 1A, 1C and 2) consisting mainly of marine sedimentary rocks (e.g., Ricci Lucchi and Ori, 1985; Ricci Lucchi, 1986; Mutti et al., 1995). The Ligurian and Subligurian Units, forming the frontal part of the advancing Ligurian accretionary wedge, were thrust over the late Oligocene-Miocene Tuscan and Romagna-Marche-Umbria Units of Adria continental margin (Fig. 1C) during and after the late Oligocene collisional event (neo-Alpine).

The study area (Figs. 1A, 1C, and 3A) is located on the foothills of the Oltrepo pavese (ESE of Voghera) along a regional, NNW-striking and NE-verging, out-of-sequence thrust that emplaced the Cassio Unit over the Bettola Unit (e.g., Gelati et al., 1974; Di Dio et al., 2005), both of which are part of the External Ligurian Units (Fig. 3B). This out-of-sequence thrust system also involves the middle Eocene–Oligocene Epiligurian wedge-top succession that unconformably overlies the Bettola Unit.

The stratigraphic succession of the Cassio Unit (see legend of Fig. 3A) mainly comprises the *Argille varicolori* (part of the Upper Cretaceous "basal complexes"), which are characterized by highly disrupted and chaotic rocks lacking layer-continuity and displaying a block-in-matrix structural fabric. The *Argille varicolori* matrix, consisting of alternating thinly layered red, green, gray and bluish deformed beds of clay and shale (i.e. *"varicolori"* is an Italian term meaning "several colors"), contains: (i) non-exotic blocks of Upper Cretaceous limestone, sandstone, manganiferous siltstone and continentally-derived "Salti del Diavolo" fine-grained conglomerate, and (ii) exotic blocks (with respect to the formation and/or the depositional environment) consisting of large (up to hundreds of meters in size) slices of the Jurassic – Lower Cretaceous radiolarite and Maiolica limestone of the Cassio Unit substratum (see Panini et al., 2002), and of the Paleocene–middle Eocene carbonate-flysch of the Bettola Unit (Val Luretta Fm., see below). The *Argille varicolori* are overlain (Fig. 3A; see also Fig. 2) by the upper Campanian – lower Paleocene succession of the Monte Cassio Flysch (Helmintoid-flysch *Auct.*) and alternating layers of claystone and limestone of the Maastrichtian–middle-Upper Eocene Viano Clays (Papani, 1971; Panini et al., 2002). The Bettola Unit, which occurs in the footwall of the regional out-of-sequence thrust (Figs. 3A and 3B; see also Fig. 1C), is represented by the Val Luretta Formation, a lower Paleocene-to middle Eocene Ligurian flysch (Di Dio et al., 2005) that consist of alternating layers of weakly deformed shale and well-bedded clay-limestone-calcarenite intercalations.

The Epiligurian succession (Fig. 3A; see also Fig. 2) unconformably overlies both the Cassio and Bettola Units and is subdivided into two main depositional cycles, corresponding to a middle Eocene–lower Miocene shallowing-upward succession (represented by the Monte Piano Marls and Ranzano Formation) and a Langhian - Tortonian deepening-upward succession (represented by the Bismantova Group and Termina Formation) (e.g., Ricci Lucchi and Ori, 1985; Di Giulio et al., 2002; Mancin et al., 2006). These two successions are separated by a regional unconformity (Fig. 3A). The upper part of the lower depositional cycle includes an early Miocene (early Aquitanian) olistostrome known as the Val Tiepido-Canossa argillaceous breccias (Panini et al., 2002 and references therein; 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). An irregular erosional surface occurs at the base of the Val Tiepido-Canossa argillaceous breccias, separating (at a regional scale) the underlying, highly deformed, pre-lower Miocene External Ligurian and Epiligurian successions from the overlying, relatively undeformed, middle-to upper Miocene Epiligurian succession (Fig. 3A; see also Fig. 2) (e.g., Papani, 1963; Gelati et al., 1974; Remitti et al., 2011 and reference therein).

3. Diverse mélange *occurrences* in the *Argille varicolori*

The *Argille varicolori* of the Northern Apennines are widely known as tectonically disrupted units or broken formations (*sensu* Hsü, 1968), characterized by the lack of exotic blocks and/or mixing of blocks of different ages (see Pini, 1999; Cowan and Pini, 2001; Vannucchi and Bettelli, 2002; Bettelli and Vannucchi, 2003). However, there are few, local examples of tectonic and sedimentary mélanges containing exotic blocks and displaying polygenetic evolutionary paths. These include the *Argille varicolori* of the Coscogno Mélange and the Val Rossena Mélange or Rio Cargnone Complex (see Bettelli and Panini, 1989; Bettelli et al., 1989b, 1989c, 2002). In addition, small-scale (non-mappable at 1:25,000 scale) chaotic bodies *of Argille varicolori* (of both tectonic and sedimentary origins) locally occur as a result of mixing of rocks of different ages within narrow shear zones along the contacts between different broken formation units (see Pini, 1999), and thin interbeds of debris flows (see Bettelli and Panini, 1989).

The *Argille varicolori* of the study area (Fig. 3) occur in the hanging wall of the regional out-of-sequence thrust, which superposes the Cassio Unit onto the Bettola Unit. These rocks differ from most of the *Argille varicolori* of the Northern Apennines in that they are composed of heterogeneously disrupted and chaotic (block-in-matrix) bodies, formed at different scales by tectonic, sedimentary and diapiric processes (Fig. 3C).

In the rest of the paper, we use the term “disrupted unit” to indicate, in a wider sense, the tectonic, sedimentary or diapiric assemblage of: (i) small-scale chaotic bodies that, according to the definition of mélange of Silver and Beutner (1980) and Raymond (1984), are not mappable at a 1:25,000 scale; thus, they cannot be described as mélanges, and/or; (ii) mappable chaotic bodies.

3.1. Tectonically Disrupted Unit (TDU)

The Tectonically Disrupted Unit is the most extensive chaotic unit of *Argille varicolori* (Fig. 3A), and consists of two types of disrupted bodies formed by different tectonic processes.

A diagnostic feature of the first type of the Tectonically Disrupted Body (TDB1) is the block-in-matrix fabric, consistent with layer-parallel extension of the originally coherent multilayered succession, which is only partially preserved. TDB1 consists of moderately- to highly-stretched, alternating layers composed of thin (up to a meter thick) varicolored shale (red, green, light bluish and dark gray), minor gray marl (Figs. 4A and 4B), and thin (up to decimeters thick) “Salti del Diavolo” sandstone and fine-grained conglomerate, manganiferous siltstone and limestone. Strong layer-parallel extension resulted in the development of pinch-and-swell structures and necking of the shaly layers, and brittle and/or ductile boudinage and separation of the more competent layers into decimeter- to meter-long blocks. This deformation produced an alignment of the blocks and the shaly and marly layers (i.e., the matrix) in a pseudo-bedding fashion. Decimeter- to meter-long, narrow reverse shear surfaces crosscut at a low-angle these pseudo-bedding horizons, defining a characteristic tectonic layering with lozenge and lenticular shapes. A pervasive scaly fabric, developed parallel to the reverse shear surfaces, affects the entire matrix.

Shaly layers are commonly folded by meter-scale disharmonic-to isoclinal folds with sub-horizontal axial surfaces, irregularly thickened and stretched hinge zones, and thinned and boudinaged limbs aligned to tectonic layering (Figs. 4A and 4B). Despite strongly transposed and refolded by later episodes of tectonic deformation (see below), the TDB1 folds are mainly NW- and/or SE-verging, as suggested by the rarely preserved axial surfaces (Fig. 4E). Locally, two-perpendicular sets of folds may occur, with their fold axes orthogonal to each other (see below TDB2 and Fig. 4E), suggesting superposed folding as a result of layer-parallel extension in two perpendicular directions. These meso-scale structures (superimposed folds) are widely described and discussed in the literature (e.g., Bettelli and Panini, 1989; Pini, 1999; Vannucchi and Bettelli, 2002; Bettelli and Vannucchi, 2003); they are typical of the *Argille varicolori* of the Northern Apennines. We refer the reader to Bettelli and Vannucchi (2003) for a complete description of these structures. Close to the main thrust faults, particularly the basal regional thrust emplacing the Cassio Unit over the Bettola Unit (Fig. 4A), this block-in-matrix fabric is overprinted by shear zones that rotated and aligned the previously formed layer-parallel tectonic features parallel to the thrust geometry (Figs. 4E and 4F).

Diagnostic features of the second type of the Tectonically Disrupted Body (TDB2) are: (i) the scale-independent, structurally ordered block-in-matrix fabric that is consistent with (and aligned to) the regional stress field related to the NE-directed overthrusting; (ii) the transition, away from the thrust faults, from a highly disrupted block-in-matrix fabric to the preserved tectonic layering of TDB1 and/or to the (partially) coherent bedding of *Argille varicolori*; and, (iii) the gradual decrease in the occurrence and size of blocks away from the regional thrust fault.

Close to the regional thrust fault, the matrix is strongly deformed by SW-dipping R and P shears. These interlacing shear planes define millimeter- to centimeter-scale, spaced lenticular lenses (“L” shear lenses *sensu* Naylor et al., 1986), which are wrapped by shear surfaces that are consistent with the NE-verging regional reverse sense of shear (Figs. 4C, 4D and 4F). The lenses are commonly included within, and are rotated by, pervasive decimeter- to meter-wide, S-C reverse shear zones, which have NW-strikes and WSW-dip directions. The shear transposition of the previously formed meso-scale isoclinal folds of TDB1 produced isolated and sheared fold hinges, with axial surfaces aligned to tectonic planar features of TDB2 (Figs. 4C and 4E). The latter are NE-verging and show mainly NW and locally SE-plunging fold axis (Fig. 4E).

Long-axes of elongated and tabular blocks are strongly aligned to tectonic features at all scales, from millimeter-size clasts embedded in the matrix to decimeter-sized blocks reoriented by P and R, and S-C shear zones (Fig. 4C). Larger blocks (tens- to hundreds of meters long) that characterize the lower part of the Tectonically Disrupted Unit (Figs. 3A and 3B) consist of lenticular and/or elongated slices of the highly deformed Upper Jurassic–Lower Cretaceous Maiolica limestone and the slightly deformed lower Paleocene–middle Eocene Val Luretta Formation. These two lithologies represent the wrenched fragments of the Cassio Unit substratum and the Bettola Unit, respectively. The blocks have their NW-striking long axes aligned parallel to the regional thrust (see, for example, to the South of Illibardi in Fig. 2) and to the mesoscale shear zones.

The regional thrust superposing the Cassio Unit onto the Bettola Unit (Figs. 3A and 3B) is marked by a high-strain zone (up to few decimeters thick) composed of dark gray clay (Fig. 5A) enveloping sub-millimeter to centimeter-scale, elongated-to equi-dimensional clasts of marl and shale rocks derived from the Cassio, Bettola and Epiligurian units. This zone includes anastomosing networks of NNW-striking and WSW-dipping argillaceous veins, which define a “fluidal” fabric. The latter is marked by the alignment of sub-millimeter to centimeter-size, elongated clasts alternating with clay and siltstone horizons (Fig. 5), which are strongly aligned at all scales to the regional thrust fault. Centimeter-scale, NE-verging disharmonic to isoclinals folds, commonly strongly transposed, also occur as shown by the deformation of the block-in-matrix assemblage. Larger clasts (up to several decimeters in size) display pinch-and-swell and asymmetric boudinage structures aligned to the shortening direction, which is consistent with the NE-verging regional stress field. Strain shadows and “sigma” type porphyroclasts with asymmetric wings (see Fig. 5F) suggest high magnitude of simple shear deformation consistent with the direction and geometry of the regional contraction. Locally, P-C fabric cuts the “fluidal” feature suggesting a later pulse of deformation. Shearing along the P and R planes facilitated the fragmentation of the elongated clasts (Fig. 5B).

