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REVISITING THE INTERNAL LIGURIAN UNITS OF THE ANTESSIO AREA (LIGURIAN APENNINES, ITALY): INSIGHTS INTO THE OCEANIC LITHOSPHERE OF THE LIGURIAN-PIEDMONT BASIN

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ABSTRACT

This paper presents a complete stratigraphic, tectonic, and structural dataset of the Internal Ligurian Units outcropping in the Antessio area (Northern Apennines), based on new geological mapping and micro- and mesoscale analyses. A stack of three Internal Ligurian Units, namely, from top to the bottom, the Gottero, Bracco-Val Graveglia and Colli-Tavarone Units, has been recognized. The general stratigraphic characteristics of these units indicate that they are derived from dismembering of a sequence derived from the Ligurian-Piedmont oceanic basin. This sequence includes Middle to Late Jurassic ophiolites, Late Jurassic to Late Cretaceous pelagic deposits, Late Cretaceous to Early Tertiary turbidites and Early Tertiary mass-transport deposits. This sequence is interpreted to have developed during the progressive trench-ward motion of a segment pertaining to the inner part of the Ligurian-Piedmont oceanic basin. In the Antessio area, the deformation history of the Internal Ligurian Units includes two deformation phases, whose features support the involvement of these units in a subduction-related accretionary wedge zone by coherent underplating followed by exhumation. This picture suggests a close correlation between the Internal Ligurian Units of the Antessio area and those of the Bracco Massif, as well as those of the Graveglia and Vara valleys.

INTRODUCTION

Accretionary wedges are dynamic, morpho-tectonic features located along active subduction zones worldwide and they form by recycling of materials, usually of oceanic affinity, mostly stemming from the subducting plate (e.g., Platt, 1986; Moore, 1989; Cawood et al., 2009; Meneghini et al., 2020; Angiboust et al., 2022). Such material can be transferred by frontal tectonic accretion or by deeper underplating (coherent or diffuse) processes at the tip and at the base of the accretionary wedge, respectively (e.g., Kukowsky et al., 2002; Sick et al., 2006; Menant et al., 2019; Haberland et al., 2020). While a direct access to the accretionary wedges is limited (e.g., Barnes et al., 2020), their remnants preserved into collisional belts offer un opportunity to detailly investigate how accretion processes operate (e.g., Crispini and Capponi, 2002; Di Rosa et al., 2020; Sanità et al., 2021; 2022a; Marroni et al., 2025).

The Northern Apennines is a segment of the Alpine collisional belt of the western Mediterranean area (Figs. 1a, b). Its uppermost part (Figs. 1b, c) is represented by a stack of tectonic units known as the Internal Ligurian (IL) Units (Elter, 1975). These units are composed of slices of lithosphere derived from the Ligurian-Piedmont Oceanic (LPO) area, a narrow basin that opened between the European and Adriatic continental margins from Middle to Late Jurassic and was subsequently closed by subduction and continental collision from Late Cretaceous to Late Eocene (Boccaletti et al., 1971; Elter and Pertusati, 1973; Bortolotti et al., 1990; Marroni et al., 2017). Their log, reconstructed by assembling data from the various IL Units, includes a Middle to Late Jurassic ophiolite sequence capped by a Late Jurassic to Early Paleocene sedimentary cover including pelagic sediments, carbonate and siliciclastic turbidites and mass-transport deposits (MTDs) (Decandia and Elter, 1972; Principi et al., 2004; Meneghini et al., 2020; Festa et al., 2021). The IL Units underwent a polyphase deformation history (Pertusati and Horremberger, 1975; van Zupthen et al., 1985; Marroni et al., 2004) developed under pressure (*P*) and temperature (*T*) conditions ranging from prehnite-pumpellyite to low blueschists metamorphic facies (Sanità et al., 2024). The deformation history was achieved during the underplating and subsequent exhumation of the IL Units within the Alpine accretionary wedge associated to the east-dipping subduction zone developed during the closure of the LPO basin (Treves, 1984; van Wamel, 1987; Marroni et al., 2017).

The stratigraphic, structural, and metamorphic characteristics of the IL Units are therefore of fundamental importance for reconstructing the history of the LPO basin. They have been studied in detail, mainly by geological mapping, in the Bracco Massif (Decandia and Elter, 1972; Cortesogno et al., 1987) as well as in the Graveglia (Decandia and Elter, 1972; Bortolotti and Principi, 2003), Vara (Marroni and Meccheri, 1993) and Lavagna (Marroni, 1991; Ducci et al., 1997) Valleys of eastern Liguria. Other areas have received less attention, including the Antessio area (Fig. 1b), where only a paper by Monteforti and Raggi (1975) followed by 1:50,000 scale geological map (Puccinelli, 2015) and the associated explanatory notes (Puccinelli et al., 2015), both produced in the frame of the Italian Cartography Project (CARG) are available. Notwithstanding, the Antessio area is a natural lab where the tectonic evolution of the IL Units may be unveiled. This is mainly due to the exceptional preservation of the sedimentary sequences. Hence, an updated picture of the geological setting for the Antessio area is pivotal to obtain a comprehensive view of the Internal Ligurian Units tectonic history.

The aim of this contribution is to provide a complete picture of the IL Units in the Antessio area (Fig. 2a) by means

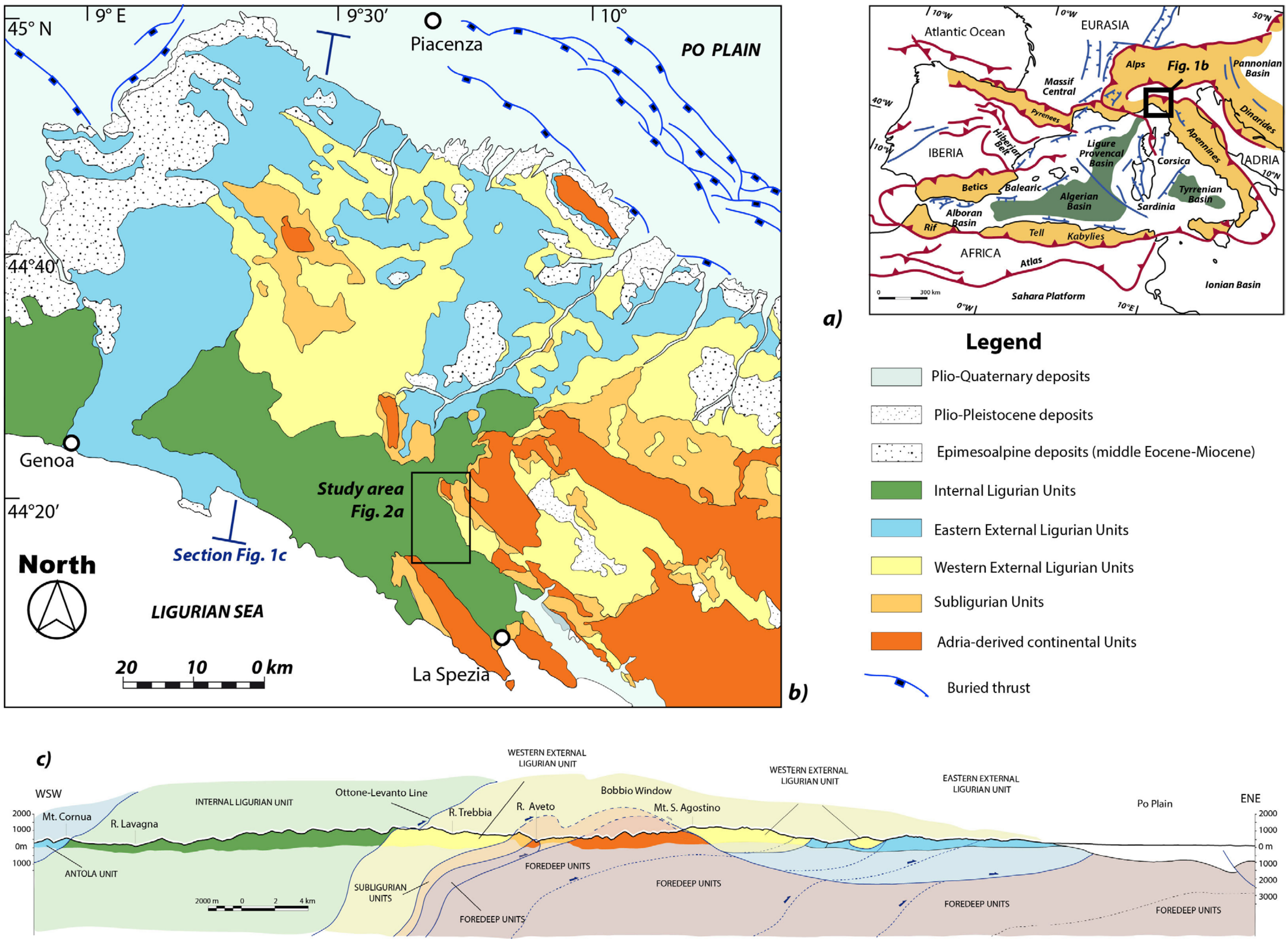

Fig. 1- a) Location of the Northern Apennines in the frame of the circum-Mediterranean collisional belt of Alpine age (light brown color). Extensional basins are indicated by green color. b) Simplified tectonic sketch of the Northern Apennine belt and (c) the related geological cross-section (modified from Marroni et al., 2017). The black box indicates the area represented in Fig. 2.

of an updated geological map at 1:10,000 scale, coupled with stratigraphic, paleontological, and structural analyses. This picture will then be compared with that of the IL Units of neighboring areas, mainly those of the Bracco Massif as well as those of the Graveglia and Vara Valleys.

