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Tectonic relationships between the Paleozoic basement and the Mesozoic cover succession in the northern Dora-Maira Massif (Susa Valley, Western Alps)

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ABSTRACT

The northernmost sector of the Dora-Maira Massif is a key area for studying the role of basement-cover detachment zones as markers for understanding the multistage tectonic evolution of orogenic belts. The 1:5,000 scale geological map highlights the tectonic relationships between the Paleozoic basement and Mesozoic cover successions, which are separated by the Bussoleno Detachment Shear Zone, representing the basement-cover interface, and are tectonically overlain by the ophiolite-bearing Foresto Shear Zone. The Dora-Maira successions and these shear zones were deformed during four main phases (*i.e.* D1, D2, D3 and D4), with the – early tectonic setting largely established during the subduction-related D1 phase. Prior to the Alpine polyphase deformation, the basement-cover interface likely originated as a weak horizon within the Early Triassic, localizing deformation and forming the primary detachment zone.

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1. Introduction

Understanding basement-cover relationships over time is essential for reconstructing the multistage tectonic evolution of orogenic belts. Basement-cover interfaces are crucial both at the onset of convergence, where they control the localization and migration of basal décollements in the lower plate (Tavani et al., 2021), and during subduction, where they facilitate tectonic underplating and nappe stacking processes (Platt, 1986). This dynamic is exemplified in the Alps, which developed during the Cenozoic convergence between the Adria upper plate, the Europe lower plate, and the interposed Jurassic-Cretaceous Ligurian-Piedmont Ocean (Coward & Dietrich, 1989; Rosenbaum & Lister, 2005; Handy et al., 2010).

In the Western Alps, the Europe-derived units are characterized by syn-rift and pre-rift Mesozoic successions mostly detached from their Paleozoic basement (Dal Piaz et al., 2003; Manatschal et al., 2022; Roda et al., 2023). In the axial sector of the belt, remnants of the European paleomargin successions are widespread exposed in the frontal part (*i.e.* the Briançonnais Nappe System; Figure 1), whereas in the inner sector, the Europe-derived units mainly consist of Paleozoic basements (*i.e.* the Dora-Maira, Gran Paradiso and Monte Rosa internal crystalline massifs; Gasco et al., 2013; Schmid et al., 2017; Ballèvre et al., 2018). Among these massifs, which are thought to be derived from the more distal part of the European

paleomargin (*i.e.* the Briançonnais microcontinent of Schmid et al., 2004), the Dora-Maira Massif (DMM) has always attracted worldwide attention for the first discovery of coesite-bearing ultra-high pressure mineral assemblages in its basement rocks (Chopin, 1984).

This paper aims to detail the geology of the northernmost sector of the Dora-Maira Massif, located in the northern side of the lower Susa Valley (Figure 1). In this sector, the basement-cover relationships have been depicted as either tectonic or stratigraphic in large-scale geological maps produced as part of French (Fudral et al., 1994) and Italian (Cadoppi et al., 2002) national mapping programs. The new geological map (Main Map) provides an updated depiction of the area, emphasizing the tectonic framework and offering a detailed description of the relationships between the Paleozoic basement and the former Mesozoic cover succession of the DMM.

2. Geology of the Dora-Maira Massif

The Dora Maira Massif (DMM) is stacked in the inner and central part of the Western Alps (Figure 1), where it is tectonically overlain by various meta-ophiolite complexes (Pognante, 1979; Balestro et al., 2019; Agard, 2021; Festa et al., 2021). The present-day dome-like structure of the DMM comprises several juxtaposed tectonic units (*i.e.* the different ‘Ensembles’ of Vialon, 1966), which exhibit variations in both inferred

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 Supplemental map for this article can be accessed online at <https://doi.org/10.1080/17445647.2025.2451785>.

