Abstract: Along the Western Alps, the oceanic units showing blueschists to eclogite facies metamorphic imprint are classically regarded as fragments of the Ligurian-Piedmont Ocean. These units recorded a strongly deformation related to their subduction, accretion and subsequent exhumation into the Alpine wedge, developed during the convergence between the Europa and Adria Plates. However, some of these units, for example the Moglio-Testico Unit, are less pervasively deformed, providing evidence of their sedimentary evolution as well as the tectono-metamorphic history. Therefore, we present original stratigraphic, structural and thermo-barometric data to characterize the tectono-metamorphic history and the sedimentary evolution of the Moglio-Testico Unit, performing different techniques including fieldwork, structural analysis and chlorite-phengite multiequilibrium thermobarometry. Our dataset indicates that the Moglio-Testico Unit can be considered as a fragment of oceanic cover whose sedimentary evolution reflects that of a portion of oceanic lithosphere approaching to the subduction zone. Structural analysis combined with the thermobarometry indicate that this unit recorded a polyphase deformation history developed under High Pressure-Low Temperature metamorphic conditions (D1: 1.2–1.0 GPa and Tpeak: 330–260 °C; D2: 0.4–0.7 GPa and 230–170 °C) during its underthrusting, accretion into the Alpine wedge and subsequent exhumation up to the shallower crustal levels.

Keywords: oceanic sedimentary cover; structural evolution; High-Pressure-Low-Temperature metamorphism; subduction; Western Ligurian Alps

1. Introduction

The Western Alps (Figure 1a) are a classic example of a double-verging collisional-type orogenic belt derived from the closure of an oceanic basin, whose fragments are still well preserved within the suture zone [1–6].
The geodynamic history of this belt started from the Triassic from a long-lived rifting process [8–13], leading in the Middle Jurassic to the opening of the Ligure-Piemontese oceanic basin between the Europa and Adria Plates. The convergence between these two plates started from the Upper Cretaceous age ([4,8,14,15] and quoted references), and...
resulted into the closure of the Ligure-Piemontese basin with development of continental subduction of eroded pieces of the upper plate, the Adria Plate [16–19]. Subsequently, during the Paleocene-Eocene, the progressive convergence led first to the subduction of the European crust [20–22] and then to the collision [23,24]. During the Oligo-Miocene, the collision produced a double-verging crustal belt [8,25–28]. In the present-day tectonic setting of the Western Alps, the Alpine oceanic units preserved in the suture zone are regarded as the remnants of the Alpine accretionary wedge developed during the subduction of the Ligure-Piemontese oceanic lithosphere [6,13,29–34]. These units can be recognized along the whole Western Alps, including their southern termination, i.e., the Ligurian Alps (Oph and Vog in Figure 1a). According with their lithostratigraphic features and their pervasive HP/LT metamorphic imprint, the Alpine oceanic units are classically divided into two different groups [2,6,26,33,35–37]. Belonging to the first group (Combin Zone [38]) are the tectonic units characterized by metasedimentary sequence made up mainly of calcschists associated with minor bodies of metaperidotites, metagabbros and metabasalts. The units from Combin Zone show a dominant blueschists metamorphic imprint [3,33,39–42]. The second group of oceanic units (Zermatt-Saas Zone, [38]) includes strongly deformed metaophiolites and subordinate metasedimentary covers (quartzites, marbles and calcschists). The units from Zermatt-Saas Zone are generally affected by eclogite metamorphic imprint even if some metaophiolite slices preserve remnants of ultra-high-pressure metamorphism (i.e., [15,36,37,43–45]).

However, some oceanic units of the Western Alps fall outside of this subdivision, and are characterized by both less pervasive deformation and lower grade metamorphic assemblages. One of the largest is the Moglio-Testico Unit, that crops out in the southwestern Alps (Western Ligurian Alps segment, Figure 1b). This unit shows a well-preserved sedimentary sequence detached from its pristine oceanic basement [46–51]. In the frame of the Western Alps, the Moglio-Testico Unit is still poorly known, in particular lacking details about its tectono-metamorphic history. This unit shows well preserved sequences showing a metamorphic imprint characterized by a low temperature condition which prevented the complete metamorphic re-crystallization at the whole-rock scale [52,53]. These features have until now prevented the reconstruction of the tectono-metamorphic evolution of the Moglio-Testico Unit and thus its geodynamic history.

However, new updates and perspectives in thermodynamic modelling, i.e., the chlorite-phengite multiequilibrium thermobarometry [54–56], allow investigation of the P–T paths of metamorphic rocks deformed under low-grade temperature conditions. This technique has been tested in a broad range of different geological settings ([57–61] and many others). It has also been applied to the Moglio-Testico Unit and combined with a detailed reconstruction of the lithostratigraphic setting and deformation history to improve the knowledge of the geodynamic history of this unit.

In this work we present the results of a geological survey performed on the northwestern Ligurian Alps (Southwestern Alps, Figures 1b and 2a) along the High Arroscia Valley.

In this sector the Moglio-Testico Unit is well exposed and it is tectonically located (Figures 1b and 2a) in between the Briançonnais Units and the Helminthoid Flysch Unit (Figure 2a, [62]; cf. San Remo-Monte Saccarello Unit of [63]). We thus present an original stratigraphic dataset, aiming to reconstruct the lithostratigraphic setting of the Moglio-Testico Unit (Figure 2b) exposed in this sector of the belt. This dataset is coupled to micro-to map-scale structural analysis used to reconstruct the deformation history (Figure 2c). Subsequently, we coupled the micro-structural analysis with the thermodynamic multi-equilibrium approach on chlorite-phengite pairs (Chl-Phg), here assumed to be in equilibrium, to unravel the tectono-metamorphic evolution of the Moglio-Testico Unit.
Figure 2. (a) Geological map of the study area; (b) stratigraphic log of the Moglio-Testico Unit; (c) geological cross-section related to the A-A' trace reported in (a). AP1: axial plane trace related to the first deformation phase; AP2: axial plane trace related to the second deformation phase; AP$_{PS}$: axial plane trace related to the post-coupling fold system.
2. Geological Frame of the Ligurian Alps

The Western Ligurian Alps represent the southern continuation of the Western Alps (Figure 1b) and they are characterized by a southwest-verging stack of units ([49,64–66] and quoted references), stemming from different domains (Ligure-Piemontese basin and Europe continental crust [49,67–69], progressively involved in a convergent setting and metamorphosed at different crustal levels (i.e., different depths) [61,70–74]. Moving from West to East, from the structurally highest to the lowest structural levels, the stack of units consists of (Figure 1b): (i) the Late Cretaceous non metamorphic Helminthoid Flysch Unit detached from its original basement whose nature is a matter of debate [63,75,76]; (ii) the Moglio-Testico Unit detached from its oceanic basement and characterized by turbiditic and chaotic pelagic deposits [46,48,50,76,77]; (iii) the Briançonnais Units characterized by a Meso-Cenozoic meta-sedimentary successions whose Paleozoic basements are well-exposed in the Calizzano and Savona Massifs (east of Figure 1b), the latter showing evidences of Variscan tectonic [69] and reworked during the Alpine events; (iv) eastward, i.e., toward the internal sector of the Alpine belt, the ophiolite tectonic units of the Voltri Massif (Vog in Figure 1a, see Voltri group of [78], i.e., Voltri Unit, Montenotte Unit and Palmaro Caffarella Unit) showing HP-LT metamorphic overprinted by greenschistes facies metamorphic conditions [71,72]. Toward the external sectors of the Alpine belt (i.e., westward), the topmost Helminthoid Flysch Unit tectonically overlies onto the Dauphinois/Helvetic Unit representative of the ancient Europe continental margin [69]. These units are characterized by a Meso-Cenozoic sedimentary cover whose Paleozoic basement is well exposed in the External Crystalline Massifs (ECM).

In the study area (High Arroscia Valley, Figure 2a) the SW-verging tectonic stack is characterized by units stemming from continental (Europe continental margin) and oceanic (Ligure-Piemontese basin) paleogeographic domains, according to [49,67]. These units, after their involvement at different crustal levels in the Alpine wedge, have been exhumed up to the shallowest crustal levels following different tectonic trajectories [61,62,64,65,67,75]. This tectonic stack is the southeastern extension of the pile of units documented by [62,75] cropping out in High Tanaro Valley and along the southwestern sector of the Marguareis Massif (NW to the study area), respectively. According to these authors, the tectonic stack, from the highest to the lowest structural levels, is formed by: (i) the Marguareis Unit (Briançonnais Domain) characterized by a Meso-Cenozoic sequence, reflecting the sedimentary evolution of a portion of the Europe margin involved in a convergent setting [68], which experienced continental subduction and subsequently exhumation processes recording HP-LT metamorphic conditions [61]; (ii) the Cretaceous-Paleocene(? Moglio-Testico Unit (Figure 2b, Ligure-Piemontese Domain) classically regarded as characterized by very low-grade metamorphic imprint [46,48,50,79]; (iii) the Late Cretaceous non metamorphic Helminthoid Flysch Unit [49,66,75,79], involved in collisional processes at very shallow crustal levels [62,75] and showing anchizone metamorphic and/or diagenetic imprint [50,73]. The Marguareis Unit extends along a NW-SE trend in the E-NE sectors of the study area (Figure 2a,c) and is represented by the Late Cretaceous-Paleocene(?) marly limestone deposits (Upega Formation, [80]) and the middle Eocene siliciclastic turbidite mixed with chaotic deposits (Boaria Formation, cf. Flysch Noir of [81]). The Helminthoid Flysch Unit instead covers the southwest sectors of the investigated area (Figure 2a,c) and is represented by its Late Cretaceous basal complex (San Bartolomeo Formation, cf. basal complexes of [79]) passing upward to the coarse-grained siliciclastic arenites (Bordighera Sandstone of [63]) and the calcareous turbiditic succession (San Remo Flysch) of Campanian-Maastrichtian age [82,83].

