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Volume 354 (2022), p. 141-157

<https://doi.org/10.5802/crgeos.124>

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Comptes Rendus
Géoscience — Sciences de la Planète
2022, 354, p. 141-157
https://doi.org/10.5802/crgeos.124

Original Article — Tectonics, tectonophysics, geodynamics

Kinematics of the Helminthoid Flysch–Marguareis Unit tectonic coupling: consequences for the tectonic evolution of Western Ligurian Alps

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Abstract. We investigated the kinematics of the coupled Helminthoid Flysch–Marguareis Unit outcropping in the High Tanaro Valley in order to constraint the tectonic evolution of the Western Ligurian Alps. Field mapping highlights a tectonic pile composed of, from top to bottom: the Marguareis Unit (Briançonnais Domain); the Helminthoid Flysch Unit (Ligurian Domain) and several continental-derived tectonic slices (Chambeuil Slices) showing affinity to the Briançonnais Domain. Each unit recorded different deformation histories represented by pre-, syn- and post-stacking structures. The syn-stacking structures are represented by thrusts and folds, both responsible for the coupling of the units and for their current structural relationships. In other sectors of the Alpine chain previous authors have highlighted similar structural architectures. We maintain that syn-stacking deformation events played a key role in the tectonic evolution of the Western Ligurian Alps.

Keywords. Kinematics, Tectonic evolution, Low-grade units, Late Eocene, Early Oligocene, Ligurian Alps.

Manuscript received 11th November 2021, revised and accepted 21st March 2022.

1. Introduction

The Ligurian Alps are a peculiar segment of the Alpine chain characterized by a long-lasting tectonic evolution [i.e. Capponi et al., 2009, Molli et al., 2010, Seno et al., 2003, Vanossi, 1986]. Starting from the middle of the last century, geologists mainly focused their attention on the Alps–Apennine relationships [Elter et al., 1966, Elter and Pertusati, 1973, Grandjacquet and Haccard, 1977, Laubscher, 1991, Marroni

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et al., 2017, Mosca et al., 2009] and/or the study of the high pressure–low temperature (HP–LT) metamorphic units with particular attention to their exhumation-related retrograde paths [i.e. Voltri Group, Spagnolo et al., 2007, Malatesta et al., 2012]. In the last twenty years, various scientific contributions [Carminati, 2001, d'Atri et al., 2016, Mueller et al., 2020, Piana et al., 2021, Sanità et al., 2020, Seno et al., 2005], were focused on the western Ligurian Alps where a SW-verging tectonic pile is composed of both continental- and oceanic-derived units [i.e. Di Giulio, 1992, Haccard, 1961, Lanteaume, 1962, 1968, Vanossi, 1986, 1991, Vanossi et al., 1994]. Unraveling the deformation history of such a crustal-scale and composite, tectonic pile is of paramount importance for a better understanding of Alpine collision tectonics in this sector of the Alpine chain [see discussions in Carminati, 2001, d'Atri et al., 2016, Di Giulio, 1988, Piana et al., 2021, Sanità et al., 2020]. In order to achieve this objective, it is necessary to identify key areas where the relationships between the different units are well exposed with a clear structural framework and relevant kinematic indicators. Such requirements are found in the High Tanaro Valley, a remarkably exposed area at the border between Piemonte and Liguria Regions, and located at the junction between Maritime and Ligurian Alps (Figure 1a), south of the Marguareis Massif, whose structural architecture was recently updated and reappraised [Sanità et al., 2020, 2021]. This work is aimed to provide new high-resolution structural data to depict the structural architecture and the deformation history of the tectonic units outcropping in this part of the Ligurian Alps and to discuss their tectonic evolution in the framework of the Western Alps geodynamics.

2. Geological context of the Western Ligurian Alps

In the Western Alps the orogenic history started in Late Cretaceous times [i.e. Dewey et al., 1989, Rebay et al., 2018, Rosenbaum et al., 2002], with the subduction of the Ligure–Piemontese Ocean due to the convergence between Europe and Adria Plates. The prolonged convergence has resulted, in the first stage, in the involvement of the European continental margin into the Alpine wedge through continental subduction, and subsequently in the collision starting from middle Eocene [Coward and Dietrich, 1989, Handy et al., 2010, Rosenbaum et al., 2002, Stampfli et al., 2001, Simon-Labric et al., 2009].

In the framework of the tectonic scenario proposed for the western Ligurian Alps [Seno et al., 2003, 2005, Vanossi et al., 1984] the lowermost portion of the SW-verging tectonic pile (Figure 1a) is represented by the Briançonnais Units characterized by a typical Meso-Cenozoic succession diagnostic of an origin from the thinned portion of the European continental margin [Decarlis et al., 2013, Vanossi et al., 1984]. The latter underwent a HP–LT metamorphic imprint that decreases progressively westward [Bonazzi et al., 1987, Messiga et al., 1981]. These units underthrust the oceanic-derived unit (Ligure-Piemontese Ocean), called Moglio–Testico Unit [Boni and Vanossi, 1972, Lanteaume, 1968], represented by Late Cretaceous–Paleocene(?) oceanic sediments showing very low-grade metamorphic imprint [Bonazzi et al., 1987, Messiga et al., 1981, Seno et al., 2005]. The Helminthoid Flysch Unit (FH) [cf. San Remo-Monte Saccarello Unit, Vanossi et al., 1984], including its basal complex (Lanteaume, 1968), forms the top of the tectonic pile (Figure 1a). It consists of a Late Cretaceous non-metamorphic sedimentary succession detached from its original basement, whose paleogeographic provenance is still debated [Di Giulio, 1992, Mueller et al., 2018, Sanità et al., 2020, Vanossi, 1991]. Interestingly, inverted superposition relationships between these units, i.e. the Briançonnais units thrust onto the FH, can be locally observed [Di Giulio, 1988, Merizzi and Seno, 1991]. In the more external sectors of the Ligurian Alps (toward west) the FH is thrust onto the Dauphinois/Provençal Units (Figure 1a) that represent the internal portions of the European continental margin [i.e. Decarlis et al., 2013].

3. High Tanaro Valley: geological overview

In High Tanaro Valley (northwestern Ligurian Alps), the tectonic pile is composed of SW-vergent continental- and/or oceanic-derived units (Figure 1b). According to the available paleogeographic reconstructions [Decarlis et al., 2013, Lemoine et al., 1986, Seno et al., 2005, Stampfli, 1993, Vanossi et al., 1984 and quoted references; Vanossi, 1991] it can be assumed that: (i) the continental units (Marguareis