3.2. Gravity-driven Chaotic Bodies (GCB)

Up to meters-thick and tens of meters-long, chaotic mass-wasting deposits (Fig. 6B) are interbedded at different stratigraphic (and structural) levels within the *Argille varicolori*, and are variably overprinted by tectonic features (of TDB2) that formed during the thrusting of the Cassio Unit onto the Bettola Unit. Only some remnants of the original, lenticular-shape of the chaotic mass-wasting bodies are locally preserved. Their lower erosional surfaces are not preserved but can be inferred from the abrupt superposition of chaotic bodies characterized by the strongly different internal block-in-matrix arrangements. The highly disordered block-in-matrix fabric corresponds to mass-wasting deposits and is herein called Gravity-driven Chaotic Bodies (GCB). These GCB are superposed onto structurally ordered ones, representing the first type of tectonically disrupted bodies (TDU1).

Both the blocks and the matrix of the Gravity-driven Chaotic Bodies were derived from the *Argille varicolori* stratigraphic succession with only native (not-exotic) block occurrence. Blocks (centimeters-to decimeters in size) are tabular to equidimensional and angular to rounded in shape, and mainly float with a random distribution in a gray (locally red) shaly matrix. However, at the base of the gravity-driven chaotic bodies, locally occurs a planar anisotropy according to the direction of mass-transport emplacement (Fig. 6B). The matrix, whose typical relative volume fraction is about 60% (exceptionally, maximum relative matrix volume attains 70%-85%), is characterized by an isotropic texture and consists of mud breccias, including millimeter- to centimeter-size, rounded to angular clasts that lack preferential orientations (Fig. 6A). In some cases, the composition of the blocks is monomictic (Fig. 6B), suggesting only local and intraformational downslope remobilization and *in situ* disruption of some coherent, bedded sediments as a mechanism of formation (see also type I mélange of Cowan, 1985). In the upper part of the *Argille varicolori* succession, where the coherent stratigraphic bedding is still partially preserved, we observe several slumped horizons (up to a few meters thick).

The overprinting of the latest NE-verging thrust-related deformation (i.e., TDB2) on the block-in-matrix arrangement of the Gravity-driven Chaotic Bodies (GCB) produced variably pervasive S-C fabric elements that aligned the long-axis of the blocks parallel to the tectonic regional stress field.

3.3. Diapirically Disrupted Unit s.l. (DDU)

This unit consists of both shale dike injections (DDB1) and diapirically disrupted bodies (DDB2) (Figs. 3A and 3C) which intrude both the tectonically disrupted *Argille varicolori* (TDU) and the overlying middle Eocene–lower Miocene Epiligurian succession (Monte Piano Marls, Ranzano

Formation and Val Tiepido–Canossa argillaceous breccias). They both display zoned deformation (see, e.g., Orange, 1990; Dela Pierre et al., 2007; Festa et al., 2010a; Festa, 2011) characterized by increasing amount of deformation toward the diapiric contacts.

3.3.1. Shale dike injections (DDB1)

These consist of steeply- to moderately-dipping, non-mappable (at 1:25,000 scale) intrusive structures that are decimeter- to few meters-wide, and up to several meter-high. They pierce through discordantly and rework both the *Argille varicolori* and the middle-upper Eocene Monte Piano Marls of the Epiligurian Units (Figs. 7A, 7B, 7D and 7E). They include flame-shaped individual injections of unconsolidated shale dikes with crosscutting relationships (Fig. 6D). Their margins are sharp and irregular, and locally display centimeter- to decimeter-wide, up-to few decimeter long, cusped features that laterally intrude the hosting sediments.

Each single shale dike injection shows internal zonation of deformation defined by millimeter- to centimeter-sized scaly cleavage and S-C fabrics aligned to the margins of the structure, and consistent with upward rise of the filling shale with respect to the hosting sediments (Fig. 7E). This is most evident in larger dikes (up to few meters wide), whereas in the smaller ones (up to decimeter-wide) the scaly cleavage commonly pervades the whole dike.

Within the larger dike injections in the *Argille varicolori*, decimeter-sized long-axis blocks derived from the Tectonically Disrupted Unit are rotated into and aligned parallel to the mesoscale shear zones and scaly cleavage surfaces (Fig. 7G) affecting the upward rising shaly matrix (Figs. 7F). Deformation associated with the scaly cleavage and shear zones gradually decreases toward the core of these shale dike injections where irregular and isolated fold hinges occur with commonly steeply plunging axes.

Where the original bedding and/or tectonic layering of the hosting sediments are still recognizable, the shale dike injections appear to propagate upward from these pre-existing surfaces. Upward decrease in the vertical rise of the unconsolidated material resulted in different geometries of the dike tip, varying from gradual spreading of the fluidal features, to cuspate lobe, or to strongly convoluted features.

At structurally higher levels, the shale dike injections become smaller in size (up to decimeter-wide and few meter-high) with respect to those described above. These injections are commonly moderately-dipping and bounded both at the top and at the bottom by sub-horizontal depositional beds and/or tectonic layers (Fig. 7F). They were propagating from the bottom, layered horizons, commonly pervaded by a sub-parallel scaly fabric, ending with a gradual alignment to the top layered horizons (Fig. 7F).

3.3.2. Diapirically Disrupted Body (DDB2)

It consists of a 300-400 meters-wide diapiric chaotic body of *Argille varicolori* (Figs. 3 and 8A) with irregular, arched to semi-concentric shape in map view, which only partially protrudes into the overlying lower Miocene Val Tiepido-Canossa argillaceous breccias of the Epiligurian succession. It consists of two minor diapiric bodies, up to 100-150-meters-wide, of varicolored scaly clays showing mutual intrusive relationships. Each minor diapiric body shows an incipient zone of deformation with a gradual decrease of deformation toward its core (Fig. 8A). At the margins, scaly cleavage and reverse shear zones (P and R shear and/or S-C shears) become parallel to the intrusive contacts and strongly deform the pseudo-bedding showing opposite vergence on the opposite margins. The blocks made of more competent rocks within this body include manganiferous siltstone, limestone and lithoarenite (i.e., the same lithologies of Tectonically Disrupted Unit) whose long axis and/or boudinaged beds are aligned parallel to the scaly cleavage and intrusive contacts. Dike (flame-shaped) injections that are up to several-meters-high and about a meter-wide shale, similar to those described above (DDB1), locally intrude the pseudo-bedding of the marginal zone reflecting the upward rise of the intruded material.

In the core of each diapiric body, pseudo-bedding and/or previously formed tectonic layering and isoclinal folds related to TDB1 are commonly preserved and irregularly refolded by convolute and asymmetric folds with moderately to steeply plunging axes. These folds have randomly distributed (Fig. 8B) and steeply dipping to subvertical axial surfaces as a result of upward extrusion of the mudstone-shale material. We observe tens of meters wide positive flower structures in the core of the diaper, in cross-section (Figs. 8C and 8D).

4. Discussion

Our detailed mesoscale structural observations indicate that the *Argille varicolori* represent a composite chaotic unit (*sensu* Dela Pierre et al., 2007) consisting of different mélange *s.l.* types. We discuss below the mutual space and time relationships, at different scales, between these mélanges *s.l.* and their superposition in forming polygenetic mélanges with the contribution of trapped fluids circulating within the frontal part of the accretionary complex. The recognition of these polygenetic mélanges, the processes involved in their formation, and the spatial-temporal relationships between these processes allow us to better define the structural evolution of the Ligurian accretionary complex of the Northern Apennines.

4.1. Polygenetic mélanges s.l in the composite chaotic unit

The Tectonically Disrupted Unit represents a polygenetic chaotic unit developed as a result of the superposition of two different tectonic chaotic products related to two different episodes of tectonic deformation. These episodes are manifested in the superposition of the younger thrust-related deformation of TDB2 (Figs. 4C and 9D) onto the older layer-parallel extensional deformation of TDB1 (Fig. 9A). The latter (TDB1) records, according to the previous studies (e.g., Bettelli and Panini, 1989; Pini, 1999; Vannucchi and Bettelli, 2002; Vannucchi and Bettelli, 2003), the accretion-related deformation of the *Argille varicolori* achieved during the late Cretaceous-middle Eocene development of the Ligurian accretionary wedge. The TDB1 corresponds to a tectonic broken formation lacking exotic blocks (see also, Bettelli and Panini, 1989; Pini, 1999; Vannucchi and Bettelli, 2002; Vannucchi and Bettelli, 2003). On the contrary, the TDB2 has been considered as a tectonic mélange, consisting of a narrow zone of tectonic mixing related to thrusting and including exotic blocks (with respect to the depositional basin of Cassio Unit) or slices (i.e., Val Luretta Fm. of the Bettola Unit, and Monte Piano Marls of the Epiligurian Units, see Fig. 3) within the *Argille varicolori* matrix (Fig. 9A).

The overprint of thrust-related deformation, forming the polygenetic Tectonically Disrupted Unit, can be observed at all scales, manifested in a structurally ordered block-in-matrix fabric (TDB2), which is consistent with the regional stress field of the late Oligocene–early Miocene collisional episodes. The intensity of this deformation diminishes gradually away from the thrust faults where the tectonic deformation related to TDB1 broken formation is still preserved (Fig. 9E).

The second type of polygenetic mélange *s.l.* developed due to the thrusting-related deformation (TDB2), overprinting the previously formed Gravity-driven Chaotic Bodies (Figs. 9A and 9D). Although the collisional tectonic deformation strongly overprints these bodies as well as the original erosional surfaces, some of the diagnostic features of sedimentary mélanges, such as a highly distorted block-in-matrix fabric and isotropic brecciated texture of the matrix, are still preserved. The tectonically-overprinted Gravity-driven Chaotic Bodies represent polygenetic mélanges *s.l.* (tectono-sedimentary intra-nappe mélanges *sensu* Festa et al., 2010a, 2010b) that are consistent with episodic emplacement of mass-wasting bodies at the front of an advancing accretionary wedges (Figs. 9A and 9D).

The intrusion at different scales of diapiric bodies and shale dike injections (Figs. 10A and 10B) strongly overprints the block-in-matrix fabric of the previously formed Tectonically Disrupted Unit (Fig. 10C). Within the shale dike injections of the DDB1, deformational features associated with tectonic processes are completely overprinted by intrusive features consisting of pervasive shear zones and scaly cleavage aligned to the margins of the dike intrusions. On the contrary, within the larger diapiric bodies of the DDB2, the previously formed tectonic block-in-matrix fabric is still preserved with a gradual increase of deformation from the core zone to the margins of the diapiric intrusions. In the core zone, the previously formed isoclinal folds of TDB1 with sub-horizontal axial surfaces are irregularly deformed forming convoluted folds with variably plunging axes (Fig. 10C). In the marginal zone, the previously formed tectonic features (folds, S-C fabrics, scaly cleavage) are commonly affected by a pervasive scaly cleavage and shear zones aligned to the intrusive contacts. In all cases of diapiric intrusions and associated deformation, the source rocks are previously dismembered tectonic broken formations (TDB1) and mélanges (TDB2) instead of bedded successions, which are reworked by both trapped and escaping fluids.

4.2. Mutual relationships between fluids and scaly fabric in the formation of polygenetic mélanges s.l.

Superposition of tectonic, sedimentary and diapiric processes occurs in a structural setting in which fluids and stratal disruption have a strong interplay during the formation of polygenetic mélanges *s.l.* In a multilayer sedimentary sequence consisting of horizons with different competence such as the *Argille varicolori*, the high fluid content is controlled by the low permeability of shaly horizons. The scaly fabric in a shale rock produces a marked anisotropy in permeability and represents a preferential pathway for fluids (Figs. 9A and 9C) as it modifies and concentrates the flow pattern in well-constrained horizons (e.g., Davis et al., 1983; Moore at al., 1988; Brown, 1990; Screaton et al., 1990; Maltman, 1994). This process induces major stratal disruption. Some studies (e.g., Carson and Berglund, 1986; Moore et al., 1986; Brown, 1990) have shown that the alignment of clay minerals along shear surfaces may enhance permeability up to 2-3 order of magnitude along the tectonic fabric (see Arch and Maltman, 1990; Maltman, 1994), although development of a scaly cleavage and centimeter- to decimeter-wide shear zones may reduce water content in unconsolidated and wet sediments. Concentrated fluid flow along a tectonic layering and/or thin scaly fabric horizons of TDB1 (Fig. 9C) may, for example, have reduced the strength of overlying sediments, facilitating mass-wasting and the emplacement of Gravity-driven Chaotic Bodies (GCB) during local episodes of dynamic instability of the wedge front of the accretionary complex (Fig. 9B).