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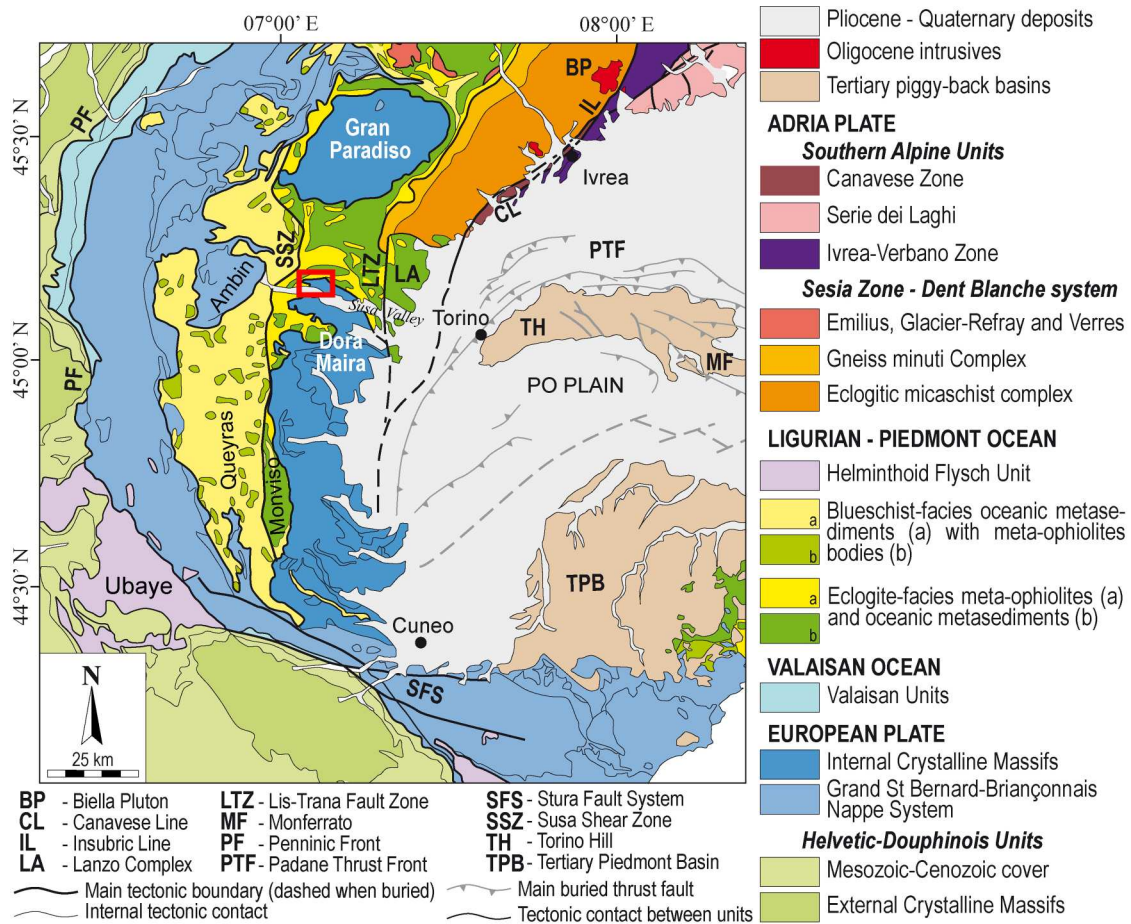


Figure 1. Tectonic map of the Western Alps (modified after Balestro et al., 2015). The red square indicates the study area.

pre-Alpine stratigraphy and the pressure-temperature (P-T) peak conditions experienced during the Alpine metamorphic cycle (Henry et al., 1993; Groppo et al., 2019; Manzotti et al., 2022). The lowermost tectonic unit, the Pinerolo Unit (Borghi et al., 1984), underwent metamorphism under blueschist-facies peak conditions (Avigad et al., 2003), and consists of Upper Carboniferous metasediments intruded by Lower Permian dioritic to granitic plutons (Bussy & Cadoppi, 1996; Manzotti et al., 2016). The uppermost eclogite and coesite-eclogite facies tectonic units (e.g. the Brossasco-Isasca, Rocca Solei, Dronero, Ricordone, Muret and Chasteiran units; Chopin et al., 1991; Compagnoni et al., 2012; Bonnet et al., 2022; Nosenzo et al., 2024) consist of a composite Variscan basement, which was intruded by Permian granitoid bodies and minor mafic dykes (Sandrone et al., 1993; Bussy & Cadoppi, 1996; Chen et al., 2023). In the southernmost sector of the DMM, these eclogite units are tectonically overlain by the blueschist-facies Dronero Unit (Michard et al., 1993; Balestro et al., 2020). This unit consists of polycyclic metasediments and of monocyclic meta-intrusive bodies and metasediments, which are locally inter-layered with Upper Permian metavolcanic rocks (Michard & Vialon, 1966; Bonioli et al., 1992; Balestro et al., 2022). The former Triassic-Jurassic cover succession occurs in the northern DMM (*i.e.* in the area

investigated here), and along the western flank of the DMM dome, where it is tectonically sliced (Balestro et al., 2011; Cadoppi et al., 2016). In the southern DMM, the cover succession is detached and forms different tectonic units arranged in an upright nappe stack (Balestro et al., 2022).