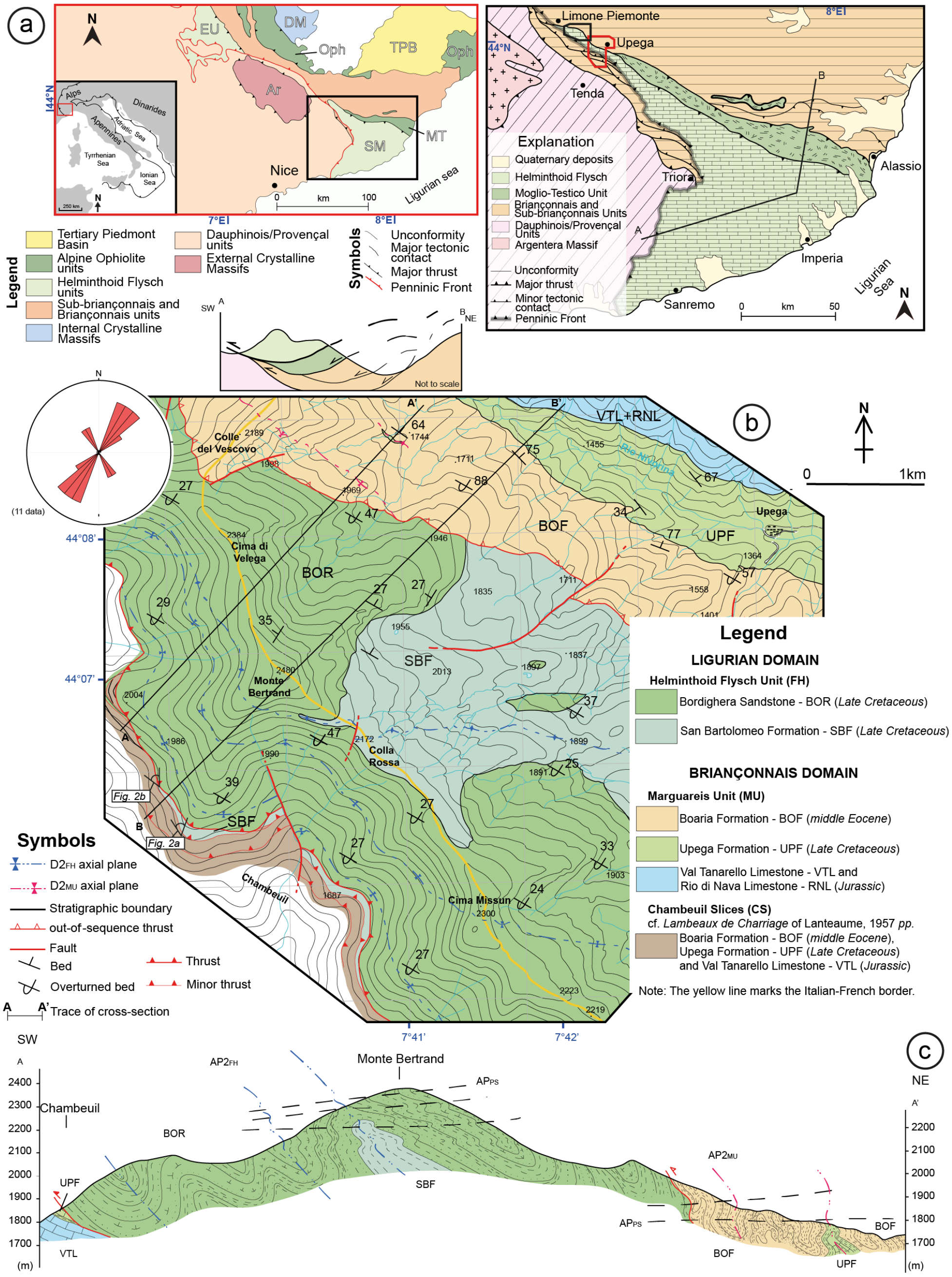

Figure 1. (a) Simplified sketch of the southwestern Alps [redrawn and modified after Molli et al., 2010] with close-up of the Western Ligurian Alps [redrawn and modified after Vanossi et al., 1984] assisted by a schematic geological cross-section showing the relationships between different tectonic units. The red box indicates the study area. TPB: Tertiary Piedmont Basin; EU: Embrunais-Ubaye; SM: San Remo-Monte Saccarello Unit; MT: Moglio–Testico Unit; Oph: Alpine Ophiolite units; DM: Dora Maira Massif; Ar: Argentera-Mercantour Massif. Geological map (b) of the study area and related geological cross-section (c). On the right corner the geometrical distribution of the fault-network is reported. $AP2_{FH}$: $F2_{FH}$-related axial plane; $AP2_{MU}$: $F2_{MU}$-related axial plane.

Unit—MU, Chambeuil Slices—CS) exhibit a Meso-Cenozoic succession typical of the Briançonnais Domain; (ii) the FH deposits are regarded as the sedimentary cover of the ocean–continent transition of the Adria Plate [Sanità et al., 2020] or conversely of an oceanic domain [see Mueller et al., 2018, and references therein]. At the regional scale, the relationships between the different tectonic units and their deformation history are still debated. According to Mueller et al. [2020], the structural setting is characterized by a SW-vergent tectonic pile in which the Late Cretaceous non-metamorphic FH [cf. Sanremo Unit of Mueller et al., 2020] is thrust onto the Dauphinois Units. These two units are separated by highly sheared Cenozoic siliciclastic turbidite deposits [i.e. Flysch Noir, or Boaria Formation of Sanità et al., 2020]. Moving from SW toward NE, the FH shows an overturned tectonic contact with the Ormea Briançonnais units [cf. Marguareis Unit of Sanità et al., 2020]. As already outlined by Cabella et al. [1987], Di Giulio [1988] or Vanossi et al. [1984], all these tectonic contacts are deformed in turn by a SW-verging later folding event that is responsible for the overturned relationships between these units. Moreover, north of the study area, in the Marguareis Massif, Sanità et al. [2020] recognized a structural architecture in which the FH is located in between Briançonnais units. All the previously cited authors recognized a finite strain pattern resulting from superposed folding events, and according to Mueller et al. [2020] or Sanità et al. [2020], the FH and the Briançonnais Units exhibit contrasting internal deformation patterns. Conversely, d'Atri et al. [2016] and Piana et al. [2021] suggested that the Helminthoid Flysch and Briançonnais units are bounded by a NW–SE-oriented high-angle fault network developed during brittle and progressive transpressional tectonics.

4. The tectonic units in High Tanaro Valley: lithostratigraphy and structural mapping

In the valley of Tanaro river (boundary between Piemonte and Liguria Regions about 50 km southwest of the town of Cuneo), we detected a well-exposed tectonic pile allowing litho-structural mapping at 1:10.000 scale to be performed (Figure 1b,c). The mapped area covers about 32 km^2 from Upega village (easternmost boundary) to Monte Bertrand area (westernmost boundary) along the Italy–French border until the Colle del Vescovo (northernmost boundary) area. The tectonic pile, from top to bottom, is composed of: (i) the MU (Briançonnais Domain), which extends to the northwest along the southwestern sector of the Marguareis Massif [Sanità et al., 2020]; (ii) the FH (Ligurian Domain) with its basal complex [*basal complexes* of Lanteaume, 1957] extends to the north-northwest until Limone Piemonte village (Figure 1a); (iii) and the CS characterized by Meso-Cenozoic sequences. Tectonic slices composed of fragments of the FH are also present along the tectonic contact separating it from CS (Figures 1b,c, 2a).

The MU is mostly represented by the Upega Formation and the Boaria Formations [Sanità et al., 2020]. The first one is composed of Late Cretaceous–Paleocene(?) hemipelagic marly limestones [i.e. *Calcshistes Planctoniques* of Fallot and Faure-Muret, 1954], whereas the second one is represented by fine-grained turbidites interlayered with chaotic deposits of middle Eocene age [Gidon, 1972, Sanità et al., 2020—cf. *Flysch Noir* of Lanteaume, 1968]. However, older formations [i.e. Val Tanarello Limestone and Rio di Nava Limestone, Boni et al., 1971] are exposed along the easternmost border of the study area (Figure 1b).

The FH consists of a non-metamorphic sedimentary succession. It is composed of its basal complex characterized by basinal plain deposits [San Bartolomeo Formation or *basal complexes* of Lanteaume, 1957] represented by red to green manganese-rich shales of Late Cretaceous age [Hauterivian–Campanian, Cobianchi et al., 1991, Manivit and Prud'Homme, 1990]. In the topmost portion, fine-grained siliciclastic turbidites represented by dm-thick lenticular beds of arenites are also present. The basinal plain deposits passing upward to deep-sea fan coarse- to medium-grained turbidites are represented by m-thick beds of siliciclastic arenites capped by marls and cm- to dm-thick beds of shales [Bordighera Sandstone, Sagri, 1980]. The calcareous nannofossil content recognized within samples collected at the bottom of the Bordighera Sandstone yielded a Campanian age in accordance with Sanità et al. [2020] and Manivit and Prud'Homme [1990].

The CS (Figures 1b,c, 2a,b) are represented by Jurassic platform deposits (i.e. Val Tanarello Limestone), Late Cretaceous–Paleocene(?) Upega Forma-

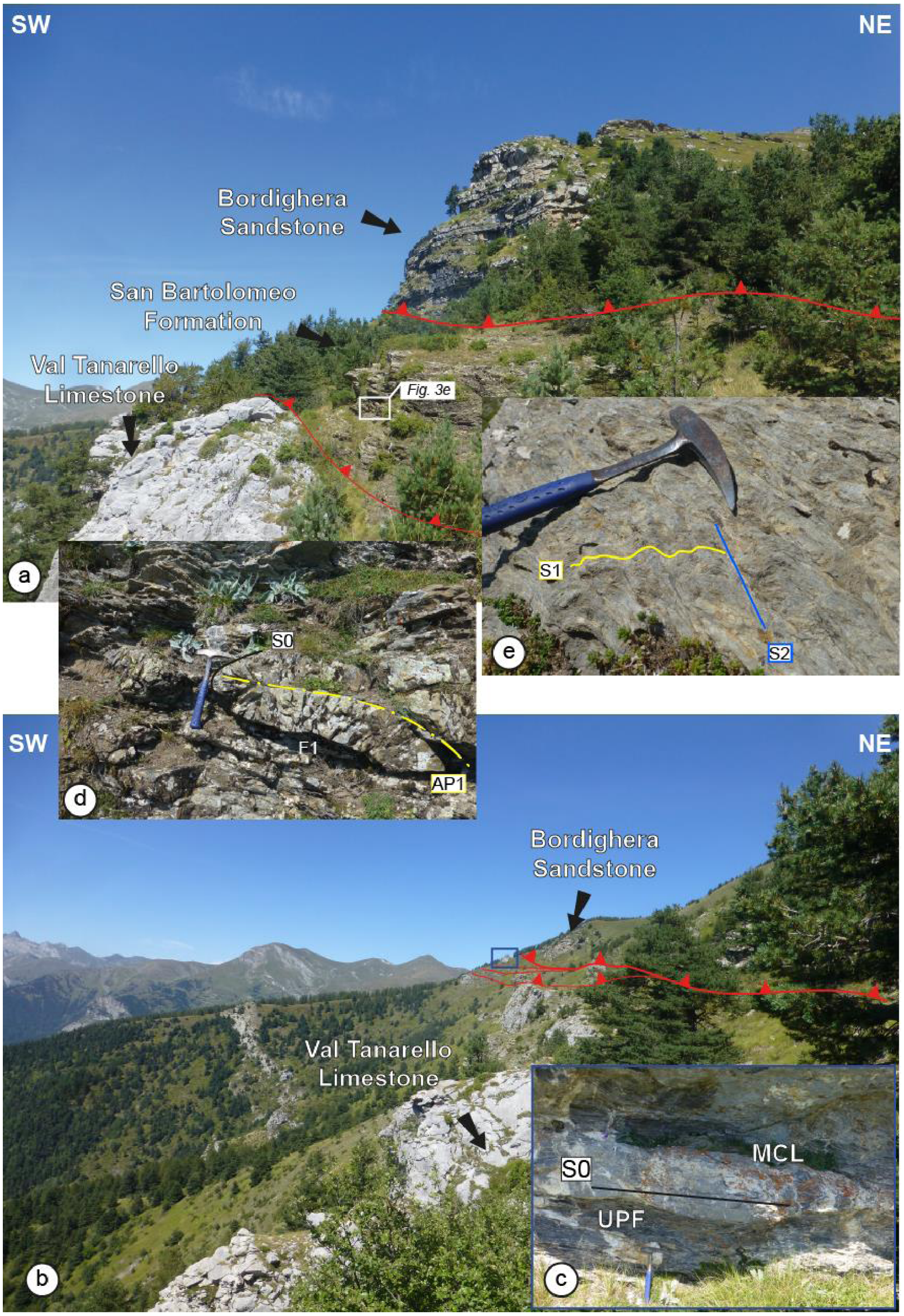

Figure 2. Panoramic views of CS (a,b) along the French side of the Monte Bertrand ridge. Photograph location is reported on the geological map of Figure 1b. The thrust contacts between CS and the Helminthoid Flysch are reported as red lines with triangles. (c) Stratigraphic boundary (S0: bedding) between Upega Formation (UPF) and Madonna dei Cancelli Limestone (MCL) preserved within a tectonic slice. (d,e) Structural features in the tectonic slices.