According to the structural reconstruction proposed by Sanità et al. [75] and Sanità et al. [62], each unit recorded a different pre-coupling deformation history, dealing with folding systems developed at different structural levels and timespan. During the coupling, the unit-bounding thrust surfaces developed and, in the field, they are marked by NW-SE striking high-strain cataclastic shear zone systems. After these thrusting events, the whole tectonic pile shares the same deformation history, the latter represented by a fold system...
with a horizontal axial plane and later a vertical to sub-vertical faulting [62,75]. According with [73,84,85], high-angle transtensive strike-slip faults segmented the whole tectonic pile without profoundly modifying the previous structural setting.

3. The Moglio-Testico Unit: Previous Interpretations

This unit was named “Serie Moglio-Testico” [46]. The authors documented a lower shale-rich portion (Moglio Shale of [86]) and an upper portion represented by marls interlayered with sandstones (Testico Formation of [86]), both of Late Cretaceous age and regarded as the remnants of an oceanic sedimentary cover. Subsequently, this unit was renamed Moglio-Testico Unit and its sedimentary sequence was investigated by many authors [47,48,50,77]. The latter reconstructed a sedimentary sequence detached from its original oceanic basement and composed by the Moglio Shale basal complex represented by thin beds of shales, arenites mixed with chaotic deposits consisting of block-in-matrix texture with clasts of arenites, carbonates and basalts, that pass upward to marly-arenaceous Testico Formation. The latter is composed of two members [48] which, from the bottom to the top, are: the shaly-arenaceous, with subordinated marls, Pieve di Teco Member and the arenaceous Cesio Member. The age of the formations is scarcely constrained. Based on the calcareous nannofossils content, [77,87] proposed a Late Cretaceous (Turonian)-Paleocene for the whole Moglio-Testico Unit.

Based on this stratigraphic dataset, the tectonic history of the Moglio-Testico Unit was constructed. Firstly, Ref. [79] documented the presence of anticlines and synclines with flat-lying axial planes confined to the Moglio-Testico Unit and showing a W-direct tectonic transport. This folding system is thought to have been developed during the coupling between the different units (i.e., the Helminthoid Flysch, at the top, and the Briançonnais Units at the bottom) during the building of the Alpine belt in a geodynamic frame characterized by an overall SW-direct horizontal movement.

Such structural architecture was supported by [88], which outlined the presence of SW-verging shear zones associated with the flat-lying folding system.

This structural model was subsequently improved by scientific contributions [66,89,90] which highlighted a much more complex structural evolution for the Moglio-Testico Unit achieved at shallower crustal levels under very low-grade metamorphic conditions [50]. These authors reconstructed a deformation history dealing with two opposite-verging fold systems. The first folding system produced SW-verging folds and top-to-SW shear zones, the latter marking the boundary of the unit [76,91,92]. The second fold system deformed all the previously described structures, including the unit-bounding shear zones and, therefore, it is shared by all the tectonic units. It produced NE-verging folds and is associated with a back-thrusting event already documented in other sectors of the southwestern Alps [93,94]. This structural model was confirmed by [49,66,95], and they document a subsequent km-scale folding event, the latter confined along the western sectors of the tectonic pile, and responsible both for the rotation of the previous folding event and for the local overturned relationships between different tectonic units (i.e., the Moglio-Testico Unit onto the Helminthoid Flysch Unit).

4. Methods

We used different techniques including field mapping, revision and upgrade of the sedimentary succession of the unit, structural and petrographic analyses, and thermobarometric estimates including thermodynamic modelling. The detailed stratigraphic reconstruction of the Moglio-Testico Unit was used as a marker to evaluate the strain and decipher the deformation history registered during subduction/exhumation.

Fieldwork was performed using a 1:10,000 scale topographic map and aimed to reconstruct the sedimentary and structural evolution of the Moglio-Testico Unit and to document the structural relationships between the other tectonic units cropping out in the area (the results of the fieldwork are summarized in the geological map of Figure 2a). The systematic collection of linear and planar structural data (i.e., fold axis, stretching and min-
erals lineations, axial planes, foliations, bedding) allowed tracking, in the geological map (Figure 2a), of the main axial plane traces associated with the folding deformation events. Such traces make explicit the overprinting relationships between different generations of fold systems. The mutual spatial relationships between linear and planar structural features are shown in stereographic projections.

During the fieldwork, selected key areas where crosscutting relationships between different deformation phases are clear were sampled. In these cases, we performed a detailed structural analysis in order to compare microstructural observations. The micro-deformation was studied on the meta-pelite samples (ED18 and ED91, see Figure 2a for the location of the samples) which were also used for the metamorphic characterization.

To estimate the $P$–$T$ conditions recorded by the unit, microstructural observations were rigorously carried out in order to check the optimal micro-domains in which the chlorite (Chl)–phengite (Phg) reached the equilibrium conditions. The strategy used in this work follows that proposed by [52]. The authors suggest that to quantify the metamorphic peak of rocks not fully re-equilibrated at different $P$–$T$ conditions and characterized by phases relic (i.e., detrital grains in meta-pelites) domains in which local chemical equilibrium is assumed to be reached between the mineral phases, in this case the Chl-Pgh couples (effective local chemical composition of [52]), must be carefully selected. In the selected micro-domains, the Chl-Pgh couples were in equilibrium, and, for this reason, the use of multi-equilibrium thermobarometry [53,96] was considered to estimate the $P$ and $T$ values. Thus, using calibrated X-ray compositional maps we can rigorously link the composition of the grains of Chl and Phg to microstructural domains (see S1, S2, S3 supplementary material). The temperature and pressure estimations were obtained by means of XmapTools and ChlMicaEqui software ([96,97], see the S1 Supplementary Materials for a detailed description of the software). We compare our results with the available geothermometer and geobarometer [57,98–100] to test the robustness of the obtained quantitative data.

5. Lithostratigraphy

In the investigated area, the Moglio-Testico Unit is characterized by an about 700 m thick turbiditic succession (Figure 2b) detached from its original oceanic basement according to [45,48,79,86,87] and showing an overall coarsening upward trend. The analysis of the calcareous nanofossils content was performed on 23 samples of marls, to constrain the age of the sedimentary sequence. Unfortunately, all the samples are barren. Therefore, the Late Cretaceous-Paleocene age range proposed by the previous authors [77,87] for the whole Moglio-Testico Unit is also used in this work also. The Unit, from the bottom to the top, consists of about 220 m of Palombini Shale (APA, Figure 3a–d; cf. Moglio Shale pp, [86] and Pieve di Teco Member pp, [48]) formation showing a plane-parallel bedding characterized by multi cm- to multi dm- thick beds of black siltstones and shales (Figure 3b) alternated with grey multi dm-thick beds of limestones showing a fine-grained arenitic bottom (Figure 3c,d).

According to [86], the stratigraphic features of these deposits indicate that the sedimentation occurred into a pelagic depositional environment. The APA formation passes upward to the 300m of the Pieve di Teco Formation (PTF, Figure 3a,e,f; cf. Pieve di Teco Member pp and the Cesio Member pp, [48]) with a plane parallel bedding that consists of decimeter-thick beds of marlstones alternated with centimeter to decimeter-thick beds of greyish marly-limestones and fine-grained arenitic turbidites, showing arkosic or sub-arkosic composition, topped by centimeter-thick layers of shales (F9 facies of [101]). The arenites/pelites (a/p) ratio is about $\leq$1. Normal grading, lamination and ripples are the most recurring sedimentary features. These sediments were deposited in a basin plane environment according to [47].
Figure 3. (a) 3D Image (from Google Earth Pro) showing the location of the outcrops (white boxes) of the Moglio-Testico Unit formations. The pale white SW-NE direct block indicates the orientation of the A-A’ geological cross section of Figure 2c. The pale green and blue areas indicate the boundary between the Palombini Shale (APA), the Pieve di Teco Formation (PTF) and the Cesio Formation (CSF); (b–d) Palombini Shale outcrops; (e,f) Pieve di Teco Formation outcrops; (g) Cesio Formation outcrop. S0: bedding.
The Pieve di Teco Formation passes upward to the Cesio Formation (CSF, Figure 3a,e; cf. the Cesio Member pp, [48]) which has a thickness of 150 m. It is characterized by centimeter-thick beds of medium- to fine-grained arenites, these showing a quartz-rich arkosic composition, and topped by centimeter-thick beds of blackish shales (F9 facies of [101]). The a/p ratio is about 1. Sedimentary features such as normal grading and plane parallel laminations can be observed. These turbidite deposits are related to a basin plane environment according with [48]. In the mapped area also chaotic deposits (Moglio Formation—MOF, cf. Moglio Shale pp of [86]) have been found as belonging to the succession of the Moglio-Testico Unit (Figure 2a,b). These deposits show a block-in matrix texture with centimeter- to decimeter-size fragments derived from the Palombini Shale, Pieve di Teco and Cesio Fms embedded in a shaly matrix (Figure 4a,b).

Figure 4. (a,b) Outcrop view of the Moglio Formation chaotic deposits. The orange dashed lines mark the boundary between the different clasts and the matrix. PTF: Pieve di Teco Formation; CSF: Cesio Formation.

