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Internal structure and tectonic evolution of an underthrust tectonic mélange: the Sestola-Vidiciatico tectonic unit of the Northern Apennines, Italy

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Abstract

The Sestola-Vidiciatico Tectonic Unit (SVTU) in the Northern Apennines is an underthrust tectonic mélange presently sandwiched between the Tuscan-Umbrian foredeep units and the overlying Ligurian/Subligurian thrust-nappe. The SVTU has been generated during the collision between the European and the Adria plates and now it separates the former oceanic accretionary wedge –Ligurian/Subligurian thrust nappe- from the underlying fold–and-thrust belt formed by Adria sedimentary units. The collision caused an eastward migrating foredeep basin and the overthrusting of the frontal part of the Ligurian/Subligurian thrust-nappe on the subducting Adria margin. Part of the inner lower-slope sediments of the migrating foredeep basin have been unconformably deposited on a frontal prism formed by material already accreted in the Ligurian/Subligurian prism gravitationally and tectonically reworked. The frontal prism and its sedimentary cover have been progressively dragged down along the plate boundary zone generating the SVTU.

The lower-slope sediments have been incorporated in the mélange as they were not completely lithified, and they show a long deformation history ranging from continuous and pervasive soft-sediment deformation to discontinuous brittle deformation concentrated along faults and mainly controlled by cycles of fluid pressure as testified by the presence of crack-and-seal texture and implosion breccia in the veins.

Keywords: tectonic mélange, syntectonic veins, accretionary prism, Northern Apennines, Sestola-Vidiciatico tectonic unit

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1. Introduction

The study of subduction processes in modern subduction margins are difficult because they are submarine and not directly accessible. Thus, fossil margins, exhumed and exposed on land, are crucial to this types of study. On the other hand fossil margins are characterized by the superposition of tectonic events, for example those responsible for their exhumation. Among the best exposed and preserved fossil subduction complexes is the Northern Apennines, where the record of convergence goes from the Late Cretaceous-early Eocene oceanic subduction, to the continental collision starting from middle-late Eocene [1; 2; 3; 4; 5]. In the early phases of the transition from subduction to collision the tectonic style has not been changed dramatically and the orogenic wedge has grown essentially by underthrusting and underplating. Adria plate sediments, in fact, are present below the accretionary prism formed during subduction of the western Tethys oceanic lithosphere (Fig. 1 and Fig. 2). Accretionary prisms and orogenic wedges (fold-thrust belts) share some characters and

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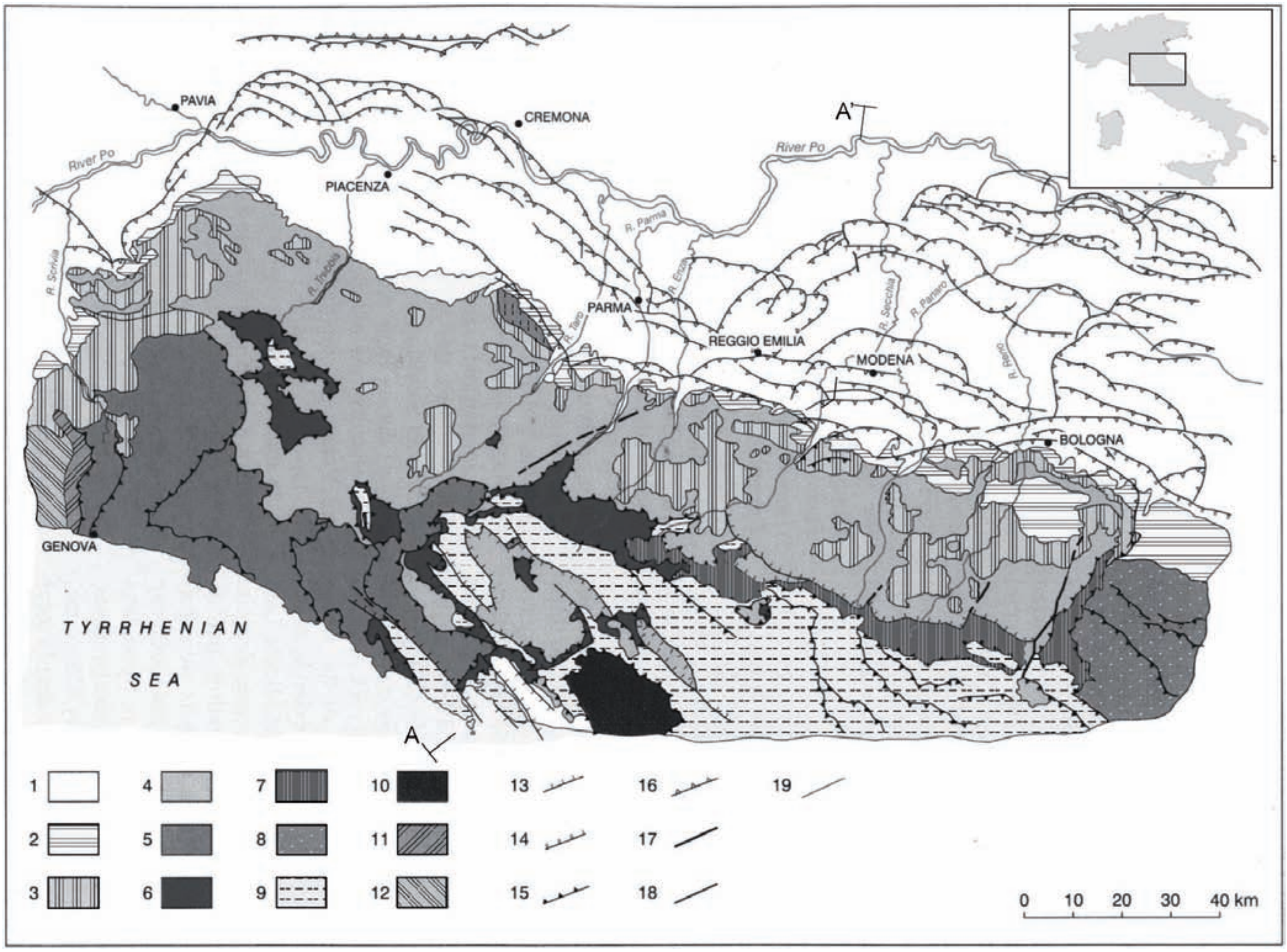

Fig. 1 –Tectonic sketch map of the Northern Apennines. Key: **1.** Quaternary deposits; **2.** Late Miocene-Pleistocene marine deposits; **3.** Epiligurian sequence; **4.** External Ligurian units; **5.** Internal Ligurian units; **6.** Subligurian units; **7.** Sestola-Vidiciatico tectonic unit; **8.** Umbria-Romagna units; **9.** Tuscan units; **10.** Metamorphic Tuscan units (Apuane Alps tectonic window); **11.** Sestri-Voltaggio Zone; **12.** Voltri Group; **13.** Normal faults; **14.** Normal faults (subsurface); **15.** Thrust faults and overthrusts; **16.** Thrust faults (subsurface); **17.** Strike-slip faults; **18.** High-angle faults of unknown displacement (subsurface); **19.** Lithological boundaries. AA' trace of the regional cross-section of Fig. 2.

a number of structural elements [6], as a basal surface of detachment (also known as a décollement zone), a large horizontal compression occurring in the wedge above the basal surface, a taper of deformed material, and a growth mechanism either by frontal accretion and/or by underthrusting and underplating. In the Northern Apennines, for example, the early collision occurred with underthrusting of the foredeep turbidites, similar to what is observed in oceanic trench. These frontal processes are well exposed in the Apennines and they may contribute to the study of the deformation history of trench turbidites. In this paper we present some deformation characteristics of the frontal wedge of the Northern Apennines in the early phases of collision showing the relationship between sedimentation, deformation and fluid flow.