OVERVIEW ON THE INTERNAL LIGURIAN UNITS OF NORTHERN APENNINES

The Alpine collision belt, that extends from Central and Western Alps to Alpine Corsica and Northern Apennines (reported as “Alps” and “Apennines” in Fig. 1a), is characterized by well-developed ophiolite sequences, all regarded as derived from the LPO basin (Abbate et al., 1986). In the Northern Apennines, these ophiolites, with the related sedimentary cover, occur within the IL Units (Decandia and Elter, 1972). These group of tectonic units overlain the External Ligurian (EL) Units along the Ottone-Levanto line (Figs. 1c, 2a), a sinistral transpressional shear zone developed during the Late Eocene-Early Oligocene (Marroni et al., 2019). The EL Units, characterized by the occurrence of carbonate turbidites of Late Cretaceous age known as Helminthoid Flysch (Figs. 1b, 2a), represent the remnants of the ocean-continent transition at the rim of the Adria plate (Marroni et al., 2001). In turn, the IL Units are thrust by the Antola Unit (Fig. 1b, c), consisting of a thick sequence of Late Cretaceous to Early Tertiary carbonate turbidites (Levi et al., 2006). Despite its occurrence in a different tectonic position, the Antola Unit has been correlated with the EL Units (Marroni et al., 2019). Both IL and EL Units are thrust during the Miocene over the Subligurian, and Tuscan Units (Figs. 1b, c) detached from the Adria continental margin (Elter, 1975).

The IL Units consist of a stack of tectonic units cropping out in the northwestern side of the Northern Apennine (Fig. 1b and 2a). These units include, from bottom to the top, the Colli-Tavarone (CT), Bracco-Val Graveglia (BG), Gottero (GT), Vermallo, Due Ponti and Portello Units (see Marroni et al., 2017 for a review). Only the first two units are characterized by an ophiolite sequence, whereas the other units include only sedimentary deposits. According to Ellero (2000), the IL Units W of the Antola Unit, include, from the bottom to the top, the Cravasco-Voltaggio, Monte Figogna, Bric Montaldo, Serra Riccò, Vellecalda and Ciaè Units (see Molli et al., 2010 for a detailed review). The last four units correspond to Mignanego, Montanesi and Ronco Units by Capponi et al. (2016).

By integrating all available data, a comprehensive log of the three main IL Units, i.e., the GT, BG and CT Units, can be drawn (Fig. 2b). The log of BG Unit includes at its base a Middle to Late Jurassic ophiolite sequence, no more than

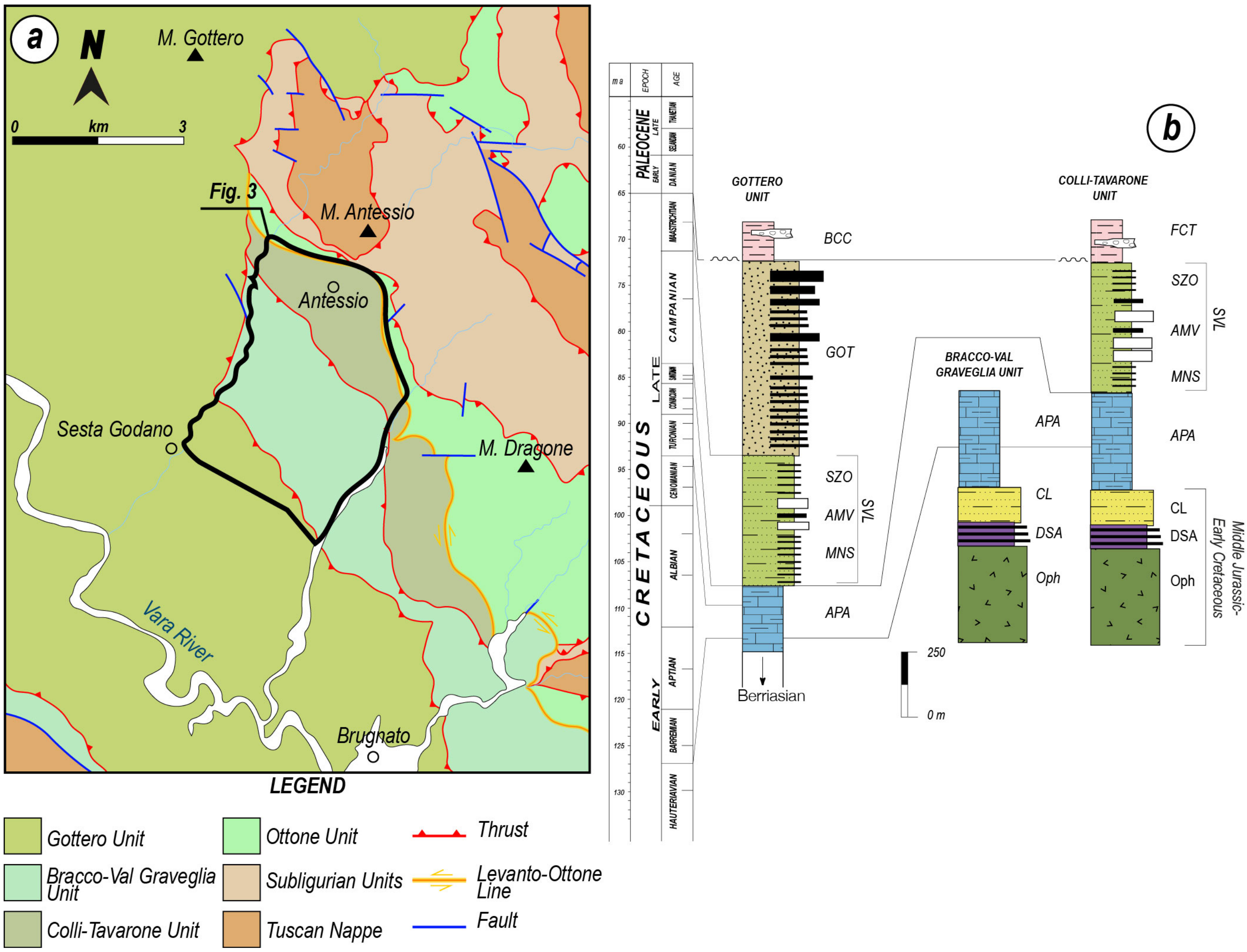

Fig. 2 - a) Tectonic sketch map (close-up of the black box in Fig. 1b) of the area surrounding Antessio village. The main tectonic units, as well as the Ottone-Levanto Line (the kinematics is indicated), are reported. The black box indicates the mapped area displayed in Fig. 3. b) Reconstructed stratigraphic logs of Gottero, Bracco-Val Graveglia and Colli-Tavarone Units are reported (modified from Sanità et al., 2024). BCC: Bocco Shale Fm.; FCT: Colli-Tavarone Fm.; GOT: Monte Gottero Sandstone Fm.; SZO: Zonati Shale Fm.; AMV: Monte Verzi Marl Fm.; MNS: Manganesiferi Shale Fm.; APA: Palombini Shale Fm.; CL: Calpionella Limestone Fm.; DSA: Monte Alpe ChertsFm.; Oph: Ophiolite sequence.

1 km thick, consisting of 500-600 m thick basement made up of serpentinized mantle peridotites intruded by bodies of gabbros (Fig. 2b). This basement is overlain by a 300-400 m thick sequence of ophiolitic breccias intercalated with pillow-lava basalts and radiolarites (Marroni et al., 2017 and reference therein). This ophiolite sequence is thought to have originated in an ultra-slow spreading ridge within a narrow oceanic basin, not larger than 500-600 km (van Wamel, 1987; Sanfilippo and Tribuzio, 2011). The ophiolite sequence is overlain by a Late Jurassic to Late Cretaceous pelagic sequence (Fig. 2b, see Principi et al., 2004) including Monte Alpe Cherts (Callovian to Kimmeridgian; Chiari et al., 2000), Calpionella Limestone (Tithonian to Early Valanginian, Cobianchi and Villa, 1992) and Palombini Shale (Late Valanginian to Santonian; Marroni and Perilli, 1990) Fms. The last two formations consist of fine-grained carbonate turbidites interbedded with hemipelagic shaly deposits (Pandolfi, 1997; Bracciali et al., 2007). These pre-convergence deposits are considered to have been sedimented below the calcite compensation depth (Marroni, 1994) in a basin plain characterized by a very low sedimentation rate. In the log of the GT and CT Units (Fig. 2b), the pelagic deposits show a gradual transition to the Late Cretaceous - Early Paleocene trench deposits (Fonnesu and Felletti, 2019) supplied by the European continental margins. They include the Manganesiferi Shale (Early Campanian), the Monte Verzi Marl (Early to Late Campanian), the Zonati Shale (Late Campanian to Early Maastrichtian) and the Monte Gottero Sandstone (Early Maastrichtian to Early Paleocene) Fms. (Fig. 2b). These turbidites, characterized by a high sedimentation rate, are considered as the signal of the beginning of the convergence that affected the LPO basin since the Campanian (Marroni et al., 2017). This convergence resulted in an east-dipping subduction leading to the building of an accretionary wedge where slices of ophiolites and its sedimentary cover were accreted (Treves, 1984). The last sedimentary event in the IL succession is represented by Early Paleocene MTDs (Fig. 2b) consisting of pebbly mudstones and slide blocks interspersed within fine-grained turbidites and hemipelagic shales. The MTDs were generated by several episodes of frontal tectonic erosion affecting the lower slope of the accretionary wedge (Meneghini et al., 2020). This sedimentary evolution is interpreted as reflecting the progressive motion of an oceanic area to a subduction zone (Treves, 1984; Marroni et al., 2017). This picture is confirmed by the