The Moglio Fm. have been recognized in a stack of slices at the base of the Moglio-Testico Unit (Figure 2a,c). This stack includes slices of Palombini Shale, Piece di Teco Fm. And Moglio Fm. Unfortunately, the Moglio Fm. do not show stratigraphic relationships with the other formations of the Moglio-Testico Unit.

6. Strain Pattern

Structural analysis performed in the whole unit highlighted the strain pattern recorded by the Moglio-Testico Unit. The clear micro- to meso- to map-scale overprinting relationships between the different deformation events allowed reconstruction of their relative chronology. This approach revealed a deformation history dealing with the overprinting of pre-, syn- and post-coupling events represented by different generations of folding, thrusting and faulting. In the next section we present the deformation events in the following framework: pre-coupling folding events (D1-D2 phases, Figures 5 and 6) which are confined to the Moglio-Testico Unit; the syn-coupling thrusting event (Figure 7) which cut the axial planes of the pre-coupling folding and the post-coupling deformations affecting all the previous structures (post-coupling folding and later fault system, Figure 8).
Figure 5. Micro- and meso-photographs of the D1 and D2 phases’ structural features. (a) S1 foliation associated to F1 micro-fold (Palombini Shale). On the bottom left, a close-up of pirite with quartz-rich re-crystallization tails is evident; (b) Microphotographs of S1 and S2 foliation; (c) Mesoscopic F1 fold (Palombini Shale); (d) Micro-scale S2-S1 cross-cutting relationships (Pieve di Teco Formation); (e) Mesoscopic F2 fold deformed by post-coupling structures; (f) Meso-scale F2-F1 interference pattern (Palombini Shale). Chl1–2: D1 and D2 phase-related chlorite; Phg1–2: D1 and D2 phase-related phengite; S0: bedding; F1: D1 phase folding system; F2: D2 phase folding system; AP1: D1 phase-related axial plane; AP2: D2 phase-related axial plane.
scattered fold axis (A1, Figure 6). The axial planes (AP1) show a NW-SE strike and dips toward SW and NE with variable angles (Figure 6).

The D2 phase produced an S2 tectonic foliation well recognizable in the whole unit (Figure 5b,d) and showing a NW-SE strike and dips toward SW and NE (Figure 6). Especially, it is well recorded in the fine-grained rocks (i.e., marls and shales) and appears as a spaced foliation. At the microscale (Figure 5b,d), the S2 foliation is spaced to discrete crenulation cleavage highlighted by syn-metamorphic Phg2 + Chl2 ± Ab and Cc and stylolitic surfaces. Along the S2 foliation, both Phg 2 and Chl2 grains are thin, never exceeding 10–15 µm in length with sharp edges (Figure 5b). The S2 foliation is parallel to the axial planes (AP2) associated with the D2 folding event (Figure 5e,f). The latter is characterized by NW-SE trending tight SW-vergence F2 folds showing similar to parallel geometry and a NW-SE trending fold axis plunging toward SW and NE with ranging angles (Figure 6). The AP2 axial planes show a NW-SE strike and dipping toward SW and NE (Figure 6).

Figure 6. Stereonet of the D1 and D2 phase-related linear and planar structural features, lower hemisphere Schmidt equal area projection. S1: D1 phase tectonic foliation; L1: D1 phase mineralogical lineation; S2: D2 phase tectonic foliation; AP1: D1 phase axial plane; AP2: D2 phase axial plane; A1: D1 phase fold axes; A2: D2 phase fold axes.

Figure 7. Mesoscopic view of the lower (a) and upper (b) unit-bounding thrust systems. The red arrows indicate the sense of movement.
Figure 8. (a,b) Outcrop-scale post-coupling folds; on the bottom right the stereoplots of the related linear and planar structural features are shown; (c) Fault plane trace (black dashed lines) cutting the S2 foliation (red lines), Pieve di Teco Formation outcrop. The red arrows indicate the sense of movement. On the top left, the geometrical distribution of the fault planes is shown; (d) Mesoscale fault plane with striae; (e) Close-up of the fault plane of (d). The red arrows indicate the sense of displacement. S0: bedding; APPS: axial plane trace of post-coupling fold system.
6.1. Pre-Coupling Deformation

The D1 phase produced the oldest and pervasive S1 tectonic foliation (Figure 5a,b) showing a roughly NW-SE direction and dips toward NE and SW with various angles (Figure 6).

The S1 appears as continuous foliation in fine-grained lithotypes (marls and shales), while in the more competent rocks (limestone or coarser arenites) it appears as a spaced surface. At the microscale (Figure 5b, in the fine-grained lithotypes, the S1 foliation is a slaty cleavage mainly marked by the preferred orientation of Chl\(_1\) + Phg\(_1\) + Cc + Ab + K-Fsp \(\pm\) ox paragenesis and anastomosed stylolitic surfaces (mineral abbreviation of \([102]\)). Along the S1 foliation, detrital altered chlorites and phengites grains are also present showing coarser size (Chl\(_1d\) about 100 \(\mu\)m, Phg\(_1d\) about 50 \(\mu\)m) and both are characterized by frayed edges, chemical zoning, and re-crystallization tails (Figure 5b). In addition, rigid objects, like pyrites, showing asymmetric quartz-rich re-crystallized tails occur (Figure 5a) and these indicate shearing during the D1 phase. The Chl\(_1\) grains growth along the S1 are stocky, reaching 30–40 \(\mu\)m in size with undulose extinctions and sharp edges, and sometimes showing re-crystallization tails (Figure 5b). As with the Chl\(_1\), the Phg\(_1\) grains show undulose extinctions and sharp edges, but they are more elongated with length ranging from 20 to 30 \(\mu\)m (Figure 5b). Along the S1 foliation, NE-SW trending L1 mineral lineations (Figure 6) represented by quartz and calcite occur and they plunge toward the SW and NE. The S1 foliation is associated with a NW-SE striking fold system characterized by a NW-vergence isoclinal to sub-isoclinal F1 fold (Figure 5c) showing similar geometry, with a thickness hinge and attenuated limbs sometimes with evidence of boudinage, and scattered fold axis (A1, Figure 6). The axial planes (AP1) show a NW-SE strike and dips toward SW and NE with variable angles (Figure 6).

The D2 phase produced an S2 tectonic foliation well recognizable in the whole unit (Figure 5b,d) and showing a NW-SE strike and dips toward SW and NE (Figure 6). Especially, it is well recorded in the fine-grained rocks (i.e., marls and shales) and appears as a spaced foliation. At the microscale (Figure 5b,d), the S2 foliation is spaced to discrete crenulation cleavage highlighted by syn-metamorphic Phg\(_2\) + Chl\(_2\) \(\pm\) Ab and Cc and stylolitic surfaces. Along the S2 foliation, both Phg\(_2\) and Chl\(_2\) grains are thin, never exceeding 10–15 \(\mu\)m in length with sharp edges (Figure 5b). The S2 foliation is parallel to the axial planes (AP2) associated with the D2 folding event (Figure 5e,f). The latter is characterized by NW-SE trending tight SW-vergence F2 folds showing similar to parallel geometry and a NW-SE trending fold axis plunging toward SW and NE with ranging angles (Figure 6). The AP2 axial planes show a NW-SE strike and dipping toward SW and NE (Figure 6).

6.2. Syn-Coupling Event

The different tectonic units are bounded by shear zone systems showing NW-SE direction and dipping toward NE and SW (see geological map of Figure 2a). Similar structures were already described in \([62,76]\). However, there is no evidence of folding associated with this thrusting event. In the study area, we documented a lower and an upper shear zone system, both characterized by a thrust kinematics. The lower shear zone system separates the Moglio-Testico Unit from the underlying Helminthoid Flysch Unit, and it is marked by a high-strain strongly foliated cataclastic zone characterized by top-to-SW kinematic indicators (Figure 7a).

The uppermost shear zone system indeed separates the Marguareis Unit from the underlying Moglio-Testico Unit (Figure 2a,c). It appears as an intensively foliated cataclastic zone with kinematic indicators pointing toward SW (Figure 7b). In both the shear zone systems, only metamorphic re-crystallization of calcite and quartz grains occurs. The axial planes of the pre-coupling folding systems (D1-D2 phases) are cut by both the shear zone systems, making high-angle intersections. These observations suggest that the syn-coupling structures developed after these folding systems at shallower structural levels.
6.3. Post-Coupling Structures

All the previous structures, including the shear zone systems, are deformed in turn by a flat-lying folding system (Figure 8a,b; post-coupling fold system, PS).

The PS folds were documented in areas where vertical or sub-vertical layering, due to the previous deformation events, was observed. This folding event produced open PS folds showing parallel geometry with the NW-SE trending fold axis (A\textsubscript{PS}) and plunging toward NW and SE (Figure 8a,b) and sub-horizontal to gently southwestward-dipping axial planes (A\textsubscript{PS}).

The whole tectonic pile, including the PS fold system, is more lately segmented by a high-angle brittle fault system (Figures 2a and 8c,d,e). The latter shows a NE-SW arrangement and locally juxtaposes different tectonic units (Figure 2a). Along the fault planes, down-dipping striae, i.e., slicken lines, and slicken fibers, the latter suggesting normal kinematics, are present (Figure 8d,e). However, this faulting event and the post-coupling fold system seems not to profoundly modify the structural pattern of the Moglio-Testico Unit.