The occurrence of a thin (decimeters thick) horizon of mud-breccias with a “fluidal” feature at the base of the regional thrust suggests that pressurized fluids facilitated thrusting by forming a pressurized thin taper exceeding the hydrostatic pressure on which *Argille varicolori* of the Cassio Unit overrode the Bettola Unit. This barely viscous and quasi-fluid horizon, which was subsequently cut by brittle shear features, does not show a diagnostic block-in-matrix fabric related to tectonics. However, we interpret these mud breccias as a tectonic mélange in considering the setting and the structural position of its formation and the mixing of clasts derived from the Cassio, Bettola and Epiligurian units.

Along the thrust surface, constant or increasing effective stress conditions may have resulted in the widespread occurrence of scaly cleavage and shear zones. These structures could in turn lead to the thickening of the shear zone due to strain hardening (*sensu* Moore and Byrne, 1987; Brown and Behrmann, 1990; Doubleday and Trenter 1992) by gradually transferring strain to surrounding sediments that were not yet affected by thrusting. Gradual decrease in deformation of TDB2 away from the regional thrust indicates diminishing effective stress. This is related to the confinement of fluid flow in only a few thin anisotropic conduits corresponding to bedding surfaces or little scaly cleavage horizons along which the fluid pressure may have increased.

The occurrence of intrusive structures at different scales, varying from subvertical shale dike injections (DDB1) to large-scale diapirs (DDB2), indicates focused mobilization of pressurized fluids (Fig. 10A), which may have been 3 or 4 orders of magnitude faster than the distributed flow (see, e.g., Moore and Vrolijk, 1992). These fluids then must have exited the system also along pressurized conduits. The mutual crosscutting relationships between both the shale dike injections (DDB1) and the large-scale diapiric bodies (DDB2) suggest that probably fluid flow was episodic and coupled to one another. We infer that the shale dike injections were sourced from the low–angle, highly sheared horizons or from bedding to pseudo-bedding surfaces that both acted as preferential conduits for pressurized fluids (Fig. 10A). The upward fluid pressure loss resulted in both dilation of fluidal conduits and the formation of a pervasive scaly cleavage along the intrusive marginal contacts that dissipated the fluid pulse, and also in the upward transition from subvertical- to medium angle shale dike injections.

Subvertical to moderately- dipping dike injections also characterize the marginal zone of the larger diapiric bodies (DDB2) that facilitated the focused fluid flow intruding steeply dipping pervasive scaly cleavage and shear zones aligned to the margin of the diapir. The anisotropic permeability of the marginal zone promotes a fluid flow from the less foliated core zone of the diapir to the strongly foliated marginal zone, which may have favored the upward rise of fluids (see, e.g., Horath, 1989, Horat and Moore, 1989; Arch and Maltman, 1990; Brown, 1990; Maltman, 1994). In this way, fluid migration strongly controlled the zonation of deformation that is diagnostic of diapiric mélanges (e.g., Orange, 1990; Dela Pierre et al., 2007; Festa et al., 2010a, 2010b; Festa, 2011).

4.3. Timing of polygenetic mélange s.l. formation

The formation of different and mutually superposed types of mélanges *s.l.* described in the *Argille varicolori* composite chaotic was related to two main tectonic episodes, as outlined below.

Late Cretaceous – middle Eocene accretionary stage.

The Tectonically Disrupted Body 1 (TDB1) was formed during accretionary processes related to subduction (e.g., Bettelli and Panini, 1989; Pini, 1999; Cowan and Pini, 2001; Vannucchi and Bettelli, 2002; Bettelli and Vannucchi, 2003). Boudinage, pinch-and-swell features and development of NW- or SE-verging isoclinal folds formed a block-in-matrix fabric, which is consistent with layer-parallel extension/contraction that occurred at the wedge front (e.g., Cowan, 1985; Pini, 1999; Bettelli and Vannucchi, 2003) of the Ligurian accretionary complex during the late Cretaceous-middle Eocene convergence between the European and Adria plates (Fig. 9A) (e.g., Principi and Treves, 1984; Vai and Castellarin, 1993; Marroni and Pandolfi, 1996; Pini, 1999). The local occurrence of Gravity-driven Chaotic Bodies (GCB) interleaved within the Tectonically Disrupted Body 1 (TDB1) (Fig. 9A) is consistent with alternating episodes of accretion and removal of material at the wedge front that controlled its dynamic equilibrium (e.g., Davis et al., 1983; Cowan, 1985; Moore and Vrolijk, 1992; Kimura et al., 1997; von Huene et al., 2000; Remitti et al., 2011).

Late Oligocene– early Miocene thrusting associated with intracontinental deformation.

The out-of-sequence thrusting of the Cassio Unit onto the Eocene-Oligocene Epiligurian wedge-top deposits (Ranzano Fm. and Monte Piano Marls, see Figs. 3A and 3C) resting unconformably on the Bettola Unit (Fig. 9D) overprinted and rotated the previously formed block-in-matrix fabric of the Tectonically Disrupted Body 1 and Gravity-driven Chaotic Bodies (GCB). This process in turn developed the Tectonically Disrupted Body 2 (TDB2) (Fig. 9E). Fluids concentrated along thrust-induced shear and scaly cleavage surfaces were the source for escaping overpressured fluids (Fig. 10A). These escaping fluids were responsible for the formation of different types of diapiric mélanges *s.l.* (i.e., DDB1 and DDB2) that intruded both the *Argille varicolori*, the middle Eocene Epiligurian sediments (Monte Piano Marls), and the base of the lower Miocene Val Tiepido-Canossa argillaceous breccias (Figs. 10A and 10B). The early Miocene regional tectonics triggered the rapid emplacement of a large-scale olistostrome (Val Tiepido-Canossa argillaceous breccias), which rapidly buried the low permeable *Argille varicolori.* This rapid increase of sedimentary loading may have triggered the upward rise of fluids exceeding the hydrostatic pressure and forming diapirism in unconsolidated sediments (Fig. 10A).

5. Conclusions

This study outlines the mode and nature of the processes that contributed to the development of a highly chaotic deposit in the Northern Apennines, represented by the *Argille varicolori*. We present this case study as a typical scale-dependent problem.

The *Argille varicolori* of the External Ligurian Units in the Northern Apennines have been widely described as a characteristic broken formation without any exotic blocks and/or mixing of blocks of different ages. It has been interpreted to have formed via tectonic disruption during the late Cretaceous – middle Eocene accretionary processes associated with the convergence between the European and Adria plates (e.g., Bettelli and Panini, 1989; Pini, 1999; Bettelli and Vannucchi, 2002; Vannucchi and Bettelli, 2003; Remitti et al., 2011). Although this interpretation is still applicable at a regional scale, our detailed field mapping and stratigraphic-structural analyses show that sedimentary (mass-transport) and diapiric processes also played a major role in their formation. We hence suggest that the *Argille varicolori* represent a composite chaotic unit consisting of different polygenetic chaotic bodies and/or disrupted units formed by the superposition of various tectonic, sedimentary and diapiric processes. The main driving force for deformation was the late Cretaceous–middle Eocene accretionary tectonics and the late Oligocene-early Miocene collisional and intra-continental thrusting.

Most of the polygenetic chaotic and disrupted bodies described in this study cannot be mapped as mélanges *s.l.* in parallel with the definition of Silver and Beutner (1980) (i.e., internally fragmented and mixed rock bodies that are mappable at 1:25,000 or smaller scales). However, their occurrence is of great significance for better understanding the scale-independent processes of mélange *s.l.* formation and the stratigraphic-structural and geodynamic evolution of an exhumed accretionary wedge. In particular, the small-scale polygenetic chaotic and disrupted bodies may record the early stages of the formation of larger-scale (mappable) chaotic bodies, controlled by close spatial-temporal relationships between fluid and stratal disruption. Our observations and data from the Northern Apennines provide significant insights into our understanding of the construction of modern accretionary complexes at mesoscopic and microscopic scales, which are nearly implausible to decipher from seismic images and submersible surveys.

ACKNOWLEDGMENTS

We thank the Editor-in-Chief, F. Storti, and the three anonymous reviewers for their careful reviews that greatly helped in focusing and clarifying our interpretations in the paper. We also thank Guest Editor Y. Ogawa for his insightful comments that helped us improve the organization and the science in our paper, and S. Cavagna for her help in the analysis of samples at the scanning electron microscope.

REFERENCES

Aalto, K.R., 1981. Multistage melange formation in the Franciscan Complex, northernmost California. Geology 9, 602-607.

Abbate, E., Bortolotti, V., Conti, M., Marcucci, M., Principi, G., Passerini, P., Treves, B., 1986. Apennines and Alps ophiolites and the evolution of the western Tethys. Mem. Soc. Geol. It. 31, 23–44.

Abbate, E., Bortolotti, Principi, G., 1980. Apennine ophiolites: a peculiar oceanic crust, in: Rocci, G. (Ed.), Ofioliti, Special Issue on Tethyan ophiolites, western area, 1, 59–96.

Anma, R., Ogawa, Y., Kawamura, K., Moore, G.F., Sasaki, T., Kawakami, S., Hirano, S., Ota, T., Endo, R., Michiguchi, Y., YK05-08 Shipboard Science Party, 2010. Structures, textures, physical properties of accretionary prism sediments and fluid flow near the Splay Fault zone in the Nankai Trough, off Kii peninsula. J. Geol. Soc. Jpn. 116 (12), 637-660 (in Japanese with English abstract).

Anma, R., Ogawa, Y., Moore, G.F., Kawamura, K., Sasaki, T., Kawakami, S., Dilek, Y., Michiguchi, Y., Endo, R., Akaiwa, S., Hirano, S., YK99-09, YK00-08, YK05-08 and YK06-02 Shipboard Science Parties, 2011. Structural profile and development of the accretionary complex in the Nankai trough, Southwest Japan: Results of submersible studies, in: Ogawa, Y., Anma, R., Dilek, Y. (Eds.), Accretionary Prisms and Convergent Margin Tectonics in the Northwest Pacific Basin. Springer, 169-196. ISBN: 978-90-481-8884-0.

Arch, J., Maltman, A.J., 1990. Anisotropic permeability and tortuosity in deformed wet sediments. J. Geophys. Res. 95, 9035-9045.

Bally, A.W., Burbi, L., Cooper, C., Ghelardoni, R., 1986. Balanced sections and seismic reflection profiles across the central Apennines. Mem. Soc. Geol. It. 35, 257-310.

Bettelli, G., Panini, F., 1985. Il mélange sedimentario della Val Tiepido (Appennino modenese). Atti Soc. Nat. Mat. di Modena 115, 91–106.

Bettelli, G., Panini, F., 1989. I mélanges dell‟Appennino settentrionale tra il T. Tresinaro ed il T. Sillaro. Mem. Soc. Geol. It. 39, 187–214.

Bettelli, G., Vannucchi, P., 2003. Structural style of the offscraped Ligurian oceanic sequences of the Northern Apennines: new hypotesis concerning the development of mélange block-in-matrix fabric. J. Struct. Geol. 25, 371-388.

Bettelli, G., Bertolini, G., Bonazzi, U., Cavazzuti, M., Cuoghi, A., Gasperi, G., Panini, F., 1987. Carta Geologica Schematica dell‟Appennino Modenese e Zone Limitrofe, in: La geologia del versante padano dell‟Appennino settentrionale, Convegno della Società Geologica Italiana, Modena, Guida all‟Escursione. Modena, STEM-Mucchi, scale 1:100,000.

Bettelli, G., Bonazzi, U., Fazzini, P., Gasperi, G., Gelmini, R., Panini, F., 1989a. Nota illustrativa alla Carta geologica dell‟Appennino modenese e zone limitrofe. Mem. Soc. Geol. It. 39, 487-498.

Bettelli, G., Bonazzi, U., Fazzini, P., Panini, F., 1989b. Schema introduttivo alla geologia delle Epiliguridi dell‟Appennino modenese e delle aree limitrofe. Mem. Soc. Geol. It. 39, 215–244.

Bettelli, G., Bonazzi, U., Panini, F., 1989c. Schema introduttivo alla geologia delle Liguridi dell‟Appennino modenese e delle aree limitrofe. Mem. Soc. Geol. It. 39, 91-126.

Bettelli, G., Panini, F., Pizziolo, M., 2002. Note illustrative della Carta Geologica d‟Italia alla scala 1:50,000, Foglio 236 „Pavullo nel Frignano‟. S.El.Ca. Firenze, 165.