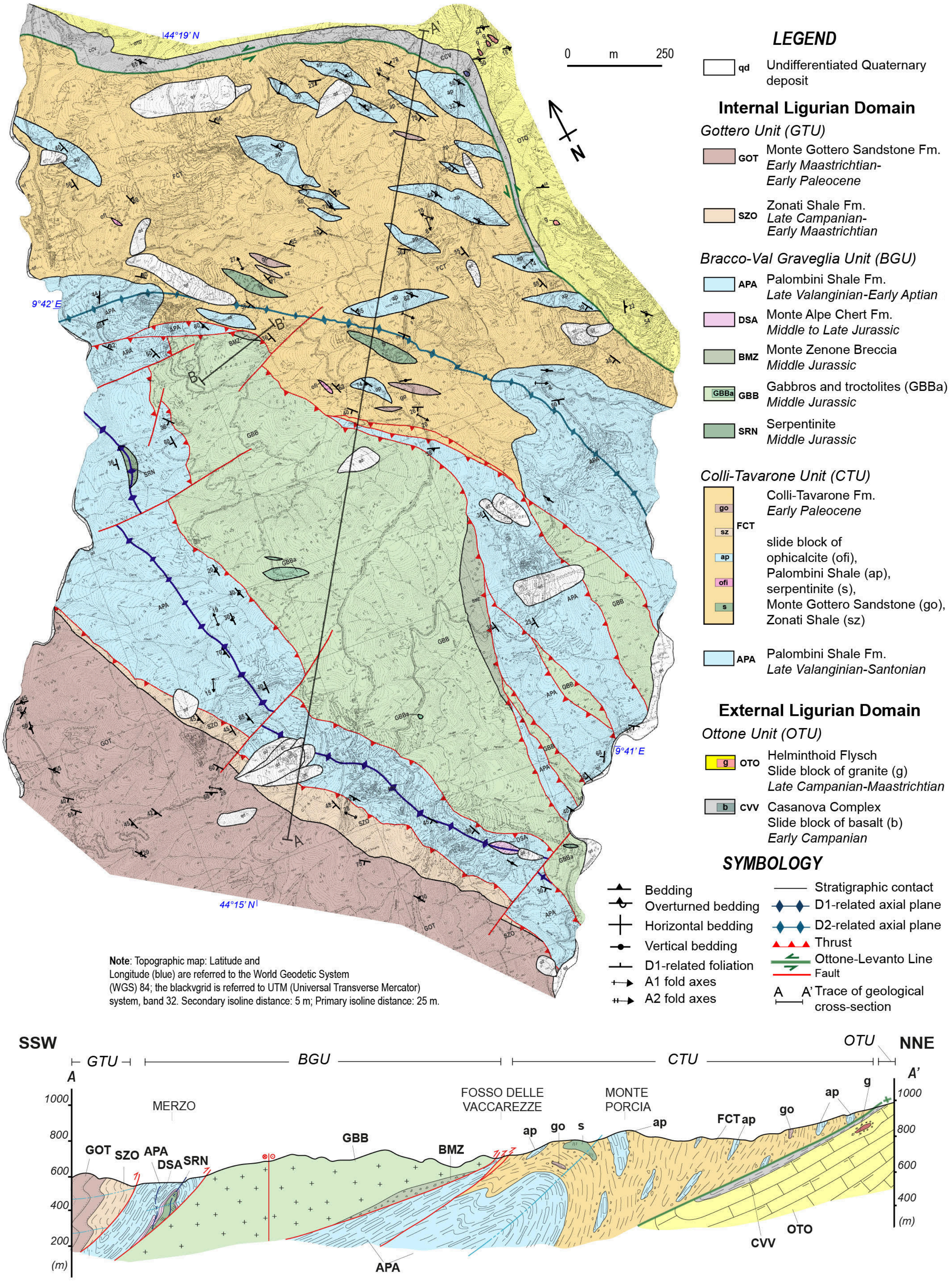

Fig. 3 - a) Geological map of the Antessio area (black box in Fig. 2) and geological cross section (the trace is reported in the map) representative of the overall tectonic pile of IL Units documented in the study area.

subsequent structural history of the IL Units which includes two main deformation phases (Marroni et al., 2004). These two deformation phases are predated by an extensive veining in the deposits of the IL Units, which is interpreted as resulting from dewatering of the sediments during underthrusting of the oceanic lithosphere beneath the accretionary wedge. The first deformation phase is characterized by isoclinal folds and the associated foliation which developed in the easternmost IL Units under *P* and *T* conditions pertaining to low blueschists (GT and Portello Units) and prehnite-pumpellyite (CT and BG Units) metamorphic facies (Meneghini et al., 2023; Sanità et al., 2024). This first phase of deformation is associated with the development of foliated cataclasites along the shear zones that bound the IL Units. The first phase is followed by a further deformation characterized by close to open folds showing sub-horizontal axial planes and a crenulation cleavage as axial plane foliation (Marroni 1991; Marroni et al., 2004). These folds are associated with low-angle shear zones showing an extensional kinematics. This finding suggests that the second deformation phase was acquired by the extensional tectonics developed during the exhumation of the IL Units within the accretionary wedge (i.e., Marroni et al., 2017). The IL Units were exhumed as early as the Early Oligocene. This reconstruction is supported by the occurrence of clasts derived from the IL Units, which have undergone two phases of deformation, within the undeformed, Early Oligocene Val Borbera Conglomerates in the north-western corner of the Northern Apennines (Di Biase et al., 1997).

METHODS

We have applied a multidisciplinary approach by combining fieldwork and lab analyses. Fieldwork has been carried out in the Antessio area covering about 20 km^2 (Figs. 2b, 3). The geological survey has been performed using a 1:10.000 topographic map and by applying the classic field techniques to build a detailed geological and structural map of the study area. Structural analysis techniques combined with an updated knowledge of the sedimentary successions has been demonstrated to be a useful tool to reconstruct in detail the deformation history of low and very-low-grade units (e.g., Frassi et al., 2020; Sanità et al., 2020; 2022b; 2023; De Cesari et al., 2025). During fieldwork, the spatial orientation of the main linear and planar structural features (fold axes, stretching and intersection lineations, fault plane-related striae, bedding, axial planes, foliations, thrust planes, shear zones, fault planes) were collected and their mutual relationships are showed in stereographic projections (Schmidt net, lower hemisphere). The systematic collection of the structural features allowed for reconstructing of the main deformation events recorded by each unit. In areas where clear meso-scale superposition relationships between different tectonic structures were well-evident, sampling of shales was performed to describe the deformations at the micro-scale (nomenclatures and classifications according to Ramsay, 1967 and Passchier and Trouw, 2005). Microstructural analysis has been performed by using an optical microscope at the Department of Earth Sciences of University of Pisa. To better constraint the stratigraphic architecture of the Colli-Tavarone Fm. we have performed a sampling for the analysis of the calcareous nannofossils content. This study was conducted at the Istitute of Geosciences and Georesources of Pisa. Samples were prepared as smear slides following standard techniques (Brown et al., 1998). Observation of smear slides was conducted under a polarized light microscope at 1,250X.

RESULTS

The Internal Ligurian Units of the Antessio area: overall map-scale architecture

The Antessio area is characterized by the superposition of the IL Units on the EL ones by the Ottone-Levanto line (Fig. 2a and 3), a high-angle, sinistral transpressive shear zone. The IL Units stack, whose stratigraphy and deformation history are described below, are composed of three units, named, from bottom to top, the CT, BG, and GT units (Fig. 3). Each of these units is characterized by an internal geometry, and they are bounded by brittle shear zones with a top-to-E kinematics. The EL Units are instead represented by the single Ottone Unit (Elter et al., 1991), which includes the Casanova Complex (Early Campanian), and the Ottone Helminthoid Flysch (Late Campanian to Maastrichtian). In the mapped area (Fig. 3), the Casanova Complex is formed by natrix-supported pebbly mudstones and clast-supported pebbly sandstones with clasts of limestones, ophiolites, cherts, and granites. The Casanova Complex shows a transition to the Helminthoid Flysch, which consists of carbonate turbidites composed of medium to thick beds of marly limestones, marlstones, and shales. In the Helminthoid Flysch, lenticular bodies of matrix-supported mudstones with slide blocks of granites have been recognized. The IL and EL Units overlay the Subligurian and Tuscan Units (Fig. 2a), both consisting mainly of Oligo-Miocene siliciclastic turbidites (Monteforti and Raggi, 1975; Elter et al., 1999; Bruni et al., 2007).

Lithostratigraphy

The lithostratigraphy of the IL Units from the Antessio area (Fig. 3) is described separately for each unit.

The uppermost unit, i.e., the GT Unit includes a thin level of Zonati Shale Fm. that grades upward to the Monte Gottero Sandstone Fm. The Zonati Shale Fm. is composed of thin-bedded siliciclastic turbidites made up by thin layers of fine-grained arenites, siltstones, and shales (Fig. 4a). Puccinelli et al. (2015) have reported in this formation the occurrence of a nannofossil assemblage of Late Santonian-Maastrichtian age characterized by *Micula decussata, Eiffelithus turreseiffelli, Prediscosphaera cretacea, Lucianorhabdis cayeuxii and Calculites obscurus*. The gradual transition to the Monte Gottero Sandstone Fm. is represented by an increase in the thickness and grain size of the arenites. The Monte Gottero Sandstone Fm. is actually made up of medium to thick beds of well-bedded, medium to fine-grained arenites alternating with thin beds of shales. Amalgamated layers are common. The thickest layers show at their base a coarse-grained level consisting of fragments of quartz, metamorphic rocks and granitoids (Fig. 4b). In these layers, rip-up clasts, groove casts, and flute casts are also common. According to Puccinelli et al. (2015), the occurrence of a nannofossils assemblage with *Micula decussata* indicates a Santonian-Maastrichtian age. In the mapped area, the Monte Gottero Sandstone Fm. includes a thin level of marlstones that has provided a nannofossil assemblage (Table 1) with *Biscutum* sp., *Cyclagelosphaera margerelii, Eiffellithus gorkae, Eiffellithus* sp., *Flabellites oblongus, Nannoconus* sp., *Retecapsa angustiforata, Retecapsa crenulata, Retecapsa* sp., *Watznaueria barnesiae, Watznaueria ovata, Zeugrhabdotus bicrescenticus* that indicates an Albian age (coherently with Puccinelli et al.,2015).

