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Tectonic coupling of oceanic and continental units in the Southwestern Alps (Western Liguria, Italy) revealed by structural mapping

Edoardo Sanità ^a, Maria Di Rosa ^a, Jean-Marc Lardeaux ^{b,c}, Michele Marroni ^{a,d} and Luca Pandolfi ^a

^aDipartimento di Scienze della Terra, Università di Pisa, Pisa, Italia; ^bGéosciences Azur, UMR CNRS Université Côte d'Azur Nice-Sophia Antipolis, Nice, France; ^cCentre for Lithospheric Research, Czech Geological Survey, Prague 1, Czech Republic; ^dConsiglio Nazionale della Ricerca, Istituto di Geoscienze e Georisorse, IGG-CNR, 1 Pisa, Italia

ABSTRACT

We described the structural architecture of a key area along the Western Ligurian Alps where a stack of oceanic and continental units showing Low- to very Low-grade metamorphic imprint is exposed. We combine a new dataset by integrating stratigraphic, structural and metamorphic data to produce an original 1:12.500 geological map. The high-resolution mapping along with multiscale structural analysis revealed a large-scale superposition of fold and thrust systems extending for more than 50 km². These field data and available thermobarometric estimates provide constraints to decipher the tectonic evolution of the Southwestern Alps and highlight the shallow crustal coupling of continental and oceanic units during top-to-the-southwest thrusting, the latter was strongly evident in the investigated area.

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Continental and oceanic units; tectonic evolution; structural mapping; Western Liguria; Southwestern Alps

1. Introduction

The study of Low- to very Low-grade (LVL-grade) units (oceanic or continental) has a first-order importance to understanding the tectonic evolution of orogens. At these structural levels, the limited capability of deformation under low-grade metamorphic conditions allows the complete preservation of the lithostratigraphic features. Therefore, fixing the stratigraphy of LVL-grade units and using it as a marker would allow us to reconstruct intricate strain patterns recorded by multilayers usually characterized by different rheology (*i.e.*, Treagus & Sokoutis, 1992). So, performing structural and lithostratigraphic analysis on LVL-grade units is definitely a robust strategy to solve structural evolution recorded by sedimentary successions involved in subduction.

In this work, we investigate the area located between Upega and Tanarello Valleys along the northwestern Ligurian Alps (Southwestern Alps, Figures 1, 2) where oceanic and continental units are affected by LVL-grade metamorphic imprint. The new 1:12.500 scale geological map synthesizes the stratigraphic and structural results to reconstruct the sedimentary successions topping the oceanic and continental crust and their structural relationships.

2. Geological setting of the Southwestern Alps

The Western Ligurian Alps are a segment of the double-verging Alpine belt (Figure 1), whose formation is the result of the convergence between the Europe and Adria plates. This convergence, starting from Late Cretaceous (Rebay et al., 2018), led to the consumption of the Ligure-Piemontese ocean first and then to the involvement of the Europe margin into the subduction zone, which evolved in a continental collision during the Oligocene (*i.e.*, Handy et al., 2010). The Alpine belt is composed of a stack of oceanic and continental units deformed under pressure-temperature ($P-T$) conditions reflecting different crustal levels (*i.e.*, Handy et al., 2010; Lardeaux, 2014). The westernmost edge of this stack consists of the fold-and-thrust belt composed of the Dauphinois/Provençal Units and the External Crystalline Massifs (Ar, Figure 1) both pertaining to the former Europe continental margin. They are tectonically overlain by Sub-Briançonnais and Briançonnais units by the early Oligocene east-dipping thrust zone known as Penninic Front (*i.e.*, Maino et al., 2015). The Sub-Briançonnais and Briançonnais units, as well as the Internal Crystalline Massifs (Decarlis et al., 2013), are regarded as the remnants of the thinned Europe continental crust deeply involved in

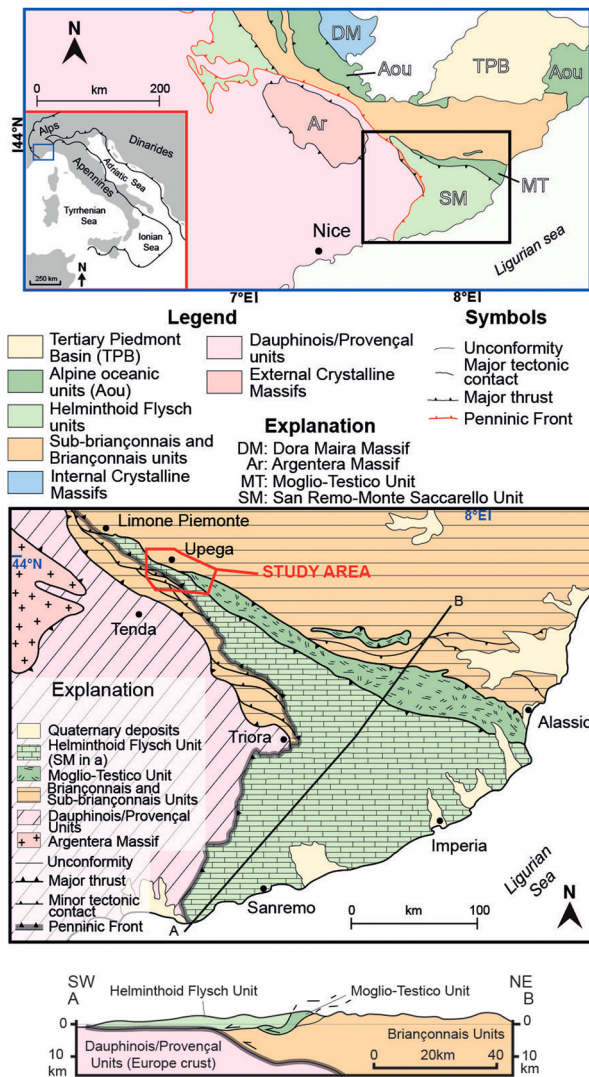


Figure 1. The geological frame of Southwestern Alps with a close-up (black box) of Western Ligurian Alps.

subduction zone. These continental units were overlain by the oceanic units interpreted as fragments of the Ligure-Piemontese ocean involved in the subduction zone (*i.e.*, Lardeaux et al., 2006; Seno et al., 2005).