7. Metamorphism

The samples ED18 and ED91 were collected in the F1 and F2 hinge zones. In ED18, two different generations of Chl and Phg grains growth along the S1 and S2 foliation (Chl\textsubscript{1}-Phg\textsubscript{1} and Chl\textsubscript{2}-Phg\textsubscript{2}, respectively) have been sampled to perform thermobarometric estimations. In the sample ED91, only couples of Chl-Phg grown along the S1 foliation (Chl\textsubscript{1}-Phg\textsubscript{1}) have been found and treated for P–T calculations (see figures in the S2 section of the Supplementary Materials). In the next sub-sections, chemical features of the Chl-Phg pairs selected along the S1 and S2 foliations and the P and T estimation will be described (see Tables in the S3 section of the Supplementary Materials).

7.1. Mineral Composition

7.1.1. Sample ED18

The Chl\textsubscript{1} grains show a higher XMg content higher than Chl\textsubscript{2} (Figure 9a). The Chl\textsubscript{2} has more homogeneous Si a.p.f.u. (atoms per formula unit) content than Chl\textsubscript{1} (Figure 9a, see Table S1 in S3 Supplementary Materials), as well as the Al\textsubscript{tot} (2.31 and 2.85 and 2.89 and 3.22 a.p.f.u. in Chl\textsubscript{1} and Chl\textsubscript{2}, respectively—Figure 9b).

The Chl\textsubscript{1} grains are also characterized by end-members composition biased toward Clc+Dph with miscibility with Sud (never exceeding 40%, Figure 9c). The Chl\textsubscript{2} grains are instead characterized by Clc + Dph and Sud end-member proportions of 1:1. Am content of all the Chl types is always less than 30% and the vacancies less than 0.5 a.p.f.u. in almost all the grains (Figure 9c, see Table S1 on S3 Supplementary Materials).

The Phg\textsubscript{1} and Phg\textsubscript{2} grains have Si content of 3.10–3.35 and 3.10–3.54 a.p.f.u., respectively (Table S1 in S3 Supplementary Materials). The Al content is higher in Phg\textsubscript{2} (2.11–2.66 a.p.f.u. Figure) than Phg\textsubscript{1} (2.03–2.36 a.p.f.u.), which has instead variable K content (0.46–0.56 a.p.f.u.; Figure 9d,e). White mica end-member proportion is intermediate between Ms, Prl and Cel in both Phg\textsubscript{1} and Phg\textsubscript{2}, with the latter tending to Cel-free solid solution more than the former (Figure 9f). The Cel content is, however, less than 40% in both Phg\textsubscript{1} and Phg\textsubscript{2} (Figure 9f).
7.1. Mineral Composition

7.1.1. Sample ED18

The Chl1 grains show a higher XMg content higher than Chl 2 (Figure 9a). The Chl2 has more homogeneous Si a.p.f.u. (atoms per formula unit) content than Chl1 (Figure 9a, see Table S1 in S3 Supplementary Materials), as well as the Al tot (2.31 and 2.85 and 2.89 and 3.22 a.p.f.u. in Chl1 and Chl2, respectively—Figure 9b).

Figure 9. Geochemistry of chlorite (a–c) and phengite (d–f) selected on the X-ray calibrated maps of the samples ED18 and ED91 with XMapTools software [98]. Chlorite and phengite structural formulas are calculated assuming 14 and 11 oxygen, respectively.

7.1.2. Sample ED91

The chlorite grains (Chl1) grown along the S1 foliation show XMg values ranging between 0.35 and 0.47, while the Si- content ranges from 2.89 and 2.93 a.p.f.u. (Figure 9a, Table S1 on S3 supplementary material). The Al- and Mg- contents range between 2.43 and 2.96 a.p.f.u. and between 1.33 and 2.12 a.p.f.u., respectively (Figure 9b). The composition of Chl1 is close to those of Clc+Dph, with minor Sud, whereas Am end-member is almost absent (Figure 9c). The vacancy are less than 0.5 a.p.f.u. (Figure 9c).

The Phg1 grains have values of Si- content ranging between 3.20 and 3.32 a.p.f.u. and Al content is slightly variable (2.16–2.45 a.p.f.u., Figure 9d and Table S1 in S3 Supplementary Materials). The K in Phg1 varies between 0.50 and 0.69 a.p.f.u. (Figure 9e). The Phg1 grains show end-member compositions close to pure Ms (always higher than 70%) with a slightly lower content of Prl (less than 30%, Figure 9f).
7.2. P–T Conditions Estimation

The Chl-Qz-wt [54] and Phg-Qz-wt [103] methods based on the activity of chlorite and phengite end-members and the water activity were applied on the samples ED18 and ED91. The Chl-Qz-wt (for details about the method see the S1 Supplementary Materials) was used on the chlorites on S1 and S2 foliations. T range was calculated setting 30 °C of equilibrium tolerance and the percentage of Fe$^{3+}$ for each chlorite analysis setting 2 different pressure values (1.2, 1.0 GPa in this case) following the procedure of Lanari and Duesterhoeft [55] (T values were considered only when the scatter between different temperature values achieved by the four reactions was <30 °C, see the S1 Supplementary Materials for more details). Among them, the P values chosen are those for which the corresponding T range included a large number of analyses and are characterized by a homogeneous Fe$^{3+}$ content. The water activity was set to 0.8 in both samples for the presence of calcite (e.g., [59,104]).

Applying the Chl-Qz-wt method, chlorite crystals recrystallized along the S1 foliation (samples ED18 and ED91) and the S2 foliation (sample ED18) are found to be in equilibrium into different T ranges (Figure 10). In both samples, Chl$_1$ are stable in the range 200–330 °C, whereas T of Chl$_2$ of the sample ED18 ranges between 120 and 300 °C (Figure 10).

![Figure 10. P/T diagram showing the results of the thermobarometric estimation performed on the samples ED18 and ED91. The light blue and grey pale squares in the P/T space indicate the areas constrained by the Chl-qz-wt [54] and Phg-qz-wt [103] methods; the yellow and red small squares and circles indicate the P–T equilibrium conditions of single selected Chl-Phg couples (see S3 Supplementary Materials for more details) obtained with Chl-Phg-qz-wt [52] method. Along the Y and X axes the used geothermobarometers are reported with the range values related to D1 and D2 phases. [57,98–100].](image)

The Phg-Qz-wt method (for more details about the method see the S1 Supplementary Materials) was used to calculate the P conditions based on the Phg analysis included in the T range obtained with the Chl-Qz-wt method (with an uncertainty of 0.2 GPa). The optimal water content obtained is 0.96% for all the Phg groups processed (i.e., Phg$_1$ of ED18...
and ED91 and Phg\textsubscript{2} of ED18; see the S1 Supplementary Materials for more details). The resulting P ranges are 0.7 and 1.4 GPa for D1 phase in ED18 and ED91, and 0.2–1.0 GPa for the D2 phase estimated with Phg\textsubscript{2} of ED18 (Figure 10).

The Chl-Phg-Qz-wt method \cite{52} identified the Chl-Phg pairs related to S1 and S2 foliations which are in equilibrium under conditions of low free energy of Gibbs. The equilibrium tolerance that we have set above which the energy is considered too high to assume that the thermobarometric equilibrium is reached is <15,000 J. Figure 10 shows the matching between the P–T estimates calculated using the Chl-Phg-Qz-wt compared with the T and P ranges defined with the previous methods. Only the couples included between the P- and T-ranges obtained through the Chl-Qz-wt and Phg-Qz-wt have been considered (see the S1 Supplementary Materials for more details). The estimates suggest that the two different deformation events were accompanied by multistage metamorphic history. Two clusters of data were observed in the samples collected from the Moglio-Testico Unit (ED18 and ED91). The first set of data is related to first Chl\textsubscript{1}-Phg\textsubscript{1} generation grown along the S1 foliation and it is associated with metamorphic peak condition (P\text{peak} = 1.0–1.2 GPa and T\text{peak} = 330–260 °C); the second data set, still related to the S1 foliation, and the second set related to Chl\textsubscript{2}-Phg\textsubscript{2} couples related to the S2 foliation and show stability at LP-LT metamorphic conditions (P = 0.4–0.7 GPa and T = 230–170 °C).

The P–T ranges obtained in this work have been compared with the geothermometers and geobarometers available in the literature. For the chlorite grains grown along the S1 foliation, the semi-empirical calibration of \cite{99} yielded a temperature ranging from 230–320 °C and 150–300 °C for those grown along the S2 foliation. The calibration for low-temperature conditions (T < 400 °C), even if the amount of Fe\textsuperscript{3+} in chlorites is unknown \cite{56}, yielded a more restricted range (Figure 10). Using this calibration, we obtained a T range of 300–260 °C for chlorites in S1 and 250–150 °C for chlorites in S2 foliation. Using the thermometer of \cite{100} which is specifically for chlorites recrystallized in a T interval between 100 and 400 °C, 300–250 °C are the T values obtained for Chl\textsubscript{1} and 230–200 °C those related to the Chl\textsubscript{2}. P was instead calculated with the geobarometer of \cite{98}. The pressure ranges of the phengites grown along the S1 and S2 foliations are 1.5–0.9 GPa and of 0.9–0.2 GPa, respectively.