The BG Unit exposed in the Antessio area is divided into several slices. Some slices contain a sequence of Palombini Shale Fm. In the westernmost slice, the Palombini Shale Fm.

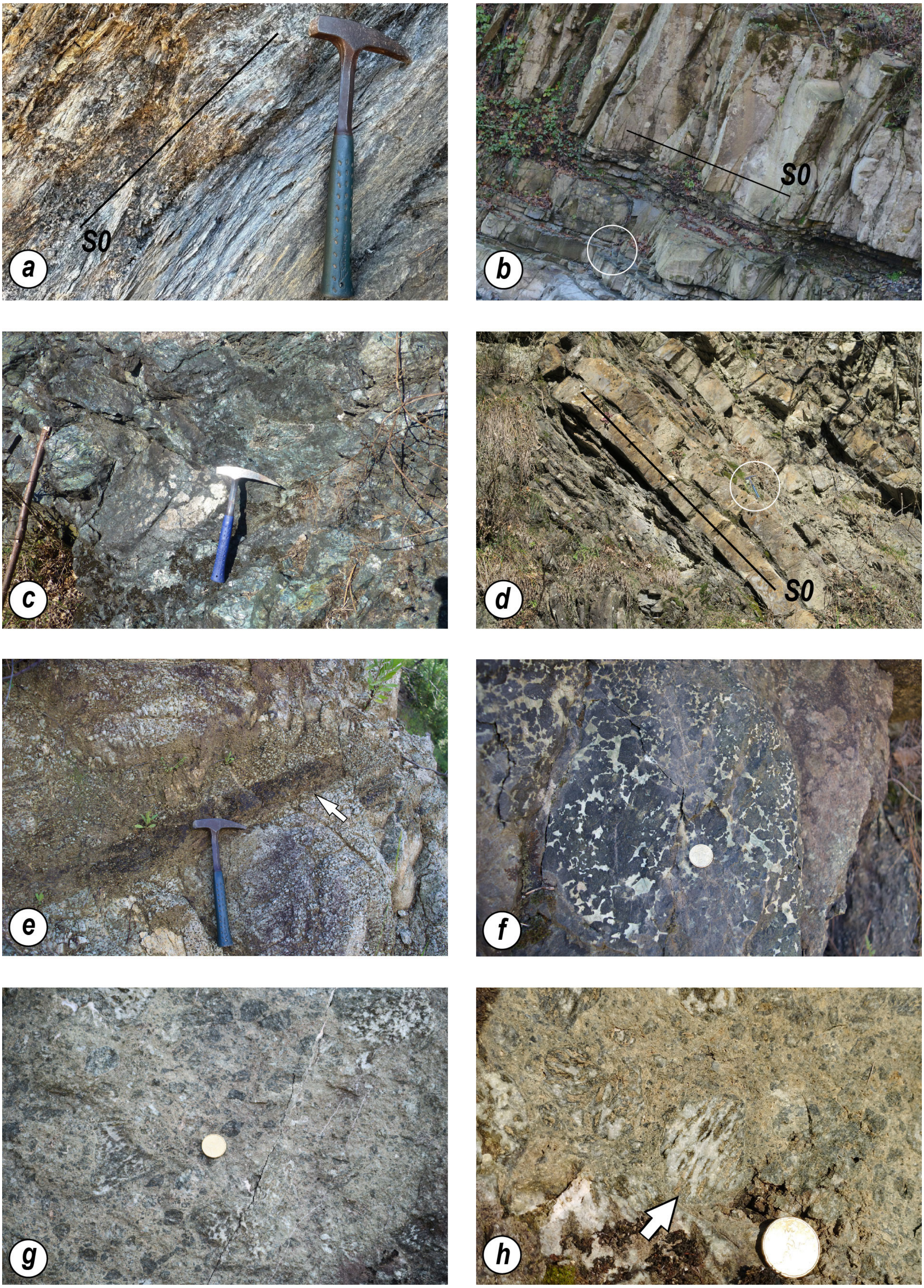

Fig. 4 - Field lithostratigraphic features of the Internal Ligurian Units. a) Zonati Shale Fm. with an evident bedding highlighted by different colors; b) representative outcrop of Monte Gottero Sandstone Fm.; c) exposure of serpentinite; d) representative outcrop of Palombini Shale Fm.; e) gabbro with compositional layering; f) close up of a troctolite exposure; g) outcrop of Monte Zenone Breccia; h) close up of Monte Zenone Breccia with a strongly foliated clast of gabbro (white arrow) due to pre-orogenic, high temperature deformation. White circles indicate the hammer.

Table 1 - List of the collected samples for the calcareous nannofossils analysis. The nannofossil assemblages, as well as the geographic location, of each sample are indicated.

Sample	Nannofossil content																						Sample location (Lat/Long)
	Biscutum sp.	*Braarudosphaera cf. africana*	*Cyclagelosphaera margerelii*	*Eiffellithus gorkae*	*Eiffellithus sp.*	*Eiffellithus turriseiffelii*	*Flabellites oblongus*	*Hayesites sp.*	*Lithraphidites sp.*	*Manivitella sp.*	*Micula sp.*	*Nannoconus spp.*	*Retecapsa angustiforata*	*Retecapsa crenulata*	*Retecapsa sp.*	*Watznaueria barnesiae*	*Watznaueria britannica*	*Watznaueria ovata*	*Watznaueria sp.*	*Zeugrhabdotus bicrescenticus*	*Zeugrhabdotus embergeri*	*Zeughrabdotus sp.*	
TTZ15	X	X	X		X	X		X	X	X		X		X	X	X	X	X			X		44°17'29"N/9°40'52"E
TTZ16			X		X				X			X		X	X	X		X					44°17'29"N/9°40'52"E
TTZ17			X		X	X			X			X		X	X	X		X		X			44°17'29"N/9°40'52"E
TTZ18			X		X							X		X	X	X		X					44°17'29"N/9°40'52"E
TTZ19	X		X	X	X		X					X	X	X	X	X		X		X			44°17'29"N/9°40'52"E
TTZ21																							44°19'03"N/9°43'17"E
TTZ22																							44°19'03"N/9°43'17"E
TTZ23																							44°19'03"N/9°43'17"E
TTZ24												X							X				44°19'03"N/9°43'17"E
TTZ25																			X				44°19'19"N/9°43'00"E
TTZ26																							44°19'19"N/9°42'58"E
TTZ27																							44°19'21"N/9°42'55"E
TTZ28																			X				44°19'20"N/9°42'49"E
TTZ29												X							X				44°18'49"N/9°42'29"E
TTZ30											X				X	X		X				X	44°18'49"N/9°42'28"E

is deformed by isoclinal folds with Monte Alpe Cherts Fm. or highly serpentinized peridotites (Fig. 4c) in the core. The Palombini Shale Fm. consists of carbonate and siliciclastic turbidites intercalated with $CaCO_3$-free shales (Fig. 4d). The carbonate turbidites are represented by thin to medium beds of limestones and marlstones, whereas the siliciclastic turbidites consist of thin beds of quartz-rich, fine-grained arenites and siltstones. According to Perilli and Nannini (1997), the base of Palombini Shale Fm. in the Rocchetta Vara area, just 7 kilometers SE of Antessio area, is Late Valanginian in age. The Monte Alpe Cherts Fm. occurs as a thin-bedded sequence of siliceous mudstones alternating with radiolarian-bearing packstones. The age of this formation, determined in the outcrops about 8 km S of the Antessio area, ranges from Middle Bathonian - Late Bathonian/Early Callovian (Chiari et al., 2000) to Tithonian (Perilli and Nannini, 1997).

The other slices of the BG Unit consist of gabbros. The thickest slice includes an overturned sequence of gabbros covered by a thin level of Monte Zenone Breccia (Puccinelli et al., 2015). In this slice, the about 400 m thick sequence is mainly composed of isotropic gabbros consisting of dominant coarse-grained clinopyroxene-rich gabbros, and minor medium to coarse-grained olivine gabbros to troctolites (Sanfilippo and Tribuzio, 2011). At the base of this sequence, layered gabbros (Fig. 4e), showing both compositional and grain-size layering, can be recognized. The gabbros also contain two about 50 m thick bodies of olivine-rich troctolites (Fig. 4f), interpreted as formed by interaction between an olivine-rich matrix and migrating melts crystallizing plagioclase and clinopyroxene (Sanfilippo and Tribuzio, 2011). Furthermore, the gabbros are cut at high angle by basaltic dikes showing chilled margins and porphyritic fabric (Marroni, 1994). The Monte Zenone Breccia always occurs at the stratigraphic top of the gabbros, with a thickness ranging from 3- to 100 m and consists of not graded and not sorted deposits with mm to cm sized, angular clasts in a dominant sandy matrix (Fig. 4g). The clasts consist of both isotropic and foliated gabbros (Fig. 4h) with different size, whereas the matrix consists of sub-millimetric fragments of gabbros. The Monte Zenone Breccia is regarded as Middle Bathonian to Early Callovian in age (Principi et al., 2004).