3. Geological overview of the Western Ligurian Alps

The Western Ligurian Alps are considered an SW-verging stack of LVL-grade continental and oceanic units (Seno et al., 2005; Vanossi, 1986) (Figure 1) that, from the top to the bottom, are the San Remo-Monte Saccarello Unit (Sagri, 1984 – cf. Helminthoid Flysch Unit, this work) characterized by a Late Cretaceous non-metamorphic sedimentary succession detached from its original basement. Here the unit is considered as stemming from the External Ligurian Domain (Sanità et al., 2020), even if alternative paleogeographic origin was proposed (Mueller et al., 2018); the Moglio-Testico Unit characterized by a Late Cretaceous-Paleocene(?) (Galbiati, 1985) pelagic to basin plain turbidite

sequence topped by chaotic deposits (Sanità et al., 2022c) and regarded as the sedimentary cover of the Ligure-Piemontese ocean (*i.e.* Haccard, 1961); the Briançonnais Units composed of a Meso-Cenozoic succession reflecting the sedimentary evolution of the European continental margin approaching the subduction zone (Decarlis et al., 2013). Sporadic overturned relationships between different tectonic units, that is, the Briançonnais Units onto the Helminthoid Flysch Unit, were regarded as result of the later folding event which produces only local modification to the main tectonic structure.

Sanità et al. (2020) and (2021) depicted a much more complex tectonic history where each tectonic unit shows different deformation strain patterns, before their coupling, developed from High-Pressure-Low-Temperature (HP-LT) to anchizone conditions. Only after the tectonic coupling, dealing with in-sequence and out-of-sequence thrusting, the whole stack shared the same deformation history.

However, strike-slip tectonics was invoked by Piana et al. (2021), which described units bounded by an Oligocene high-angles strike-slip to the transpressive fault system the latter driving the tectonic evolution of the investigated area.

4. Methods

The geological map (hereafter Main map) covers about 50 km² (Figure 2) and it was built using the classic field-based approach. Two 1:10.000 topographic maps were used during the fieldwork, which were subsequently joined and scaled to obtain the 1:12.500 version of the Main map. For the Northwestern sector of the Main map, we used the dataset of Sanità et al. (2021). To unravel the strain patterns in the Briançonnais (here represented both by the Marguareis Unit and the Chambeuil Slices, Sanità et al., 2022a), Helminthoid Flysch and Moglio-Testico Units, the sedimentary successions (Figure 2) mapped by Sanità et al. (2020) and Sanità et al. (2022c) were used as deformation markers together with the linear and planar structural features. The latter are plotted using stereographic projections for each tectonic unit and the cross-cutting relationships were used as the main criteria to reconstruct their relative chronology. In the Main map, the superposed relationships between different deformation events were plotted into three geological cross-sections.

5. Stratigraphy of tectonic units

In the mapped area (Figure 2, Main map), the topmost Marguareis Unit (MU, Briançonnais Domain) is represented by Jurassic platform limestones (Val Tanarello Limestone, VTL; Fallot & Fauret-Muret, 1954, Figure 3(a)), Late Cretaceous-Paleocene(?)

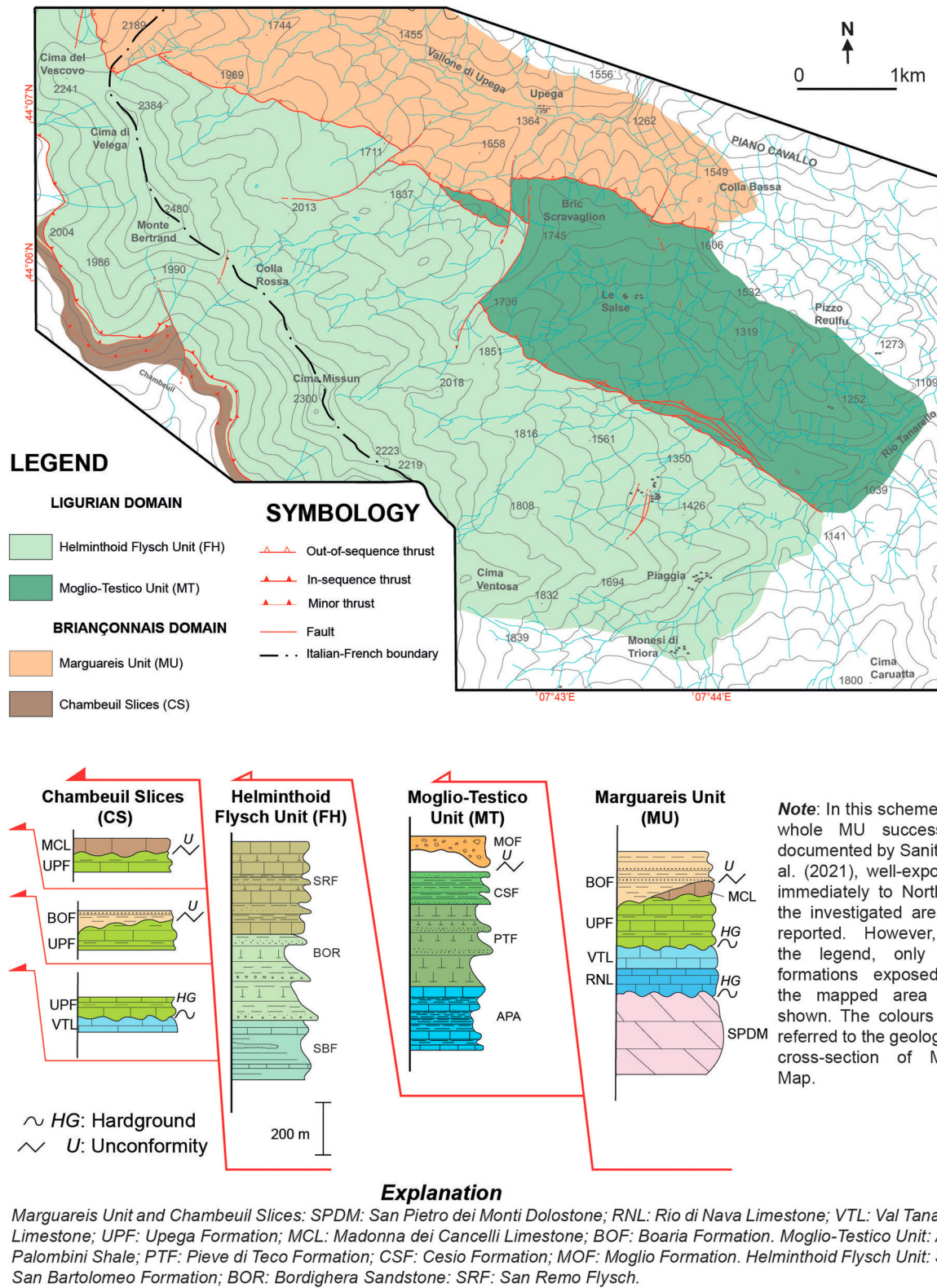


Figure 2. Tectonic sketch of the mapped area with the stratigraphic logs of each unit.

hemipelagic marly-limestones (Upega Formation, UPF; cf. *Calcschistes Planctoniques* of Fallot & Fauret-Muret, 1954, Figure 3(b)) and middle Eocene deep-sea fan turbidite deposits consisting of fine-to medium-grained arenites topped by black shales (Boaria Formation, BOF; cf. *Flysch Noir* of Lanteaume, 1968, Figure 3(a)). The same lithotypes were documented in the Chambeuil slices (CS, Briançonnais

Domain, cf. *Lambeaux de Charriage* of Lanteaume, 1968), as well as middle Eocene carbonate deposits (Madonna dei Cancelli Limestone, MCL).