8. Discussion

8.1. The Moglio-Testico Unit Sequence: The Pre-Deformation Frame

The Moglio-Testico Unit is characterized by a sedimentary succession detached from its original oceanic basement according to previous authors (i.e., \cite{46,48,77,86,87,105}). However, the Moglio-Testico Unit succession suggests a different sedimentary evolution, supported by our new stratigraphic dataset discussed in the following. The described sedimentary and stratigraphic features indicate a transition from pelagic/hemipelagic (here represented by the Palombini Shale; cf. Moglio Shale pp of \cite{86}; and Pieve di Teco Member pp of \cite{48}) to fine-grained turbidite deposits related to basin plane environment (Pieve di Teco Formation and Cesio Formation; cf. Pieve di Teco Member and Cesio Member, respectively, of \cite{48}) with an upward increasing of the siliciclastic component. The chaotic deposits occurring within a tectonic slice are made up by centimeter- to decimeter-sized blocks embedded into a shaly matrix. The lithologies from the blocks that derive from the youngest formations (i.e., Cesio Formation and/or Pieve di Teco Formation) documented in the mapped area, suggested that these deposits are at the top of the succession of the Moglio-Testico Unit. These observations seem to suggest a different evolution of the Moglio-Testico Unit with respect those proposed until now. A similar sedimentary sequence was described for the Internal Ligurian Units exposed in the Northern Apennine (\cite{106,107} and quoted references). In fact, these units are composed of a Jurassic oceanic basement with radiolarites (Diaspri Formation), an Early Cretaceous oceanic cover (i.e., Calpionella Limestone and Palombini Shale), a Late Cretaceous turbiditic sequence (Manganeseiferi Shale, Monteverzi Marl, Zonati Shale, Gottero Sandstone; \cite{107–109}) topped by Late Cretaceous-Paleocene trench/slope chaotic deposits (Bocco Shale, see \cite{110,111} for
further details). The Internal Ligurian Unit sequence is regarded as reflecting the sedimentary evolution of an area of the Ligurian Piedmont oceanic lithosphere approaching the subduction zone before to be underthrusted, accreted and subsequently exhumed into the alpine accretionary wedge [106,107]. The Internal Ligurian Units succession was recently used as proxy to unravel the tectonic evolution of other oceanic-derived units cropping out in the Western Alps [44,112] where primary features (i.e., stratigraphic and sedimentary features) are partially or completely deleted because of the strong deformation recorded by all of them. For these reasons, we suggest that the Internal Ligurian Units succession can be a powerful tool to also decipher the sedimentary evolution of the Moglio-Testico Unit. In fact, the sequence of the Moglio-Testico Unit reconstructed in this work seems to correspond, at least partially, with that largely described of the Internal Ligurian Units. This interpretation allowed us to re-appraise the stratigraphic meaning of the chaotic deposits of the Moglio Shale classically located at the bottom of the Moglio-Testico Unit sequence. Our stratigraphic observations indicate that the Moglio Shale chaotic deposits show characteristics typically described for the trench/slope deposits largely documented at the top of the Internal Ligurian Unit sedimentary sequence and exposed in the Northern Apeninnes (cf. Bocco Shale of [110]). Therefore, in this frame, we propose that the sequence of the Moglio-Testico Unit can be considered as witness of a sedimentary oceanic cover approaching the alpine subduction zone.

8.2. Tectonic Interpretation

The structural data the Moglio-Testico Unit highlighted a much more complex deformation history than proposed by previous authors [50,66,76,95] dealing with the superposition of pre-, syn- and post-coupling events. Two pre-stacking deformation phases (D1 and D2) have been recognized and they can be well observed in the whole tectonic unit. D1 phase produced the S1 tectonic foliation associated with a SW-vergence similar fold system and characterized by the oldest metamorphic assemblage recognized in this unit. The structural features associated with the D1 phase suggest its development during high-strain conditions, i.e., in a ductile shear zone characterized by a top-to-SW sense of movement. The D2 phase is instead associated with a F2 folding event producing parallel to similar tight folds associated with a well-developed S2 crenulation cleavage. After retrodeformation from the subsequent syn- and post-coupling events, the D2 folds show a NE-vergence and a flat-lying axial plane or gently dipping toward SW. The structural model proposed by [95], according to [66], proposed a structural model in which the different vergence of the folding systems recognized in different areas, i.e., in the external (toward West) and in the internal (toward East) sectors of the unit, is due to a regional-scale folding event affecting the whole unit including the unit-bounding thrust surfaces. However, in this work no evidence of this regional-scale folding event affecting the whole Moglio-testico Unit was observed. Thus, bearing this in mind, we believe that the present-day geometry and vergence of the D2 folding events do not correspond to that event. Its current attitudes (geometry and vergence) are, therefore, the results of the subsequent deformation events i.e., thrusting (syn-coupling events), folding and, lately, faulting (post-coupling events).

The thrust surfaces developed during the syn-coupling events are all characterized by a top-to-SW sense of movement. They cut the axial planes of all the previously described structures indicating a clear relative chronology between each other as is appreciable in the geological map of Figure 2a. The meso- and micro-structural observations on thrust surfaces suggest their development at shallow structural levels, and they are also responsible for the present-day structural architecture of the stack of units before the post-coupling structures development. This syn-coupling tectonic was already largely documented by previous authors in the Upega area [100], and in the southwestern sector of the Marguareis Massif to North (syn-stacking tectonics of [75,113]). The same authors call for the role played by the syn-coupling tectonics, invoking their paramount importance during the tectonic evolution of this sector of the Alpine belt. In fact, the authors proposed that this syn-coupling tectonics is responsible first for the thrusting (in-sequence thrust) of the Helminthoid
Flysch Unit onto the already exhumed Briançonnais Units; and then for the thrusting (with an out-of-sequence thrust) of the Briançonnais Units (here represented by the Marguareis Unit) onto the Helminthoid Flysch Unit.

The stacks recognized in the investigated area include the Helminthoid Flysch Unit at the bottom, the Moglio-Testico Unit, and the Marguareis Unit at the top (Figure 2a,c) separated by the upper and lower thrust systems. These thrusts can be regarded as the result of the SW-vergence out-of-sequence thrusting event already described in this area of the Southwestern Alps [62,64,65,75,113]. Thus, this out-of-sequence event would be responsible for the thrusting of the Briançonnais Units (here the Marguareis Unit) onto the Moglio-Testico Unit, and for the latter onto the Helminthoid Flysch Unit.

The post-coupling tectonics are represented by the PS fold with sub-horizontal axial planes and a rarely observed tectonic foliation without evidence of metamorphic recrystallization and subsequent high-angles faulting. They deformed all the previously described structures including the thrust surfaces and resulted in vertical shortening developed at very shallow crustal levels. This kind of deformation is typically associated with the very shallow tectonic levels, the latter already documented in other sectors of the Alps [62,75,94,113–115]. A high-angle normal to transcurrent fault system cuts at high-angle all the previously described structures, including the thrust surface and the PS fold system. They locally juxtapose different tectonic units (see the map of Figure 2a) without profoundly modify the pre-existing stack. We regard this faulting as the shallowest deformation event developed during the final stage of the deformation history of the Moglio-Testico Unit, playing a later and not significant role in its tectonic evolution.

8.3. P–T Path

Contrary to the previous authors [50,69], which considered the Moglio-Testico Unit as characterized by a very low-grade metamorphic imprint based on the distribution of the illite crystallinity, P–T estimates obtained from Chl-Phg couples grown during the D1 and D2 events portray a P–T path typical (Figures 10 and 11) of the oceanic subduction setting [34,116].

In Figure 11, the pale green ellipsis representing the P–T estimates obtained in this work, with the related uncertainties, indicate HP-LT metamorphism. They are aligned along a geothermal gradient of 8 °C/km coherent with the range of the subduction gradient estimated for the Schistes Lustrés complex cropping out in the Western Alps (5–10 °C/km, [3]).

The P–T estimates indicate that no prograde path is recorded and that the chlorite and phengite grains growth along the S1 and S2 foliations portrayed the retrograde one only. The metamorphic peak conditions of 1.2–1.0 GPa and 330–260 °C were recorded by the chlorite-phengite pairs grown during the D1 phase (Figures 10 and 11), testifying thus the underthrusting and accretion of the Moglio-Testico Unit into the Alpine wedge. The D2 phase is instead characterized by chlorite-phengite couples re-equilibrated at 0.7–0.4 GPa and 230–170 °C (Figures 10 and 11) without significant heating events. Therefore, P–T estimates for the D2 phase constrain the retrograde path of the Moglio-Testico Unit, indicating exhumation toward shallower crustal levels into the Alpine wedge during this deformation phase. The different P values recorded by the Phg1 and Pgh2 are of paramount importance because they are the witnesses of vertical movement of this unit into the Alpine accretionary wedge, i.e., from the deeper up to shallower structural levels as already documented for other oceanic units cropping out in in the Western Alps [3,6].

In this scenario, the distribution of the illite crystallinity performed by [50], indicating temperature conditions corresponding to the anchizone (200–250 °C) for the Moglio-Testico Unit, could seem apparently in contrast with the results obtained in this work. However, the illite crystallinity was measured on very smaller grain (<2 µm) of phyllosilicates [50], which are mostly located along the S2 foliation. This observation suggests that the temperatures estimated by [50] are related to the D2 deformation event (probably recorded by white mica grains during the final stage of the exhumation) and, therefore, they do not
represent the $T$ peak recorded by the Moglio-Testico Unit during its metamorphic history. In our scenario, the temperature estimation obtained by means of illite crystallinity [50] and indicating metamorphic conditions related to the anchizone region, is coherent with the temperature conditions estimated for the D2 phase recorded by the Moglio-Testico Unit during its exhumation.