The CT Unit includes the Palombini Shale Fm. unconformably covered by the Colli-Tavarone Fm. The Antessio area provides good outcrops of the Colli-Tavarone Fm., which consists of MTDs, like pebbly mudstones and slide blocks, interspersed with fine-grained, thin-bedded siliciclastic turbidites. The slide blocks consist of lenticular bodies up to 40-50 m thick derived from peridotites as well as from Palombini Shale, Zonati Shale and Monte Gottero Sandstone Fms. The slide blocks of Zonati Shale Fm. have provided a nannofossils assemblage with cf. *Micula* sp., *Retecapsa* sp., *Watznaueria barnesiae, Watznaueria ovata, Zeughrabdotus* sp. indicating a generic Cretaceous age (according to Puccinelli et al., 2015 – see Table 1). In between, highly tectonized and serpentinized bodies of peridotites cut by a complex network of calcite veins have been found near the village of Antessio. The slide blocks, with a coherent internal stratigraphy, are surrounded by levels of monomict pebbly mudstones with variable thickness and consisting of cm- to m-sized blocks of more competent lithologies, all derived from the slide blocks and set in a shaly matrix (Fig. 5 a,b). The distribution of the slide blocks belonging to the same formation appears to be aligned along the same stratigraphic horizon. The MTDs are interbedded with fine-grained turbidites consisting of minor quartz-rich siltstones alternating with dominant shales (Fig. 5c, d). These deposits are largely affected by soft-sediment deformations as slumps, scours and syn-sedimentary folds. These deposits have provided only *Watznaueria* sp. nannofossils

Fig. 5 - Lithostratigraphic features of the Colli-Tavarone Fm. a) Pebbly mudstones made up of calcilutite clasts interspersed into a shaly matrix; b) detail of the pebbly mudstone surrounding a slide block of Monte Gottero Sandstone Fm. Close to the hammer, a block of sandstone occurs; c, d) Details of the shaly matrix of the Colli-Tavarone Fm. with fragments of disrupted strata.

due to the bad preservation (Table 1). Puccinelli et al. (2015) reported the occurrence of *Watznaueria barnesae, Cretarhabdus crenulatus* and *Prediscosphaera cretacea*. Minor bodies of monomict and polimict pebbly mudstones, with dominant limestone clasts, are set in the matrix. The Colli-Tavarone Fm. unconformably overlies the Palombini Shale Fm., as attested by Marroni and Pandolfi (2001) in the Vara Valley few km NW of the Antessio area. The Palombini Shale Fm. has the same characteristics as that found in the BG unit.

Deformation history

The deformation history of the IL Units from Antessio area has been reconstructed in the Palombini Shale Fm. of the BG and CT Units. The Palombini Shale Fm. is the most suitable formation to record deformation events and is also the most exposed (Fig. 3), making the reconstruction of the deformations reliable. For comparison, the deformation history was also analyzed in the Zonati Shale Fm. of the GT Unit, where the Palombini Shale Fm. is missing (Fig. 3). We have observed superimposed folding systems confined to each unit, here called D1 and D2 phases, subsequently deformed by thrust and high-angle faults.

The D1 phase is characterized by meso- to micro-scale isoclinal to sub-isoclinal folds with boudinaged limbs and rounded, thickened hinge zones (Fig. 6a). In each tectonic unit, the A1 fold axes show a NW-SE to N-S trend toward southern and northern sectors (see D1 phase in Fig. 7). D1 phase map-scale structures are recognized in the uppermost slice of the BG Unit, where isoclinal folds with cherts or peridotites at their core have been recognized (Fig. 3 with the related geological cross-section). The F1 folds are associated to pervasive S1 foliation, which is well-recorded in the less competent lithotypes like shales and/or marlstones. In the most competent layers (e.g., limestones, sandstones), S1 foliation usually appear as a spaced cleavage at low angle to the primary bedding (S0). In the BG and CT Units, S1 foliation displays a NW-SE to N-S strike with a dip toward eastern and western sectors (Fig. 7). The relationships between S1 foliation and S0 bedding clearly indicate a dominant westward vergence (Fig. 6b). The same spatial orientation is observed for the GT Unit (see the stereoplots of Fig. 7). At the micro-scale, S1 foliation can be classified as a slaty cleavage defined by cleavage domains surrounding quartz-rich granoblastic domains (Fig. 6c). The cleavage domains are made up by recrystallized, elongated minerals, as phengite, chlorite, quartz and calcite and black films, the latter corresponding to pressure solution surfaces. Microscale isoclinal folds with boudinaged limbs affecting the granoblastic domains are common along the S1 foliation. (Fig. 6d). Also, relict minerals like quartz, feldspar (albite?) wrapped by aligned syn-metamorphic grains of chlorite, white mica, quartz, and carbonate are observed indicating that dissolution-precipitation and metamorphic recrystallization were the main deformation mechanisms during the D1 phase. Along the S1

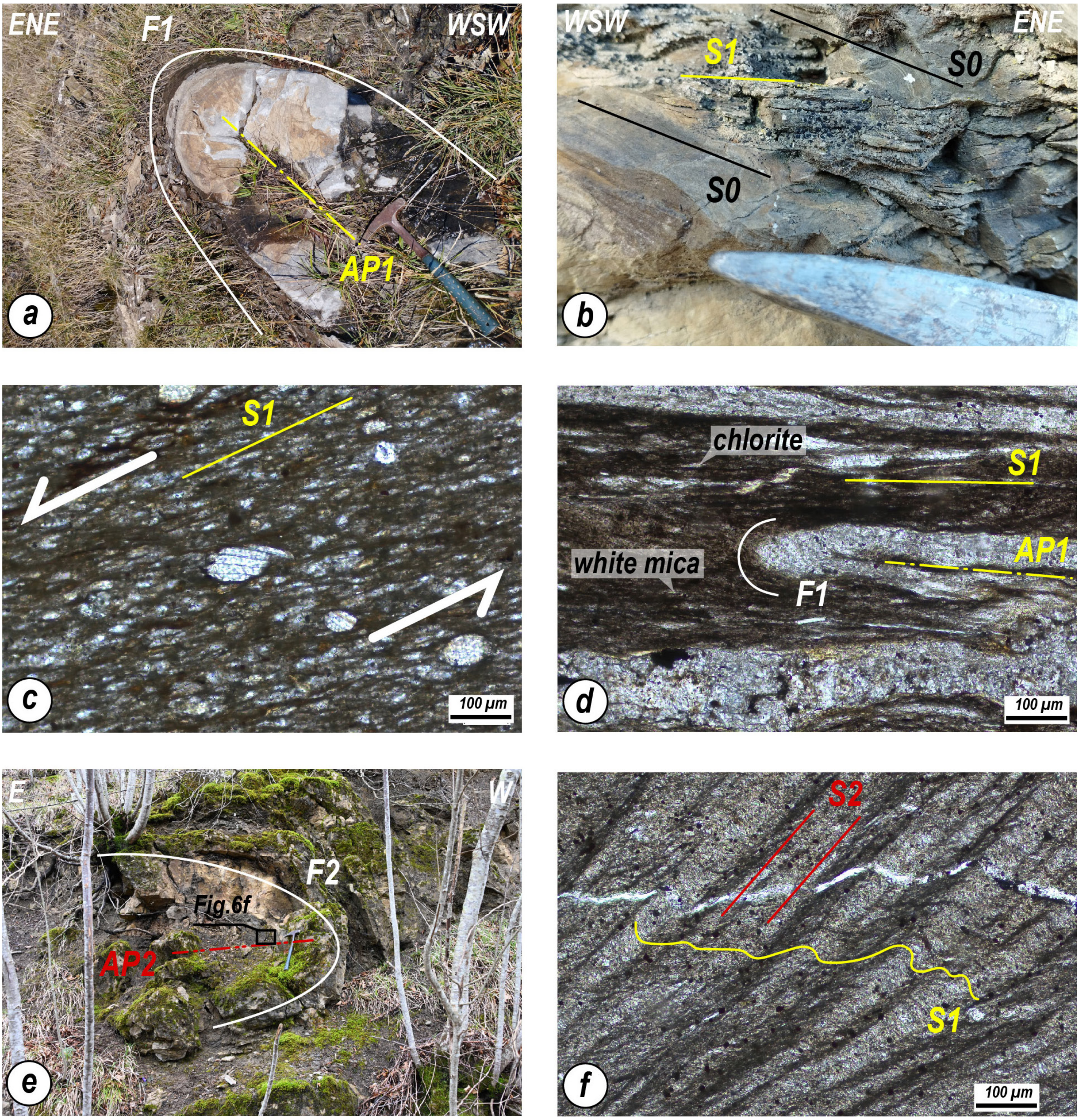

Fig. 6 - Meso- and micro-scale D1- and D2-related structural features of the Internal Ligurian Units cropping out in the study area. a) F1 fold in the Palombini Shale Fm.; b) meso-scale S1-S0 relationships in an overturned bed; c) microscale picture of S1 foliation consisting of a slaty cleavage with sin-kinematic phyllosilicates and re-oriented chlorite showing bookshelf-like structures due to D1-related shearing (white arrows); d) micro-scale F1 fold and associated S1 foliation highlighted by syn-kinematic white mica, chlorite, quartz and alternating films of pressure solution surfaces; e) meso-scale F2 fold with a sub-horizontal axial plane; f) microscale picture of S2 foliation consisting of a crenulation cleavage.

foliation, rigid objects like pyrites show quartz- and calcite-rich recrystallized tails indicating that shearing occurred during the development of this phase.