2. The Sestola-Vidiciatico tectonic unit: a tectonic mélange formed during the initial stages of the Northern Apennines collisional history

2.1. Geological setting

The Northern Apennines are a complex Cenozoic fold-and-thrust belt formed as a consequence of the convergence and collision of the European and Adria plates [7, 8]. The consumption of the western Tethys oceanic crust, originally interposed between the two plates, from Late Cretaceous-early Eocene [9; 8; 10; 11; 12; 13, 14; 15; 16; 17; 18; 19] generated an intraoceanic submarine accretionary prism [20; 12; 11; 21; 17; 22], formed of accreted and underplated sediments [23; 24; 25; 26; 27]. The prism is now preserved as a large thrust-nappe - the Ligurian/Subligurian thrust-nappe - at the top of the orogenic wedge.

The collision started in the late Oligocene time and caused both an eastward migrating deformation of the crust, associated with failure and thickening, and the overthrusting of the frontal part of the Ligurian/Subligurian thrust-nappe/accretionary prism on the subducting Adria margin (Fig.1; Fig. 2 and Fig. 3). From the late Oligocene to mid-late Miocene, in front of the advancing submarine accretionary prism, the lithospheric flexure generated an eastward migrating foredeep basin which has been filled up by

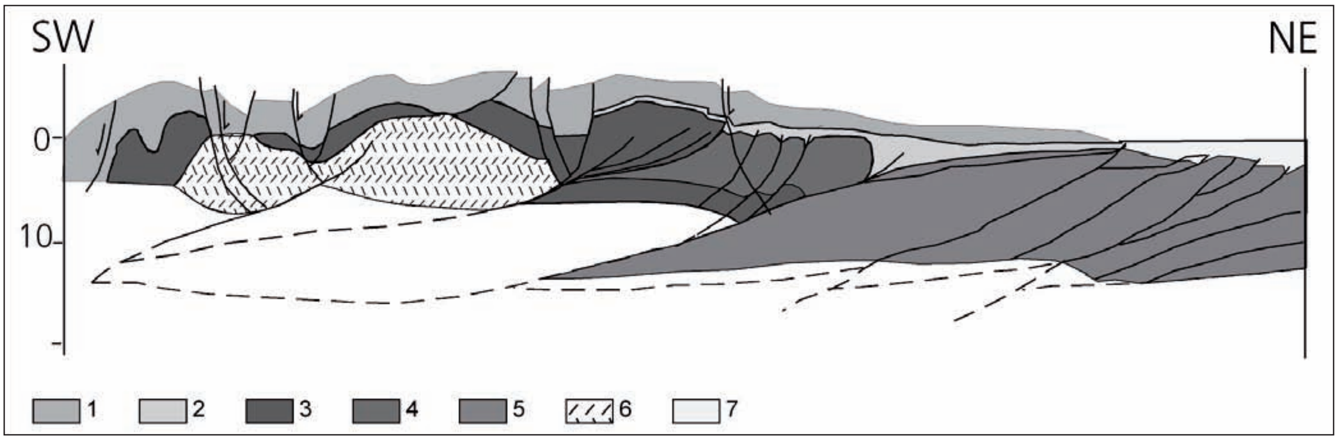

Fig. 2 – Schematic regional cross section through the Northern Apennines, showing the main chain units. After Labaume [84] (redrawn and modified). **1.** Ligurian Units; **2.** Sestola-Vidiciatico tectonic unit; **3.** Tuscan Nappe; **4.** Cervarola Group; **5.** Marnoso-arenacea Fm.; **6.** Tuscan metamorphic unit; **7.** Present day foredeep. The more internal part of the SVTU mélange has been complexly folded and faulted at the map scale together with the structurally underlying Tuscan Nappe and Cervarola foredeep turbidite sequences, while the more external part of SVTU mélange is overthrusting the Marnoso-arenacea formation through a low-angle, rather continuous structural surface with no large folds and thrusts. This same character is shown by the overthrusting surface separating the SVTU mélange from the overlying External Ligurian units.

different deep-water, siliciclastic turbidite “flysch” sediments (the upper part of the late Oligocene-late Miocene Tuscan-Umbrian units -Fig. 1 and Fig. 2-, i.e. the Macigno-Modino Cervarola and Marnoso-arenacea turbidite sequences [e.g., 28; 29; 30; 31; 32; 33; 34; 35; 36; 37; 38; 39; 40; 41; 42]).

The overriding of the continental crust did not scrap-off the sediments of the margin in front of the Ligurian/Subligurian accretionary prism, but it rather caused their dragging down along the interplate zone and faulting and folding occurred only when they were deeply buried. The only exception is the smooth and long-wave synsedimentary deformation related to the detachment/fault-propagation folds observed in the Marnoso-arenacea Fm. [43; 44; 45; 46; 41]. As a consequence, the accretionary prism is presently on top of the foreland fold-and-thrust belt developed from the deformation of the Adria continental paleomargin (Fig. 2).

From mid Eocene to Tortonian, the upper slope was characterized by the deposition of the Epiligurian sequence, deposited on top of the Ligurian accretionary wedge [48; 30; 49; 50]. The sequence crops out on the Adriatic side of the Northern Apennines and represents the sediments of the slope apron and of the piggy-back basins, formed on the ridged inner upper-slope of the foredeep. At the same time lower-slope sediments of the migrating foredeep were unconformably deposited - at least partially - on a newly formed frontal prism (Fig. 3). This prism, the Sestola-Vidiciatico proto-mélange, (Fig. 3) was formed by material gravitationally [51] and tectonically reworked from rocks already accreted to the Ligurian/Subligurian prism (Fig. 3) [47]. The frontal prism, its sedimentary cover and the foredeep turbidites were progressively underthrust originating a tectonic mélange (Fig. 3). This mélange is presently sandwiched between the Tuscan-Umbrian foredeep flysch units and the overlying Ligurian/Subligurian thrust-nappe (Fig. 2). Therefore, this mélange represents an extensive chaotic rock-body now separating a former oceanic accretionary wedge from the underlying fold-and-thrust units of the Adria margin.

A single large paleogeographic domain has been dramatically divided in two separate structural units during the eastward overthrusting of the Ligurian accretionary wedge/thrust-nappe. The inner upper slope Epiligurian sequence has been translated on top of the upper plate without experiencing large deformation whereas the inner lower slope deposits were underthrusted and pervasively deformed under the overburden of the Ligurian thrust-nappe.

In the more recent geological literature of the Northern Apennines this tectonic mélange has several names (e.g., Modino Unit, Monte Modino mélange, Tagliole Mélange, Ventasso tectonic sub-unit, Pievepelago tectonic sub-unit, Sestola-Vidiciatico tectonic unit, Firenzuola mélange, Pievepelago-Modino and Sestola-Vidiciatico Shuppen Zone, etc.: [52; 53; 54; 55; 56; 57; 58; 59; 60 and references therein; 42]) depending on its composition and the local geometrical relations with the different foredeep successions (i.e. Macigno-Modino, Cervarola and Marnoso-arenacea sequences). In this paper, we will refer to it as the “Sestola-Vidiciatico tectonic unit” (SVTU) irrespective of its composition and basal foredeep turbidite sequence.

The SVTU largely crops out in the south-eastern sector of the Emilia Apennines in two continuous, but differently trending, NW-SE and SW-NE, belts (Fig. 1 and [58]). The NW-SE trending belt is parallel to the main NW-SE Apennines structural trend and it marks the boundary between the Tertiary foredeep folded and thrust Tuscan units and the Ligurian units. In this area the contact between the SVTU and the Ligurian units is represented by a large, NW-SE normal fault (Fig. 1) [57; 58]. The second, SW-NE trending belt is orthogonal to the main NW-SE Apennines structural trend - i.e. parallel to the direction of tectonic trasport (Fig. 1). In this area (corresponding to the Sillaro transverse lineament: 61; 62; 63; 64; 65; 52; 66; 67; 58) the SVTU is separating the underthrust Marnoso-arenacea Miocene foredeep sequence from the overlying overthrust Ligurian units (Fig. 1).