Figure 11. $P$–$T$ path of the Moglio-Testico Unit (pale green thin arrow in the $P/T$ space) obtained in this work. The $P$–$T$ paths related to the oceanic-derived units exposed along the Western Alps are also reported (thick green lines in the $P/T$ space, Schistes Lustrés complex data from [3,6,36,42]). The green elliptic areas indicate the point clouds reported in the $P/T$ diagram of Figure 10.

The exhumation pattern continues with the subsequent deformation events, including the thrusting and post-coupling structures, the latter developed at very shallow crustal levels. This kind of HP-LT path was already described in other sectors of the Western Alps [6,33,35,36,44,117] for the oceanic units including their cover rocks. However, some authors proposed different strain patterns for the Moglio-Testico Unit [118].

8.4. Timing Constraints for the Moglio-Testico Unit Tectonic Evolution

The absolute ages of the deformation events described in this work and affecting the Moglio-Testico Unit are poorly constrained. Taking in mind the paleontological time ranges proposed by [77], the Paleocene is assumed to be a minimum age for the development of the pre-coupling deformation events. The maximum age is more difficult to constrain. In fact, the thrust surfaces described in this work and separating the three tectonic units are poorly constrained. The late Eocene-early Oligocene timespan [119] was proposed for the thrusting of the Helminthoid Flysch Unit onto the Briançonnais Units based on the U-Th/He method on zircons. The same timespan was subsequently confirmed in the
tectonic evolutionary model of [62,75], proposing a late Eocene-early Oligocene timespan for the thrusting events responsible for the coupling of the units in the southwest sectors of the Marguareis Massif and in the Upega areas. Based on these observations and given the present-day structural position of the Moglio-Testico Unit in the nappe pile and the crosscutting relationships between the syn- and pre-coupling structures, we propose a Paleocene-late Eocene timespan for the development of the D1 and D2 deformation events. This age range was proposed also for other oceanic-derived tectonic units exposed in the Western Alps [3–5] and for the Internal Ligurian Units in the Northern Apennines [106,107]. Based on the reconstruction proposed in this work, the post-coupling structures developed starting from the early Oligocene age in accordance with [62,75].

9. Conclusions

In this work original stratigraphic, structural and thermo-barometric datasets about the Moglio-Testico Unit are presented. Our results allowed us to re-appraise the sedimentary evolution of the Moglio-Testico Unit as well as to constrain the Pressure-Temperature-Deformation path recorded during its deformation history. Our results indicate that:

- The Moglio-Testico Unit is characterized by a Late Cretaceous-Paleocene sedimentary cover characterized by the transition from pelagic to basin plain turbidite and chaotic deposits. These features are coherent with the migration of a portion of oceanic lithosphere toward the subduction zone, as proposed for the Internal Ligurian Units in the Northern Apennines.
- The deformation strain pattern and P–T estimates recorded by the Moglio-Testico Unit are compatible with initial metamorphism in a subduction zone and subsequent accretion and exhumation into the Alpine accretionary wedge and recorded by HP-LT metamorphism associated to the D1 and D2 phases.
- Metamorphic peak conditions were achieved during the D1 phase (1.2–1.0 GPa and 330–260 °C). The exhumation toward shallow crustal levels started during the D1 phase and continued during the D2 event at lower P–T conditions (0.7–0.4 GPa and 230–170 °C). This tectono-metamorphic evolution is probably Paleocene-late Eocene. The subsequent syn-coupling (thrust surfaces) and post-coupling structures (folding and faulting) deformed all the previously described structures and developed at shallower structural levels during the Alpine collisional phase. The first, as already suggested by previous authors, played a key role in the tectonic evolution of the units in this sector of the belt and they are responsible for their coupling; the second testify to the last stage of the deformation history of the Moglio-Testico Unit and did not deeply modify the whole stack.
- Based on our results, we suggest that the Moglio-Testico Unit represents a further HP/LT metamorphic slice derived from the oceanic lithosphere of the Ligure-Piemontese basin.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min12111343/s1. Material S1: Thermobarometry, S2. Supplementary figures and diagrams. Figure S1: Fe in chlorite in the micromap of sample ED18 (intensity map: Fe Kα), Figure S2: K in phengite in the micromap of sample ED91 (intensity map: K Kα), Figure S3: Distribution of pressure in sample ED18, S3. Supplementary tables, Table S1: Chlorite and phengite analysis selected on X-ray calibrated map with XMapTools software.

Author Contributions: Conceptualization, E.S., J.-M.L., M.M. and L.P.; methodology, E.S. and M.D.R.; software, E.S. and M.D.R.; validation, M.D.R., J.-M.L., M.M. and L.P.; formal analysis, E.S., M.D.R. and J.-M.L.; investigation, E.S.; resources, M.M. and L.P.; data curation, E.S., M.D.R.; writing—original draft preparation, E.S.; writing—review and editing, E.S., M.D.R., J.-M.L., M.M. and L.P.; visualization, E.S., M.D.R.; supervision, J.-M.L., M.M. and L.P.; project administration, E.S. and L.P.; funding acquisition, M.M. and L.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.
**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Acknowledgments:** We thank the reviewers for their critical and stimulating suggestions. We thank Andrea Risplendente for technical support during EPMA data acquisition. This study was supported by University of Pisa (PRA project).