Bigi, G., Cosentino, D., Parotto, M., Sartori, R., Scandone, P., 1983. Structural Model of Italy: Geodynamic project, C.N.R., S.El.Ca. Firenze, scale 1:500,000, 9 sheets.

Boccaletti, M., Coli, M. (Eds.), 1982. Carta strutturale dell‟Appennino settentrionale. Progetto Finalizzato Geodinamica, Sottoprogetto 5: CNR, Pubbl. 429. S.El.Ca. Firenze.

Boccaletti, M., Coli, M., Decandia, F.A., Giannini, E., Lazzarotto, A., 1980. Evoluzione dell'Appennino settentrionale secondo un nuovo modello strutturale. Mem. Soc. Geol. It. 21, 359-373.

Bortolotti, V., Marroni, M., Pandolfi, L., Principi, G., 2005. Mesozoic to Tertiary tectonic history of the Mirdita ophiolites, northern Albania. Island Arc 14, 471-493.

Bortolotti, V., Principi, G., Treves, B., 2001. Ophiolites, Ligurides and the tectonic evolution from spreading to convergence of a Mesozoic Western Tethys segment, in: Vai, G.B., Martini, I.P. (Eds.), Anatomy of an Orogen: the Appennines and Adjacent Mediterranean Basins. Kluwer Academic Publishers, Great Britain, 151-164.

Brown, K.M., 1990. The nature and hydrogeologic significance of mud diapirs and diatremes for accretionary systems. J. Geophys. Res. 95, 8969–8982.

Brown, K.M., Behrmann, J., 1990. Genesis and evolution of small scale structures in the toe of Barbados Ridge accretionary wedge, in: Moore,A., Mascle, A. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, Leg 110. College Station, Texas, Ocean Drilling Program, 229-243.

Camerlenghi, A., Pini, G.A., 2009. Mud volcanoes, olistostromes and Argille scagliose in the Mediterranean region. Sedimentology 56, 319-365.

Carson, B., Berglund, P. L., 1986. Sediment deformation and dewatering under horizontal compression: Experimental results, in: Moore, J. C. (Ed.), Structural fabric in Deep Sea Drilling Project cores from forearcs. Geol. Soc. Am. Mem. 166, 135–150.

Castellarin, A., 1994. Strutturazione eo-mesoalpina dell‟Appennino Settentrionale attorno al “nodo ligure”, in: Capozzi, R., Castellarin, A. (Eds.), Studi preliminari all‟acquisizione dati del profilo CROP 1–1A La Spezia–Alpi orientali, Studi Geologici Camerti, Volume Speciale 1992/2: Camerino, Università degli Studi di camerino, 99-108.

Cavazza, W., Roure, F., Ziegler, P.A., 2004. The Mediterranean area and the surrounding regions: active processes, remnants of former Tethyan oceans and related thrust belts, in: Cavazza, W., Roure, F., Spakman, W., Stampfl i, G.M., Ziegler, P.A. (Eds.), The TRANSMED Atlas: The Mediterranean Region from crust to mantle. Springer, 1–29.

Cowan, D.S., 1985. Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America. Geol. Soc. Am. Bull. 96, 451-462.

Cowan, D.S., Pini, G.A., 2001. Disrupted and chaotic rock units in the Apennines, in: Vai, G.B., Martini, I.P. (Eds.), Anatomy of a Mountain Belt: The Apennines and Adjacent Mediterranean Basins. Kluwer Academic Publishers, Dordrecht, 165-176.

Davis, D., Suppe, J., Dahlen, F.A., 1983. Mechanics of fold-and-thrust belts and accretionary wedges. J. Geophys. Res. 88, 1153-1172.

Dela Pierre, F., Festa, A., Irace, A., 2007. Interaction of tectonic, sedimentary and diapiric processes in the origin of chaotic sediments: an example from the Messinian of the Torino Hill (Tertiary Piedmont Basin, NW Italy). Geol. Soc. Am. Bull. 119, 1107-1119.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.W.H., Knott, S.D., 1989. Kinematics of the western Mediterranean, in: Coward, M.P., Dietrich, D., Park, R.G. (Eds.), Alpine Tectonics. Geol. Soc. London Spec. Publ. 45, 265-283.

Di Dio, G., Piccin, A., Vercesi, P.L., 2005. Note Illustrative della Carta Geologica d'Italia alla scala 1:50,000, Foglio 179 Ponte dell'Olio, S.El.Ca. Firenze. Servizio Geologico d'Italia – Regione Emilia Romagna, 108.

Di Giulio, A., Mancin, N., Martelli, L., 2002. Geohistory of the Ligurian orogenic wedge: first inferences from Epiligurian sediments. Boll. Soc. Geol. It., Vol. Spec., 375-384.

Dilek, Y., 2006. Collision tectonics of the Eastern Mediterranean region: Causes and consequences. Geol. Soc. Am. Spe. Pap. 409, 1-13. DOI: 10.1130/2006.2409(1).

Dilek, Y. and Ahmed, Z., 2003. Proterozoic ophiolites of the Arabian Shield and their significance in Precambrian tectonics: In, Dilek, Y. and Robinson, P.T. (Eds.), Ophiolites in Earth History, Geol. Soc. London Spec. Publ. 218, 685-701.

Dilek, Y., Furnes A., 2011. Ophiolite genesis and global tectonics fingerprinting of ancient oceanic lithosphere. Geol. Soc. Am. Bull. 123, 387-411. DOI: 10.1130/B30446.1.

Dilek, Y. and Polat, A., 2008. Suprasubduction zone ophiolites and Archean tectonics. Geology 36, 430-432. DOI: 10.1130/Focus052008.1.

Dilek, Y., Shallo, M. and Furnes, H., 2005. Rift-drift, seafloor spreading, and subduction zone tectonics of the Albanian ophiolites. Int. Geol. Rev. 47, 147-176. DOI: 10.2747/0020-6814.47.2.147.

Doubleday, P.A., Trenter, T.H., 1992. Modes of formation and accretion of oceanic material in the Mesozoic fore-arc of the Central and Southern Alexander Island, Antarctica: A summary, in: Yoshida, Y., Kaminuma, K., Shiraishi, K. (Eds.), Recent progress in Antarctic Earth Science. Tokyo, Terra Scientific Publishing Company (TERRAPUB), 377–382.

Elter, P., 1975. L‟ensemble ligure. Bull. Soc. Géol. France 17, 984–997.

Elter, P., Grasso, M., Parotto, M., Vezzani, L., 2003. Structural setting of the Apennine-Maghrebian thrust belt: Episodes. J. Int. Geosci. 26 (3), 205–211.

Fazzini, P., Tacoli, M.L., 1963. La serie oligo-miocenica del versante padano dell‟Appennino settentrionale e la sua posizione nella tettonica regionale. Atti Soc. Nat. Mat. di Modena 94, 33–52.

Festa, A., 2011. Tectonic, sedimentary, and diapiric formation of the Messinian melange: Tertiary Piedmont Basin (northwestern Italy), in: Wakabayashi, J., Dilek, Y. (Eds.), Melanges: Processes of formation and societal significance. Geol. Soc. Am. Spec. Pap. 480, 215-232. doi:10.1130/2011.2480(10).

Festa, A., Pini, G.A., Dilek, Y., Codegone, G., 2010a. Mélanges and mélange-forming processes: a historical overview and new concepts, in: Dilek, Y. (Ed.), Alpine Concept in Geology. Int. Geol. Rev. 52 (10-12), 1040-1105. DOI: 10.1080/00206810903557704.

Festa, A., Pini, G.A., Dilek, Y., Codegone, G., Vezzani, L., Ghisetti, F., Lucente, C.C., Ogata, K., 2010b. Peri-Adriatic mélanges and their evolution in the Tethyan realm, in: Dilek, Y. (Ed.), Eastern Mediterranean geodynamics (Part II). Int. Geol. Rev. 52 (4-6), 369-406. DOI: 10.1080/00206810902949886.

Gelati, R., Bruzzi, D., Catasta, G., Cattaneo, P.C., 1974. Evoluzione stratigrafico-strutturale nell‟Appennino vogherese a nord-est della Val Staffora. Riv. It. Paleont. Strat. 80 (3), 479-514.

Ghikas, C., Dilek, Y. and Rassios, A.E., 2010. Structure and tectonics of subophiolitic mélanges in the Western Hellenides (Greece): Implications for ophiolite emplacement tectonics, in: Dilek, Y. (Ed.), Eastern Mediterranean geodynamics (Part II). Int. Geol. Rev. 52 (4-6), 423-453.

Hashimoto, Y., Kimura, G., 1999. Underplating process from mélange formation to duplexing: Example from the Cretaceous Shimanto Belt, Kii Peninsula, southwest Japan. Tectonics 18, 92–107.

Horath, F., 1989. Permeability evolution in the Cascadia Accretionary Prism:Example from the Oregon Prism and Olympic Peninsula mélange, M.S. thesis, Univ. of Calif., Santa Cruz.

Horath, F., Moore, J.C., 1989. Permeability evolution in the Cascadia Accretionary Prism: Examples from the submarine prism and uplifted shear zones. Geol. Soc. Am. Abstr. Progr. 21, A312.

Hsü, K.J., 1968. Principles of melanges and their bearing on the Franciscan-Knoxville paradox. Geol. Soc. Am. Bull. 79, 1063-1074.

Kawamura, K., Ogawa, Y., Anma, R., Yokoyama, S., Kawakami, S., Dilek, Y., Moore, G.F., Hirano, S., Yamaguchi, A., Sasaki, T., YK05-08 Leg 2, YK06-02 Shipboard Scientific Parties, 2009. Structural architecture and active deformation of the Nankai Accretionary Prism, Japan: Submersible survey results from the Tenryu Submarine Canyon. Geol. Soc. Am. Bull. 121;1629-1646. DOI: 10.1130/B26219.1.

Kimura, G., Silver, E.A., Blum, P., Shipboard Scientific Party, 1997, Proceedings of the Ocean Drilling Program, Initial Reports 170, Ocean Drilling Program, College Station, 458.

Lucente, C.C., Pini, G.A., 2003. Anatomy and emplacement mechanism of a large submarine slide within the Miocene foredeep in the Northern Apennines, Italy: a field perspective. Am. J. Sci. 303, 565-602.

Lucente, C.C., Pini, G.A., 2008. Basin-wide mass-wasting complexes as markers of the Oligo-Miocene foredeep-accretionary wedge evolution in the Northern Apennines, Italy. Basin Res. 20, 49-71.

Maltman, A., 1994. Introduction and overview, in: Maltman, A. (Ed.), The geological deformation of sediments. London, Chapman & Hall, 1–35.

Mancin, N., Martelli, L., Barbieri, C., 2006. Foraminiferal Biostratigraphic and Paleobathymetric constraints in Geohistory analysis: the exemple of the Epiligurian succession of the Secchia Valley (Northern Apennines, Mid Ecocene-Late Miocene). Boll. Soc. Geol. It. 125 (2), 163-186.

Marroni, M., Pandolfi , L., 1996. The deformation history of an accreted ophiolite sequence: The internal Liguride units (northern Apennines, Italy). Geodin. Acta 9, 13–29.

Marroni, M., Pandolfi, L., 2001. Debris flow and slide deposit at the top of the Internal Liguride ophiolitic sequence, Northern Apennines, Italy: a record of frontal tectonic erosion in a fossil accretionary wedge. Island Arc 10, 9-21.

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. Int. Geol. Rev. 52, 1160-1192.

Marroni M., Molli G., Montanini A., Tribuzio R.,1998. The association of continental crust rocks with ophiolites (northern Apennine, Italy): implications for the continent-ocean transition. Tectonophysics 292, 43-66.

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

Marroni, M., Molli, G., Montanini, A., Ottria, G., Pandolfi, L., Tribuzio, R., 2002. The External Liguride units (Northern Apennine, Italy): from rifting to convergence history of a fossil ocean–continent transition zone. Ofioliti 27 (2), 119–131.

Moore JC, Byrne T., 1987. Thickening of fault zones: a mechanism of mélange formation in accreting sediments. Geology 15, 1040–1043.

Moore, J.C, Vrolijk P., 1992. Fluids in accretionary prisms. Rev. Geophys. 30, 113–135.