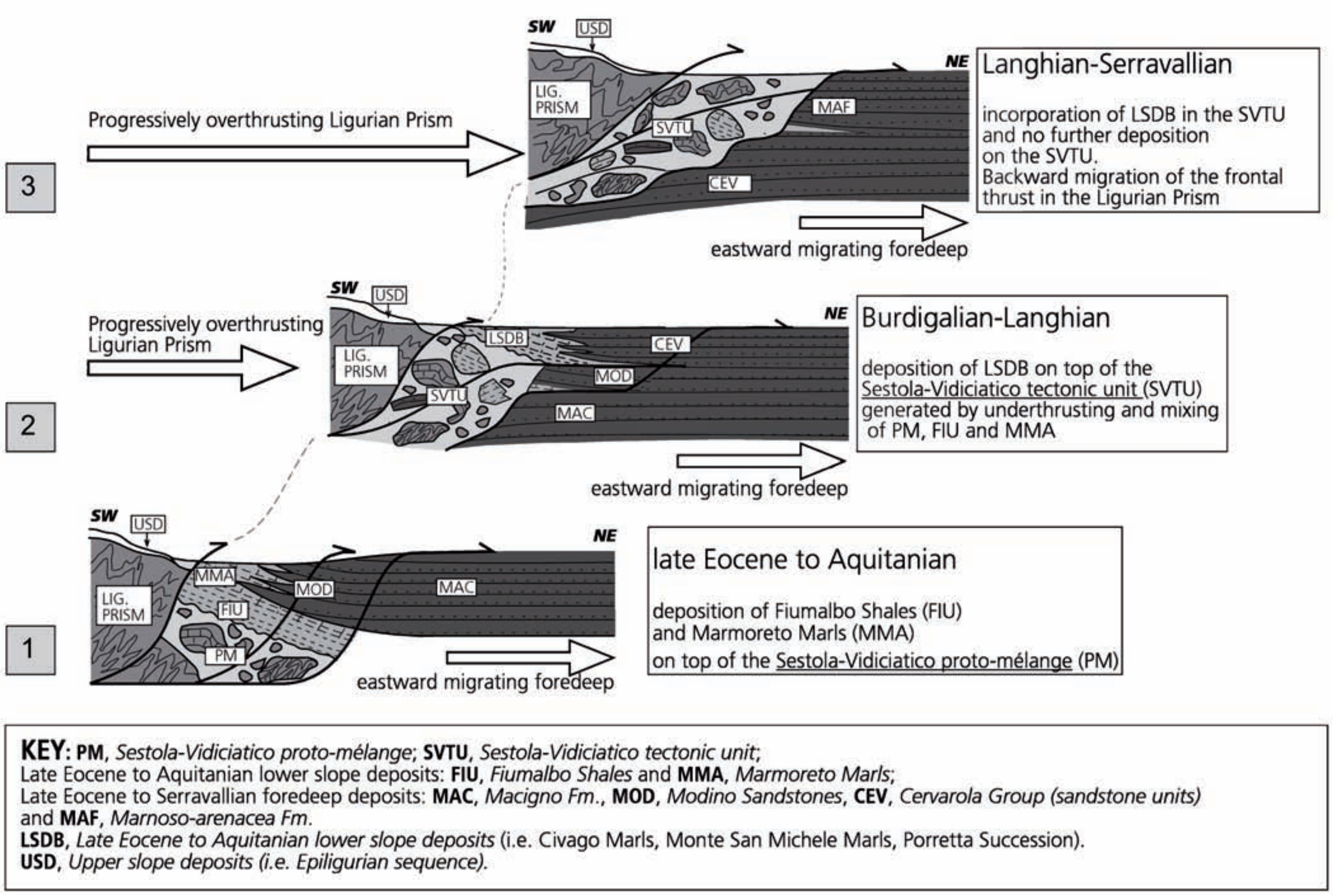

Fig. 3 – Evolutionary scheme showing the main different stages of formation of the Sestola-Vidiciatico tectonic unit (SVTU). 1st stage: before the formation of the Sestola-Vidiciatico tectonic unit. Before and during the deposition of the first foredeep unit (Macigno-Modino foredeep flysch turbidites), lower slope deposits ranging in age from the late Eocene to Aquitanian (Fiumalbo Shale and Marmoreto Marl) have been deposited on top of the Sestola-Vidiciatico proto-mélange formed by the sedimentary and tectonic intermixing of slices of Ligurian and Subligurian Units and debris flow deposits. 2nd stage: generation of the Sestola-Vidiciatico tectonic unit. During the underthrusting below the Ligurian prism, the tectonic intermixing of the Sestola-Vidiciatico proto-mélange and late Eocene to Aquitanian lower slope deposits caused the formation of the Sestola-Vidiciatico tectonic unit. After the deformation, on top of the SVTU, lower slope deposits of Burdiganian and Langhian age (LSDB: i.e. Civago Marls, Porretta Succession; Monte San Michele Marls) have been deposited duringthe deposition of the foredeep units of the Cervarola Group. The LSDB are then tectonically incorporated inside the SVTU. 3rd stage: progressive underthrusting of the SVTU during the deposition of the Marnoso-arenacea Fm. and backward migration of the frontal thrust inside the Ligurian prism. Contemporary inclusions have not been found within the SVTU.

Therefore, the two different trends of the SVTU potentially expose changes in composition and internal deformation both parallel and perpendicular to the chain axis allowing the observation of the mélange in three dimensions.

Besides, in the NW-SE trending belt the mélange unit clearly has been complexly folded and faulted at the map scale together with the structurally underlying Macigno-Modino and Cervarola foredeep turbidite sequences, while in the SW-NE trending belt the extensive scale, low-angle overthrusting on the Marnoso-arenacea formation forms a rather continuous structural surface with no large folds and thrusts (Fig. 1 and Fig. 2) [52; 58] although locally slightly deformed by later tectonic events [52; 66; 67]. The same character is shown by the overthrusting surface separating the mélange from the overlying Ligurian units (Fig. 2) [52; 58]. For this reason, the overall structure in this sector of the Northern Apennines has been described as a large, mountain-chain scale tectonic duplex [52; 67].

2.2. Main components, spatial changes in composition and internal structure of the tectonic mélange

2.2.1. Major lithological components

In this paper we focus on the SVTU tectonic mélange which overlies the late Oligocene-Burdigalian Macigno-Modino and Cervarola foredeep turbidite sequences. Nevertheless some references will be also made to the most external parts of the mélange overlying the Langhian to late Tortonian Marnoso-arenacea formation along the Sillaro transverse lineament [61; 62; 63; 64; 65; 52; 66; 67; 58] in order to stress the spatial changes in composition.

Although the mélange composition seems to vary a lot at the local scale, three main components may be recognized at the regional extent which are represented by: 1) wide blocks deriving from the External Ligurian and Subligurian units,