tion, middle Eocene *nummulite*-rich limestones (Madonna dei Cancelli Limestone) and middle Eocene Boaria Formation of Sanità et al. [2020]. Despite the intense deformation, in each slice the primary stratigraphic relationships between different formations are preserved (Figure 2c). Tectonic slices with comparable structural position, i.e. located at the base of the Helminthoid Flysch–Briançonnais couple, were documented also in the Embrunais-Ubaye sector and they are regarded as witnesses of the Sub-Briançonnais Domain [see Thum et al., 2015, and quoted references]. However, based on widely accepted stratigraphic observations, we reaffirm that the CS outcropping in the study area can be regarded as fragments of Briançonnais units (see also Section 6).

5. Deformation history recorded by the tectonic units

Detailed mapping and micro- to map-scale structural analysis, were performed in order to unravel the finite strain pattern of the different units outcropping in the investigated area. We preferred to retain the labelling and the deformational event classifications used in Sanità et al. [2020] to avoid any misunderstanding among the readers.

Structural analysis allowed us to reconstruct specific internal strain patterns for each unit and to distinguish in the whole area of interest the superposition of pre- (Section 5.1) syn- (Section 5.2) and post-stacking (PS) (Section 5.3) tectonic structures.

5.1. *The pre-stacking structures*

The MU recorded two well-distinct deformation events called $D1_{MU}$ and $D2_{MU}$. The $D1_{MU}$ event is mostly represented by a $S1_{MU}$ pervasive foliation preserved as relict foliation between $D2_{MU}$ microlithons. At the microscale (Figure 3b), the $S1_{MU}$ is a slaty cleavage highlighted by syn-metamorphic white micas, quartz, plagioclase, calcite and chlorite with strong preferred shape orientations, as well as stylolitic surfaces underlined by concentrations of insoluble minerals, particularly oxides. $S1_{MU}$ shows a NW–SE trend and dips toward NE and SW with variable angles (Figure 4). F1 folds are rarely observed and they show (Figure 3a) similar geometry and scattered fold axes with axial planes of NW–SE strike and dips toward SW and NE (Figure 4). The $D2_{MU}$ is the most prominent deformation event that can be observed in this area of the MU, thus $S2_{MU}$ foliation is the dominant structural feature and is represented by a pervasive spaced crenulation cleavage (Figure 3c,d). At the microscale (Figure 3d) it is marked by stylolitic surfaces, rare syn-metamorphic white micas, re-oriented grains of calcite, quartz, chlorite and oxides. $S2_{MU}$ foliation is associated with NE-verging $F2_{MU}$ fold system developed from micro- to map-scale (Figures 1b,c, 3c). F2 folds (Figure 3c) show parallel to similar geometry with NW–SE trending fold axes plunging toward NW and SE and axial planes with NW–SE direction and dips toward SW and NE with variable angles (Figure 4).

In the FH the oldest deformation event ($D1_{FH}$) is testified by $S1_{FH}$ foliation, mostly preserved as relict in hinge zone of $D2_{FH}$-related microlithons. In thin section (Figure 3f), $S1_{FH}$ is a slaty cleavage outlined by stylolitic surfaces, phyllosilicates with strong preferred shape orientation, elongated grains of calcite, quartz and feldspars. At mesoscale $S1_{FH}$ can be well observed in the hinge zone of the $F2_{FH}$-related folds. It is also present in the slices at the bottom of the FH where it is associated with F1 folds (Figure 3e) characterized by a NE–SW trending fold axes plunging NE and SW and axial planes with NE–SW direction and dips toward the SE (Figure 4). The $D2_{FH}$ phase is the most prominent deformation event recorded in the FH. It is testified by $S2_{FH}$ foliation well-evident only in the fine-grained rocks (marls and shales). At the microscale (Figure 3i) $S2_{FH}$ is a crenulation cleavage marked by stylolitic surfaces and re-oriented grains of calcite, quartz. The $S2_{FH}$ is associated with SW-verging F2 fold system (Figures 1b,c, 3h) showing parallel geometry, NW–SE trending fold axes plunging toward NW and SE and axial planes with NW–SE direction and dips toward SW and NE (Figure 4).

The CS located at the bottom of the FH recorded the same polyphase pre-stacking deformation history (Figure 2d,f) to the ones we documented in the MU. Therefore, we reaffirm that the deformations observed in the tectonic slices can be correlated with those of the MU.

5.2. *The syn-stacking structures*

The syn-stacking deformation events, which were largely observed in the whole study area, are re-

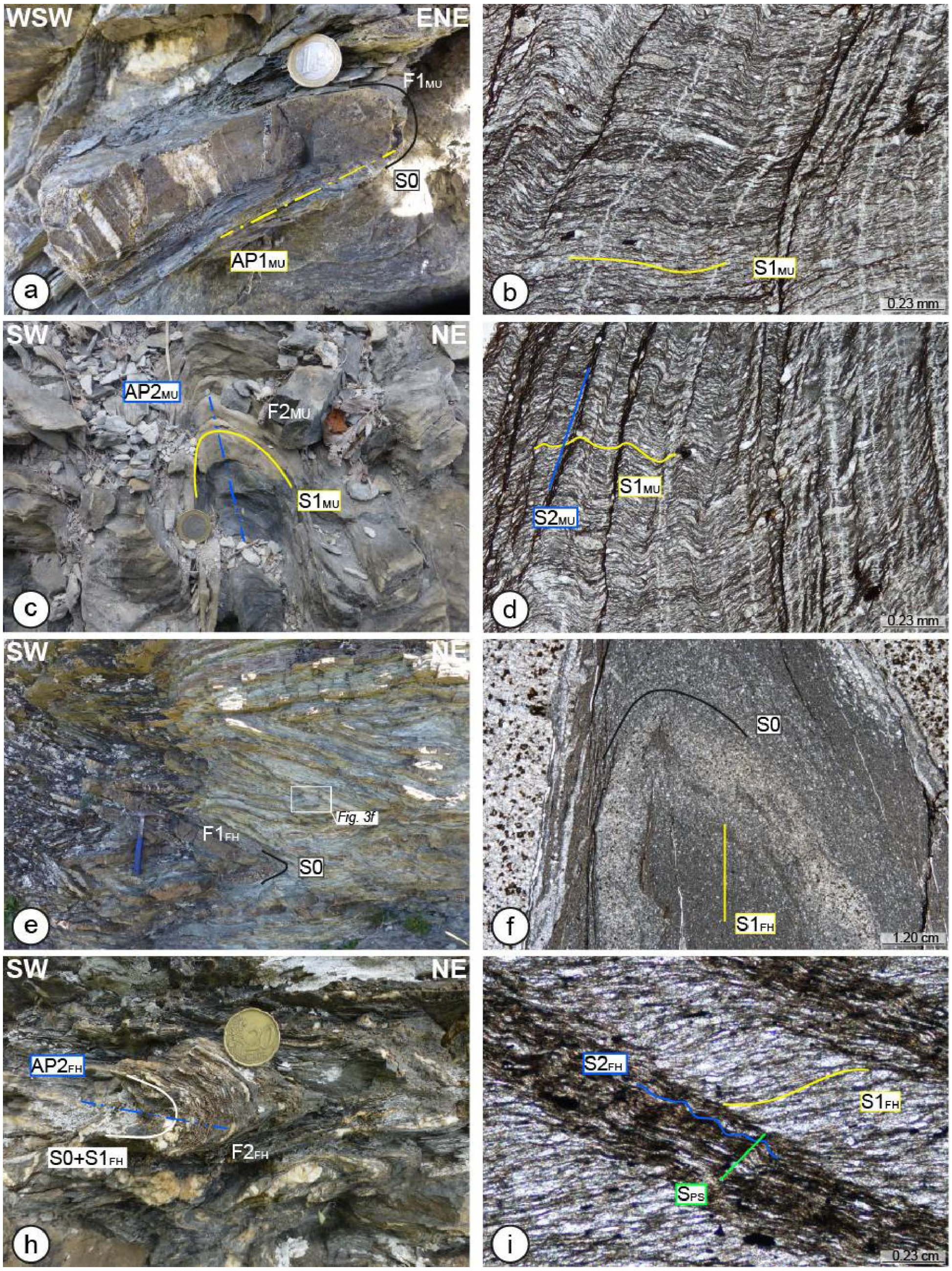

Figure 3. Meso- and micro-scale structural features of the Helminthoid Flysch and the Marguareis Unit. (a) Isoclinal $F1_{MU}$ fold and related axial plane ($AP1_{MU}$) in Boaria Formation. Microphotograph (b) of $S1_{MU}$ foliation. Hinge zone of $F2_{MU}$ fold (c) in the Upega Formation. The related axial plane is indicated as $AP2_{MU}$. $S1_{MU}$–$S2_{MU}$ relationships at the microscale (d). Outcrop-scale tight $F1_{FH}$ folds in the San Bartolomeo Formation (e). White box indicates the sample site of (f). (f) Microphotograph of the hinge zone of $F1_{FH}$ fold. The corresponding foliation $S1_{FH}$ is reported. (h) Outcrop-scale $F2_{FH}$ fold in the Bordighera Sandstone folding the $S1_{FH}$–S0 surface. The related axial plane ($AP2_{FH}$) is reported. (i) Microscale cross-cutting relationships between $S2_{FH}$–$S1_{FH}$ and PS foliation (S_{PS}). S0: bedding.