Moore, J.C, Mascle A, Shipboard Scientific Party, 1988. Tectonics and hydrogeology of the northern Barbados Ridge: results from Ocean Drilling Program Leg 110. Geol. Soc. Am. Bull. 100, 1578–1593.

Moore, J.C., Orange, D., Kulm, L., 1990. Interrelationships of fluid venting and structural evolution: Alvin observations from the frontal accretionary prism, Oregon. J. Geophys. Res. 95, 8795-8808.

Moore, J.C., Roeske, S., Lundberg, N., Schoonmaker, J., Cowan, D., Gonzalesa E., Lucas, S., 1986. Scaly fabrics from Deep Sea Drilling Project cores from forearcs, in: Structural Fabrics in Deep Sea Drilling Project Cores from Forearcs. Geol. Soc. Am. Mem. 166, 55-73.

Mutti, E., Papani, L., di Biase, D., Davoli, G., Mora, S., Degadelli, S., Tinterri, R., 1995. Il bacino terziario epimesoalpino e le sue implicazioni sui rapporti tra Alpi e Appennino. Mem. Sci. Geol. 47, 217–244.

Naylor, M.A., Mandl, G., Sijpestein, C.H.K., 1986. Fault geometries in basement-induced wrench faulting under differential initial stress state. J. Struct. Geol. 8, 737–752. DOI: 10.1016/0191-8141(86)90022-2.

Ogawa, Y., 1998. Tectonostratigraphy of the Glen App area, Southern Uplands, Scotland: anatomy of Ordovician accretionary complex. J. Geol. Soc. London 155, 651-662.

Ogawa, Y., Anma, R., and Dilek, Y., 2011. Accretionary Prism and Convergent Margin Tectonics in the Northwest Pacific Basin. Springer Science (Dordrecht, The Netherlands), Book Series in Modern Approaches in Solid Earth Sciences, Springer Science+Business Media B.V. 2011, ISBN 978-90-481-

884-0.

Orange, D.L., 1990. Criteria helpful in recognizing shear-zone and diapiric mélanges: examples from the Hoh acretionary complex, Plympic Peninsula, Washington. Geol. Soc. Am. Bull. 102, 935-951.

Ori, G.G., Friend, P.F., 1984. Sedimentary basins formed and carried piggy-back on active thrust sheets. Geology 12, 475-478.

Panini, F., Fioroni, C., Fregni, P., Bonacci, M., 2002. Le rocce caotiche dell‟Oltrepo Pavese: note illustrative della Carta Geologica dell‟Appennino vogherese tra Borgo Priolo e Ruino. Atti Tic. Sci. Terra 43, 83-109.

Papani, G., 1963. Su un olistostroma di „Argille Scagliose‟ intercalato nella serie oligomiocenica del subappennino reggiano (nota preliminare). Boll. Soc. Geol. It. 82 (3), 195–202.

Papani, G., 1971. Geologia della struttura di Viano (Reggio Emilia). Mem. Soc. Geol. It. 10, 121-165.

Pini, G.A., 1999. Tectonosomes and olistostromes in the Argille Scagliose of the Northern Apennines, Italy. Geol. Soc. Am. Spec. Pap. 335, 73.

Principi, G., Treves, B., 1984. Il sistema Corso-Appenninico come prisma di accrezione. Riflessi sul problema generale del limite Alpi-Appennini. Mem. Soc. Geol. It. 28, 549-576.

Raymond, L.A., 1984. Classification of mélanges, in: Raymond L.A. (ed.), Mélanges: their nature, origin and significance. Geol. Soc. Am. Spec. Pap. 198, 7-20.

Remitti, f., Vannucchi, P., Bettelli, G., Fantoni, L., Panini, F., Vescovi, P., 2011. Tectonic and sedimentary evolution of the frontal part o fan ancient subduction complex at the transitino from accretion to erosion: the case of the Ligurian wedge of the northern Apennines, Italy. Geol. Soc. Am. Bull. 123, 51-70.

Ricci Lucchi, F., 1986. The Oligocene to Recent foreland basin of the northern Appennines, in: Allen, P.A., Homewood, P. (Eds.), Foreland basins. Int. Assoc. Sedim. Spec. Publ. 8, Freiburg, Blackwell, 105–139.

Ricci Lucchi, F., Ori, G.G., 1985. Field Excursion D: Syn-orogenic deposits of migrating basin system in the NO Adriatic Foreland: Examples from Emilia Romagna region, northern Apennines, in: Allen, P., Homewood, P., Williams, G. (Eds.), Excursion Guidebook: Cardiff, International Symposium on Foreland Basins, 137–176.

Sample, J.C., Moore, J.C., 1987. Structural style and kinematics of an underplated slate belt, Kodiak and adjacent islands, Alaska. Geol. Soc. Am. Bull. 99, 7–20.

Screaton, E.J., Wuthrich, D.R., Dreiss, S.J., 1990. Permeabilities, fluid pressures and flow rates in the Barbados ridge complex. J. Geophys. Res. 95, 8997-9007.

Silver, E.A., Beutner, E.C., 1980. Melanges. Geology 8, 32-34.

Tankut, A., Dilek, Y., and Önen, P., 1998. Petrology and geochemistry of the Neo-Tethyan volcanism as revealed in the Ankara Melange, Turkey. Journal of Volcanological and Geothermal Research 85, 265-284.

Ujiie, K., 2002. Evolution and kinematics of an ancient décollement zone, mélange in the Shimanto accretionary complex of Okinawa Island, Ryukyu Arc. J. Struct. Geol. 4, 937-952.

Vai, G.B., Castellarin, A., 1993. Correlazione sinottica delle unità stratigrafiche nell‟Appennino Settentrionale, in: Capozzi, R., Castellarin, A. (Eds.), Studi preliminari all‟acquisizione dati del profilo CROP 1-1a La Spezia-Alpi orientali. Studi Geologici Camerti, Vol. Spec. 2, 171-185.

Vannucchi, P., Bettelli, G., 2002. Mechanism of subduction accretion as implied from the broken formations in the Apennines, Italy. Geology 30 (9), 835-838.

Vezzani L., Festa, A., Ghisetti, F., 2010. Geology and Tectonic evolution of the Central-Southern Apennines, Italy. Geol. Soc. Am. Spec. Pap. 469, 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: 10.1130/2010.2469

von Huene, R., Ranero, C.R., Weinrebe, W., Hinz, K., 2000. Quaternary convergent margin tectonics of Costa Rica, segmentation of the Cocos Plate, and Central American volcanism. Tectonics 19, 314–334. DOI: 10.1029/1999TC001143.

Yamamoto, Y., Mukoyoshi, H., Ogawa, Y., 2005. Structural characteristics of shallowly buried accretionary prism: rapidly uplifted Neogene accreted sediments on the Miura-Boso Peninsula, Central Japan. Tectonics 24, TC5008. DOI: 10.1029/2005TC001823.

Yamamoto, Y., Nidaira, M., Ohta, Y., Ogawa, Y., 2009. Formation of chaotic rock units during primary accretion processes: examples from the Miura-Boso accretionary complex, central Japan. Island Arc 18, 496-512.

Figure Captions

Figure 1 – Structural sketch map (A) of the northwestern Italy (modified from Bigi et al., 1983; Marroni et al., 2010; Vezzani et al., 2010). (B) Location of Figure 1A. (C) Geological cross section across the Northern Apennines (modified from Boccaletti and Coli, 1982).

Figure 2 – Stratigraphic columns showing the reconstruction of the inner (oceanward) and external (continentward) Ligurian Units in the Northern Apennines and overlying Epiligurian Units (modified from Marroni et al., 2001, 2010; Marroni and Pandolfi, 2001).

Figure 3 – Simplified geological-structural map (A) of the studied area. Location in Fig. 1A. (B) Geological cross section across the studied area (location in Fig. 3A) showing the structural relationships between the different tectonic units and the mélanges *s.l.* occurrence. (C) Schematic column (not to scale) showing the vertical piling of the different mélange types.

Figure 4 – Tectonically Disrupted Unit (TDU). (A) Disharmonic-to isoclinal and transposed folds of the Tectonically Disrupted Body 1 (TDB1) with sub-horizontal axial surfaces aligned parallel to the tectonic layering and/or pseudo-bedding. (B) Drawing of Fig. 3A showing layer-parallel extension resulted in the development of pinch-and-swell structures and boudinage of the shaly layers. The arrow indicates the younging direction of the folded stratigraphic succession. (C) Shear transposition and overprinting of the previously formed isoclinal folds of TDB1 that forms isolated fold hinges with axial surfaces aligned to planar NE-verging shear zones and mesoscale thrust faults resulting in the production of the Tectonically Disrupted Unit 2 (TDB2). The black arrows indicates the younging direction of the folded beds. (D) Close-up of the structurally ordered block-in-matrix fabric of TDB2 resulting from tectonic disruption related to NE-verging thrusting. (E) Mesoscale data (Schmidt net, lower hemisphere) showing that the folds related to TDB1 and TDB2 are characterized by the same orientation of axial surfaces and different distribution of fold axes. (F) Mesoscale data from TDB2 showing the alignment of the long axis of elongated blocks and the mesoscale thrust and reverse shear zones (Schmidt net, lower hemisphere).

Figure 5 – Tectonically Disrupted Unit (TDU). (A) Detail of the high-strain horizon, about 20 cm-thick, that marks at the base the regional thrust superposing Cassio Unit onto Bettola Unit. White and dark clasts of marl and shale rocks of Cassio, Bettola and Epiligurian units are aligned parallel to the basal thrust fault defining a "fluidal" fabric. (B) Close-up of Fig. 5A. Polished cut of the high-strain "fluidal" mud breccias horizon showing a strong alignment of clasts parallel to fluidal features of the matrix, and an asymmetric boudinage of the larger clasts. (C) Polished cut of the high-strain "fluidal" horizon that shows mm-sized elongated clasts and cm-sized axial surfaces of disharmonic isoclinals folds aligned parallel to the flow direction. (D) Drawing of Fig. 5C. (E) Detail of polished cut of the high-strain fluidal horizon showing the alignment of mm-sized elongated and asymmetric clasts in a fine grained matrix. In the central part of the photograph the elongated clasts show a P-C fabric. (F) Scanning Electron Microscope (SEM) image of the matrix of the sample of Fig. E. The fine-spaced alignment of the clay particles wraps around an equidimensional clast defining a sigma-type feature with asymmetric wings.

Figure 6 – Gravity-driven Chaotic Bodies (GCB). (A) Brecciated texture of the matrix. (B) Rounded and elongated blocks of calcareous limestone showing a planar anisotropy.

Figure 7 – Shale dike injections (DDB1). (A) Irregular flame-shaped injection piercing the middle – upper Eocene Monte Piano Marls. (B) Drawing of Fig. 7A showing the shear deformation of the matrix along the margins of the dike. (C) Close-up of Fig. 7B showing the sub-vertical scaly fabric and fluidal features that affect the margins of the dike injection. (D) Irregularly-shaped injections within the *Argille varicolori*. (E) Drawing of Fig. 7D showing deformation of the matrix within the shale injections. (F) Small-scale injection within the *Argille varicolori* piercing the tectonic layering of TDB1. Blocks of "Salti del Diavolo" continental fine-grained conglomerates are rotated, dragged upward and aligned parallel to the margins of the shale injections (hammer for scale). (G) Mesoscale data from DDB1 showing the alignment of the scaly cleavage of the marginal zone to the intrusive contacts of the dikes and the distribution of long axis of elongated blocks (Schmidt net, lower hemisphere).

Figure 8 – Diapirically Disrupted Body (DDB2). (A) Detailed map of the Diapirically Disrupted Bodies 2 (see location in Fig. 3A) showing their internal zonation of deformation which consists of marginal and

core zones. (B) Mesoscale data from the southern Diapirically Disrupted Body (Schmidt net, lower hemisphere); legend in B. (C) and (D) Line drawings of panoramic view of the core zone of the DDB2 showing upward divergent structures that depict a sort of “flower structure”. Arrows indicate the upward rise of unconsolidated sediments. Location in Fig. 8A. The black arrows indicates the younging direction “Y” of the deformed succession.