The D2 phase is the most prominent deformation in the Antessio area, and it is superposed to the D1 phase from micro- to map-scale. D2 phase is represented by open to close asymmetric folds showing rounded to sub-rounded hinge zones and sub-horizontal AP2 axial planes (Fig. 6e). The A2 fold axes display N-S to NW-SE trend with plunges toward the southern and northern sectors (see D2 phase in Fig. 7) with angles no higher than 30-35°. At map scale, the D2 phase generated the antiforms within the CT Unit, at the core of which the Palombini Shale Fm. occurs. The F2 folds system is characterized by an E-vergence in all the investigated units. The F2 folds are associated to S2 foliation, parallel to the AP2 axial plane. In all the units exposed in the study area, it displays a gently dipping toward eastern and western sectors. This foliation can be classified as a crenulation cleavage,

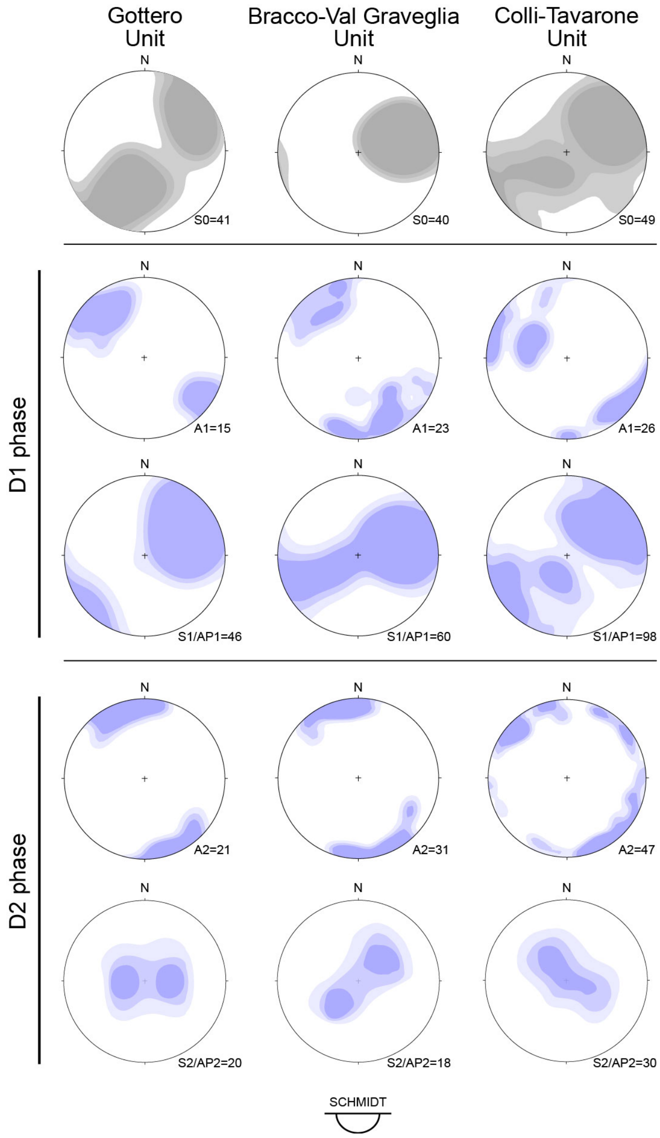

Fig. 7 - Stereonets of planar and linear structural data for the D1 and D2 phases collected in the Gottero, Bracco-Val Graveglia and Colli-Tavarone Units.

well-observed in the shales from micro- to meso-scale. At microscopic scale, the crenulation cleavage is defined by pressure solution surfaces with no evidence for syn-metamorphic recrystallization and by passive re-orientation of the pre-existing minerals (Fig. 6f).

The structural analyses in the Zonati Shale Fm. have revealed the same deformation pattern as that detected in the Palombini Shale Fm (Fig. 3). The Zonati Shale Fm. are affected by a D1 phase characterized by isoclinal folds with a well-developed S1 axial plane foliation, generally recognized at low angle to the S0 bedding. In the shales the S1 foliation can be classified as a slaty cleavage showing the same metamorphic recrystallization as those detected in the Palombini Shale Fm. The D2 phase in the Zonati Shale Fm. includes rare open to close F2 folds with rounded hinges and a sub-horizontal axial plane. As observed in the Palombini Shale Fm., the S2 foliation in Zonati Shale Fm. can be classified as a crenulation cleavage with no evidence of metamorphic recrystallization.

A good example of the interference between D1 and D2 phases was observed 200 m NE of the village of Godano in the Palombini Shale Fm. of the BG Unit. Here, good and continuous exposures allowed a detailed analysis of the D1-D2 cross-cutting relationships. In this outcrop, F1 fold can be observed with a N-S striking and shallow S dipping A1 axis (Fig. 8). This F1 folds is characterized by an AP1 and associated S1 foliation, both N-S striking and dipping to W and E, at medium to high angles. Both the AP1 and S1 surfaces are clearly folded by a F2 fold. This F2 folds is characterized by a sub-horizontal AP2 and an N-S striking A2 axis (Fig. 8). Along the F2 limbs, the S1 foliation forms a small angle with the S0 and progressively they became parallel towards the F2 fold hinge zone. The overprint between the F2 and F1 fold systems produces a type 3 interference pattern (Ramsay, 1967), resulting from the superposition of two approximately coaxial fold systems of folds with axial planes at high angles.

The tectonic units exposed in the study area are bounded by northeast-verging thrusts, which show a NW-SE strike and cut all the previously described folding structures. In the field, they are characterized by brittle shear zones marked by foliated cataclasites (Figs. 3 and 9). When they are well exposed, foliated cataclasites are defined by metre-thick, high-strain zones with kinematic indicators like sigmoidal-shaped clasts, and S-C structures clearly indicating a top-to-NE sense of movement. One of the best examples of this thrust is represented by the shear zone along which the BG Unit overlaps the CT Unit. This shear zone, along which the Colli-Tavarone Fm. is covered by the gabbros and/or the associated Monte Zenone Breccia, show well-developed kinematic indicators consistent with to-the-E sense of shear (Fig. 9). Stretching lineations are rarely exposed but, when they are, they display a NE-SW trend. These thrusts are also responsible for the slicing of the BG Unit (Fig. 2).

DISCUSSION

The Internal Ligurian Units from Antessio area: a dismembered ophiolite sequence

The data obtained from the geological mapping (Fig. 3) and the stratigraphic and structural analyses confirm that the IL Units of the Antessio area are derived from the dismembering of an ophiolite sequence and its sedimentary cover, as assessed in the Bracco massif or in the Graveglia and Vara Valleys (Decandia and Elter, 1972; Cortesogno et al., 1987; Marroni and Meccheri, 1993; Bortolotti and Principi, 2003). In the study area, only the BG Unit preserves the ophiolites in their original stratigraphic position, i.e., at the base of the sedimentary cover. In this unit, the easternmost section (see Fig. 3) is characterized by a thick gabbroic sequence covered by sediments represented by ophiolitic breccias, i.e., the Monte Zenone Breccia of Middle Bathonian to Early Callovian age. S of Antessio, the Monte Zenone Breccia shows a stratigraphic transition to Monte Alpe Cherts Fm. (Puccinelli et al., 2015). This evidence indicates that the gabbros were exhumed, exposed on the seafloor, and subsequently covered by the ophiolitic breccia and then by cherts. This reconstruction is consistent with an origin of the IL ophiolite sequence in an ultra-slow spreading ridge where a low magmatic budget was associated with extensional tectonics by low angle normal faults able to exhume down the oceanic mantle or the lower crust. Notably, the Ligurian oceanic lithosphere is thought to be a fossil analogue of Atlantis Massif (Mid-Atlantic Ridge) and Atlantis Bank (Southwest Indian Ridge) (Dick et al., 2003). Remnants of the deformation developed during the extensional tectonics are represented by foliated gabbros

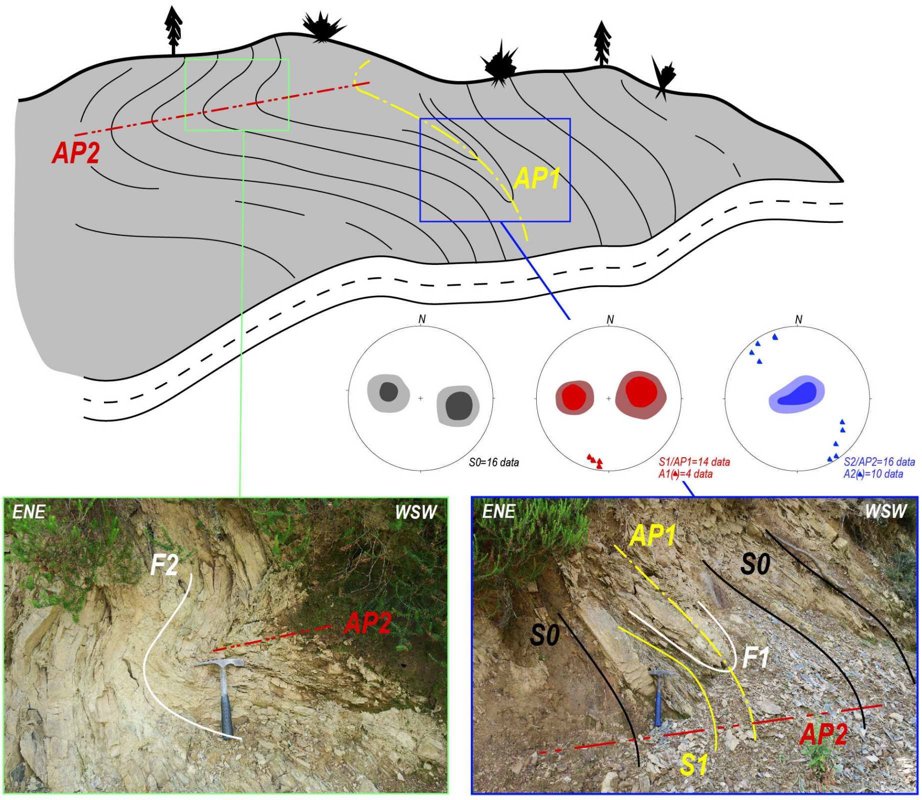

Fig. 8 - Simplified sketch of an outcrop of Palombini Shale Fm., east to Godano village (see geological map of Fig. 3), where meso-scale D1-D2 relationships are clearly exposed. The picture is related to F1 and F2 folds. The stereographic projections of the main structural features of D1 and D2 phases are also reported, including the spatial distribution of the S0 bedding.