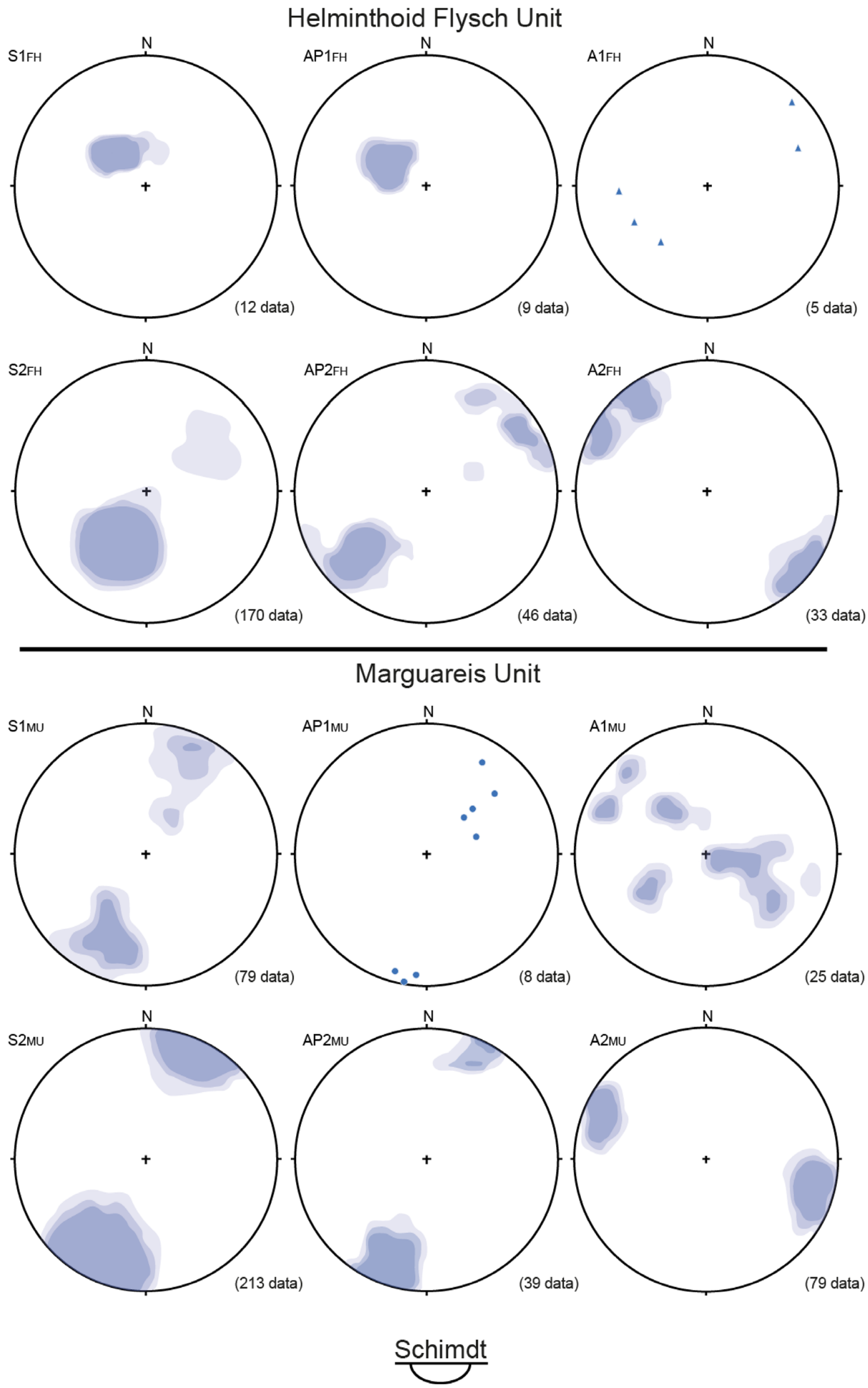

Figure 4. Stereographic projections of the main structural features for each unit.

sponsible for the coupling of the units and for their folding. The thrust surfaces are testified by two main unit-bounding shear zone systems marked by decametric-thick high-strain cataclastic zones (Figure 5a,b). The lowermost is located at the bottom of the FH (Figure 5) and regarded as in-sequence thrusting events. It shows NW–SE strike and dips toward NE and SW with medium- to high-angles (Figure 5e). The stretching lineations on the fault planes show NE–SW trend and plunge NE and SW (Figure 5e). Top-to-SW kinematic indicators are present and they are represented by sigma-shaped dm-sized siliciclastic and carbonate clasts (Figure 5c) observed in various lithologies (i.e. Bordighera Sandstone, Boaria Formation and Upega Formation). The uppermost shear zone system separates the overlying MU from the underlying FH (Figure 5) and is regarded as an out-of-sequence thrusting event. It shows NW–SE strike and dips at various angles towards NE and SW (Figure 5f). The stretching lineations show NE–SW trend and plunge NE and SW (Figure 5f). Kinematic indicators pointing toward SW are represented by cm-sized sigma-shaped carbonate and siliciclastic clasts (Figure 5d).

A major knee-shaped folding event affecting only the MU is observed. It is characterized by a NW–SE trending fold axes plunging NW and SE and axial planes showing a NW–SE direction and a generally northeastward dipping axial plane (Figure 5). This event was already documented in the MU exposed in the southwestern sectors of the Marguareis Massif [$D3_{MU}$ of Sanità et al., 2020] and is geometrically consistent with the out-of-sequence thrusting event. The tectonic foliation related with this folding event is rarely observed and it is not associated with metamorphic re-crystallization. This suggests that this folding event took place at very shallow structural levels [as suggested by Sanità et al., 2020, 2021].

5.3. *The post-stacking deformation events*

All the previously described pre- and syn-stacking structures are deformed by the so-called PS fold system and faults. The PS fold system is mostly located in zones where vertical or sub-vertical layering is present (Figures 1b,c, 5a). PS fold system is testified by recumbent open folds showing parallel geometry and rounded hinge-zone (Figure 6a–c). The PS fold system shows (Figure 6e) a NW–SE trending fold axes (A_{PS}) and sub-horizontal to southwestward-dipping axial planes (AP_{PS}). In the field the associated tectonic foliation is only observed in the less competent rocks (shales or marls). In thin section (Figure 6d) it is marked by stylolitic surfaces (S_{PS}) without any metamorphic re-crystallization, suggesting its development at shallow structural levels. The faults show a NNE–SSW main direction (Figure 1b) and cut at high angles all the previously described structures including the AP_{PS}. A minor NW–SE-oriented fault system is also present.

6. The role of thrust tectonics in Helminthoid Flysch–Briançonnais relationships and comparison with other key areas of the Western Alps

The geological survey carried out in the junction area between Maritime and Ligurian Alps first clearly confirms that the relationships between the major Alpine tectonics units of interest can only be interpreted in the framework of a polyphase tectonic evolution and not as a result of a single transpressive brittle tectonic event as proposed by Piana et al. [2021]. Secondly, it demonstrates that the very low-grade FH is located in between tectonic units (i.e. Briançonnais Units, Figures 1b,c, 5) showing higher metamorphic conditions. In Figure 7 we report two geological cross-sections showing the structural architecture of two areas located in the southwestern sector of the Marguareis Massif (Figure 7a,b) and in the area investigated in this paper (Figure 7c). The two cross-sections clearly highlight amazing structural analogies. In both the sections the MU forms the topmost portion of the tectonic pile and is thrust, with an out-of-sequence thrust, onto the FH and its basal complex. The FH is thrust onto Briançonnais units both represented by tectonic slices (i.e. Cima del Becco Slice, and CS in this paper) and units [i.e. the Cabanaira Unit, Sanità et al., 2020]. Each unit recorded different pre-stacking deformation histories responsible for development of fold systems at different structural levels. The related axial planes are cut by the unit-bounding shear zone systems, which show a top-to-SW sense of shear, and are responsible for the coupling of the units. Thus, this indicates that the thrusting events superimposed onto the pre-stacking structures. So, the thrusting events are suggested to have occurred during the syn-stacking tectonics.