According to Sanità et al. (2022c), the Moglio-Testico (MT, Internal Ligurian Domain) is composed of a Late Cretaceous-Paleocene(?) hemipelagic deposits (Palombini Shale, APA; Figure 3(d)) to basin plain turbidites (Pieve di Teco Formation, PTF; Cesio

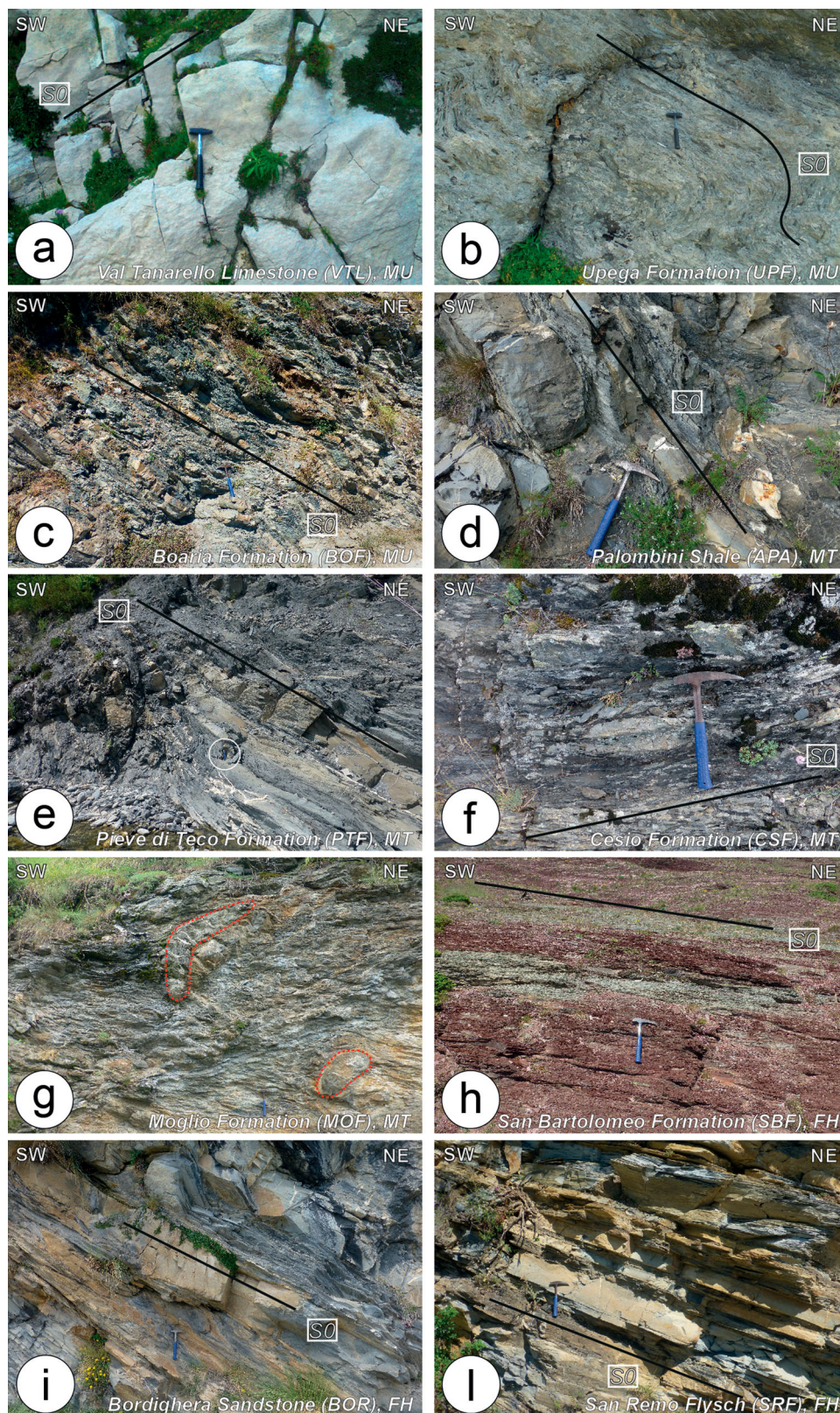


Figure 3. Lithostratigraphy of the units. (a) White limestones. (b) Marly limestones. (c) Fine-grained turbidites capped by black shales. (d) Pelagic limestones interbedded with black shales. (e) Marls interbedded with fine-grained turbidites. (f) fine-grained turbidites topped by black shales. (g) Chaotic deposits at the base of MT showing classic block-in-matrix (red dashed lines mark the blocks) textures. (h) Red to green shales. (i) Coarse-grained siliciclastic turbidites. (l) Calcareous turbidites. MU: Margareis Unit; MT: Moglio-Testico Unit; FH: Helminthoid Flysch Unit; S0: bedding.

Formation, CSF; **Figures 3(e,f)**). Chaotic deposits (Moglio Formation, MOF; **Figure 3(g)**) crop out into a tectonic slice at the base of MT (see Main map). According to **Sanità et al. (2022c)**, the Moglio Fm.

deposits are located at the top of MT succession and regarded as sedimented in a trench/slope environment.