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Lagabrielle, Y. Les Ophiolites: Marqueurs de l’histoire Tectonique des Domaines Océaniques. Ph.D. Thesis, Univ. Bretagne Occidentale, Brest, France, 1987.
2. Lemoine, M.; Tricart, P. Les Schistes Lustrés piémontais des Alpes Occidentales: Approche stratigraphique, structurale et sédimentologique. *Ec. Geol. Hel.* **1986**, *79*, 271–294.
3. Agard, P.; Jolivet, L.; Goffe, B. Tectonometamorphic evolution of the Schistes Lustrés Complex: Implications for the exhumation of HP and UHP rocks in the western Alps. *Bull. Soc. Geol. Fr.* **2001**, *172*, 617–636. [CrossRef]
4. Dal Piaz, G.V. The Italian Alps: A journey across two centuries of Alpine geology. *J. Virt. Explor.* **2010**, *36*, 77–106. [CrossRef]
5. Schmid, S.M.; Fügenschuh, B.; Kissling, E.; Schuster, R. Tectonic map and overall architecture of the Alpine orogen. *Ec. Geol. Hel.* **2004**, *97*, 93–117. [CrossRef]
6. Agard, P. Subduction of oceanic lithosphere in the Alps: Selective and archetypal from (slow-spreading) oceans. *Earth Sci. Rev.* **2021**, *214*, 103517. [CrossRef]
7. Molli, G.; Crispini, L.; Malusà, M.G.; Mosca, M.G.; Piana, F.; Federico, L. Geology of the Western Alps-Northern Apennine junction area—A regional review. *J. Virt. Explor.* **2010**, *36*, 1–49. [CrossRef]
8. Handy, M.R.; Schmid, S.M.; Bousquet, R.; Kissling, E.; Bernoulli, D. Reconciling plate tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps. *Earth Sci. Rev.* **2010**, *102*, 121–158. [CrossRef]
9. Spalla, M.I.; Zanon, D.; Marotta, A.M.; Rebay, G.; Roda, M.; Zucali, M.; Gosso, G. The transition from Variscan collision to continental break-up in the Alps: Insights from the comparison between natural data and numerical model predictions. *Geol. Soc. London Spec. Publ.* **2014**, *405*, 363–400. [CrossRef]
10. Schmid, S.M.; Kissling, E.; Diehl, T.; Van Hinsbergen, D.J.J.; MOLLI, G. Ivrea mantle wedge, arc of the Western Alps, and kinematic evolution of the Alps–Apennines orogenic system. *Swiss J. Geosc.* **2017**, *110*, 581–612. [CrossRef]
11. Marotta, A.M.; Roda, M.; Conte, K.; Spalla, M.I. Thermo-mechanical numerical model of the transition from continental rifting to oceanic spreading: The case study of the Alpine Tethys. *Geol. Mag.* **2018**, *155*, 250–279. [CrossRef]
12. Roda, M.; Regorida, A.; Spalla, M.I.; Marotta, A.M. What drives A lpine T ethys opening? Clues from the review of geological data and model predictions. *Geol. J.* **2019**, *54*, 2646–2664. [CrossRef]
13. Agard, P.; Handy, M. Ocean subduction dynamics in the Alps. *Elements* **2021**, *17*, 9–16. [CrossRef]
14. Thöni, M.; Miller, C.; Zanetti, A.; Habler, G.; Goessler, W. Sr–Nd isotope systematics of high-REE accessory minerals and major phases: ID-TIMS, LA-ICP-MS and EPMA data constrain multiple Permian–Triassic pegmatite emplacement in the Koralpe, Eastern Alps. *Chem. Geol.* **2008**, *254*, 216–237. [CrossRef]
15. Rebay, G.; Zanon, D.; Langone, A.; Luoni, P.; Tiepolo, M.; Spalla, M.I. Dating of ultramafic rocks from the Western Alps ophiolites discloses late Cretaceous subduction ages in the Zermatt–Saas Zone. *Geol. Mag.* **2018**, *155*, 298–315. [CrossRef]
16. Polino, R.; Gosso, G.; Dal Piaz, G.V. Un modello attualistico sulla genesi delle Alpi. *Mem. Soc. Geol. It.* **1990**, *45*, 71–75.
17. Lardeaux, J.M.; Spalla, M.I. From granulites to eclogites in the Sesia Zone (Italian Western Alps): A record of the opening and closure of the Piemont Ocean. *J. Metam. Geol.* **1991**, *9*, 35–59. [CrossRef]
18. Gerya, T.; Stöckhert, B. Two-dimensional numerical modeling of tectonic and metamorphic histories at active continental margins. *Int. J. Earth Sc.* **2006**, *95*, 250–274. [CrossRef]
19. Roda, M.; Spalla, M.I.; Marotta, A.M. Integration of natural data within a numerical model of ablative subduction: A possible interpretation for the Alpine dynamics of the Austroalpine crust. *J. Metam. Geol.* **2012**, *30*, 973–996. [CrossRef]
20. Chopin, C. Coesite and pure pyrope in high-grade blue schists of the western Alps: A first record and some consequences. *Cont. Min. Petrol.* **1984**, *86*, 107–118. [CrossRef]
21. Duchene, S.; Lardeaux, J.M.; Albarède, F. Exhumation of eclogites: Insights from depth-time path analysis. *Tectonophysics* **1997**, *280*, 125–140. [CrossRef]
22. Rubatto, D.; Hermann, J. Exhumation as fast as subduction? *Geology* **2001**, *29*, 3–6. [CrossRef]
23. Simon-Labric, T.; Rolland, Y.; Dumont, T.; Heymes, T.; Authemayou, C.; Corsini, M.; Fornari, M. $^{40}$Ar/$^{39}$Ar dating of Penninic Front tectonic displacement (W Alps) during the Lower Oligocene (31–34 Ma). *Terra Nova* **2009**, *21*, 127–136. [CrossRef]
24. Bellashen, N.; Mouthereau, F.; Boutoux, A.; Bellanger, M.; Lacombe, O.; Jolivet, L.; Rolland, Y. Collision kinematics in the western external Alps. *Tectonics* **2014**, *33*, 1055–1088. [CrossRef]
25. Coward, M.P.; Dietrich, D. Alpine tectonics—An overview. In *Alpine Tectonics*; Coward, M.P., Dietrich, D., Park, R.G., Eds.; Special Publication: London, UK, 1989; Volume 45, pp. 1–29.
26. Dal Piaz, G.V.; Bistacchi, A.; Massironi, M. Geological outline of the Alps. *Episodes* **2003**, *26*, 175–180. [CrossRef]
27. Rosenbaum, G.; Lister, G.S.; Duboz, C. Relative motions of Africa, Iberia and Europe during Alpine orogeny. *Tectonophysics* **2002**, *359*, 117–129. [CrossRef]
28. Stampfli, G.M.; Borel, G.D.; Cavazza, W.; Mosar, J.; Ziegler, P.A. Paleotectonic and paleogeographic evolution of the western Tethys and Peri Tethyan domain (ICGP Project 369). *Episodes* **2001**, *24*, 222–228. [CrossRef]
29. Lemoine, M.; Trumpy, R. Pre-oceanic rifting in the Alps. *Tectonophysics* **1987**, *133*, 305–320. [CrossRef]
30. Dewey, J.F.; Helman, M.L.; Turco, E.; Hutton, D.H.W.; Knott, S.D. Kinematics of the western Mediterranean. In *Alpine Tectonics*; Coward, M.P., Dietrich, D., Park, R.G., Eds.; Special Publication: London, UK, 1989; Volume 45, pp. 265–283.
31. Wortmann, U.G.; Weisshart, H.; Funk, H.; Hauck, J. Alpine plate kinematics revisited: The adria problem. *Tectonics* **2001**, *20*, 134–147. [CrossRef]
32. Stampfli, G.M.; Borel, G.D. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth Plan. Sc. Let.* **2002**, *196*, 17–33. [CrossRef]
33. Agard, P.; Yamato, P.; Jolivet, L.; Burov, E. Exhumation of ocean blueschists and eclogites in subduction zones: Timing and mechanisms. *Earth-Sci. Rev.* **2009**, *92*, 53–79. [CrossRef]
34. Lardeaux, J.M. Deciphering orogeny: A metamorphic perspective. Examples from European alpine and Variscan belts. *Bull Soc. Géol. E Fr.* **2014**, *185*, 93–114. [CrossRef]
35. Schwartz, S.; Lardeaux, J.M.; Tricart, P.; Guillot, S.; Labrin, E. Diachronous exhumation of HP–LT metamorphic rocks from south-western Alps: Evidence from fission-track analysis. *Terra Nova* **2007**, *19*, 133–140. [CrossRef]
36. Agard, P.; Plunder, A.; Angiboust, S.; Bonnet, G.; Ruh, J. The subduction plate interface: Rock record and mechanical coupling (from long to short time scales). *Lithos* **2018**, *320–321*, 537–566. [CrossRef]
37. Balestro, G.; Festa, A.; Borghi, A.; Castelli, D.; Gattiglio, M.; Tartarotti, P. Role of Late Jurassic intra-oceanic structural inheritance in the Alpine tectonic evolution of the Monviso meta-ophiolite Complex (Western Alps). *Geol. Mag.* **2017**, *155*, 233–249. [CrossRef]
38. Bearth, P. Die Ophiolithe der Zone von Zermatt–Saas-Fee; Stämpfli and Cie: Bern, Switzerland, 1967.
39. Philippot, P. Opposite vergence of nappes and crustal extension in the French–Italian Western Alps. *Tectonics* **1990**, *9*, 1143–1164. [CrossRef]
40. Schwartz, S.; Guillot, S.; Reynard, B.; Lafay, R.; Nicollet, C.; Debret, B.; Auzende, A.L. Pressure–temperature estimates of the lizardite/antigorite transition in high pressure serpentinites. *Lithos* **2013**, *178*, 197–210. [CrossRef]
41. Lagabrielle, Y.; Brovarone, A.V.; Ildefonse, B. Fossil oceanic core complexes recognized in the blueschist metaophiolites of Western Alps and Corsica. *Earth-Sci. Rev.* **2015**, *141*, 1–26. [CrossRef]
42. Herviou, C.; Agard, P.; Plunder, A.; Mendes, K.; Verlaguet, A.; Deldicque, D.; Cubas, N. Subducted fragments of the Liguro-Piemont ocean, Western Alps: Spatial correlations and offscraping mechanisms during subduction. *Tectonophysics* **2022**, *827*, 229267. [CrossRef]
43. Balestro, G.; Festa, A.; Dilek, Y.; Tartarotti, P. Pre-Alpine extensional tectonics of a peridotite-localized oceanic core complex in the late Jurassic, high-pressure Monviso ophiolite (Western Alps). *Episodes* **2015**, *38*, 266–282. [CrossRef]
44. Ellero, A.; Loprieno, A. Nappe stack of Piemonte-Ligurian units south of Aosta Valley: New evidence from Urtier Valley (Western Alps). *Geol. J.* **2017**, *53*, 1665–1684. [CrossRef]
45. Luoni, P.; Zanoni, D.; Rebay, G.; Spalla, M.I. Deformation history of Ultra High-Pressure ophiolitic serpentinites in the Zermatt-Saas Zone, Crétone, Upper Valtournanche (Aosta Valley, Western Alps). *Ophiolit* **2019**, *44*, 111–123.
46. Lanteaume, M.; Haccard, D. Stratigraphie et variation de facies de formations constitutives de la nappe du Flysch à Helminthoides des Alpes Maritimes franco-italiennes. *Bol. Soc. Geol. It.* **1962**, *80*, 101–113.