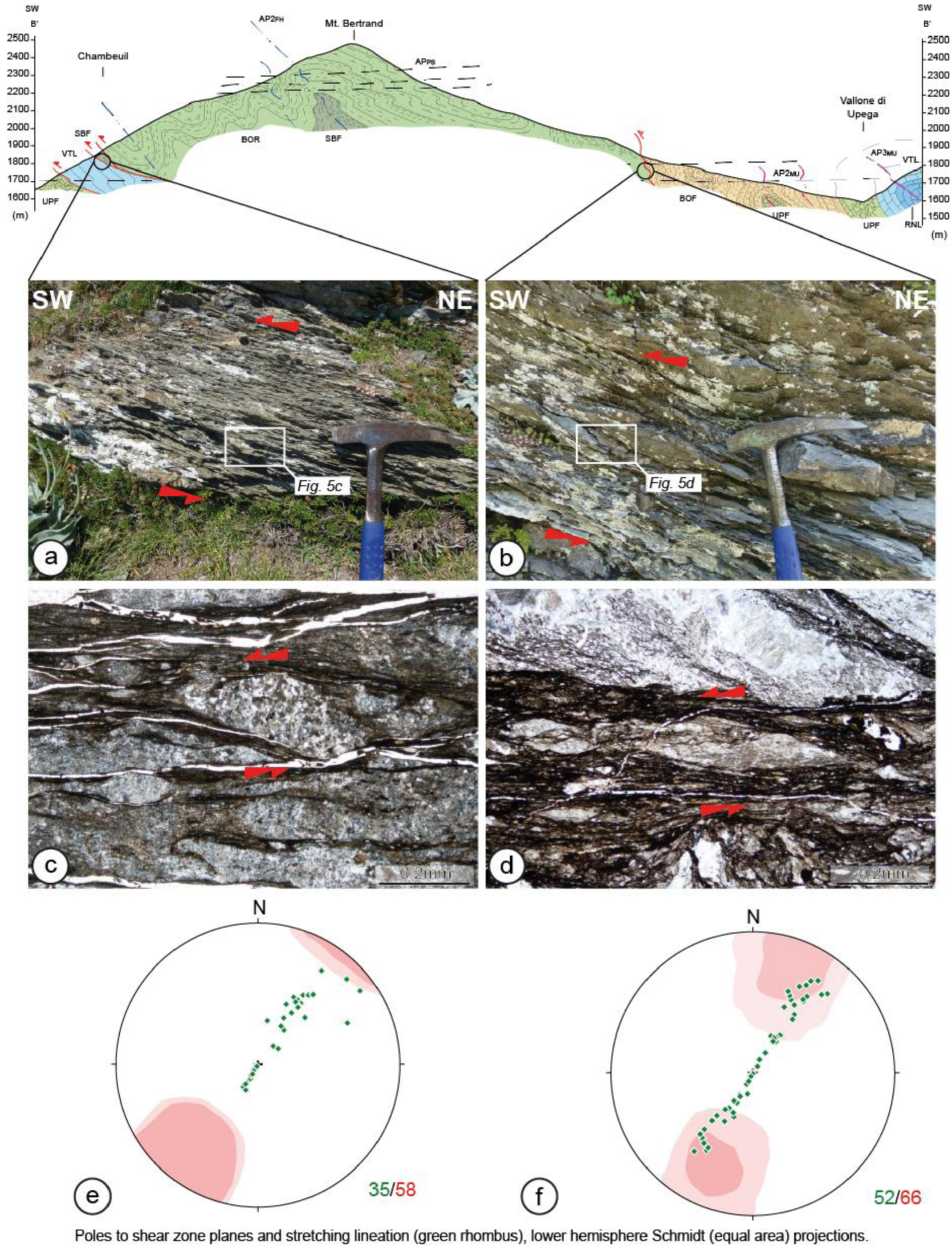

Figure 5. Meso- (a,b) and micro-scale (c,d) structural features of the *top-to-SW* unit-bounding thrusts. The location of the outcrops is indicated in the geological cross-section whose trace is reported in the geological map of Figure 1b. Stereographic plot of the main cataclastic foliation planes (red) carrying the stretched lineations generated by granular flow (green) (e,f).

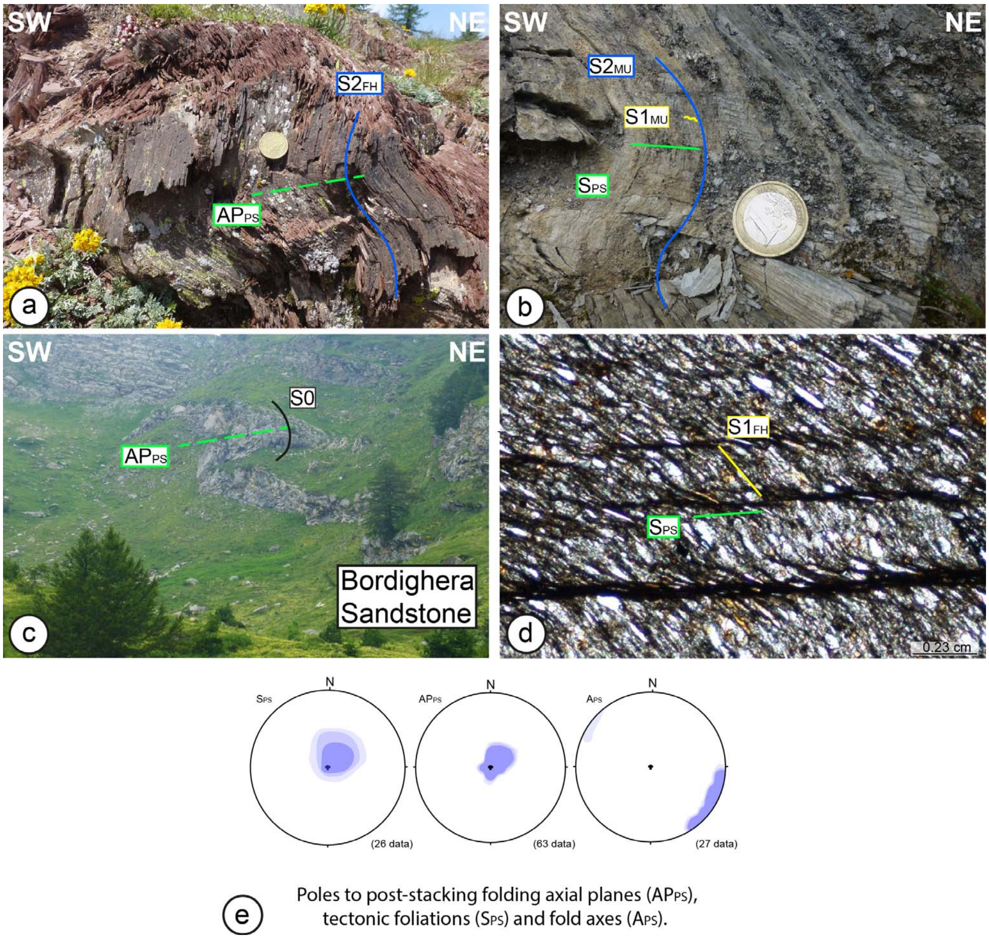

Figure 6. Meso- and micro-scale structural features of the post-stacking folding (PS). Cross-cutting relationships (a) between $S2_{FH}$ and post-stacking fold axial plane (AP_{PS}) in the FH (San Bartolomeo Formation). Overprint relationships (b) between $S1_{MU}$–$S2_{MU}$ couple and S_{PS} foliation in the Marguareis Unit (Upega Formation). (c) PS fold in the Bordighera Sandstone bedding (S0). (d) Microphotographs of the S_{PS} tectonic foliation. Stereoplots in (e) report mutual relationships between the structural features of the post-stacking folding system (Schmidt net, lower hemisphere).

Recognizable in the geological cross-sections, the out-of-sequence thrusting and the associated knee-shaped folding affecting the MU can be observed from Upega village to Col di Perla area (Figure 7), thus on more than 70 km. In contrast with the previous authors [Di Giulio, 1988, Merizzi and Seno, 1991, Mueller et al., 2020, Piana et al., 2021], we hold that the reconstructed thrust surfaces and the associated knee-shaped folding must be considered as first-order structural features in this area and, consequently, that syn-stacking tectonics played a significant role in the finite structural architecture of the units exposed in the junction area between Maritime and Ligurian Alps (Figure 8). This hypothesis is corroborated by the fact that the inverted structural relationships between the FH and Briançonnais Units (Figure 7) can be appreciated at the regional scale and not just at the local scale. This type of scenario was detected not only by Sanità et al. [2020] in the Marguareis Massif (north of the study area, but also in the Embrunais-Ubaye sector [French western Alps, see Figure 7 of Merle and Brun, 1984]. In this emblematic key target for studying the lithology and the structure of the Helminthoid Units [see Kerckhove, 1963, 1969, with references therein], a tectonic evolution entirely consistent with the one proposed