The Helminthoid Flysch Unit (FH, External Ligurian Domain) consists of a Late Cretaceous

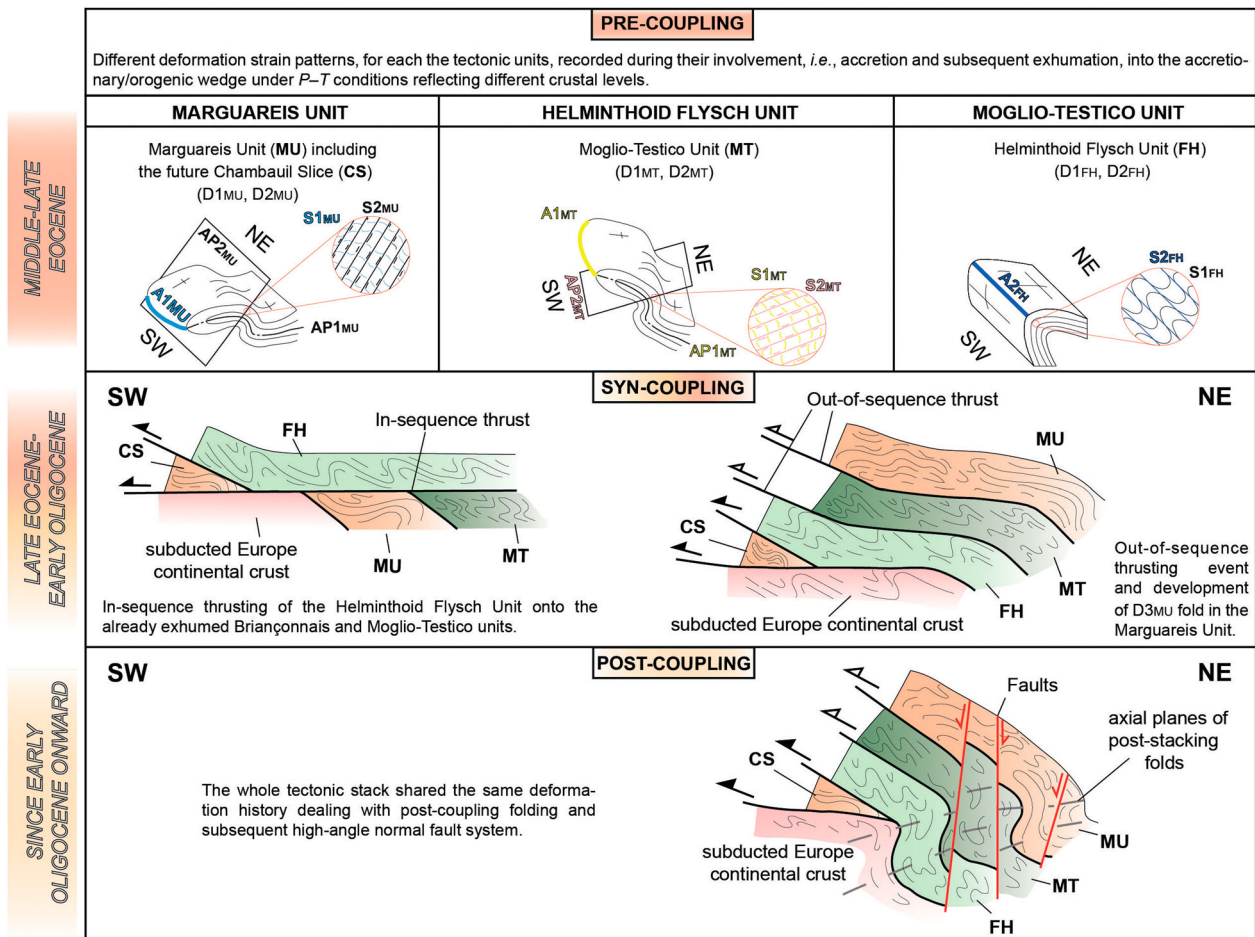


Figure 4. Scheme summarizing the tectonic evolution of the units exposed in the study area.

sedimentary succession that starts with basin plain shales (San Bartolomeo Formation, SBF; Figure 3 (h)). They pass upward to deep-sea fan turbidite sequence (Sagri, 1984) represented by medium- to coarse-grained arenites topped by marl and shale organized as a lobe system (Bordighera Sandstone, BOR; Figure 3(i)) that underlies carbonate levels interbedded with medium-grained arenites (San Remo Flysch, SRF; Figure 3(l)).

6. Tectono-metamorphic history of the tectonic units

The geological investigation outlined that each unit shows evidence of polyphase deformation history related to a long-lived convergence (Mueller et al., 2020; Sanità et al., 2022c, Figure 4) made evident by the superposition of pre-syn- and post-coupling structures (Figures 5–7). The pre-coupling history is characterized by superposed folding events, confined to each unit and developed under *P–T* conditions reflecting the accretion depths of these units into the Alpine wedge at different times before Oligocene (Sanità et al., 2022a, 2022c). The syn-coupling structures were produced by thrusting and folding events and were responsible for the finite tectonic stacking of the units. The whole stack shares the same post-

coupling tectonics. Labeling of deformation for each tectonic unit follows that used by Sanità et al. (2022a) and (2022c). Owing to the correlation between MU and CS (Sanità et al., 2022a), only the pre-coupling deformations of the first one are shown.

6.1 Strain patterns and metamorphic imprint of the tectonic units

All the tectonic units exposed recorded two pre-coupling folding events ($D1_{MU}$, $D2_{MU}$, $D1_{MT}$, $D2_{MT}$, $D1_{FH}$, $D2_{FH}$). In MU, $D1_{MU}$ produced an NW-SE striking $S1_{MU}$ foliation dipping to SW and NE (Figure 5) marked (Figure 6(a)) by syn-metamorphic chlorite, phengite and quartz. $S1_{MU}$ is associated with SW-verging isoclinal similar $F1_{MU}$ folds (Figure 6(b)) with scattered $A1_{MU}$ fold axes (Figure 5) and SW- to NE-dipping axial planes ($AP1_{MU}$). $D2_{MU}$ phase produced an NW-SE striking $S2_{MU}$ foliation, dipping toward SW and NE (Figure 5), marked by a new generation of chlorite, phengite and quartz (Figure 6(c)) and associated with SW-verging similar to parallel tight $F2_{MU}$ folds (Figure 6(d)) with NW-SE trending $A2_{MU}$ fold axes plunging toward NW and SE and SW- to NE-dipping $AP2_{MU}$ axial planes. *P–T* estimates indicate an *HP* metamorphism ($D1_{MU}$: 330–280 °C and 1.0–0.9 GPa; $D2_{MU}$: 300–230 °C and 0.9–