The northernmost sector of the DMM is tectonically overlain by the Susa and Lanzo valleys meta-ophiolites (De Togni et al., 2024), and it is characterized by a Paleozoic basement, consisting of (i) polycyclic garnet- and chloritoid-bearing micaschist with metres-sized bodies of metabasite, and (ii) monocyclic coarse-grained augen gneiss (Cadoppi & Tallone, 1992; Gasco et al., 2011). The Mesozoic cover succession mainly consists of Middle to Upper Triassic metadolostone (Cadoppi & Tallone, 1992; Ghignone et al., 2020a). Both the Paleozoic and Mesozoic rocks were deformed during four Alpine deformation phases, corresponding to the subduction-related D1 phase and the early (D2) to late (D3 and D4) exhumation-related phases (Cadoppi et al., 2002; Gasco et al., 2011; Perrone et al., 2011).

3. Methods

The 1:5,000 scale geological map presented here (Main Map) covers the northern side of the lower Susa Valley

(Figure 1). Data were stored in a GIS database (coordinate system WGS 84 UTM Zone 32N) and represented on a vector topographic map derived from the Carta Tecnica Regionale Vettoriale of the Regione Piemonte (vector_10 series, Edition 1991–2005). Lithological characterization was supported by thin section observations, while deformation phases were identified through overprinting relationships among mesoscale structures, analysed using stereographic projections (equal-area lower-hemisphere).

4. Tectonic setting

The Main Map includes (i) the Paleozoic basement and the (detached) Mesozoic cover of the DMM, (ii) the Bussoleno Detachment Shear Zone, formally corresponding to the DMM basement-cover interface, and (iii) the Foresto Shear Zone. The Quaternary cover consists of alluvial, fluvio-glacial and glacial deposits.

4.1. The Paleozoic basement of the DMM

The Paleozoic basement succession mainly consists of coarse-grained garnet- and chloritoid-bearing micaschist derived from pre-Carboniferous sediments and considered polycyclic (*i.e.* metamorphosed during the Variscan and Alpine orogenic cycles). The mineral assemblage of the micaschist is in fact characterized by the occurrence of multistage garnet crystals with homogeneous pre-Alpine cores and zoned Alpine mantles and rims (Gasco *et al.*, 2011). The micaschist hosts metre-sized bodies of fine-grained greenish metabasite, also considered pre-Carboniferous in age. Additionally, the basement includes coarse-grained augen gneiss, distinguished by centimetres-sized K-feldspar porphyroclasts. Partially preserved magmatic texture suggests that the gneiss is derived from acidic rocks of either intrusive or subvolcanic origin. Comparisons with similar rocks in the DMM dated to the Permian (Bussy & Cadoppi, 1996) indicate a similar age for the augen gneiss. Leucocratic gneiss occurs within both the augen gneiss and the micaschists (Figure 2(a)), likely originating from acidic differentiated dykes.

4.2. The Mesozoic cover of the DMM

The Mesozoic cover succession consists of micaschist, dolomitic marble, and metadolostone, arranged from bottom to top. The micaschist is fine- to medium-grained (Figure 2(b)), and differs from the polycyclic one by the occurrence of carbonate in its mineral assemblage. This micaschist is a few metres thick and locally associated with several decimetre-thick levels of greenish-grey to white quartzite, likely derived from siliciclastic sediments of Early Triassic

age (the ‘Werfenian quartzites’; Michard, 1967). The micaschist is locally overlain by metre-thick horizons of fetid dolomitic marble. Fine-grained and greyish in color, it contains white mica and quartz in its mineral assemblage. The metadolostone is the prevalent lithology in the Mesozoic cover succession. It is whitish, massive, and fine-grained (Figure 2(c,d)), with a mineral assemblage mainly composed of dolomite, minor calcite and white mica crystals. The metadolostone is derived from a carbonate platform succession of Middle to Late Triassic age (Franchi, 1898).

4.3. The Bussoleno Detachment Shear Zone

The Bussoleno Detachment Shear Zone (BDSZ), which ranges in thickness a few metres (around the Piani locality, see Main Map) to hundreds of metres (along Rio Moletta), primarily separates the Paleozoic basement of the DMM from the Mesozoic metasedimentary cover (Figure 3(a,b)), but also occur between different bodies of the Mesozoic succession (Figure 3(c)). consists of non-mappable, and elongated tectonic slices, reaching up to several metres in size. These slices are either monolithologic or composed of different lithologies and are tectonically juxtaposed with or without consistent stratigraphic relationships.