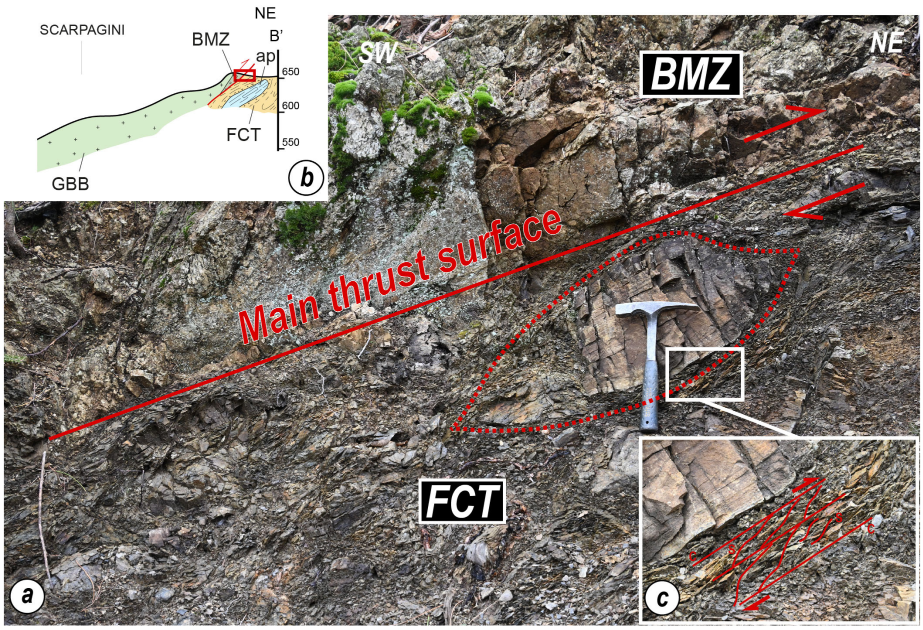

Fig. 9 - Meso-scale frame of the NE-verging unit-bounding thrust. a) Thrust surface between the Monte Zenone Breccia (Bracco-Val Graveglia Unit) and the Colli Tavarone Fm. (Colli-Tavarone Unit). The map-scale relationships between the units are summarized in the geological cross section reported in (b) whose trace is indicated in geological map of Fig. 3. The red box indicates the location of the outcrop of (a). c) Detail of the S-C structures clearly indicating a top-to-NE sense of movement.

with mylonitic to ultramylonitic textures. These metamorphic rocks, developed under HP/LT conditions in an oceanic environment (Cortesogno et al., 1975; Molli, 1996), are thought to have originated in deep extensional shear zones that were subsequently exhumed and eroded to provide the clasts found in the Monte Zenone Breccia.

In the westernmost section of the BG Units (see map and geological cross-section of Fig. 3), a mainly sedimentary succession, including the Monte Alpe Cherts and the Palombini Shale Fms., is preserved. This succession is hypothesized to represent the original sedimentary cover of the ophiolite sequence, as preserved in the easternmost section, such as in the Graveglia Valley (Bortolotti and Principi, 2003). However, information about the ophiolite sedimentary cover is mostly provided by the GT and CT Units, where different types of deposits are well preserved. The pelagic deposits, i.e., the Palombini Shale Fm., are well exposed in the CT Unit. These deposits include hemipelagic, $CaCO_3$-free shales interbedded with both carbonate and siliciclastic, fine-grained turbidites. The Palombini Shale Fm. were deposited below the calcite compensation depth in an oceanic basin plain with low sedimentation rate (Marroni, 1994) where distal, fine-grained carbonate and siliciclastic turbidites and hemipelagic shales were coexisting. The fine-grained siliciclastic turbidites were probably transported parallel to the basin axes, i.e., along strike, fed from the south by the African margin (Jacobs et al., 2025), whereas the carbonate ones were supplied from the neighboring continental margins. These features, as well as the lack of ophiolite-bearing, clastic levels, indicate that during the Palombini Shale Fm. sedimentation, no evidence of orogenic-controlled source areas where the ophiolites were exposed, can be detected. This deposition setting lasted until the Santonian, i.e., the age of the top of Palombini Shale Fm. (Marroni and Perilli, 1990). After the Santonian, the onset of subduction in the LPO Basin resulted in a sudden sedimentation of large volume of turbidites (Marroni et al., 2017). These deposits can be observed only in the GT Unit, where the Zonati Shale and Gottero Sandstone Fms. are preserved. In other area, the turbidite deposits include also the Early to Late Campanian Manganesiferous Shale and Monte Verzi Fms. (Marroni et al., 2017), that are however lacking in the Antessio area. All the turbidite deposits are characterized by a high sedimentation rate, an order of magnitude higher than the pelagic deposits (Marroni, 1994). Also, the turbidites are interbedded with very thin levels of CaCO3-free shales indicating their sedimentation below the CCD. The petrographic analysis indicates that the arenites from these two formations can be classified as arkoses and subarkoses (Pandolfi, 1997), dominated by monocristalline quartz and feldspar fragments, and by lithic fragments represented by granitoids and very low-grade metamorphic rocks. These deposits are representative of a fan system supplied by the European passive continental margin and deposited in the LPO basin (Nilsen and Abbate, 1983; Valloni and Zuffa, 1984; van de Kamp and Leake, 1995). In addition, the characteristics of these deposits also indicate their sedimentation in a confined basin, i.e., a trench bounded toward the Adria plate by an accretionary wedge. In this frame, the occurrence of an intercalation of marlstones bearing a reworked nannofossils assemblage of Albian age can provide further insights for the depositional setting. These marlstones are generally associated to pebbly mudstones, mostly with limestone angular clasts, that have been found in both Zoned Shale and Monte Gottero Sandstone Fms., as recognized in the High Vara Valley (Puccinelli et al., 2015). In the upper part of the late Cretaceous turbidite sequences there are intercalations of deposits resulting from mudflow and cohesive debris-flow processes, likely triggered by active submarine landslides in the frontal part of the accretionary prism. The nature of the carbonate fragments in the pebbly-mudstones, as well as the Albian age of the reworked nannofossils in the mud-flow marls, indicate that the submarine landslides occurred mainly in the Palombini Shale Fm., already accreted in the frontal part of the accretionary wedge.

Notwithstanding, the most interesting feature of the IL Units of the Antessio area is the widespread presence of the MTDs represented by the Colli-Tavarone Fm. that occurs only in the CT Unit. These deposits, which represent the last sedimentary event before the onset of deformation, are known under various names, such as Bocco Shale, Giaiette Shale and Lavagnola Fms., all of Early Paleocene age. In the Antessio area, the main feature of the Colli-Tavarone Fm. is the occurrence of several slide blocks, all derived from the IL succession. Soft-deformation structures in the sediment around the blocks suggest their emplacement as a consequence of submarine landslides. In addition, the occurrence of slide blocks of ophiolites, pelagic and turbidite deposits within the Colli-Tavarone Fm., suggests that its source area was composed by as assemblage of slices derived from the LPO lithosphere, i.e., the Alpine accretionary wedge, as already proposed by Marroni and Pandolfi (2001), Meneghini et al. (2020), Festa et al. (2021) and Sanità et al. (2022b) for analogue units exposed in the Northern Apennines and Western Alpine belt. This setting calls for a geological scenario in which the slope of the accretionary wedge episodically underwent perturbations resulting from subduction-related deformation events producing large volume of MTDs. According to Marroni and Pandolfi (2001), this deformation can be related to underthrusting of a rugged morphology inherited from the oceanic phases in an ultra-slow spreading ridge.

Overall, the IL Units in the Antessio area preserve a complete magmatic-sedimentary record of the history of an LPO segment, from the spreading phase to convergence-related sedimentation, passing through a long period of pelagic sedimentation without evidence of deformation.

The deformations in the IL Units as record of the subduction history

The polyphase deformation history (Figs. 6, 7 and 8) reconstructed in the Palombini Shale and Zonati Shale Fms. of Antessio area can be interpreted as the result of the underthrusting, accretion, and subsequently exhumation of the IL Units within the Alpine accretionary wedge formed during the closure of the LPO basin (Treves, 1984; van Wamel, 1987; Marroni, 1994).