Figure 9 – (A) Conceptual model of evolution of the Ligurian accretionary wedge during subduction deformational stage (Late Cretaceous – middle Eocene) showing local emplacement of mass-wasting deposits (Gravity-driven Chaotic Bodies, GCB) over the Tectonically Disrupted Body 1 (TDB1). VE ca. 2X = twofold vertical exaggeration. (B) Close-up of the relationships between the emplacement of mass-transport chaotic deposits (GCB) and tectonics. (C) Potential mechanism of focused fluids migration along anisotropic discontinuities (e.g., scaly fabric, scaly cleavage, shear zones, faults) (Modified from Moore at al., 1990). VE ca. 2X = twofold vertical exaggeration. (D) Conceptual model of evolution of the Ligurian accretionary wedge during collision-to intracontinental deformation stages (late Oligocene – early Miocene), showing out-of-sequence thrusting. (E) Block-diagram showing the overprinting of previously formed block-in-matrix fabric and isoclinal folds of TDB1 by thrust-related tectonics forming TDB2. The latter consists of imbricated blocks and S-C shear zones defining a NE-verging structurally ordered block-in-matrix fabric. Note the decrease of stratal disruption away from thrust faults.

Figure 10 – (A) Conceptual model of evolution of the Ligurian accretionary wedge during early Miocene intracontinental deformation showing the emplacement of the Val Tiepido-Canossa argillaceous breccias (early Miocene) on the top of the accretionary wedge. Shale dike injections (DDB1) and large-scale diapiric bodies (DDB2), triggered by the rapid increment of sedimentary loading, intrude both the Ligurian and Epiligurian Units. VE ca. 2X = twofold vertical exaggeration. (B) Line drawing of a panoramic view showing the diapiric intrusion of Upper Cretaceous *Argille varicolori* (corresponding to DDB2) in the lower Miocene Val Tiepido-Canossa argillaceous breccias. (C) Line drawing showing an isoclinal fold associated to TDB1 (with sub-vertical axial surface) refolded by the diapiric upward rise movement, and fluidal deformation of the matrix that embeds boudins of manganiferous siltstone. Note the orthogonal interference between the two subvertical axial surfaces.

Figure 1

Click here to download high resolution image

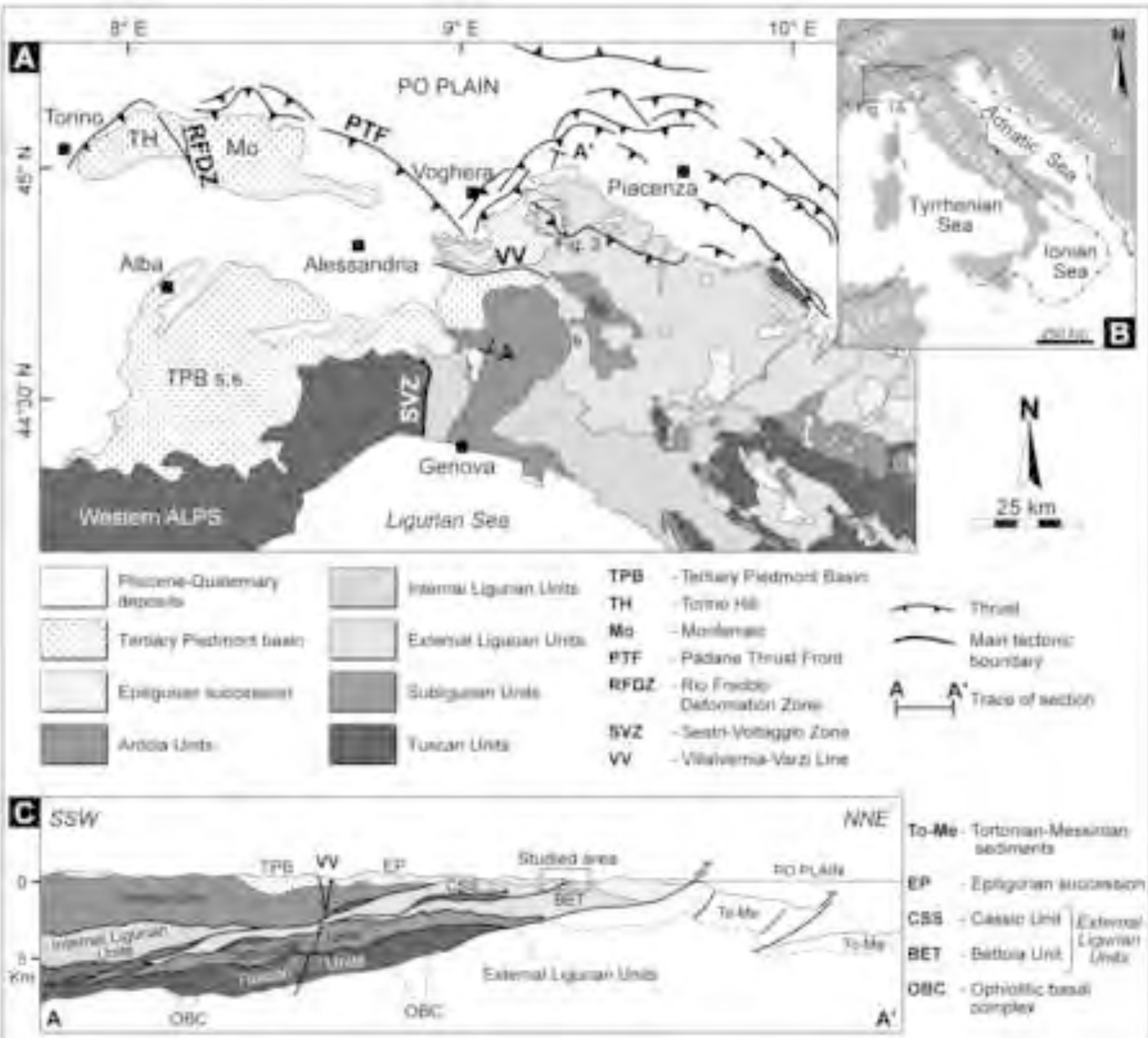

Figure 1 - Codegone et al.

Figure 2

Click here to download high resolution image

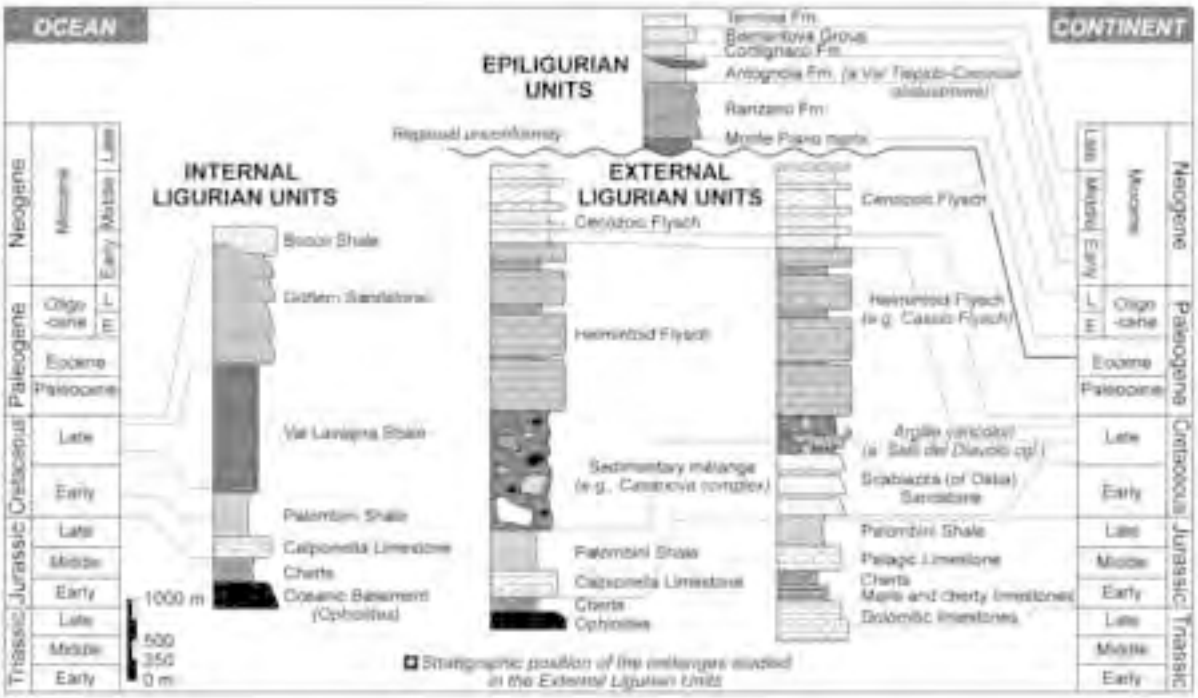

Figure 2 - Codegone et al.

Figure 3
Click here to download high resolution image

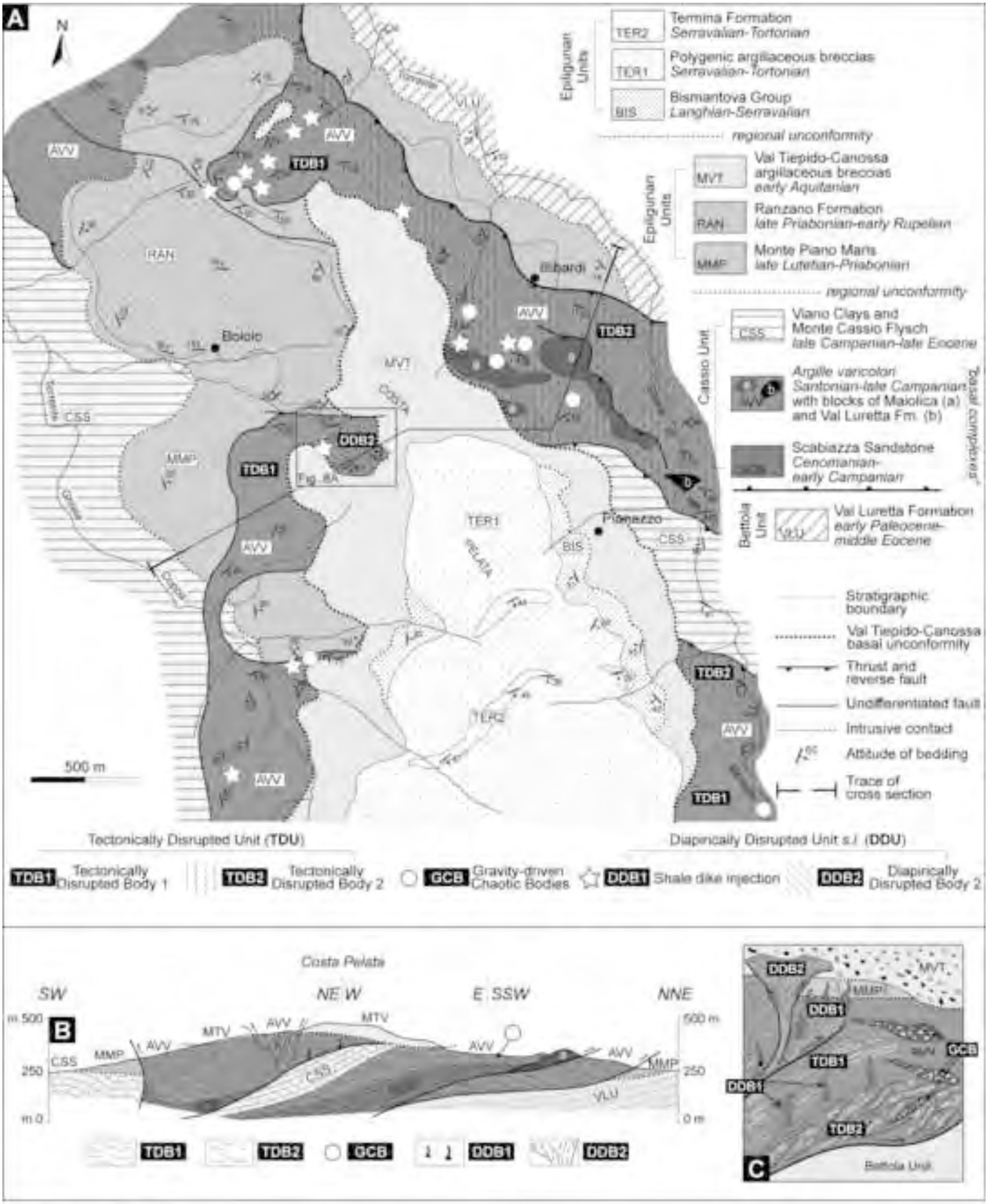

Figure 3 - Codegone et al.