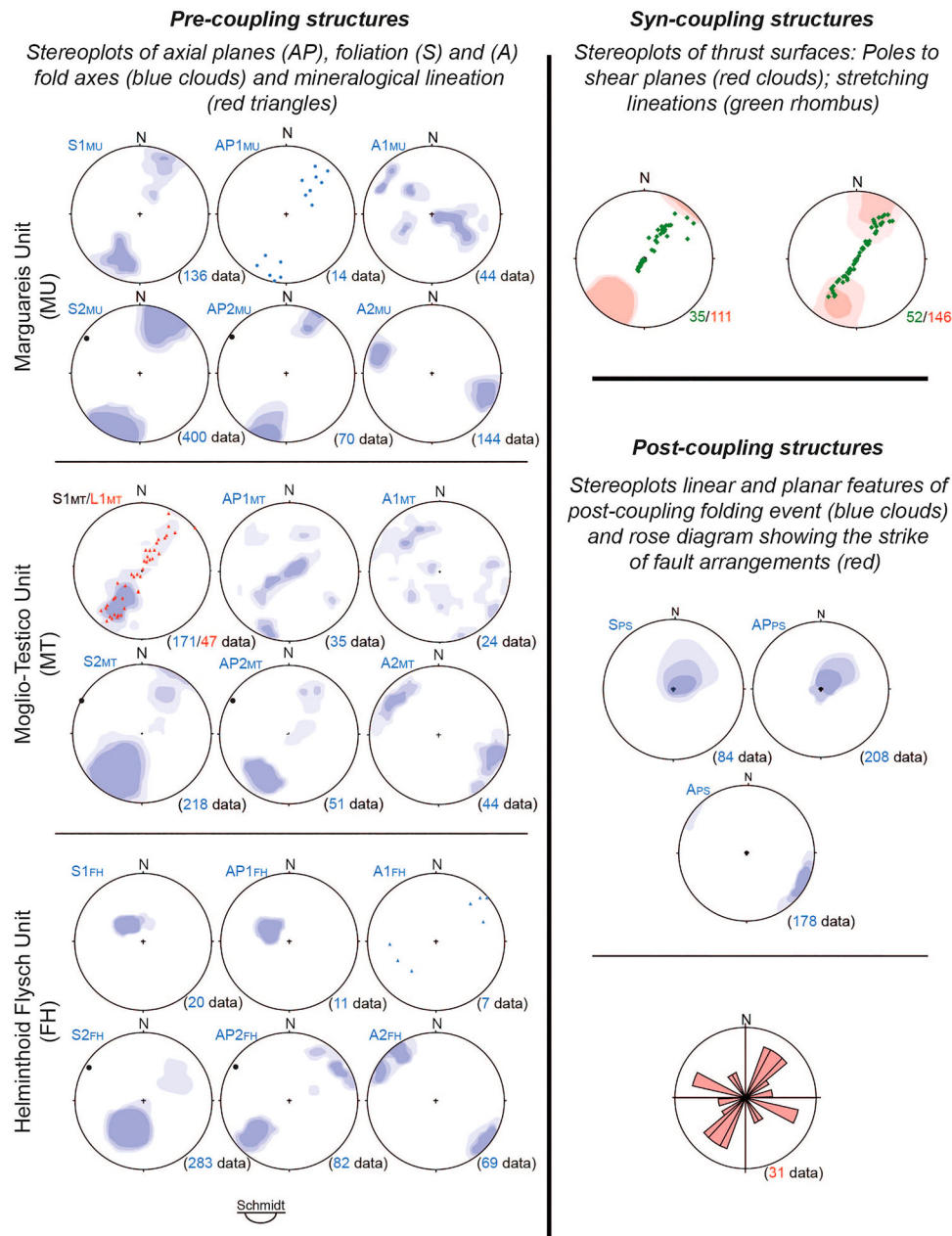


Figure 5. Stereoplots of linear and planar structural features for each tectonic unit.

0.7 GPa, Sanità et al., 2022b) recorded during underthrusting, accretion and exhumation into the Alpine wedge during the middle to late Eocene (Figure 4).

In MT, D1_{MT} produced an NW–SE striking S1_{MT} foliation (Figure 5), dipping to SW and NE, marked by syn-metamorphic chlorite, phengite and quartz (Figure 6(e)) and associated with SW-verging isoclinal similar F1_{MT} folds (Figure 6(f)) with SW- to NE-dipping AP1_{MT} axial planes and scattered A1_{MT} fold axes (Figure 5). The D2_{MT} phase produces an NW–SE striking S2_{MT} foliation dipping to SW and NE (Figure 5), marked by crenulation cleavage with a new generation of chlorite, phengite and quartz (Figure 6(e)). S2_{MT} is associated with SW-verging sub-isoclinal to tight F2_{MT} folds (Figure 6(f)) with SW- and NE-dipping AP2_{MT} axial planes and NW-SE trending A2_{MT}

fold axes plunging toward NW and SE (Figure 5). *P–T* estimates indicate *HP* metamorphism (D1_{MT}: 330–260 °C and 1.2–1.0 GPa; D2_{MT}: 240–170 °C and 0.7–0.4 GPa, Sanità et al., 2022c) recorded during underthrusting, accretion and subsequent exhumation of MT into the Alpine accretionary wedge (Figure 4).

In FH, D1_{FH} produced a NE–SW strike S1_{FH} slaty cleavage, dipping to NW and SE (Figure 5), marked by phyllosilicates and associated with NW-verging tight parallel F1_{FH} folds (Figure 6(g,h)) with NE–SW trending A1_{FH} fold axes and SW-dipping AP1_{FH} axial planes (Figure 5). D2_{FH} produced an NW–SE striking S2_{FH} disjunctive cleavage dipping toward SW and NE (Figures 5 and 6(i)). S2_{FH} is associated with SW-verging parallel F2_{FH} folds (Figure 6(l))