The D1 phase includes isoclinal folds with boudinaged limbs and well-developed axial plane S1 foliation. In the shales, the S1 foliation can be classified as a slaty cleavage with evidence of pervasive metamorphic recrystallization. The overall features of this phase coupled with the data collected in the other IL Units (Meneghini et al., 2023; Sanità et al., 2024) indicate that the D1 phase-related deformations developed at a depth ranging from 13 to 35 km with an estimated geothermal gradient for the metamorphic peak of 7-15 °C/km. Given the pre-deformation sedimentary history of the IL Units, this gradient, coherently with that proposed for analogue oceanic units exposed in the Western Alpine belt from Agard et al. (2018), is indicative of a deformation in a subduction environment. In a subduction setting, the slices of oceanic lithosphere can be accreted into the accretionary wedge by off-scraping at depths less than 8-10 km or by underplating at greater depths (>15 km), the latter mechanism being achieved by coherent or diffuse underplating (Platt, 1986; Moore, 1989; Clift and Vannucchi, 2004; Stern, 2004; Ruh et al., 2015; Royden and Faccenna, 2018; Stern and Gerya, 2018; van Hinsbergen et al., 2020; Ruh, 2020; Zhu et al., 2021; Chizzini et al., 2025). For the IL Units, including those of the Antessio area, the mechanism of accretion can be identified in the coherent underplating. The lack of tectonic mélanges, the depth of the D1 phase deformation (from 13 to 35 km, see Sanità et al., 2024) and the prevalent deformation by folding suggest this frame. In other areas of the Alps-Apennines collisional belt, many authors proposed similar tectonic mechanisms for oceanic- (Ellero, 2000; Capponi et al., 2016; Sanità et al., 2022b; 2023; De Cesari et al., 2025) and continental-derived units (Sanità, et al., 2020; 2021; 2022b; Di Rosa et al., 2024), reinforcing the reliability of our findings. One of the map-scale F1 fold is represented by the isoclinal folds with the cherts at its core identified in the Palombini Shale Fm. of BG Unit. The vergence of the D1 phase is westward, as suggested by the S0-S1 interference pattern, which is coherent with the geodynamic reconstruction proposed for the LPO subduction (e.g., Molli, 2008; Marroni et al., 2017; Schmid et al., 2017). The D1 phase is the main slicing event of the oceanic lithosphere, as shown by the different *P* and *T* conditions for peak metamorphism detected in the IL Units. However, it is difficult to observe the pristine characteristics of the shear zones developed during the D1 phase as they are largely reworked during subsequent deformation events.

The subsequent D2 phase is instead characterized by deformations developed at a shallower structural level, as suggested by the S2 foliation, i.e., a crenulation cleavage without significant metamorphic recrystallisation. Consequently, the D2 phase can be considered to have been reached during the progressive exhumation of the IL Units within the accretionary wedge until to their exposure at the surface in the Early Oligocene (Marroni et al., 2004; Di Biase et al., 1997). According to Marroni et al. (2004), this exhumation is thought to be acquired during an extensional tectonic regime as suggested by the occurrence of open to close F2 folds with sub-horizontal AP2 axial plane, whose development requires a vertical shortening. Extensional tectonics-related folding has been widely recognized in other sectors of the Northern Apennine and the Western Alpine belt (e.g., Froitzheim, 1992; Ratschbacher et al., 1989; Wheeler and Butler, 1994). Extensional tectonics is a common mechanism in the accretionary wedge which induces the exhumation of the underplated slices of oceanic lithosphere due to continuous accretion at the base of the wedge controlled by the downward displacement of the decollement zone (e.g., Platt, 1986; Sue et al., 2007; Ring et al., 2010; Jolivet et al., 2018). In this frame, the absence of D2-related top-to-west shear folding structures suggests that processes such as the upward displacement of material into a subduction channel at the base of the accretionary wedge (Cloos and Shreve, 1988) cannot be considered responsible for exhumation.

The structures of the D1 and D2 phases are cut by the east-verging thrust (Fig. 9) that bounds the IL Units in the Antessio area. These thrusts can probably be linked to the superposition on the IL and EL Units onto the Subligurian and Tuscan Units, but this hypothesis is not supported by reliable data.

Correlations with the neighboring areas

The stack of the tectonic units and their structural architecture described in the Antessio area, i.e., the thrusting of the GT Unit onto the BG and the CT Units, is analogous to that reconstructed in the Bracco Massif as well as in the Graveglia and Vara Valleys (Decandia and Elter, 1972; Cortesogno et al., 1987; Marroni and Meccheri, 1993). In all these areas, the two lowermost IL Units are thrust by the GT Unit that occurs at the top of a large upright antiform. In the Vara Valley this large antiform grades eastward to an upright synform whose west-dipping limb is represented by the GT Unit cropping out in the Antessio area. So, the GT Unit cropping out in the Bracco Massif and Val Graveglia area is in physical continuity with that of the Antessio area. In this frame, the characteristics of the BG and CT Units of the Graveglia and Vara Valleys can be compared with those of Antessio area. In both areas, beneath the GT Unit – represented by a normal succession composed solely of the Zonati Shale and Monte Gottero Sandstone Fms. – the BG Unit crops out. In its easternmost exposures, the BG Unit consists of an overturned succession that includes a basement of mantle peridotites intruded by gabbro bodies, as observed in the Bargone area (Bortolotti and Principi, 2003). As observed in the Monte Alpe area, the gabbros are covered by Monte Capra Breccia, pillow-lava basalts and then by Monte Zenone Breccia and Monte Alpe ChertsFm. Thus, the ophiolite sequences in the Bargone and Antessio areas are broadly comparable, differing mainly in the presence, in Bargone, of a sequence of Monte Capra breccias and pillow-lava basalts interposed between the gabbros and the Monte Zenone Breccia. However, this difference is consistent with the great complexity of the morphology of the LPO basin, which is characterized by fault-bounded, structural highs and basins. In the latter, the gabbros, after being exhumed on the seafloor, were covered by several types of breccias intercalated with pillow-lava basalts, whereas the gabbro highs were covered only by a thin layer of breccias, as observed in the Antessio area.

Close to this area, i.e., in the Vara Valley, the BG Unit overlays the CT one characterized by a well-developed succession of the Colli-Tavarone Fm. (Marroni and Meccheri, 1993). Here, the Colli-Tavarone Fm., is characterized by a normal succession where slide blocks and associated pebbly mudstones are interlayered with fine-grained, siliciclastic turbidites with evidence of soft-sediments deformations (Meneghini et al., 2020). In these deposits an Early Paleocene microfossils assemblage has been found (Galbiati and Rampoldi, 1968). Slide blocks of different lithologies from ophiolites to siliciclastic turbidites, all derived from the IL Units, have been also described in the Vara Valley (Marroni

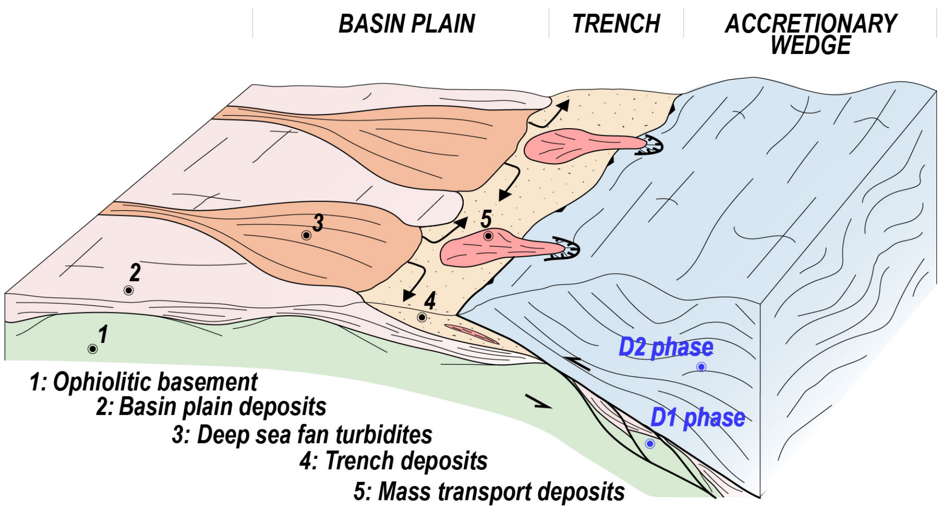

Fig. 10 - Location of the main sedimentary and tectonic events recognized in the IL Units of Antessio area within a 3D subduction system. The different types of deposits with their sedimentary environments are also shown, as well as the location of the D1 and D2 phases recorded by the IL Units.

and Meccheri, 1993). In addition, the stratigraphic and structural relationships, specifically, the Colli-Tavarone Fm. unconformably overlying the Palombini Shale Fm., with both involved in the same folding systems, are similar to those observed in the Antessio area.

The stratigraphic and structural evolution reconstructed in the Antessio area (Fig. 10) confirms the picture derived from the surrounding areas, thus providing a homogeneous framework for the all the IL Units, complementing the tectonic setting of the Northern Apennines.

CONCLUSIONS

The stratigraphic and structural data collected in the Antessio area indicate the presence of a stack of three IL Units consisting, from bottom to top, of CT, BG, and GT Units. The GT, which is in physical continuity with its outcrops of the Vara Valley, includes the Zonati Shale and the Monte Gottero Sandstone Fms., both composed of deep-sea to trench siliciclastic turbidites. The BG Unit, on the other hand, is divided into several slices: some are made up of a gabbro sequence capped by Monte Zenone sedimentary breccia whereas the others are made up of Palombini Shale, showing map-scale, isoclinal folds with serpentinized peridotites or cherts in the core. Finally, the CT Unit, redefined in its stratigraphic setting, includes the Palombini Shale Fm. and the Colli-Tavarone Fm. The Palombini Shale Fms. consists of pelagic deposits unconformably overlain by the Colli-Tavarone Fm. composed of MTDs. These three units are derived from the dismembering of a single Middle Jurassic-Early Tertiary sequence representative of the LPO lithosphere. As reconstructed in other areas of the Ligurian Apennines, the IL Units of the Antessio area are affected by two deformation phases, the D1 and D2 phases, acquired during the involvement of the IL Units in a subduction zone by coherent underplating and subsequent exhumation within an accretionary wedge. All these features allow a close correlation of the IL Units of the Antessio area with those of the Bracco Massif as well as with those of Val Graveglia and Vara Valleys, giving a complete picture of the Northern Apennine fragments derived from the LPO basin.

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