47. Boni, A.; Vanossi, M. Carta geologica dei terreni compresi tra il Brianzono ligure s.l. ed il Flysch ad Elmntoidi s.s. *At. Is. Geol. Univ. Pavia* **2014**, 23, plate 24.
48. Marini, M. Litol. Strat. E Sedimentol. Della Form. Di Testico (Alpi Marittime Liguri). *Boll. Soc. Geol. It.* **1995**, *114*, 497–516.
49. Marini, M.; Terranova, R. Nuovi dati sulla litotratigrafia dei flysch della Liguria occidentale e sui loro rapporti strutturali. *At. Soc. Tos. Sc. Nat.* **1985**, *92*, 95–163.
50. Bonazzi, A.; Cobianchi, M.; Galiatti, B. Primi dati sulla cristallinità dell’illite nelle unità tettoniche più esterne e strutturalmente più elevate delle Alpi Liguri. *At. Tic.I Sc. Ter.* **1987**, *31*, 63–77.
51. Frey, M.; Robinson, D. Low-Grade Metamorphism; Blackwell Science: Oxford, England, 1999.
52. Lanari, P.; Engi, M. Local bulk composition effects on metamorphic mineral assemblages. *Rev. Min. Geochem.* **2017**, *83*, 55–102. [CrossRef]
53. Vidal, O.; Parra, T. Exhumation paths of high-pressure metapelites obtained from local equilibria for chlorite-phenelite assemblage. *Geol. J.* **2000**, *35*, 139–161. [CrossRef]
54. Vidal, O.; De Andrade, V.; Lewin, E.; Munoz, M.; Parra, T.; Pascalelli, S. P-T deformation Fe3+/Fe2+ mapping at the thin section scale and comparison with XANES mapping: Application to a garnet-bearing metapelite from the Sambagawa metamorphic belt (Japan). *J. Metam. Geol.* **2006**, *24*, 669–683. [CrossRef]
55. Lanari, P.; Duesterhoeft, E. Modeling metamorphic rocks using equilibrium thermodynamics and internally consistent databases: Past achievements, problems and perspectives. *J. Petrol.* **2019**, *60*, 19–56. [CrossRef]
56. Lanari, P.; Guillot, S.; Schwartz, S.; Vidal, O.; Tricart, P.; Riel, N.; Beyssac, O. Diachronous evolution of the alpine continental subduction wedge: Evidence from P-T estimates in the Briançonnais zone houillère (France-Western Alps). *J. Geodyn.* **2012**, *56*, 39–54. [CrossRef]
57. Lanari, P.; Wagner, T.; Vidal, O. A thermodynamic model for di-treocahedral chlorite from experimental and natural data in the system MgO-FeO-Al_2O_3-SiO_2-H_2O: Applications to P-T sections and geothermometry. *Cont. Min. Petrol.* 2014, 167, 968. [CrossRef]
58. Malasoma, A.; Marroni, M. HP/LT metamorphism in the Volparone Breccia (Northern Corsica, France): Evidence for involvement of the Europe/Corsica continental margin in the Alpine subduction zone. *J. Metam. Geol.* 2007, 25, 529–545. [CrossRef]
59. Di Rosa, M.; Frassi, C.; Meneghini, F.; Marroni, M.; Pandolfi, L.; De Giorgi, A. Tectono-metamorphic evolution in the European continental margin involved in the Alpine subduction. New insights from the alpine Corsica, France. *C. R. Geosci.* 2019, 351, 384–394. [CrossRef]
60. Frassi, C.; Di Rosa, M.; Farina, F.; Pandolfi, L.; Marroni, M. Anatomy of a deformed upper crust fragment from western alpine Corsica (France): Insights into continental subduction processes. *Int. Geol. Rev.* 2022, 64, 1–21. [CrossRef]
61. Sanità, E.; Di Rosa, M.; Lardeaux, J.M.; Marroni, M.; Pandolfi, L. Metamorphic peak estimates of the Marguareis Unit (Briançonnais Domain): New constrains for the tectonic evolution of the south-western Alps. *Terra Nova* 2022, 34, 305–313. [CrossRef]
62. Sanità, E.; Lardeaux, J.M.; Marroni, M.; Padolfi, L. Kinematics of the Helminthoid Flysch-Marguareis Unit tectonic coupling: Consequences for the tectonic evolution of the Western Alps. *C. R. Geosci.* 2022, 354, 141–157. [CrossRef]
63. Sagri, M. Litologia, stratimetria e sedimentologia delle torbiditi di piana di bacino del Flysch di San Remo (Cretaceo superiore, Liguria occidentale). *Mem. Soc. Geol. Lt.* 1984, 28, 577–586.
64. Seno, S.; Dallagiovanna, G.; Vanossi, M. Palaeogeography and thrust development in the Penninic domain of the Western Alpine Chain: Examples from the Ligurian Alps. *Bol. Soc. Geol. lt.* 2003, 122, 223–231.
65. Seno, S.; Dallagiovanna, G.; Vanossi, M. A kinematic evolutionary model for the Penninic sector of the central Ligurian Alps. *Int. J. Earth Sci.* 2005, 94, 114–129. [CrossRef]
66. Vanossi, M.; Cortesogno, L.; Galbiati, B.; Messiga, B.; Piccardo, G.; Vannucci, M. Geologia delle Alpi Liguri: Dati, problemi, ipotesi. *Mem. Soc. Geol. lt.* 1986, 28, 5–75.
67. Lemoine, M.; Bas, T.; Arnaud-Vanneau, A.; Arnaud, H.; Dumont, T.; Gidon, M.B.; De Graciansky, P.C.; Rudkiwicz, J.L.; Megard-Galli, J.; Tricart, P. The continental margin of the Mesozoic Tethys in the Western Alps. *Mar. Pet. Geol.* 1986, 3, 179–199. [CrossRef]
68. Decaris, A.; Dallagiovanna, G.; Lualdi, A.; Maino, S.; Seno, S. Stratigraphic evolution in the Ligurian Alps between Variscan heritages and the Alpine Tethys opening: A review. *Earth-Sci. Rev.* 2013, 125, 43–68. [CrossRef]
69. Messiga, B.; Oxilia, M.; Piccardo, G.B.; Vanossi, M. Fasi metamorfiche alpine nel Brianzonese e Prepiemontese esterno delle Alpi liguri: Un possibile modello evolutivo. *Ren. Soc. It. Min. Pet.* 1981, 38, 261–280.
70. Cabella, R.; Cortesogno, L.; Dallagiovanna, G.; Vannucci, R.; Vanossi, M. Vulcanismo, sedimentazione e tettonica nel Brianzone ligure esterno durante il Permo-Carbonifero. *At. Tic. Sc. Ter.* 1988, 31, 269–296.
71. Capponi, G.; Crispini, L. Structural and metamorphic signature of alpine tectonics in the Voltri Massif (Ligurian Alps, North-Western Italy). *Ec. Geol. Hel.* 2002, 95, 31–42.
72. Capponi, G.; Crispini, L.; Federico, L.; Piazza, M.; Fabbri, B. Late Alpine tectonics in the Ligurian Alps: Constraints from the Tertiary Piedmont Basin conglomerates. *Geol.* 2009, 44, 211–224. [CrossRef]
73. Piana, F.; Battaglia, S.; Bertok, C. Ilite (K1) and chlorite (Al) “crystallinity” indices as a constraint for the evolution of the External Briançonnais Front in Western Ligurian Alps (NW Italy). *It. J. Geos.* 2014, 133, 445–454. [CrossRef]
74. Mueller, P.; Langone, A.; Patacci, M.; Di Giulio, A. Detrital signatures of impending collision: The deep-water record of the Upper Cretaceous Bordighera Sandstone and itsbasal complex (Ligurian Alps, Italy). *Sedim. Geol.* 2018, 377, 147–161. [CrossRef]
75. Sanità, E.; Lardeaux, J.M.; Marroni, M.; Gosso, G.; Pandolfi, L. Structural relationships between Helminthoid Flysch and Briançonnais Units in the MarguareisMassif: A key for deciphering the finite strain pattern in the external southwestern Alps. *Geol. J.* 2020, 56, 2024–2040. [CrossRef]
76. Galbiati, B.; Rodi, E. Caratteri strutturali dell’Unità di Moglio-Testico tra Alassio e Laigueglia (Liguria occidentale). *Bol. Soc. Geol. It.* 1989, 108, 491–502.
77. Galbiati, B. L’unità di Borghetto ed i suoi legami con quella di Moglio-Testico (Alpi Liguri): Conseguenze paleogeografiche. *Riv. It. Paleont. Strat.* 1985, 90, 205–226.
78. Chiesa, S.; Cortesogno, L.; Forcella, F.; Galli, M.; Messiga, B.; Pasquar, G.; Pedemonte, G.M.; Piccardo, G.B.; Rossi, P.M. Assetto strutturale ed interpretazione geodinamica del Gruppo di Voltri. *Bol. Soc. Geol. lt.* 1975, 94, 555–581.
79. Lanteaume, M. Contribution à l’étudégéologique des Alpes Maritimes franco-italiennes. *Mém. Cart. Géol. Fr.* 1968, 405.
80. Fallot, P.; Faure-Muret, A. Sur le Secondaire et le Tertiaire aux a bords sud-orientaux du Massif de l’Argentera-Mercantour (feuille 491 de Saint Martin Vésubie, Tende et Vieuze 50.000). *Bul. Cart. Géol. Fr.* 1954, 52, 283–319.
81. Gidon, M. Leschainons Briançonnais et subbriançonnais de la rive gauche de la Stura entre le Val de l’Arma (province de Cuneo Italie). *Géologie Alp.* 1972, 48, 87–120.
82. Cobianchi, M.; Di Giulio, A.; Galbiati, B.; Mosna, S. Il “Compresso di base” del Flysch di San Remo nell’area di San Bartolomeo, Liguria occidentale (nota preliminare). *At. Tic. Sc. Ter.* 1991, 34, 145–154.
83. Manivit, H.; Prud’Homme, A. Biostratigraphiedu Flysch à Helminthoides des Alpes maritimes franco-italiennes. Nannofossiles de l’unité de San Remo-Monte Saccarelo. Comparaison avec les Flyschs à Helminthoides des Apennins. *Bull. Soc. Géol. Fr.* 1990, 8, 95–104. [CrossRef]
114. Menardi-Noguera, A. Structural evolution of a briançonnais cover nappe, the Caprauna–Armetta unit (Ligurian Alps, Italy). *J. Struct. Geol.* 1988, 10, 625–637. [CrossRef]

115. Michard, A.; Avigad, D.; Goffé, B.; Chopin, C. The high-pressure metamorphic front of the southwestern Alps (Ubaye-Maira transect, France, Italy). *Schweiz. Mineral. Und Petrogr. Mitt.* 2004, 84, 215–235.

116. Goffé, B.; Schwartz, S.; Lardeaux, J.M.; Bousquet, R. Explanatory Note to the Map: Metamorphic Structure of the western and Ligurian Alps. *Mitt. Österr. Mineral, Gesell.* 2004, 149, 125–144.

117. Regorda, A.; Spalla, M.I.; Roda, M.; Lardeaux, J.M.; Marotta, A.M. Metamorphic facies and deformation fabrics diagnostic of subduction: Insights from 2D numerical models. *Geochem. Geophys. Geosyst.* 2021, 22, e2021GC009899. [CrossRef]

118. Mueller, P.; Maino, M.; Seno, S. Progressive deformation pattern from an Accretionary Prism (Helminthoid Flysch, Ligurian Alps, Italy). *Geosciences* 2020, 26, 26. [CrossRef]

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