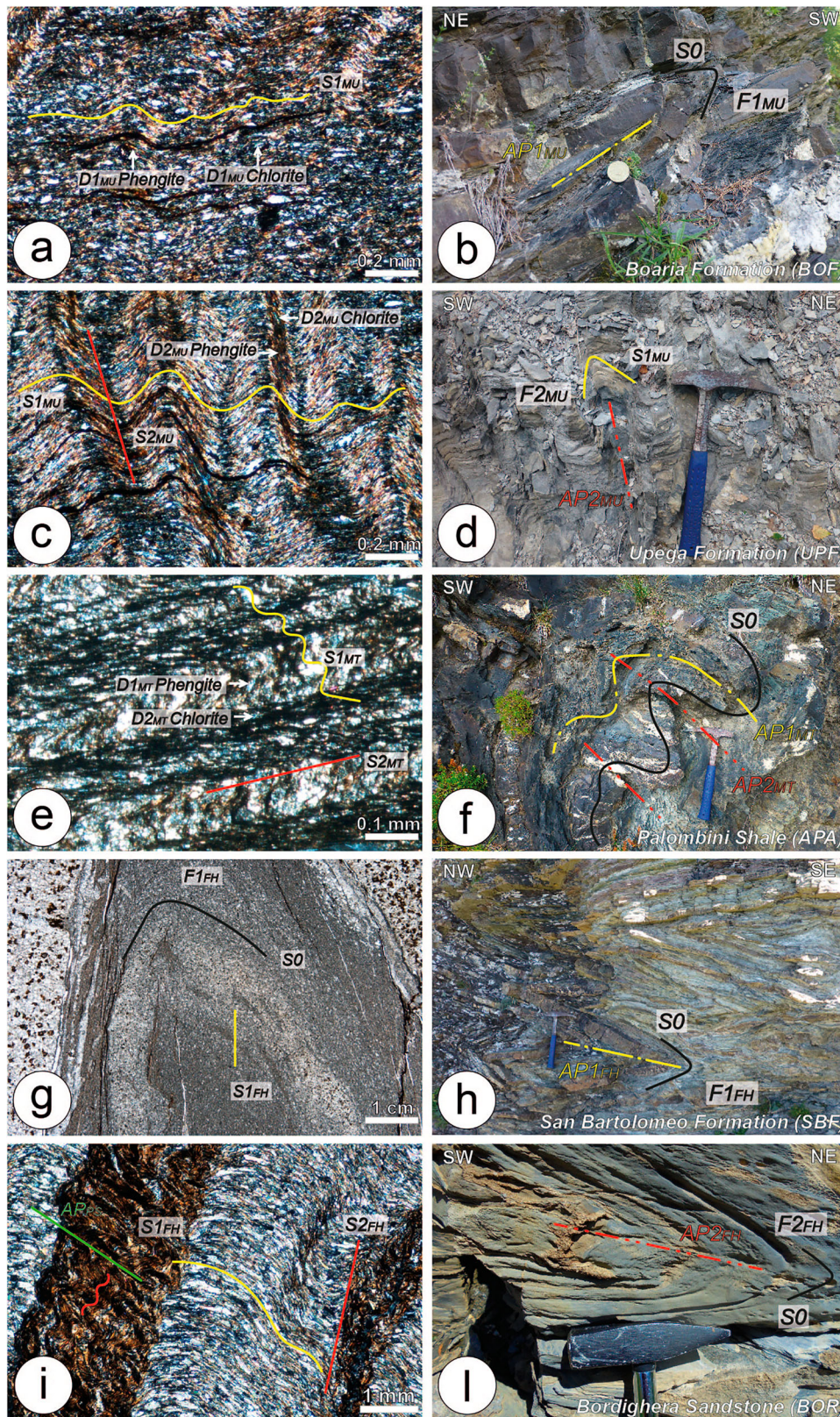


Figure 6. Micro- to meso-scale structural features for each unit. (a) $S1_{MU}$ foliation (Boaria Formation). (b) $F1_{MU}$ folding system. (c) $S2_{MU}$ crenulation (Boaria Formation). (d) $F2_{MU}$ folding system and $S1_{MU}$ - $S2_{MU}$ interference. (e) $S1_{MT}$ - $S2_{MT}$ interference (Palombini Shale). (f) outcrop-scale $F1_{MT}$ - $F2_{MT}$ interference. (g) Micro $F1_{FH}$ folds (San Bartolomeo Formation). (h) Outcrop-scale $F1_{FH}$ folds. (i) Micro-scale $S1_{FH}$ - $S2_{FH}$ interference. (l) Outcrop-scale $F2_{FH}$ fold. AP1-2: D1 and D2 axial plane; A1-2: D1 and D2 fold axes; S0: bedding.

with NW-SE striking $AP2_{FH}$ axial planes dipping to SW and NE and NW-SE trending $A2_{FH}$ fold axes plunging to SE and NW (Figure 5). FH shows

anchizonal metamorphism (Piana et al., 2014) suggesting its involvement in the Alpine wedge at shallower crustal levels than MT and MU (Figure 4).

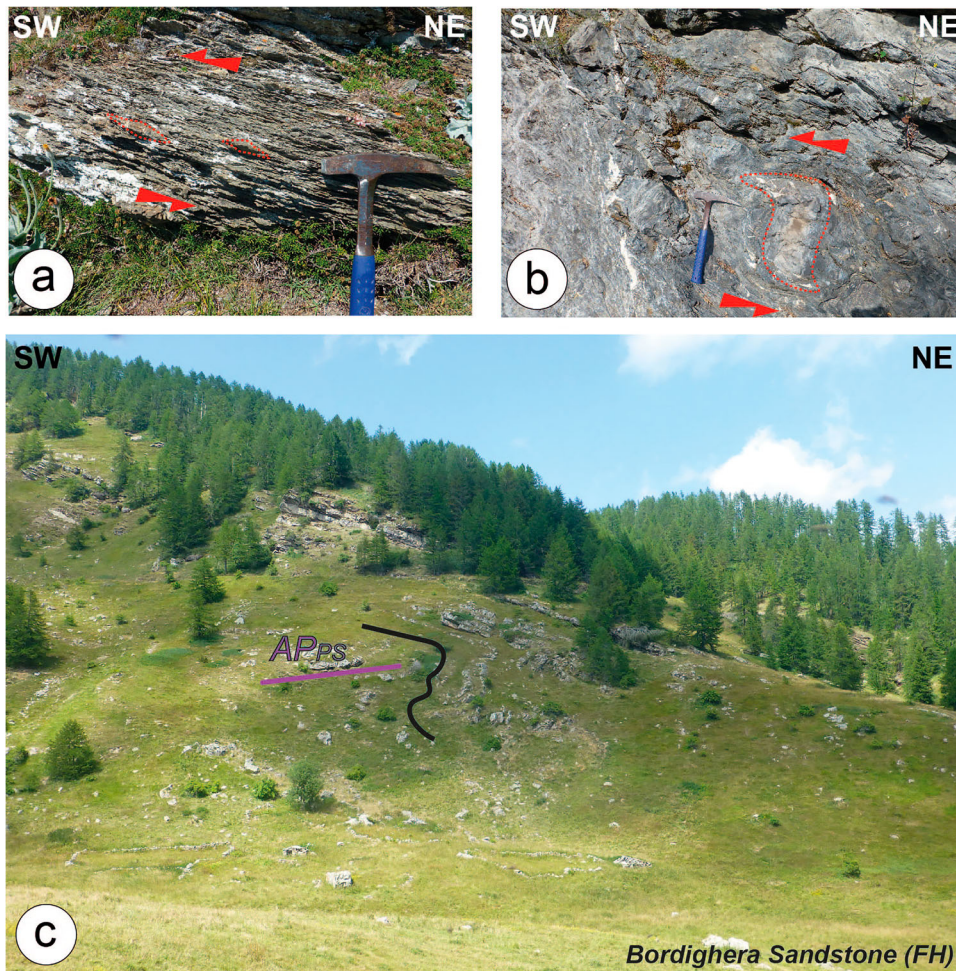


Figure 7. Outcrop-view of in-sequence (a) and out-of-sequence (b) thrust (red dashed lines mark kinematic indicators) and post-coupling (c) folding system.