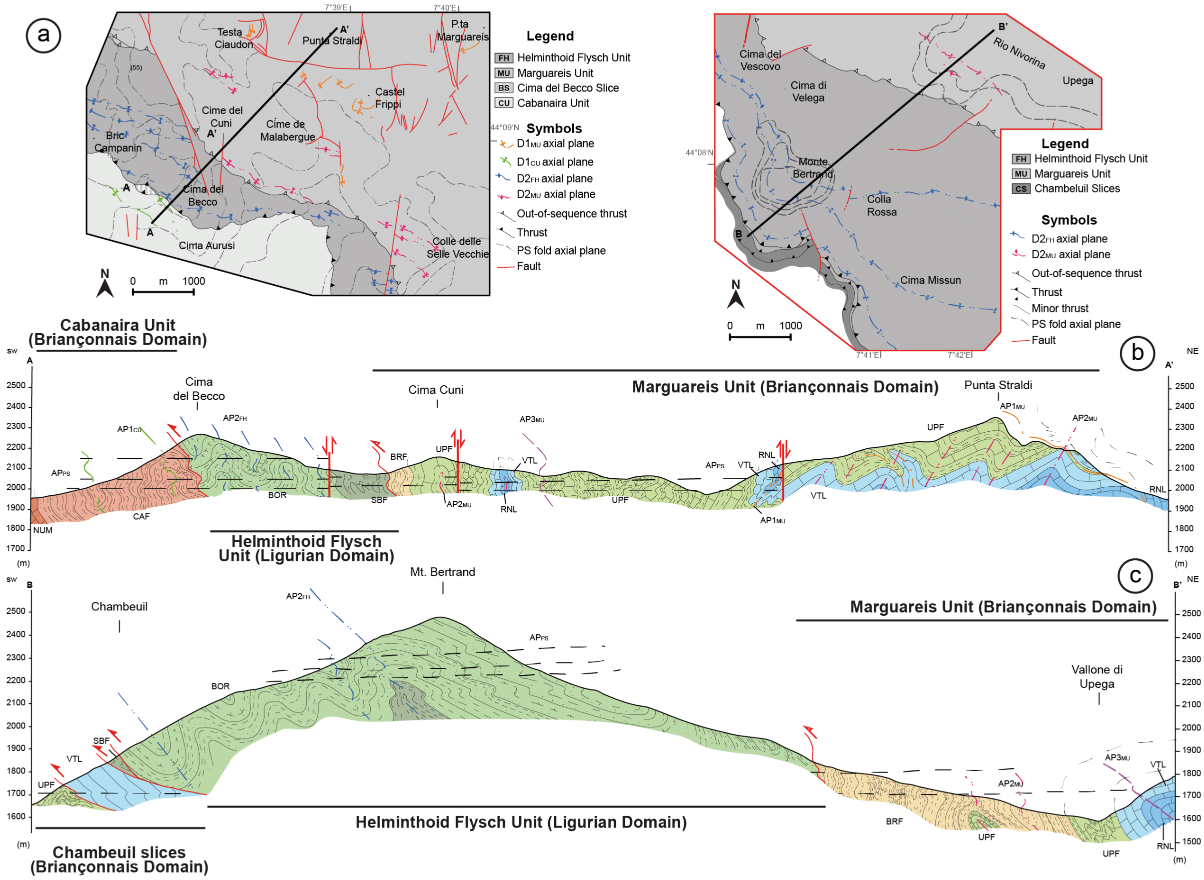

Figure 7. Comparison between the Marguareis Massif [from Sanità et al., 2021] and Upega-Bertrand (this paper) areas. In (a) the geographic location and the structural sketches of the contiguous areas are indicated [redrawn and modified from Vanossi et al., 1984]. The traces of geological cross-sections (b,c) are reported in the sketches of 8a. SBF: San Bartolomeo Formation; BOR: Bordighera Sandstone; NUM: Nummulitic Limestone; CAF: Cima Aurusi Formation; RNL: Rio di Nava Limestone; VTL: Val Tanarello Limestone; UPF: Upega Formation; BOF: Boaria Formation.

in this paper was reconstructed [cf. Figures 8 and 7 of Merle and Brun, 1984].

7. Kinematic interpretation in the framework of Alpine collision tectonics

The pre-stacking structures documented in the Briançonnais Units exposed in the study area (i.e. the MU and the CS) demonstrate that the $D1_{MU}$ phase developed under ductile conditions during a southwest-ward motion of the unit, as proposed by Carminati [2001] and Sanità et al. [2020]. The same authors also considered that the metamorphic peak conditions were reached during this deformation phase in accordance with the mineral recrystallizations along the $S1_{MU}$ tectonic foliation. Some authors [Dumont et al., 2012] proposed an early N–S to NW-directed compressional phases in the Emrunais-Ubaye sector close to the Pelvoux Massif and mostly recorded into the Dauphinois units. To the contrary, in the study area this roughly N-directed compressional phase is not recorded by the Briançonnais units. However, at the scale of the western Alps, the $D1_{MU}$ phase is the witness to the involvement (underthrusting) of the European continental units (here Briançonnais units) in the Alpine continental collision as proposed by Lanari et al. [2014]. The $D2_{MU}$ phase can be related to a NE-directed-backthrusting

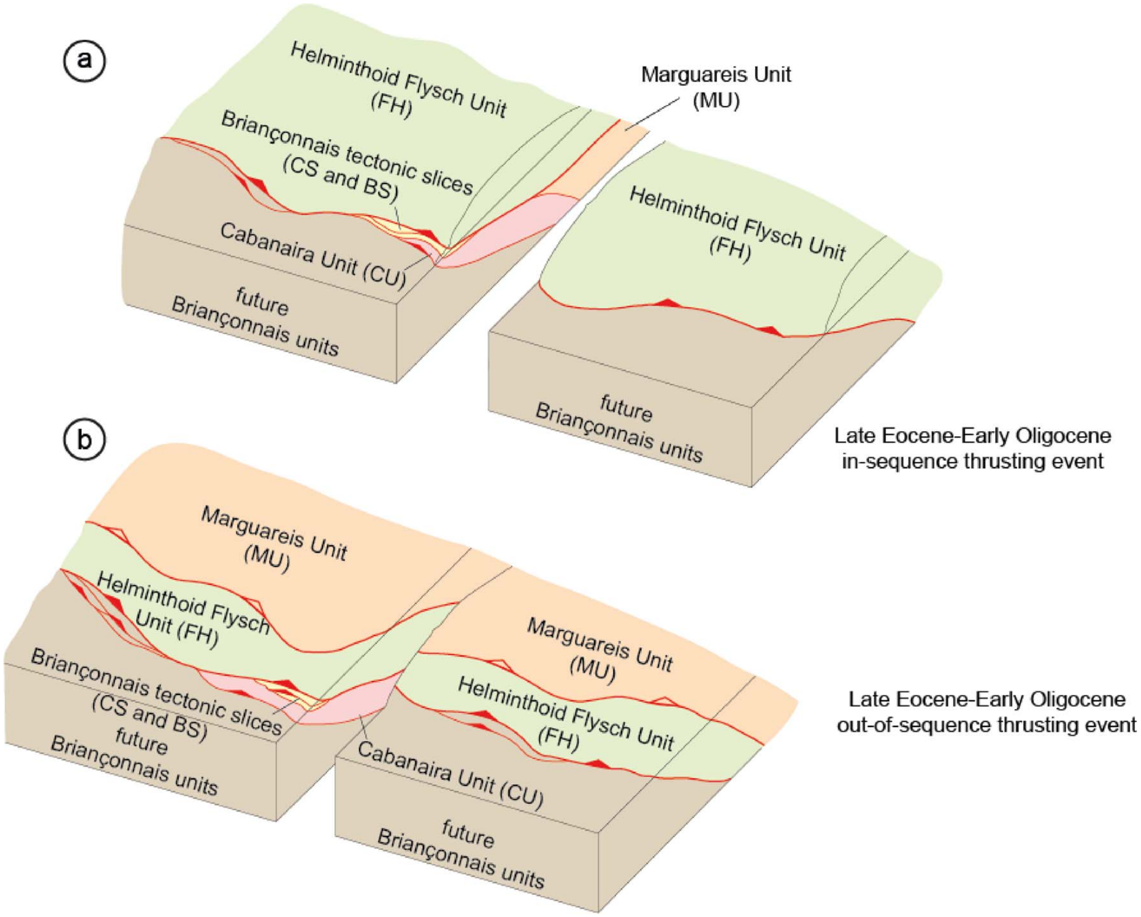

Figure 8. Simplified 3D tectonic sketch showing the (a) in-sequence and (b) out-of-sequence thrusting events developed during the syn-stacking tectonics.

event, developed at lower P–T metamorphic conditions, during which the Briançonnais units start to be exhumed [as suggested by Carminati, 2001]. Based on these considerations, we confirm the reconstruction proposed by Sanità et al. [2020] in which the pre-stacking deformation history recorded by the Briançonnais Units are the result of the involvement in the suture zone of the thinned Europe continental margin that underwent underthrusting, accretion and later exhumation into the Alpine orogenic wedge.

The FH, instead, recorded a different deformation history developed at shallow structural levels as suggested by the recrystallization along the related $S1_{FH}$ and $S2_{FH}$ foliations. They are associated with two different fold systems. The $F1_{FH}$ folds and kinematic indicators indicated a NW-directed tectonic transport, whereas the structural features related to $D2_{FH}$ phase indicate a tectonic transport direction toward southwest. These kinematic interpretations for the FH emphasize an origin from the innermost sectors of the Alpine chain. These structural evidences are consistent with the stratigraphic analogies between the FH and the External Ligurian units successions [Northern Apennine, Elter et al., 1966, Marroni et al., 2010], which are regarded as the sedimentary cover of the ocean–continent transition along the Adria Plate [Marroni et al., 2017, and quoted references].