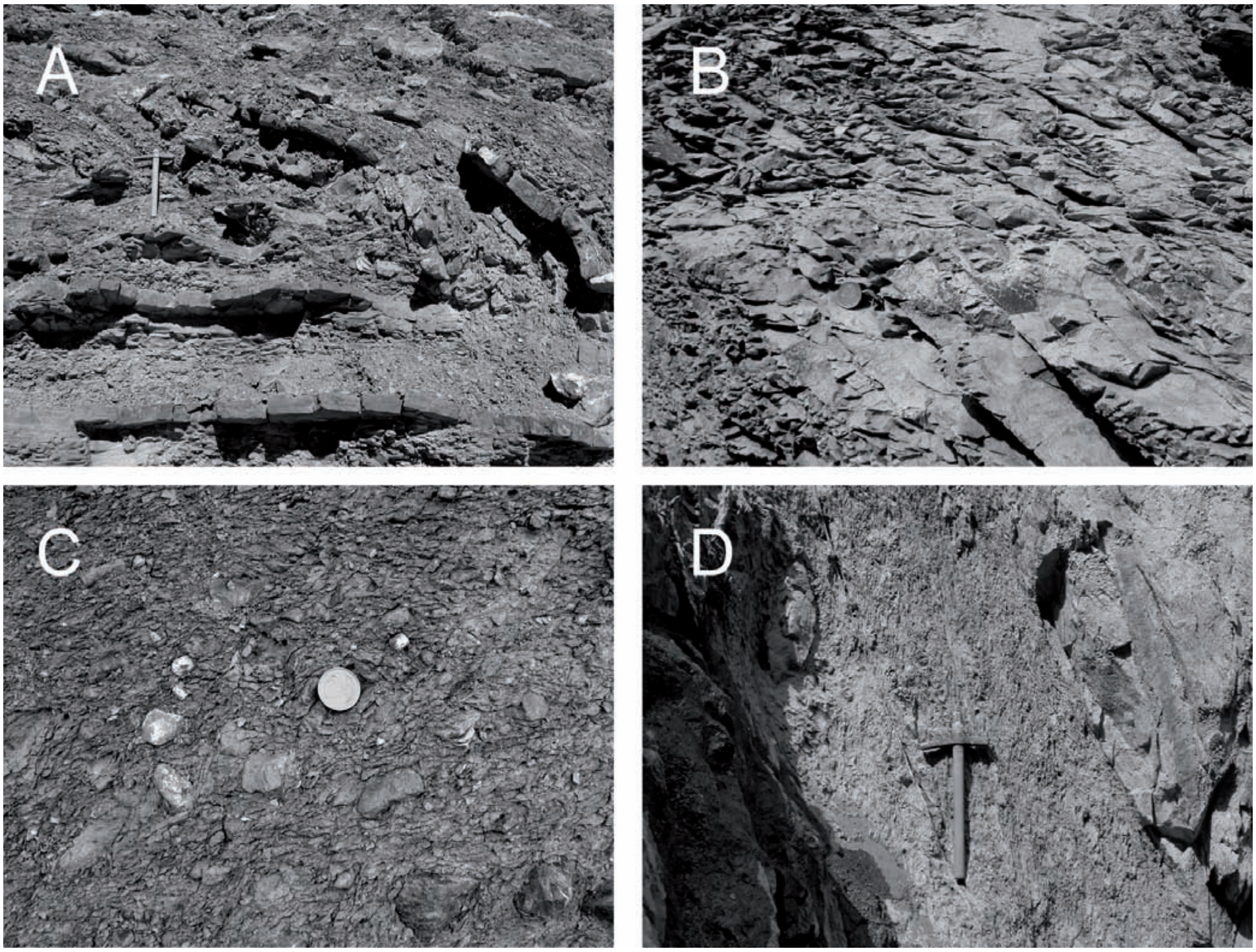

Fig. 4 - **A.** A mappable inclusion of the External Ligurian Units (Abetina Reale Formation, late Campanian) within the Sestola Vidiciatico mélange preserving the deformational structures (close-to-isoclinal folds) inherited from the Ligurian tectonic phase (early-mid Eocene). **B.** The Marmoreto Marls (Rupelian-Chattian) outcropping along the Dolo Valley cross-cut by a web of brittle shear surfaces.**C.** Polymictic breccia interpreted as generated by submarine debris flow. **D.** Close-up of the sheared basal contact of the Sestola Vidiciatico tectonic unit (right) on the Cervarola Group sandstone unit (left) outcropping near Vidiciatico (BO).

2) large slabs of late Eocene to early Miocene shaly and marly foredeep lower-slope deposits and, 3) various amounts of polymictic sedimentary breccias (Fig. 3).

1) The extensive slices of Ligurian/Subligurian units (Fig. 4A) have dimensions that can reach several kilometres. The most frequent rock-types are dismembered or broken formations (Fig. 4A) with prevailing dark grey shales and interbedded micritic carbonate turbidites ranging in age from Early-Late Cretaceous to middle Eocene. The structural style of these large blocks is strictly corresponding to the structural style of the Ligurian/Subligurian units which they come from. The latter units, accreted during the early-middle Eocene tectonic phase (Ligurian or meso-Alpine tectonic phase), form the bulk of the Ligurian accretionary prism/thrust-nappe and their style of deformation has been described in detail in recent works [27; 26]. The most important and typical structural features are: a systematic block-in-matrix fabric; rootless, coaxially refolded isoclinal folds at all scales; a pervasive scaly fabric in the shaly component; a mesoscopic foliation developed from transposition of the original bedding caused by isoclinal folds and boudinage of competent layers [27; 26].

2) The late Eocene to early Miocene shaly and marly foredeep lower-slope deposits (Fig. 4B) are present as coherent slabs that can reach few kilometres in length and several hundred metres in thickness. They are formed by dark grey or reddish silty mudstones (late Eocene to early Oligocene Fiumalbo Shales) and very thick packages of marls (late Oligocene to Aquitanian Marmoreto Marls: Fig. 4B) both characterized by sparse, thin-bedded turbidite sandstones of different grain composition. These sediments have been unconformably deposited in a lower slope setting, on the frontal prism of the Ligurian accretionary wedge at the inception (Fiumalbo Shales) and

during (Marmoreto Marls) the infilling of the Macigno-Modino foredeep. This younger frontal prism is composed by tectonically disrupted Ligurian/Subligurian rocks, locally emplaced by mass wasting processes (Fig. 3), and intermixed sedimentary breccias forming the Sestola-Vidiciatico proto-mélange.

The late Eocene to early Miocene lower-slope deposits have been incorporated in the proto-mélange during the following stages of its evolution: during the overthrusting on the late Oligocene-early Miocene Macigno/Modino foredeep flysch sequences, and the underthrusting below the Ligurian accretionary prism. These later stages of mélange growth are testified also by few inclusions of more recent slope or basin-margin deposits (Lower slope deposits of Burdigalian-Langhian age (LSDB): Civago Marls, Monte San Michele Marls, Baigno Marls/Suviana Sandstones) with ages ranging from Aquitanian to Langhian and perhaps early Serravallian [52; 66; 57; 59]. The inclusions represent inner slope remnants of the most recent Cervarola and Marnoso-arenacea clastic foredeep sequences (of early Miocene and Langhian to Tortonian age, respectively).

3) The polymictic sedimentary breccias (Fig. 4C) consist of a prevailing pelitic matrix with dispersed clasts of harder rocks, generally limestones, marlstones, siltstones, sandstones and claystones, of all sizes. The breccias have been interpreted as generated by submarine debris flow/mud flow processes in the lower part of the foredeep/inner slope during the different stages of mélange growth. The material in these chaotic bodies comes from the already deformed Ligurian/subligurian units. The complex and long structural history of the mélange prevents the knowledge of the exact age of each sedimentary breccia, but the existing data point over a long interval of time from the late Eocene up to the Langhian [60; 57; 59].

2.2.2. *Spatial changes in composition*

The mélange shows a compositional trend from SW to NE marked by the inclusion of materials deriving from External Ligurian units. Moving toward NE the rocks involved in the mélange derive from units progressively located in a more internal position within the former Ligurian accretionary prism as inferred at present from their respective arrangement in the Ligurian thrust-nappe and paleogeographical reconstructions. This spatial change in composition may be clearly observed along the above-mentioned SW-NE trending belt in which the mélange is exposed, i.e. along the Sillaro transverse lineament (Fig. 1). There, two partially overlapping mélange units have been recognised previously by Bettelli and Panini (1992) [52]. The main composition of the internal (SW) mélange unit is quite similar to what we have been described above as the usual composition, whereas the external mélange unit is prevalently made up of large blocks of Early Cretaceous to Paleocene varicoloured shales (Val Samoggia or Val Sillaro Varicoloured Shales) and blocks of early-mid Eocene Monte Morello and Savigno formations (early-middle Eocene) [52; 68]. Therefore, the material forming the SVTU external mélange unit is deriving from Ligurian rocks originally deposited in a paleogeographical domain more internal with respect to the domain in which were deposited the Ligurian rocks forming the inclusions of the SVTU internal mélange unit.