Figure 4
Click here to download high resolution image

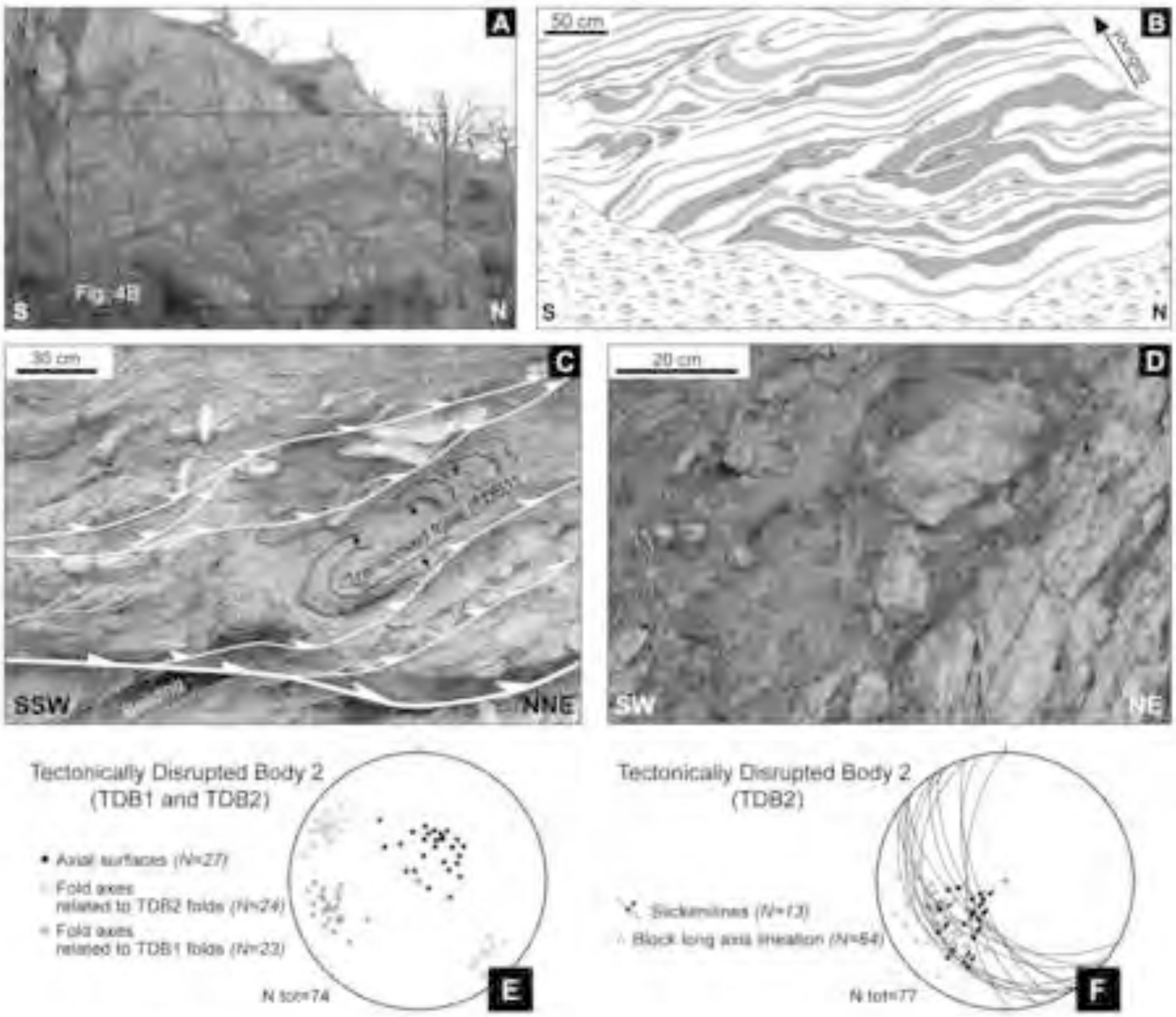

Figure 4 - Codegone et al.

Figure 5
Click here to download high resolution image

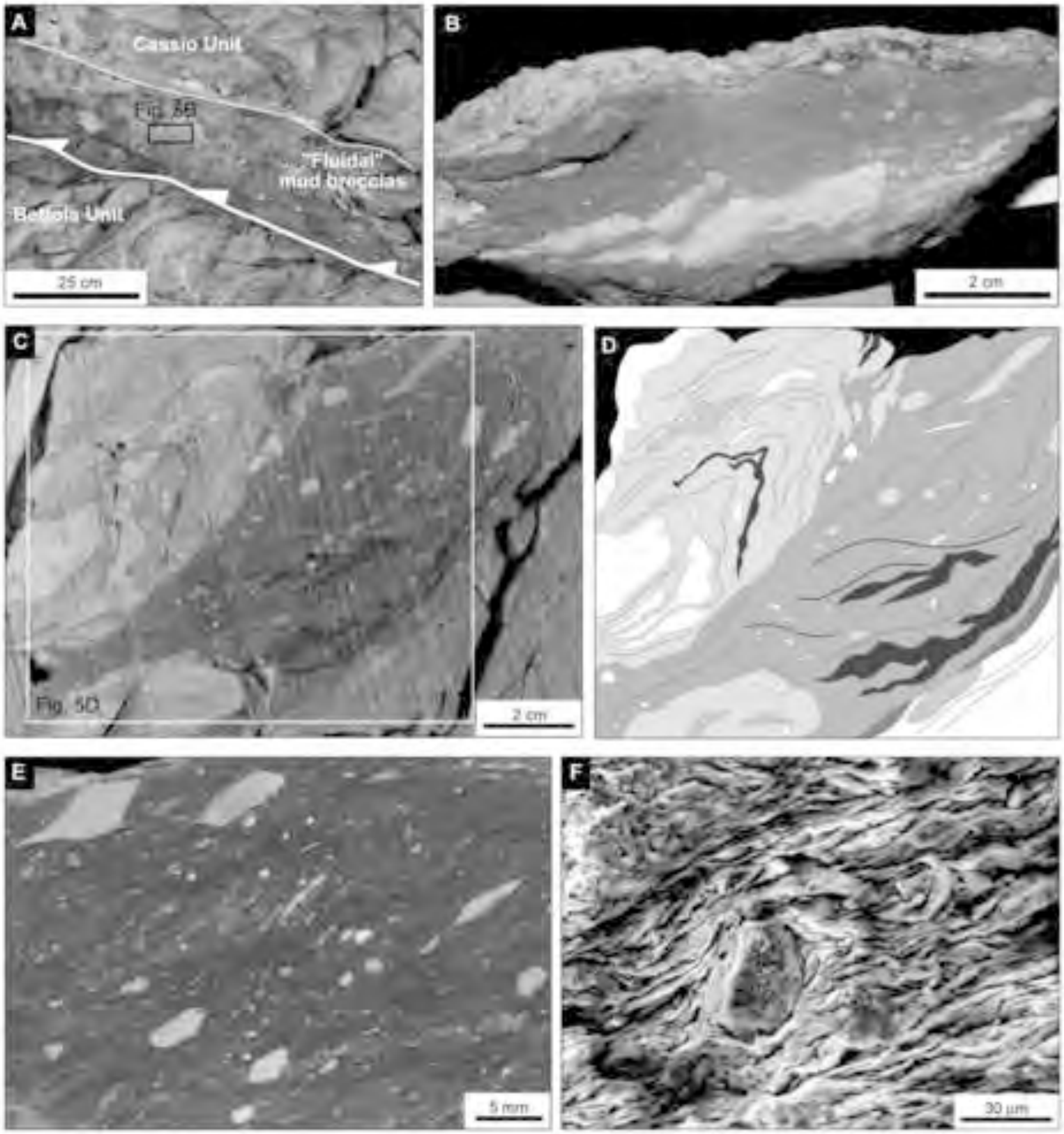

Figure 5 - Codegone et al.

Figure 6
Click here to download high resolution image

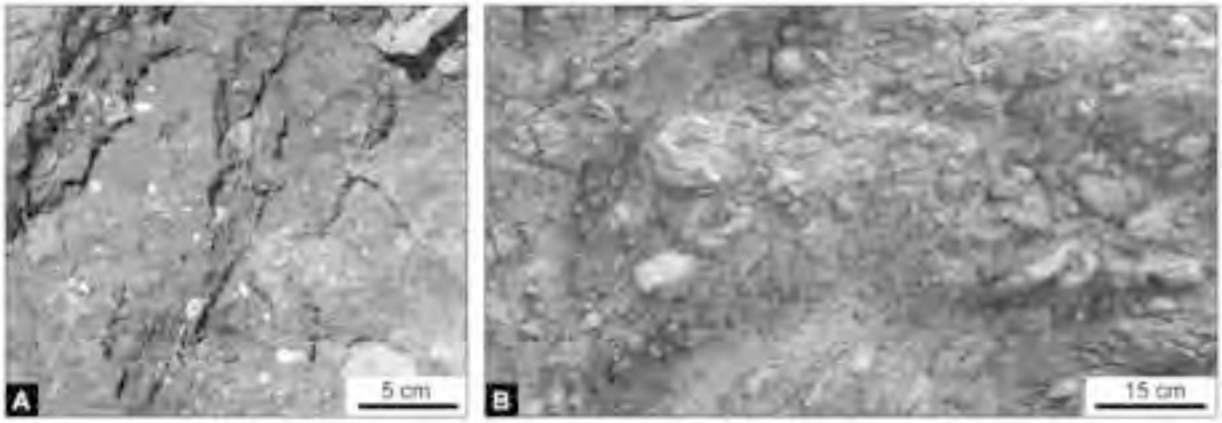

Figure 6 - Codegone et al.

Figure 7
Click here to download high resolution image

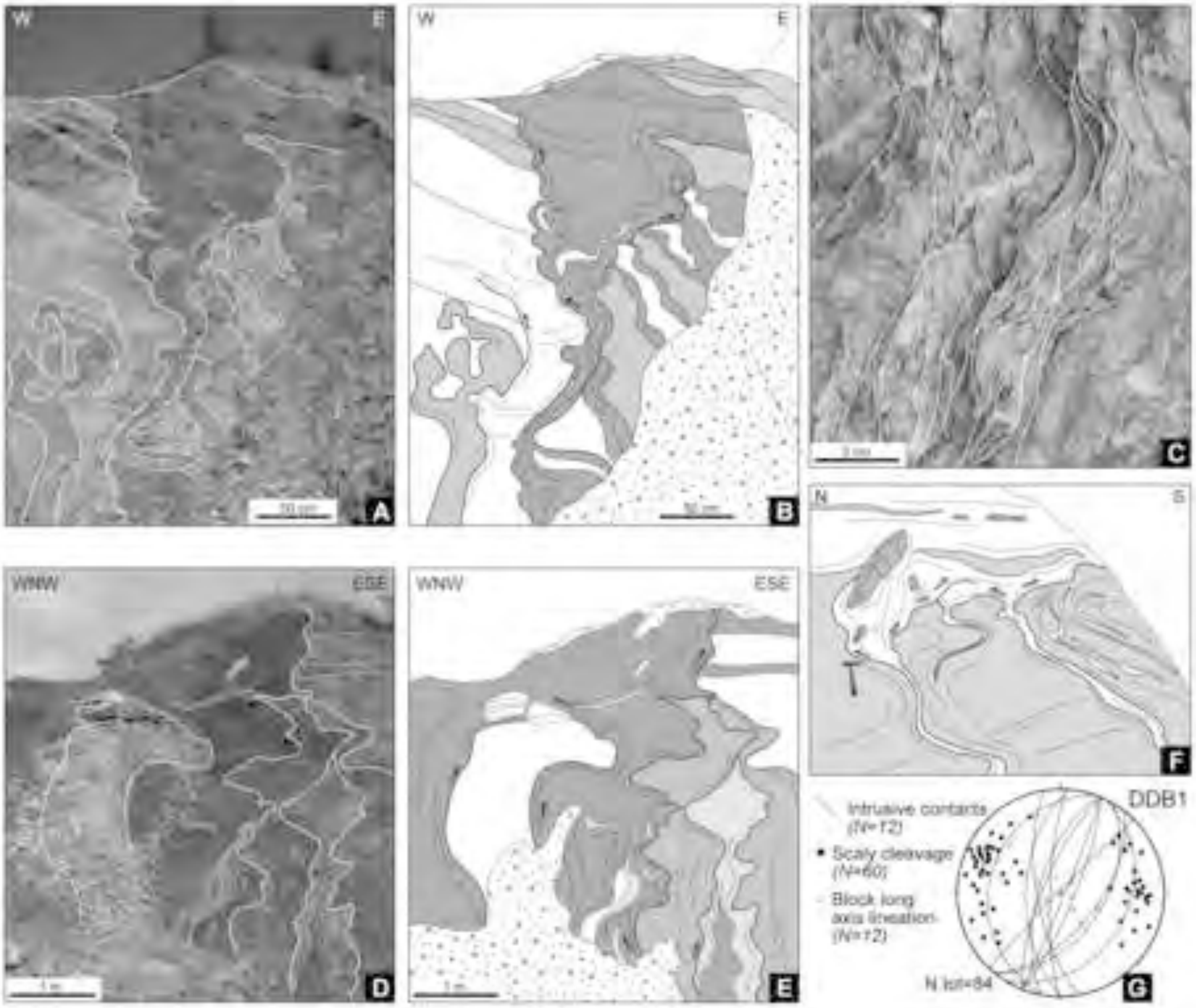

Figure 7 - Codegone et al.