Geochronological data on the age of the deformations recorded by each unit are not yet available. Nevertheless, based on the age of deposits at the top of the sedimentary sequences and, the cross-cutting relationships between different tectonic structures a possible timing for the tectonic evolution considered can be proposed at the regional scale. In the Marguareis Massif (north of the study area), structural and stratigraphic constraints support a Middle to Late Eocene time span for the development of the pre-stacking structures [Sanità et al., 2020]. This is in agreement with the 45 Ma ^{40}Ar–^{39}Ar age on mica obtained by Lanari et al. [2014].

The syn-stacking events, responsible for the coupling of the units, is represented here by the unit-bounding shear zone system and by the knee-shaped folding event, both developed at shallow structural levels. Consequently, this structural setting was acquired after the main exhumation of the Briançonnais Units and in uppermost Late Eocene time [Maino et al., 2015, Vanossi et al., 1984]. In such a case both the out-of-sequence thrusting and knee-shaped folding can be constrained to the Late Eocene–Early Oligocene time span, in accordance with the onset of compressional deformation in the former European continental margin [i.e. External Crystalline Massifs, Simon-Labric et al., 2009, Sanchez et al., 2011].

The post-stacking deformation history is represented by fold and fault system development. We propose to interpret the post-stacking fold system as the result of vertical shortening and folding of preexisting inclined layers starting from Early Oligocene. This kind of deformation is typical of extensional tectonics as outlined in other sectors of the Alpine chain [Froitzheim, 1992, Ratschbacher et al., 1989, Wheeler and Butler, 1994]. The last deformation event depicted in the study area is represented by a sub-vertical fault system with NE–SW direction that locally juxtaposes different tectonic units. However, the faulting event did not play a significant role in the finite strain pattern recorded by the units exposed in this area of the western Ligurian Alps as proposed instead by some authors [d'Atri et al., 2016, Piana et al., 2021].

8. Conclusion

In this paper we document a tectonic pile of units exposed in High Tanaro Valley (Ligurian Alps). These intricate finite strain patterns recorded are characterized by the superimposition of pre-, syn- and post-stacking structures, developed in different time spans and at different structural levels. Our investigations demonstrate that:

- The tectonic coupling is the result of a polyphase ductile tectonic evolution and not the result of a single transpressive brittle tectonic event.
- The syn-stacking tectonic events correspond to *top-to-SW* thrusting and folding developed during Late Eocene–Early Oligocene times. They brought the units to a specific and original structural configuration in which the non-metamorphic FH is tectonically located in between the Briançonnais units, the latter showing higher metamorphic conditions.
- The pre-stacking ductile structures documented in the Briançonnais units are the witness to the underthrusting of the European thinned continental margin during the Alpine continental collision.
- The kinematic indicators observed in the FH unit, document first a NW-directed tectonic transport followed by a motion toward the SW (i.e. tectonic coupling with Briançonnais units). The early tectonic and kinematic indicators are compatible with an origin of the FH in innermost sectors of the Alpine belt, probably at the boundary with the Adria Plate.

Conflicts of interest

Authors have no conflict of interest to declare.

Acknowledgements

We thank the reviewers for their constructive and challenging tips. We thank also the editor, Carole Petit, for the editorial work. The authors are thankful to University of Pisa (PRA project) for financial support of this project.

References

Bonazzi, A., Cobianchi, M., and Galbiati, B. (1987). Primi dati sulla cristallinità dell'illite nelle unità tettoniche più esterne e strutturalmente più elevate delle Alpi Liguri. *Atti Tic. Sci. Terra*, 31, 63–77.

Boni, A., Cerro, A., Gianotti, R., and Vanossi, M. (1971). Note illustrative della Carta Geologica d'Italia alla scala 1:100.000, foglio Albenga-Savona (92–93). Servizio Geologico D'Italia.

Boni, A. and Vanossi, M. (1972). Carta geologica dei terreni compresi tra il Brianzonese ligure s.l. ed il Flysch ad Elmintoidi s.s. *Atti Ist. Geol. Univ. Pavia*, 23. Tav. 24.

Cabella, R., Cortesogno, L., Dallagiovanna, G., Vannucci, R., and Vanossi, M. (1987). Vulcanismo, sedimentazione e tettonica nel Brianzonese ligure esterno durante il Permo-Carbonifero. *Atti Tic. Sci. Terra*, 31, 269–326.

Capponi, G., Crispini, L., Federico, L., Piazza, M., and Fabbri, B. (2009). Late Alpine tectonics in the Ligurian Alps: Constraints from the Tertiary Piedmont Basin conglomerates. *Geol. J.*, 44, 211–224.

Carminati, E. (2001). Incremental strain analysis using two generations of syntectonic coaxial fibres: An example from the Monte Marguareis Briançonnais cover nappe (Ligurian Alps, Italy). *J. Struct. Geol.*, 23, 1441–1456.

Cobianchi, M., Di Giulio, A., Galbiati, B., and Mosna, S. (1991). Il “Complesso di base” del Flysch di San Remo nell’area di San Bartolomeo, Liguria occidentale (nota preliminare). *Atti Tic. Sci. Terra*, 34, 145–154.

Coward, M. P. and Dietrich, D. (1989). Alpine tectonics-an overview. In Coward, M. P., Dietrich, D., and Park, R. G., editors, *Alpine Tectonics*, pages 1–29. Geol. Soc. Spec. Pub., London, UK.

d’Atri, A., Piana, F., Barale, L., Bertok, C., and Martire, L. (2016). Geological setting of the southern termination of Western Alps. *Int. J. Earth Sci.*, 105, 1831–1858.

Decarlis, A., Dallagiovanna, G., Lualdi, A., Maino, M., and Seno, S. (2013). Stratigraphic evolution in the Ligurian Alps between Variscan heritages and the Alpine Tethys opening: A review. *Earth Sci. Rev.*, 125, 43–68.

Dewey, J. F., Helman, M. L., Turco, E., Hutton, D. H., Knott, S. D., et al. (1989). Kinematics of the western Mediterranean. In Coward, M. P. et al., editors, *Alpine Tectonics*, pages 265–283. Geol. Soc. Spec. Publ., London, UK.

Di Giulio, A. (1988). Evoluzione strutturale delle Unità di Moglio-Testico e di S. Remo-M. Saccarello (Piemontese-Ligure delle Alpi Marittime): nuovi dati. *Atti Tic. Sci. Terra*, 31, 54–62.

Di Giulio, A. (1992). The evolution of the Western Ligurian Flysch Units and the role of mud diapirism in ancient accretionary prisms (Maritime Alps, NW Italy). *Geol. Rundsch.*, 81, 655–668.

Dumont, T., Schwartz, S., Guillot, S., Simon-Labric, T., Tricart, P., and Jourdan, S. (2012). Structural and sedimentary records of the Oligocene revolution in the Western Alpine arc. *J. Geodyn.*, 56–57, 18–28.

Elter, G., Elter, P., Sturani, P., and Weidmann, M. (1966). Sur la prolongation du domaine ligure de l’Apennin dans le Monferrat et les Alpes et sur l’origine de la Nappe de la Simme s.l. des Préalpes romandes et chaiblaisiennes. *Arch. Sci.*, 176, 279–377.

Elter, P. and Pertusati, P. C. (1973). Considerazioni sul limite Alpi-Appennino e sulle relazioni con l’arco delle Alpi Occidentali. *Mem. Soc. Geol. It.*, 12, 359–375.

Fallot, P. and Faure-Muret, A. (1954). Sur le Secondaire et le Tertiaire aux bords sud-orientaux du Massif de l’Argentera-Mercantour (feuille 491 de Saint Martin Vésubie, Tende et Viève, au, 1/50.000). *Bull. Carte Géol. France*, 52, 283–319.

Froitzheim, N. (1992). Formation of recumbent folds during synorogenic crustal extension Austroalpine nappes, Switzerland. *Geology*, 20, 923–926.

Gidon, M. (1972). Les chaînons Briançonnais et subbriançonnais de la rive gauche de la Stura entre le Val de l’Arma (province de Cuneo Italie). *Géol. Alp.*, 48, 87–120.

Grandjacquet, C. and Haccard, D. (1977). Position structurale et rôle paléogéographique de l’unité du Bracco au sein du contexte ophiolitique liguropiémontais. *Bull. Soc. Géol. France*, 19, 901–908.

Haccard, D. (1961). La série du Flysch de Moglio-Testico de la nappe du Flysch à Helminthoides des Alpes maritimes franco-italiennes. *C. R. Acad. Sci. Fr.*, 252, 3609–3611.

Handy, M. R., Schmid, S. M., Bousquet, R., Kissling, E., and Bernoulli, D. (2010). Reconciling platetectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. *Earth Sci. Rev.*, 102, 121–158.

Kerckhove, C. (1963). Schéma structural de la nappe du Flysch à Helminthoïdes de l’Embrunais-Ubaye. *Géol. Alp.*, 39, 7–24.

Kerckhove, C. (1969). La « zone du Flysch » dans les nappes de l’Embrunais-Ubaye. *Géol. Alp.*, 45, 5–204.