The BDSZ includes tectonic slices from both the Paleozoic basement and the Mesozoic cover, as well as lithologies not present in these successions. These lithologies include yellowish carbonate breccia with whitish clasts of metadolostone and quartzite, alternating layers of mylonitic impure marble and carbonate-bearing quartzite, iron-rich reddish metadolostone, grey banded marble passing to mylonitic carbonate-rich calcschist, whitish to greenish-grey quartzite and mylonitic quartzschist (Figure 3(a,b)).

Lithologies from the Paleozoic basement include garnet- and chloritoid-bearing mylonitic micaschist (Figure 3(d)), minor gneiss with no preserved magmatic textures, and recrystallized metabasite. Those from the Mesozoic cover include carbonate-bearing mylonitic micaschist, whitish metadolostone with levels of grey dolomitic marble, and cataclastic metadolostone with vacuolar textures.

4.4. The Foresto Shear Zone

Unlike the BDSZ, the Foresto Shear Zone (FSZ) includes not only DMM successions but also ‘exotic’ blocks (*sensu* Festa *et al.*, 2022) of meta-ophiolites and oceanic metasediments. The FSZ consists of elongated slices, up to several hundreds of metres long, of (i) calcschist of Cretaceous age (Marthaler *et al.*, 1986), (ii) blue grey quartz- and white mica-bearing marble, locally characterized by centimetres-sized dark bluish aggregates of calcite, and (iii) metadolostone. The fine- to medium-grained calcschist exhibits