In the external mélange unit the Ligurian-derived components are complexly intermixed with shaly matrix-supported sedimentary breccias (submarine debris flow deposits) made up of the same material forming the remaining part of the mélange unit [52]. Moreover, in this latter mélange unit inclusions of slope deposits younger than Aquitanian are completely missing or possibly so small to remain still undiscovered [52].

2.2.3. *Internal structure: relations between the main components*

The SVTU is a complex, polydeformed and long-lived chaotic body, which started to form prior to the late Eocene (the SVTU proto-mélange) and lasted up to early-mid Miocene (the SVTU mélange) as testified by the more recent inclusions. As a consequence of this time-protracted structural history (Fig. 3), the various components of the SVTU mélange are now complexly mixed at all the scales of observation. However, many blocks of different rock types are large enough to be mapped separately. Although in the last decade a large effort has been made to distinguish and map the major mélange blocks [52; 60; 57; 59] their mutual relationships still remain poorly understood given the lack of suitable exposures.

On a regional scale the most widely distributed rock types are the blocks of Ligurian broken formations, some of which are sufficiently large to locally contain preserved primary contacts between different superimposed Ligurian rock-units [60 and references therein]. Apart from these particular occurrences all the contacts between the various mélange materials are sheared and clearly structural. However, the conclusion that they all represent fault contacts is probably incorrect. The widespread presence of massive inclusions of shaly matrix-supported sedimentary breccias (debris flow deposits) suggests that some large, coherent or incoherent Ligurian/Subligurian blocks may form by mass wasting processes active on the inner lower slope of the Oligo-Miocene foredeeps [52; 53; 54].

The late Eocene to early Miocene slope sediments inclusions are less deformed than the older rock types but they are sheared and jumbled together the other components or they are tectonic slices along the contact between the mélange and the underlying foredeep deposits [52; 66; 60].

In summary, the mélange can be considered essentially a large shear zone (“Schuppen Zone”: 56) containing relatively few, less deformed or, more rarely, intact blocks.

2.3. *Lower and upper contacts*

The lower structural contact of the Sestola-Vidiciatico tectonic mélange on the Macigno-Modino and Cervarola foredeep sequences where it may be directly observed (Fig. 4D)

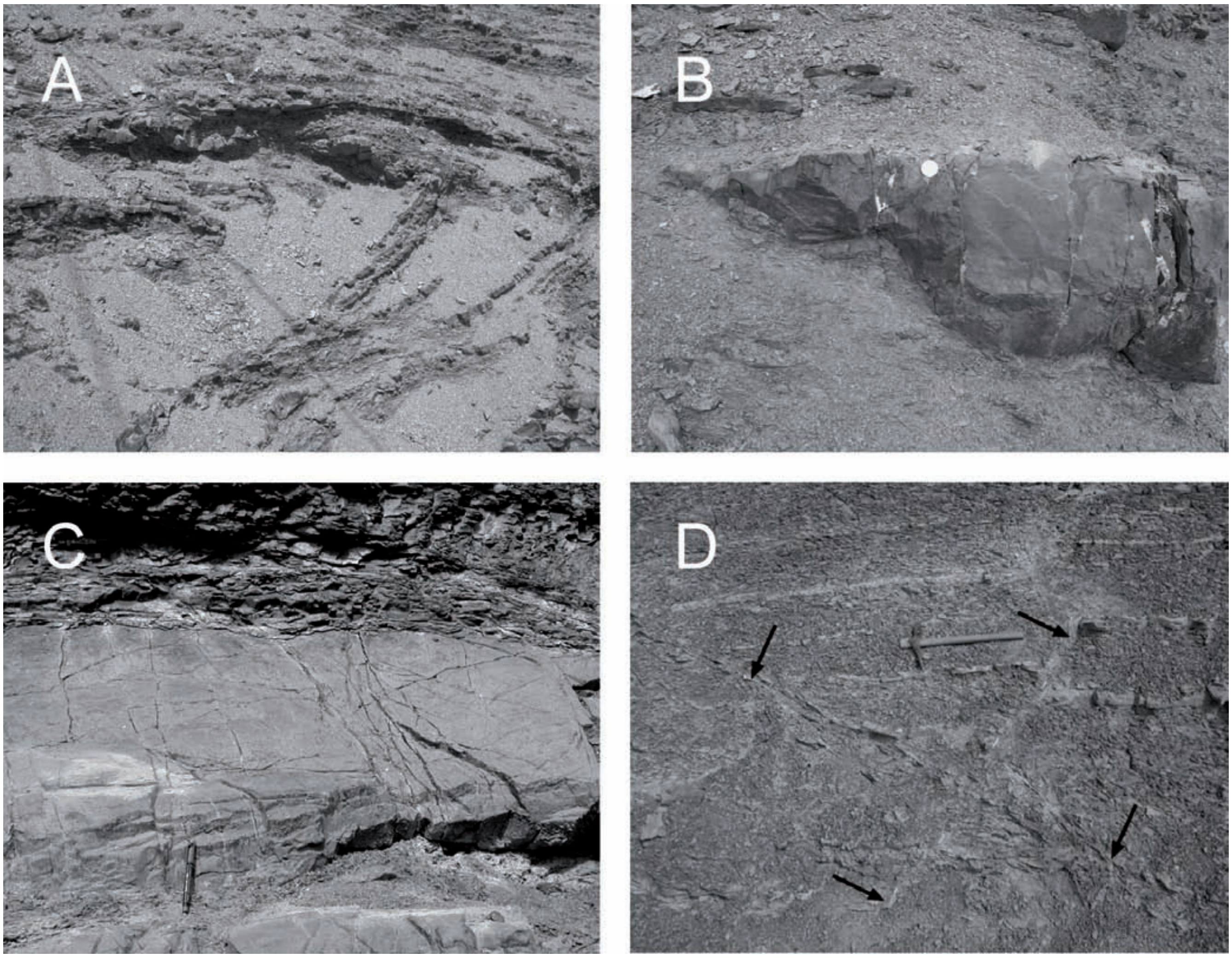

Fig. 5 - **A.** Slumped unit within the Fiumalbo Shales (Bartonian-Rupelian). Close fold embedded within packages of unfolded strata. **B.** Boudin showing pinch-and-swell termination on the limb of a slump-related fold in the Fiumalbo Shales. **C.** Interbedded shales and turbidite sandstones lithofacies of the Fiumalbo Shales. The shales show a penetrative scaly fabric (top) whereas the sandstone layer displays a brittle symmetric boudinage (bottom) developed in unlithified sediment. **D.** Fault arrays coated by calcite veins (black arrows) in the Fiumalbo Shales.

represents one of the better exposed tectonic contacts in the Northern Apennines [69; 70; 71; 72; 73; 60]. As stated above, the lower contact - and hence the mélange itself - is complexly faulted and folded [60] together with the footwall rocks by a series of large scale thrusts and associated mappable folds, often tight and overturned [71; 57; 58;59; 60]. Therefore, these latter thrusts and folds have been originated after the overthrusting of the mélange on the foredeep deposits and during the underthrusting of both by the Ligurian thrust-nappe.

On a mesoscopic scale the overthrust zone appears as a web of wavy anastomosing shear surfaces bounding slices of various sizes (horses) and the contact is presenting a regional ramp and flat geometry where the flats are nearly parallel to the bedding of the foredeep rocks in the footwall. Small normal faults, pressure-solution structures, drag folding and pervasive foliation are associated along the contact to the major fold structures [70]. Fault surfaces are often coated by shear calcite veins about 1 cm thick. In contrast to the important deformation of the hanging wall, the footwall is slightly deformed for at most 10 m below the contact.

Unfortunately, the upper tectonic contact of the mélange with the overlying Ligurian thrust-nappe cannot be directly observed. In fact, in the NW-SE trending outcropping area (Fig. 1) this contact at present is represented, as described above, by a later large normal fault, whereas in the SW-NE outcropping area the upper contact of the mélange with the Ligurian thrust-nappe may be mapped but no direct observations are possible due to the total absence of exposures.