Syn-coupling tectonics is represented by thrusting and folding structures (Figures 7(a,b)). The thrust surfaces are marked by NW–SE striking lower (in-sequence) and upper (out-of-sequence) cataclastic shear zones (Figures 7(a,b)), dipping toward SW and NE (Figure 5), showing the SW sense of shearing. The folding event produced a map-scale $F3_{MU}$ with NE-dipping axial plane ($AP3_{MU}$) and NW–SE trending $A3_{MU}$ fold axes affecting MU only (A–A' section in the Main map).

The whole stack shared the same post-coupling (Figure 4) tectonic history represented by post-coupling (PS) open parallel F_{PS} folds with NW–SE trending A_{PS} fold axes and sub-horizontal AP_{PS} axial planes (Figures 5 and 7(c)). The last deformation feature is represented by high-angle normal faulting coherent with a Riedel system (Figure 5) characterized by three arrangements ($N30^{\circ}$ – 50° , $N90^{\circ}$ – 120° and $N150^{\circ}$ – 160°).

6.2. Map-scale structures

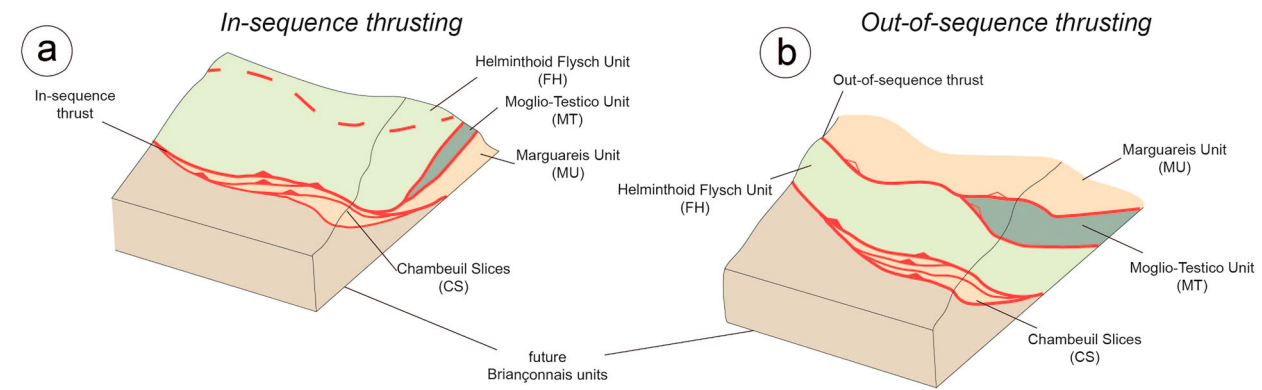
6.2.1 Pre-coupling structures

In MU, map-scale $D1_{MU}$ – $D2_{MU}$ interference patterns are not appreciable. The main map-scale pre-coupling structures are represented by $F2_{MU}$

anticlines and synclines largely documented in the BOF and UPF (see Main map). The major $F2_{MU}$ are located East of Colle del Vescovo (Colle del Vescovo Syncline, N of Main map) and Colla Bassa (Colla Bassa Syncline, SE of Main map). Minor $F2_{MU}$ folds occur along the Rio Nivorina stream like synclines and anticlines with the BOF and the UPF at the core, respectively. Probably these $F2_{MU}$ folds are minor structures linked to Colla Bassa Syncline.

In MT, map-scale $F1_{MT}$ fold is located along the southern wall of Bric Scravaglione ridge, where an anticline with the APA at the core occurs; it can be followed until the Rio Monaglie stream (SE of Main map). Immediately N of Valcona Sottana, a map-scale $F1_{MT}$ syncline with the CSF at the core occurs. Map-scale $F2_{MT}$ folds are largely documented in the whole unit, particularly in the Le Salse area. Map-scale $D1_{MT}$ – $D2_{MT}$ interference patterns can be appreciated in the Colletta delle Salse area and along the southern wall of the Bric Scravaglione ridge (B–B' section). Here a type 3 interference pattern due to the superposition of $D2_{MT}$ folds, with roughly upright to SW-verging axial planes, on $F1_{MT}$ folds characterized by flat-lying attitude ($AP1_{MT}$ and $S1_{MT}$), can be appreciated.

In-sequence and out-of-sequence thrusting in the mapped area (late Eocene-early Oligocene)



Comparison between the structural frame of Marguareis Massif and the mapped area after the syn-coupling event (late Eocene-early Oligocene)

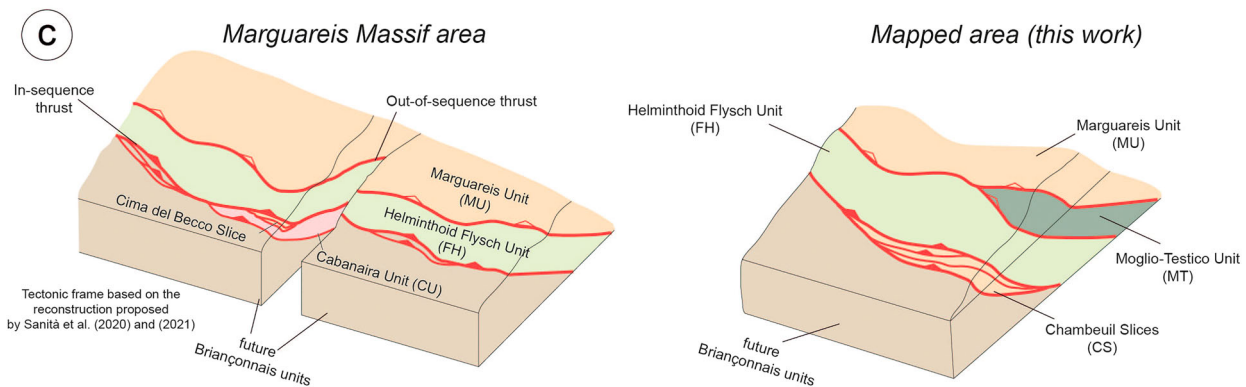


Figure 8. 3D diagrams showing the syn-coupling tectonic evolution: (a) in-sequence and (b) out-of-sequence thrusting. The red dashed line in (a) marks the future trace of the out-of-sequence thrust surface. (c) Comparison between the tectonic structure of the Marguareis Massif and the study areas.