Lanari, P., Rolland, Y., Schwartz, S., Vidal, O., Guillot, S., Tricart, P., and Dumont, T. (2014). P-T-t estimation of deformation in low-grade quartz-feldsparbearing rocks using thermodynamic modelling and $^{40}Ar/^{39}Ar$ dating techniques: example of the Plan-de-Phasy shear zone unit (Briançonnais Zone, Western Alps). *Terra Nova*, 26, 130–138.

Lanteaume, M. (1957). Nouvelles données sur le Flysch a Helminthoïdes de la Ligurie occidentale (Italie). *Bull. Soc. Géol. France*, 7, 115–123.

Lanteaume, M. (1962). Considérations paléogéographiques sur la patrie supposée des nappes de Flysch à Helminthoïdes des Alpes et des Apennins. *Bull. Soc. Géol. France*, 4, 627–643.

Lanteaume, M. (1968). *Contribution à l'étude géologique des Alpes Maritimes franco-italiennes*. Mém. Carte Géol. France. Impr. nationale, Paris, France.

Laubscher, H. (1991). The arc of western Alps today. *Ec. Geol. Hel.*, 84, 631–659.

Lemoine, M., Bas, T., Arnaud Vanneau, A., Arnaud, H., Dumont, T., Gidon, M., Bourbon, M., de Graciansky, P. C., Megard Galli, J., and Tricart, P. (1986). The continental margin of the Mesozoic Tethys in the Western Alps. *Mar. Petrol. Geol.*, 3, 179–199.

Maino, M., Casini, L., Ceriani, A., Decarlis, A., Di Giulio, A., Seno, S., and Stuart, F. M. (2015). Dating shallow thrusts with zircon (U-Th)/He thermochronometry: The shear heating connection. *Geology*, 43, 495–498.

Malatesta, C., Crispini, L., Federico, L., Capponi, G., and Scambelluri, M. (2012). The exhumation of high pressure ophiolites (Voltri Massif, Western Alps): insights from structural and petrologic data on metagabbro bodies. *Tectonophysics*, 568–569, 102–133.

Manivit, H. and Prud'Homme, A. (1990). Biostratigraphie du Flysch à Helminthoïdes des Alpes maritimes franco-italiennes. Nannofossiles de l'unité de San Remo-Monte Saccarello. Comparaison avec les Flyschs à Helminthoïdes des Apennins. *Bull. Soc. Géol. France*, 8, 95–104.

Marroni, M., Meneghini, F., and Pandolfi, L. (2010). Anatomy of the Ligure-Piemontese subduction system: Evidence from Late Cretaceous-Middle Eocene convergent margin deposits in the Northern Apennines, Italy. *Int. Geol. Rev.*, 52, 1160–1192.

Marroni, M., Meneghini, F., and Pandolfi, L. (2017). A revised subduction inception model to explain the Late Cretaceous, double-vergent orogen in the pre-collisional western Tethys: Evidence from the Northern Apennines. *Tectonics*, 36, 2227–2249.

Merizzi, G. and Seno, S. (1991). Deformation and gravity-driven translation of the S. Remo–M. Saccarello nappe (Helminthoid Flysch, Ligurian Alps). *Boll. Soc. Geol. It.*, 110, article no. 757770.

Merle, O. and Brun, J. P. (1984). The curved translation path of the Parpaillon nappe (French Alps). *J. Struc. Geol.*, 6, 711–719.

Messiga, B., Oxilia, M., Piccardo, G. B., and Vanossi, M. (1981). Fasi metamorfiche alpine nel Brianzonese e Prepiemontese esterno delle Alpi liguri: un possibile modello evolutivo. *Rend. SIMP*, 38, 261–280.

Molli, G., Crispini, L., Malusà, M. G., Mosca, M. G., Piana, F., and Federico, L. (2010). Geology of the Western Alps-Northern Apennine junction area – A regional review. *J. Virt. Exp.*, 36, 1–49.

Mosca, P., Polino, R., Rogledi, S., and Rossi, M. (2009). New data for the kinematic interpretation of the Alps–Apennines junction (Northwestern Italy). *Int. J. Earth. Sci.*, 99, 833–849.

Mueller, P., Langone, A., Patacci, M., and Di Giulio, A. (2018). Detrital signatures of impending collision: The deep-water record of the Upper Cretaceous Bordighera Sandstone and its basal complex (Ligurian Alps, Italy). *Sed. Geol.*, 377, 147–161.

Mueller, P., Maino, M., and Seno, S. (2020). Progressive deformation patterns from an accretionary prism (Helminthoid Flysch, Ligurian Alps, Italy). *Geosciences*, 10, article no. 26.

Piana, F., Barale, L., Bertok, C., d'Atri, A., Irace, A., and Mosca, P. (2021). The Alps–Apennines Interference zone: a perspective from the Maritime and Western Ligurian Alps. *Geosciences*, 11, article no. 185.

Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S. M., and Neugebauer, J. (1989). Extension in compressional orogenic belts: The eastern Alps. *Geology*, 17, 404–407.

Rebay, G., Zanoni, D., Langone, A., Luoni, P., Tiepolo, M., and Spalla, M. (2018). Dating of ultramafic rocks from the Western Alps ophiolites discloses Late Cretaceous subduction ages in the Zermatt–Saas Zone. *Geol. Mag.*, 155, 298–315.

Rosenbaum, G., Lister, G. S., and Duboz, C. (2002). Relative motions of Africa, Iberia and Europe during Alpine orogeny. *Tectonophysics*, 359, 117–129.

Sagri, M. (1980). Le arenarie di Bordighera: una conoide sottomarina nel bacino di sedimentazione del flysch ad Elmintoidi di San Remo (Cretaceo superiore, Liguria occidentale). *Boll. Soc. Geol. Ital.*, 98–99, 205–226.

Sanchez, G., Rolland, Y., Schneider, J., Corsini, M., Oliot, E., Goncalves, P., Verati, C., Lardeaux, J. M., and Marquer, D. (2011). Dating low-temperature deformation by $^{40}Ar/^{39}Ar$ on white mica, insights from the Argentera-Mercantour Massif (SW Alps). *Lithos*, 125, 521–536.

Sanità, E., Lardeaux, J. M., Marroni, M., Gosso, G., and Pandolfi, L. (2020). Structural relationships between Helminthoid Flysch and Briançonnais Units in the Marguareis Massif: A key for deciphering the finite strain pattern in the external southwestern Alps. *Geol. J.*, 56, 2024–2040.

Sanità, E., Lardeaux, J. M., Marroni, M., Gosso, G., and Pandolfi, L. (2021). Deciphering large-scale superoposed fold systems at shallow crustal levels in collision zones: Insights from the Marguareis Massif (southwestern Alps). *J. Maps*, 17, 559–568.

Seno, S., Dallagiovanna, G., and Vanossi, M. (2003). Palaeogeography and thrust development in the Penninic domain of the Western Alpine chain: examples from the Ligurian Alps. *Boll. Soc. Geol. It.*, 122, 223–231.

Seno, S., Dallagiovanna, G., and Vanossi, M. (2005). A kinematic evolutionary model for the Penninic sector of the central Ligurian Alps. *Int. J. Earth Sci.*, 94, 114–129.

Simon-Labric, T., Rolland, Y., Dumont, T., Heymes, T., Authemayou, C., Corsini, M., and Fornari, M. (2009). Ar-40/Ar-39 dating of Penninic Front tectonic displacement (W Alps) during the Lower Oligocene (31–34 Ma). *Terra Nova*, 21, 127–136.

Spagnolo, C., Crispini, C., and Capponi, G. (2007). Late structural evolution in an accretionary wedge: insights from the Voltri Massif (Ligurian Alps, Italy). *Geodin. Acta*, 20, 21–35.

Stampfli, G. M. (1993). The Brianconnais, exotic terrane in the Alps? *Ec. Geol. Hel.*, 86, 1–45.

Stampfli, G. M., Borel, G. D., Cavazza, W., Mosar, J., and Ziegler, P. A. (2001). Palaeotectonic and palaeogeographic evolution of the western Tethys and Peri Tethyan domain (IGCP Project 369). *Episodes*, 24, 222–228.

Thum, L., De Paoli, R., Stampfli, G. M., and Moix, P. (2015). The Piolit, Pelat and Baiardo Upper Cretaceous flysch formations (western Alps): geodynamic implications at the time of the Pyrenean tectonic phases. *Bull. Soc. Géol. France*, 186(4–5), 209–222.

Vanossi, M. (1986). *Geologia delle Alpi liguri*, volume 28 of *Mem. Soc. Geol. It.*

Vanossi, M. (1991). *Guide Geologiche Regionali: 11 itinerari, Alpi liguri. A cura della Soc. Geol. It.* BE-MA, Milano. 1 pl.

Vanossi, M., Cortesogno, L., Galbiati, B., Messiga, B., Piccardo, G. B., and Vanucci, R. (1984). Geologia delle Alpi Liguri: dati, problemi, ipotesi. *Mem. Soc. Geol. It.*, 28, 5–57.

Vanossi, M., Perotti, C. R., and Seno, S. (1994). The Maritime Alps arc in the Ligurian and Thyrrhenian systems. *Tectonophysics*, 230, 75–89.

Wheeler, J. and Butler, R. W. H. (1994). Criteria for identifying structures related to true crustal extension in orogens. *J. Struct. Geol.*, 16, 1023–1027.