3. Deformation

The deformation history of the mélange has been investigated through the detailed meso- and microstructural analysis of the components of late Eocene to early Miocene age.

These components are: shales (Fiumalbo Shales, late Eocene to early Oligocene) and marls (Marmoreto Marls,

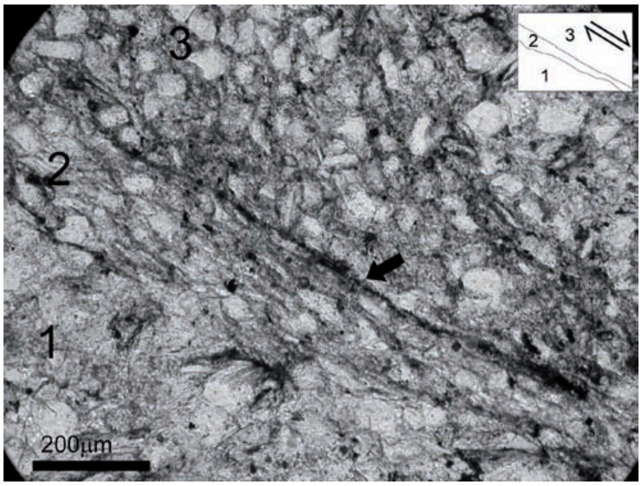

Fig. 6 - Deformation band in a sandstone layer of the Fiumalbo Shales (Bartonian-Rupelian). **Zone 1:** undeformed sandstone with preserved micas laminae, the micas gentle bend near zone 2. **Zone 2:** external part of the deformation band with few crushed grains and well-defined alignment of micas in the shear direction. **Zone 3:** central zone of the band with cataclasis of the micas between the quartz grains and widespread cementation overprinted by compaction and development of a pressure-solution seam (black arrow).

late Oligocene to early Aquitanian: Fig. 4B) deposited on the lower slope and at the toe of the overthrusting submarine Ligurian accretionary wedge, which progressively buried them through underthrusting.

The study was focused on these younger components of the mélange because they have not been affected by the older Ligurian tectonic phase (early-mid Eocene). During underthrusting the parameters influencing the rheological behaviour of the various mélange inclusions and the shear stress partitioning are the lithology and the distance from the deformation front below the Ligurian wedge. While the lithology acts mainly through the influence on lithification rate, the distance from the deformation front influences the pressure and temperature conditions and the lateral confinement during deformation. These two factors are strictly related and, for instance, both influence the fluid pressure through the control of the permeability and fluid pressure and therefore the fluid expulsion rate from the sediments.

3.1. Structures

The present state of strain of the mélange is the result of a long-lasting deformation history which started in the late Eocene with the initial continental subduction and continued during the collisional stages of the Northern Apennines orogeny up to the Langhian (Fig. 3). The tectonic evolution of this complex chaotic rock-mass can be interpreted in terms of progressive deformation with changing mechanisms following the changes of lithification, pressure and temperature. For simplicity, the tectonic evolution will be described in three main stages, even though there are not real gaps between the different deformation events.

3.1.1. Synsedimentary deformation: slumps and related boudinage/pinch and swell structures

The oldest, late Eocene-early Oligocene sedimentation event took place on a tectonically active slope before the development of the foredeep basin (Fig. 3) and the associated oldest siliciclastic turbidites of the Northern Apennines – i.e the Chattian-Aquitanian Macigno formation. The unstable environment caused common slope failures with several slumps preserved in the alternating shale and sandstone lithofacies of the slope apron (i.e. Fiumalbo Shales: Fig . 5A). The slumped units are characterized by mesoscopic, mostly disharmonic, tight to isoclinal folds with randomly oriented hinge lines embedded within packages of unfolded strata. On fold limbs the arenitic layers are stretched with development of pinch-and-swell structures and symmetric boudins (Fig. 5B). The arenitic layers experienced an apparent "ductile" stretching with the extension entirely accommodated by the inflow of the host shaly rock, suggesting that both the arenitic and shaly layers were unlithified at the time of deformation.

3.1.2. Pervasive deformation: soft-sediment and brittle boudinage, scaly fabric

The younger Oligocene-Miocene blocks present in the mélange show pervasive deformation leading, in some cases, to the complete loss of primary bedding. The only exception is represented by turbidites bodies included in the Marmoreto Marls. These turbidites (Vallorsara Sandstones, Monte Sassolera Member) are characterized by a great amount of sandstone with a sandstone/shale ratio >>1. The sandstone layers are also preserving a good lateral continuity and they appear almost undeformed at the mesoscopic scale, except for conjugate sets of extensional shear fractures dying out as they approach the interface with the shales. These shear fractures, curved and rough, are well developed as steps on the lower surface of the sandstone turbidite bed, but they do not have a visible physical expression within the sandstone layer. These are characters typical of "hydroplastic" shear fractures formed when the sandstone were not completely lithified (e.g.: [75; 27]). The contact between these weakly deformed sandstone bodies and the embedding marls occurs by shear surfaces detaching the two lithologies, because of their different mechanical behaviour.

If the sandstone/shale ratio is <<1, the bedding is still preserved, and the sandstone layers are stretched and boudinaged in two perpendicular directions while the shaly interbeds show a pervasive scaly fabric (Fig. 5C). In the first stage the boudin terminations show hydroplastic shear fractures that vanish in the centre of the layer. The fractures are almost planar, even though they have small scale irregularities and often they tend to branch near the top or the bottom of the layer. Their optical analysis in thin section confirm their similarity with the microstructure of deformation bands characteristic of unlithified sand [76; 77]. The microstructures (Fig. 6), in fact, show a transition from

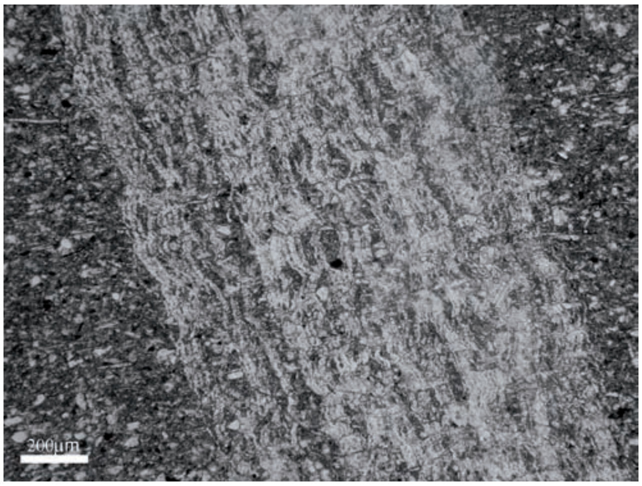

Fig. 7 - Crack-and-seal extensional calcite vein parallel to the terminations of a boudin in the Fiumalbo Shales (Bartonian-Rupelian).

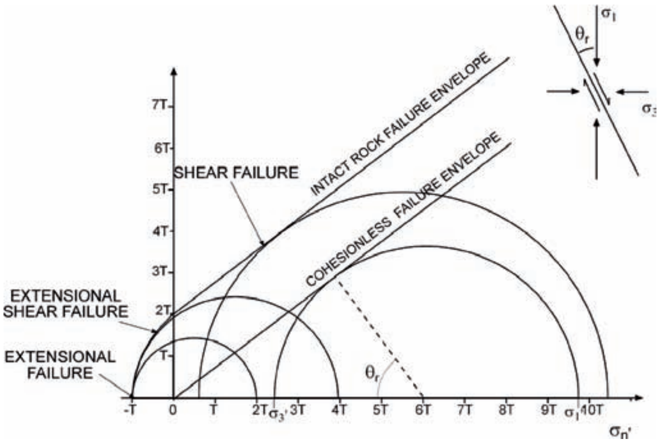

Fig. 8 - Mohr diagram with composite failure envelopes for intact isotropic rock with tensile strength, T, and for cohesionless fault, illustrating the stress conditions and orientations with respect to the stress field of extensional failure, extensional-shear failure, shear failure.

bands with no cataclasis to bands with cataclasis and with little positive dilatancy [78; 79; 76; 77], at least in correspondence of bends of the shear surface. Each shear zone is about 1 mm thick and shows a displacement estimated in the order of about 2 cm. This displacement, is mainly accommodated in the central zone of the band where there are evidence for the initiation of a real slip plane. At the edge of the shear zone the mica grains of the sandstone tend to be re-oriented without evidence of breakage. On the contrary, in the central zone the micas are crushed between the grains of quartz that instead preserve the original sizes. This central zone is characterized also by a higher amount of carbonates cementing the particles than the host rock and by precipitation of oxides giving a brown-red colour. As the shearing progresses, there is compaction and development of dissolution surfaces.