In FH, $F1_{FH}$ folds occur only into a tectonic slice made up of San Bartolomeo Fm., which is located under the thrust separating FH from CS (see the Main map) along the southwestern wall of Monte Bertrand. Otherwise, map-scale $F2_{FH}$ folds largely occur in the whole unit. The best example of the $F2_{FH}$ fold system can be appreciated along the western side of the Cima di Velega-Monte Bertrand ridge (see Main map). Here a set of anticlines and synclines affects the Bordighera Sandstone. Along the southern wall of Monte Bertrand, an $F2_{FH}$ anticline with the San Bartolomeo Formation at its core is present.

6.2.2 Syn-coupling structures

Thrust surfaces cut all the axial planes of the pre-coupling structures documented in each unit (see Main map). In map view, the uppermost shear zone system separates MU from the underlying FH, to the North (A-A' section) and from the underlying MT to the South (B-B' section). Indeed, the lower shear zone system separates FH from the underlying CS slices (West of the Main map). $F3_{MU}$ folding reworked all the pre-coupling structures recorded by MU (A-A' section). The $A3_{MU}$ trend and the strikes of the $AP3_{MU}$ and

upper shear zone systems are sub-parallel indicating their coeval development at shallower structural levels according to Sanità et al. (2022a). At map-scale, along the Rio Nivorina stream, the $F3_{MU}$ sub-vertical limb can be appreciated while its normal limb is located to the East of the Main map.

6.2.3 Post-coupling structures

F_{PS} fold system is well evident in the areas characterized by the sub-vertical layering such as in Monte Bertrand, Rio Nivorina and Le Salse areas. Map-scale type 3 interference patterns caused by the superposition of flat-lying AP_{PS} axial planes onto the SW-verging to upright $D2_{MT}$, $D2_{MU}$ and $D2_{FH}$ structures can be detected. This folding system cuts also the unit-bounding thrust surfaces highlighting the relative chronology.

A normal to transcurrent faulting system cuts at a high angle all the previous structures including the axial planes of the post-coupling folding system and the thrust surfaces. Locally this fault system juxtaposes different tectonic units (see Main map): Along the Rio Giaireto stream a NE-SW striking fault juxtaposes the Moglio-Testico and Helminthoid Flysch units, while

South of the Colle del Vescovo area an NW-SE fault separates the FH and the MU.

7. Discussion

The described structural frame of the area is the result of a tectonic evolution typical of long-lived thrust tectonics (Figure 4), as already proposed by Seno et al. (2005), Mueller et al. (2020) and Sanità et al. (2022a). In this framework, each tectonic unit (oceanic and/or continental), recorded a polyphase pre-coupling deformation history developed under *P* and *T* conditions reflecting their involvement in the Alpine wedge at different crustal levels.

The in-sequence thrusting and out-of-sequence thrusting are responsible for the coupling of the units at shallower structural levels after their diachronic involvement into the Alpine wedge. The cross-cutting relationships between pre-, syn- and post-coupling structures suggest the following tectonic coupling order: (i) the thrusting (in-sequence, Figure 8(a)) of FH onto the already exhumed Briançonnais Units, that is, MU including CS, and MT; (ii) the out-of-sequence thrusting of MU above MT and the latter in turn onto FH (Figure 8(b)). According to the age yielded for the thrusting of FH onto the Briançonnais Units (Maino et al., 2015), the syn-coupling tectonics developed during the late Eocene-early Oligocene.

The last structures described in the investigated area are represented by post-coupling folding and faulting systems whose characteristics are typical of very shallower crustal levels.

The key feature of the structural architecture described in this work is represented by the syn-coupling thrust surfaces which caused the regional-scale inverted structural relationships, that is, FH tectonically underlying MU and MT. The similar structural architecture was proposed for the Marguareis Massif area (Figure 8(c); cf. Sanità et al., 2021). The authors described a structural frame in which the Helminthoid Flysch Unit is sandwiched between the Briançonnais Units. The structural setting described in the Marguareis Massif area is confirmed in this work and the same tectonic coupling order, that is, syn-coupling event, can be extended toward the southern limit of the Main map for more than 100 km². These observations clearly outline the importance of thrust tectonics during the building of the stack and its essential role in understanding the regional-scale tectonic evolution of the shallow structural levels of the Southwestern Alps.

8. Conclusions

The presented scale geological map provides a new picture of the structural setting of the western Ligurian

Alps. The accuracy of the Main map was obtained using a robust stratigraphic dataset, which combined with multi-scale structural analyses, allows us to unravel the strain pattern of the study area providing a key example of the Southwestern Alps tectonic evolution. The mapped area is characterized by a polyphase deformation history attested by the superposition of pre-, syn- and post-coupling structures. Our results confirm the following:

- The key role played by the syn-coupling tectonics, already outlined by the previous authors, in deciphering the tectonic evolution of the western Ligurian Alps;
- The robustness of high-resolution field investigations performed within LVL-grade metamorphic units. Indeed, preserved sedimentary sequences provide a good stratigraphic dataset allowing significant implementation first of geological maps but also reconstruction of complex structural patterns extending for several kilometers in collisional belts.

Software

The main map and stereo plots were constructed using Illustrator and Stereonet Allmendinger, respectively.

Geolocation information

The main map covers an area about 50 km² inside a square-shaped region within 44° 8' 29"N – 7° 39' 08"E and 44° 04' 59"N – 7° 46' 53"E.

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Disclosure statement

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Data availability statement

Data are available from the authors on request.

ORCID

Edoardo Sanità  <http://orcid.org/0000-0002-5488-9832>

Maria Di Rosa  <http://orcid.org/0000-0002-1154-7429>

Jean-Marc Lardeaux  <http://orcid.org/0000-0001-7666-7109>

Michele Marroni  <http://orcid.org/0000-0002-2947-3739>
Luca Pandolfi  <http://orcid.org/0000-0002-6129-647X>

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