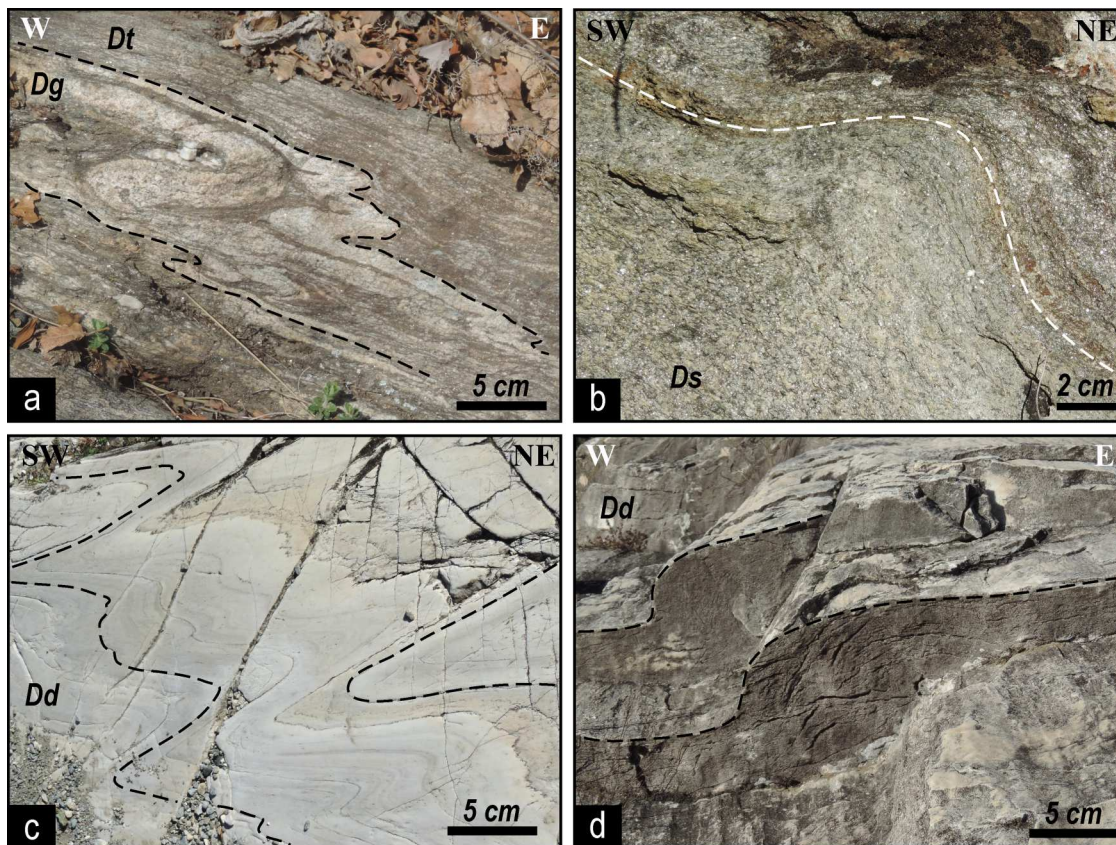


Figure 2. Close-up field images of different lithologies and structures occurring in the DMM successions. (a) Levels of leucocratic gneiss (Dg) within the polycyclic micaschist (Dt) deformed by D2 folds (dashed black lines mark the S1 foliation; Paleozoic basement; C. Trucco, 45°9'3"N, 7°8'33"E). (b) Carbonate-bearing micaschist (Ds) wherein the S2 foliation (dashed white line) is deformed by D3 folds (Mesozoic cover; ENE of Foresto, 45°8'39"N, 7°7'27"E). (c) Whitish metadolostone (Dd) wherein the S1 foliation (dashed black lines) is deformed by D2 folds (Mesozoic cover; ENE of Foresto, 45°8'39"N, 7°7'19"E). (d) Whitish metadolostone (Dd) wherein the S1 foliation (dashed black lines) is deformed by W-verging D4 folds (Mesozoic cover; Foresto, 45°8'35"N, 7°6'57"E).

a mylonitic structure, and locally embeds metres-sized blocks of (i) garnet- and chloritoid-bearing micaschist, (ii) metadolostone (Figure 3(e)), (iii) medium-grained serpentinite passing to serpentine schist, and (iv) medium-grained greenish metabasite. The serpentinite and metabasite are likely tectonic remnants of the Jurassic meta-ophiolites overlying the DMM. The blue grey quartz- and white mica-bearing marble, considered Jurassic in age, occurs as thin horizons stratigraphically overlying the metadolostone, suggesting partially preserved primary stratigraphic contacts. Unlike the metadolostone of the Mesozoic cover, the metadolostone occurring in the commonly shows a mylonitic structure and is partly transformed into carbonate tectonic breccia with vacuolar textures.

5. Structural evolution

Four main deformation phases (*i.e.* D1, D2, D3 and D4) have been recognized in the study area (see the stereographic projections in the Main Map). These phases are recorded in the DMM, BDSZ, and FSZ, and are described in the following by distinguishing mesoscale structures from the map scale ones.

5.1. Mesoscale structures

The D1 phase is primarily defined by the S1 foliation, whose fabric is pervasive across all lithologies. However, due to the overprinting by the D2 phase, it is best preserved in the more massive metadolostone (Figure 2(c)). The orientation of the S1 is scattered but generally aligns along a NNW-striking best-fit great circle, consistent with subsequent folding stages. S1 is parallel to the axial plane of rare D1 folds, which exhibit elongated isoclinal limbs and sharp hinges. The A1 fold axes are approximately parallel to the L1 mineral stretching lineations, indicating non cylindrical character of the D1-folding system. Both of these linear structural features are scattered but show slightly preference for a NNW-SSE trend.

The D2 phase marks a significant stage of folding and shearing deformation in the study area. D2 folds are close to isoclinal with rounded hinges (Figure 2(a,c)), and their axial plane correspond to the S2 foliation, which is well developed across all the lithologies except for the metadolostone. This new foliation is roughly distributed along a NNW-striking best-fit great circle. The S2 foliation is nearly parallel to the S1 foliation due to D2-related transposition processes.