Hence the most important mechanism in the shear band seems to be a diffuse sliding and rolling between the quartz grains. The shear is associated to a preferential circulation of fluids along the structure, due to the increase of the permeability connected to the dilatancy and leading to a preferential cementation of the zone. The movement tends to concentrate on a slip plane often predated by an intermediate stage of compaction.

After the deformation bands, extensional veins (Fig. 7) start to grow at the edge of the boudins. These veins contain calcite and barite or, in some cases, calcite and quartz and they are characterized by a crack-and-seal texture [80]. This structure is due to the rise of the fluid pressure until the tensile overpressure condition ($P_f > \sigma 3$) is reached. Hence an extensional vein opens with a consequent permeability rise and fluid pressure drop causing the mineral precipitation and the sealing of the fracture [80]. To open an extensional vein the rock must be cohesive, otherwise shear fractures are formed (Fig. 8). In a granular material cohesion is due to cementation, therefore at this stage the sandstone must have been cemented. The extensional veins end in correspondence of the shaly layers because of the different mechanical properties probably due to their uncomplete lithification.

Thin bedded shales with sparse beds of turbiditic sandstones - e. g. Fiumalbo Shales - and shaly layers in general develop an intense scaly fabric (e.g.: [81]). This fabric is characterized by a complex array of variably anastomosing polished surfaces enclosing lenticles of less foliated material.

In the marls (Marmoreto Marls, Monte San Michele Marls, Civago Marls) the bedding is completely lost because of pervasive deformation (Fig. 4B). At all the scales of observation these marly units are penetratively cut either by shear surfaces with normal or strike-slip movement. These latter subdivide the rock in lozenge-shaped slivers which are cut again by a web of minor surfaces reproducing the same geometry up to the centimeter scale.

The lozenge shape of the slivers is produced through the intersection of four sets of gently dipping shear fractures paired in two perpendicular directions easily recognizable at the outcrop scale. Crosscutting relationship suggests a contemporaneous development of these shear surfaces that are parallel to the contacts between the different rock-types. At a minor scale the shear surfaces are curviplanar and tend to splay and amalgamate. Each shear surface is finely striated and the second order structures usable as shear sense indicators [82] are mainly lunate fractures and offsets of markers. These indicators show that the mean directions of movement are normal to the strike of the sets of shear surfaces. On the more prominent shear surfaces a thin band of cataclastic breccia is often present [71] .

The shear surfaces are not mineralized, even though a thin coating of opaque minerals commonly occurs because of pressure-solution or circulating fluids along the fractures. The overall deformation results in a stretching parallel to the lower contact of the SVTU.

3.1.3. Localized deformation: shear zones and faulting

The diffuse deformation evolves to concentrated shear especially in the shales, with the development of brittle shear zones from 10 cm to 1 m thick. These shear zones are characterized by the presence of a dense array of extensional veins, often originating an anastomosing pattern. Their dilatant character implies that fluid pressure was, at least locally, higher than σ_3.

These shear zones are further cut by mesoscopic faults (Fig. 5D) with a good lateral continuity coated by calcite veins about 1cm thick.

Shear zones and faults have a spacing of about tens of meters and each fault accommodates a total displacement varying from 1 cm to tens of centimetres originated by a great number of repeated events. The faults are preferentially developed in the marl or shale, but they may also be found in the other lithologies as in the blocks of Ligurian and Subligurian Units and in the sedimentary breccias forming the mélange. The no longer growth of shear zones at the bounding edges of the blocks indicates that the mechanical behavior difference in the mélange was reduced or completely removed probably because of the complete lithification of all the components.

The faults have quite random strike orientations and could be steep or horizontal often re-using pre-existent discontinuities as lithological contacts or shear surfaces. The calcite slikenfibers and the calcite patches formed in the steps of the faults represent good kinematic indicators [82; 83] showing that the directions of movement are consistent in neighbouring faults, most being normal or strike-slip faults. The main direction of movement is parallel to the tectonic transport direction but the slikenfibers on these surfaces show also displacements in the perpendicular direction (Fig. 9).

At this stage the veins have the typical internal structures of the striped veins [84; 85; 86; 83; 87] with calcite filling and minor presence of quartz and barite. The formation of this microstructure is connected to the initial presence of dilational stepovers on the fault surfaces allowing the opening of void space during the movement of the fault (Fig. 10). The texture is characterized by a crack-and-seal fabric (Fig. 10) that testifies a cyclical fluid pressure rise and drop followed by mineral precipitation.

Often, within the veins, there are evidence of brecciation involving both the previously precipitated calcite and the wall rocks. This brecciation could be related to the action of the friction during the movement on the fault or, more probably, is due to the fluid pressure. In fact, since brecciation develops only within dilational jogs (Fig. 10), probably it is triggered by the implosion related to the local fluid pressure drop [88; 89; 90]. In this type of veins the interplay between the fluid pressure and the movement on the fault is complicated by both the geometrical shape of the surface and the role of the tips of the two overlapping faults. In fact the shape of the extensional veins (Fig. 11) linking the shear surfaces tends to fit the trajectories of the principal stresses inside a dilational stepover obtained from several numerical models [91; 92]. In the same models it has been calculated that the principal stresses inside the dilational jog are smaller than the far field stresses. As a consequence, the opening of the extensional vein terminating on the shear surface needs a $P_f > (\sigma_{3lf} + T)$ where $\sigma_{3ff} > \sigma_{3lf}$ (σ_{3lf} is the σ_3 inside the dilational jog and σ_{3ff} is the σ_3 outside the dilational jog).

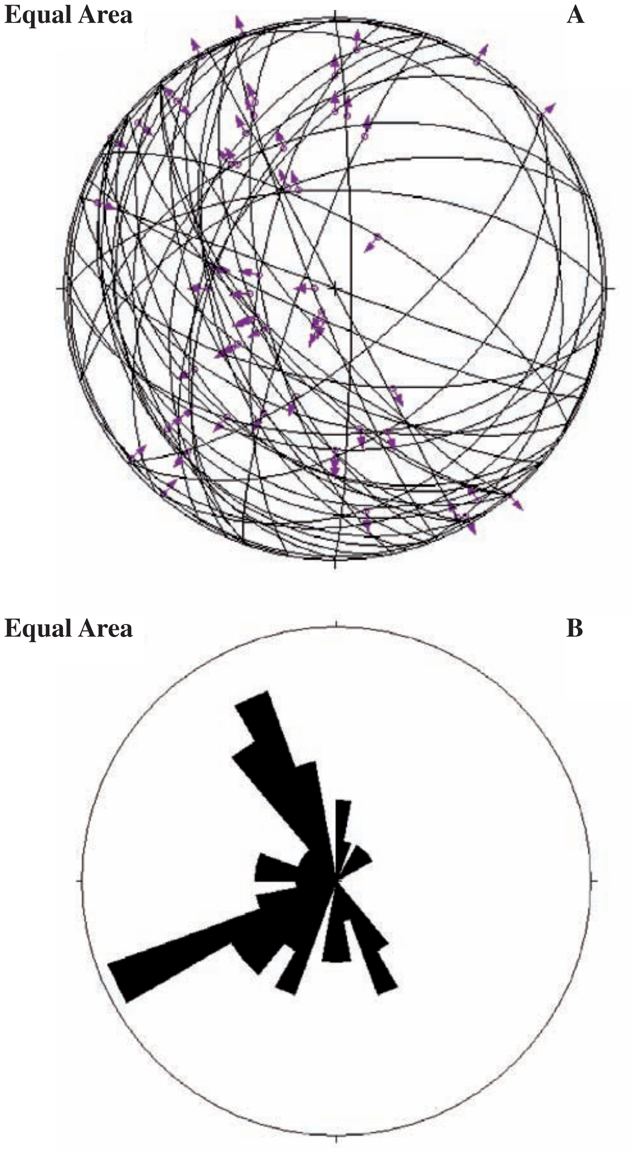

Fig. 9 - **A. and B.** Stereoplot and rose diagram of the faults coated by clacite veins within the Marmoreto Marls. In spite of the random orientation of the faults, the striations clusters in two main directions.