Figure 8

Click here to download high resolution image

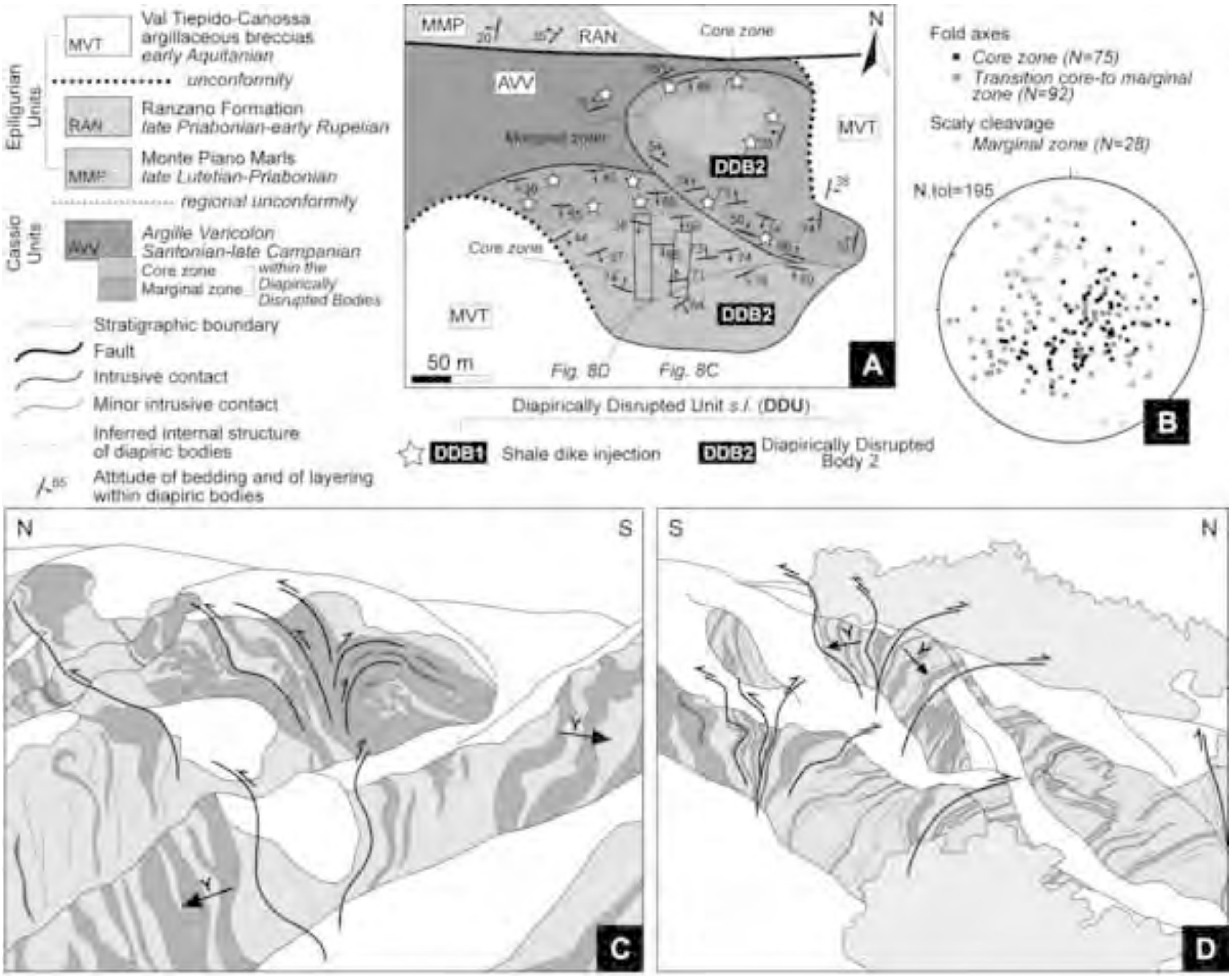

Figure 8 - Codegone et al.

Figure 9

Click here to download high resolution image

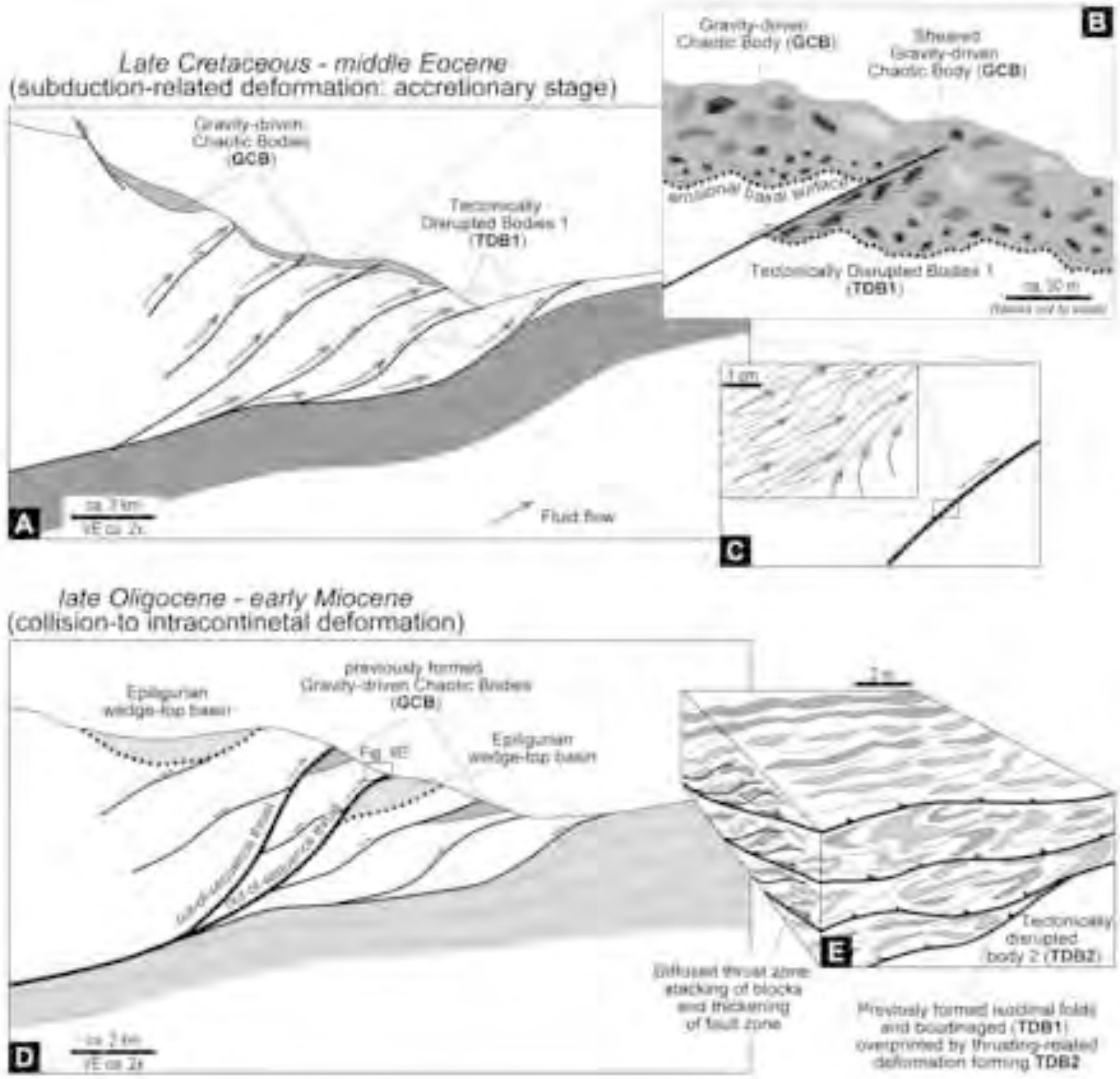

Figure 9 - Codegone et al.

Figure 10

Click here to download high resolution image

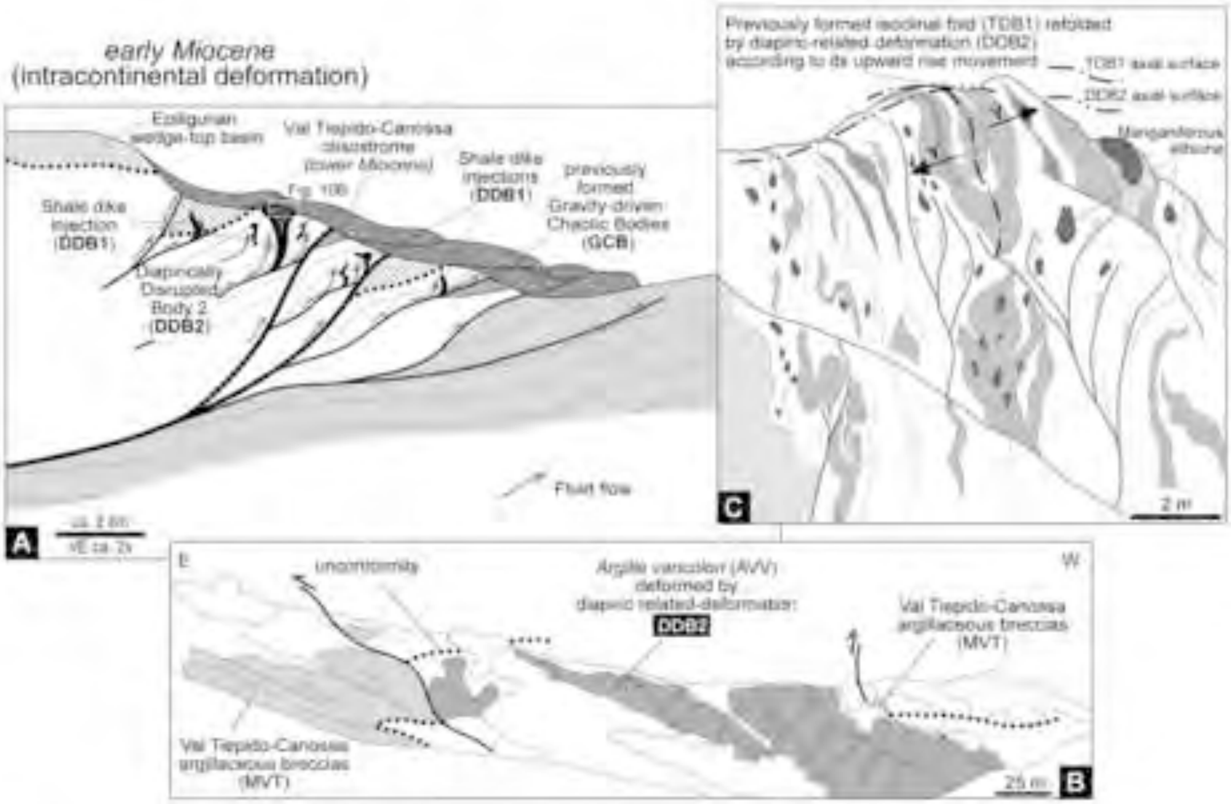

Figure 10 - Codegone et al.