The mechanism controlling the opening of these veins is cyclical and repeating themselves hundreds of times and probably connected to the rise of the fluid pressure until the conditions for the movement on the faults are reached. This stage is followed by the drop of the fluid pressure linked to both the increasing fracture permeability (fault valve behavior [93]) and, at least in some cases, to the opening of a dilational jog. This opening may decrease the fluid pressure to values below the hydrostatic value driving the formation of implosion breccias (Fig. 12) [88; 90] and perhaps stops the propagation of the movement along the fault [88].

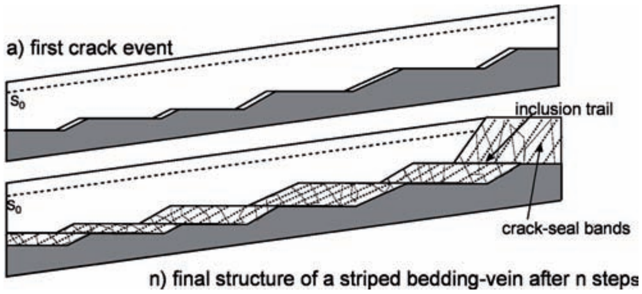

Fig. 10 - Diagram showing the stage of formation of a striped vein due to irregularities on the fault surface. (modified from Koehn and Passchier, 2000).

4. Conclusions

The Sestola-Vidiciatico tectonic unit in the Northern Apennines is a tectonic mélange formed through underthrusting mechanisms at the transition from subduction to collision, and during the collision. The SVTU has been originated from the pre-existing Ligurian/Subligurian oceanic prism through tectonic and mass wasting processes at the toe of the wedge and it has been further reworked by tectonic processes along the décollement surface during the underthrusting (Fig. 3).

The mélange is formed by three main components:

a) wide blocks of External Ligurian and Subligurian units preserving the deformation acquired during accretion in the Ligurian phase;

b) polymictic sedimentary breccias with clasts of deformed Ligurian/Subligurian units;

c) large, coherent slabs of late Eocene to early Miocene shaly and marly deposits of the foredeep lower-slope.

The analysis has been focused on the younger component of the mélange that has been deposited on the frontal prism generated by the tectonic and sedimentary reworking of the former Ligurian accretionary wedge (Fig. 3). Several slumps preserved in the alternating shale and sandstone lithofacies testifies that these units have been deformed at a very early stage of diagenesis.

In the initial stages the distinct lithological characters of each inclusion plays a key role in the deformation with the development of detachment surfaces between the different components and the concentration of deformation in the shales and the marls. These slices are pervasively deformed with the development of a penetrative scaly fabric in the shales and a web of anastomosing brittle shear surfaces in the marls. The different rheological properties of the individual components and their consequent different mechanical behavior is mainly related to their lithification rate; in fact the marls shows, yet at the initial stage, a brittle style of deformation while the shales are still able to flow also when the sandstone layers are completely cemented as suggested by the development of extensional veins.

Despite the release of large amount of water due to the compaction and lithification processes, in these stages of the progressive deformation no veins have been formed in the shales and marls along the brittle shear surfaces. In the last stages of evolution, the lithification of each component brought to a more uniform mechanical response of the mélange inclusions and the consequent deactivation of the detachment surfaces separating the different lithologies. Hence the deformation became more distributed within the mélange, even though the spacing of the shear surfaces and the movement along the single faults increased considerably causing the passage from a bulk deformation to a deformation concentrated along the faults.

The deformation of the mélange is probably continuous in time both when the deformation was mainly plastic and when it was brittle and diffuse. Instead the internal crack-and-seal microstructures of the veins present along the faults clearly show that in the last stages of the deformation the relative movement of the blocks became discontinuous in time and probably related to cycles of fluid pressure.

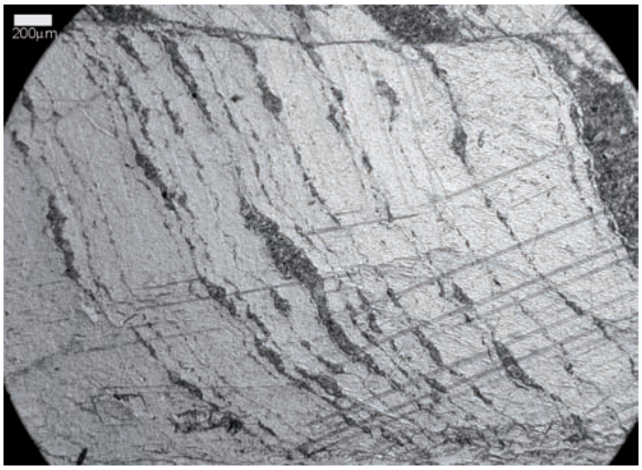

Fig. 11 - Geometry and calcite-fill fabric of the crack-and-seal vein coating the faults. The sigmoidal shape of the extensional vein mimic quite well the predicted trajectories of the principal stresses in a dilational jog (see Fig. 4 a and b in Ohlmacher & Aydin, 1997).

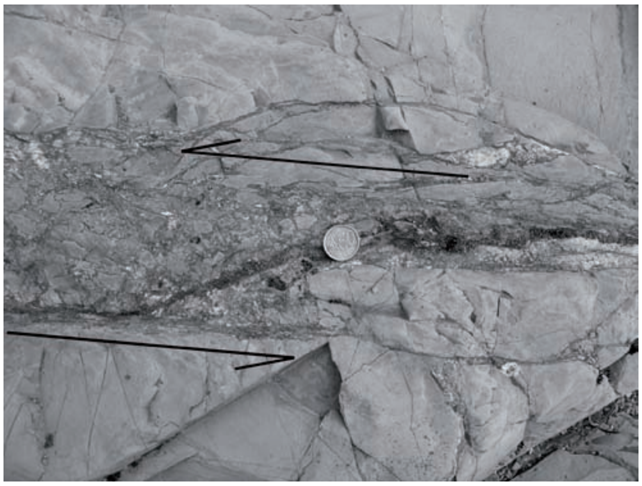

Fig. 12 - Breccia in a dilational jog interpreted as due to localized transient reduction of fluid pressure during the movement on the fault (Sibson, 1985, 2000). Coin for scale.

The development of implosion breccia in the dilational stepover, which testifies a drop of fluid pressure under the hydrostatic value, suggests that the cycle of fluid pressure may be related also to the no longer active propagation of the movement along the faults [88].

Considering that the mélange has been generated under conditions ranging from the shallow diagenetic environment at the toe of the prism to temperatures of around 120°C [94; 95; 44; 42], the SVTU represents a good fossil analogue for accretionary prisms. Moreover since the up-dip limit of the seismogenic zone is considered thermally controlled and located at around 100°-150°C (e.g. [96; 97; 98]), the SVTU could provide key information on the structural evolution prior of reaching seismogenic conditions. These shallow structures are rarely preserved in other ancient convergent margins and they are directly comparable to the structures found in the frontal part of active prisms.

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