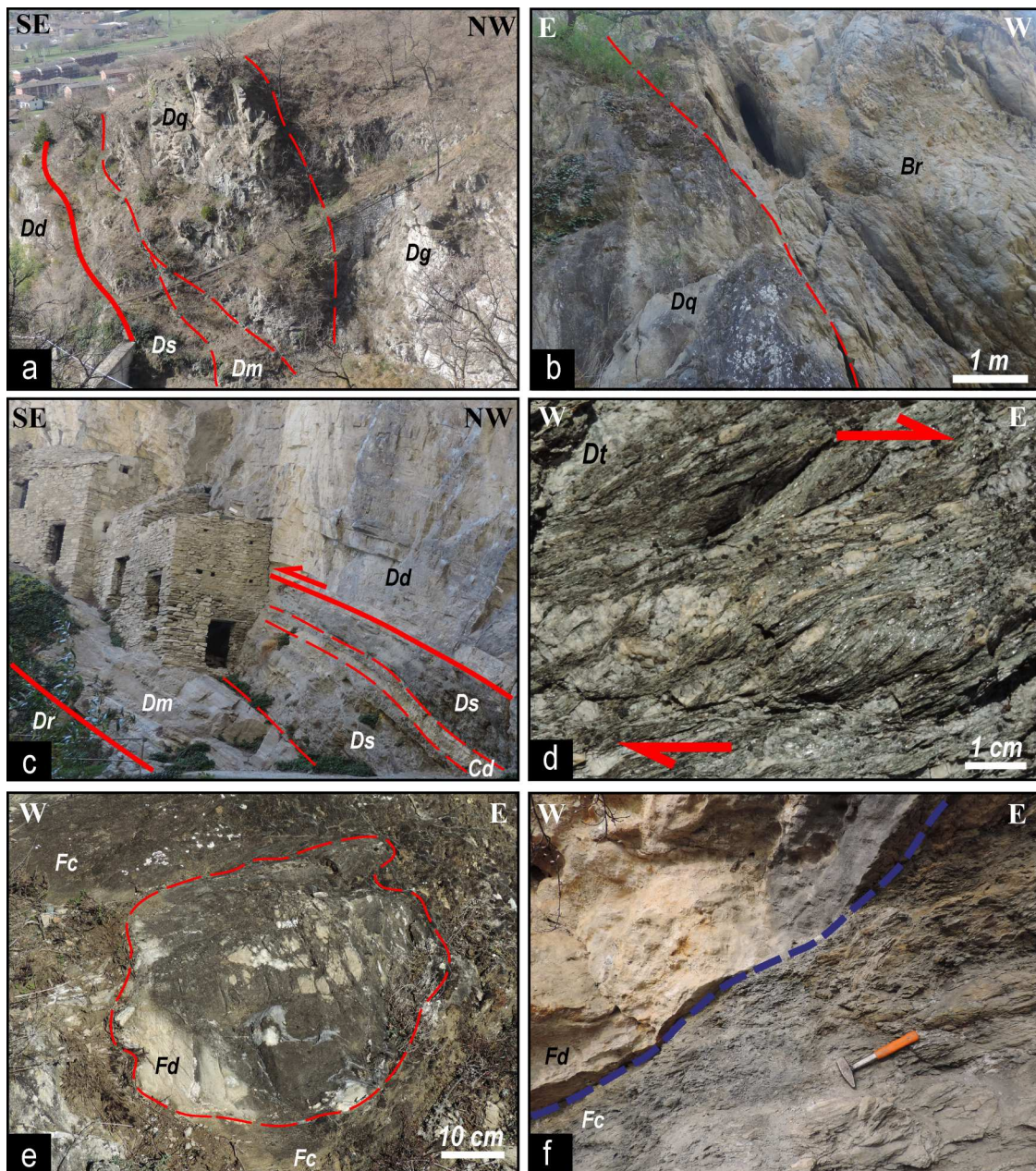


Figure 3. Images of different mesoscale structures occurring along the BDSZ and FSZ. (a) Upper part of the BDSZ along the Rio Moletta ($45^{\circ}8'53''\text{N}$, $7^{\circ}8'28''\text{E}$). The whitish metadolostone (Dd) is overlain by tectonic slices of carbonate-bearing mylonitic micaschist (Ds), banded marble passing to mylonitic carbonate-rich calcschist (Dm), quartzite and mylonitic quartzschist (Dq) and gneiss (Dg). The red line and the dashed red lines correspond to the boundary of the BDSZ and of the different tectonic slices, respectively. (b) Contact (dashed red line) between two tectonic slices of the BDSZ, consisting of mylonitic quartzschist (Dq) and of alternating layers of impure marble and carbonate-bearing quartzite passing to yellowish carbonate breccia (Br) (Rio Moletta, $45^{\circ}8'55''\text{N}$, $7^{\circ}8'29''\text{E}$). (c) BDSZ (red lines) separating dark grey dolomitic marble (Dr) and whitish metadolostone (Dd) of the DMM Mesozoic cover, and showing reverse top-to-SE kinematic. The dashed red lines mark the contacts between different tectonic slices mainly consisting of banded marble passing to mylonitic carbonate-rich calcschist (Dm), carbonate-bearing mylonitic micaschist (Ds) and cataclastic metadolostone (Cd) (Foresto, $45^{\circ}8'37''\text{N}$, $7^{\circ}6'53''\text{E}$). (d) Close up view of a mylonitic polycyclic micaschist (Dt) showing SC fabrics with top-to-E (red arrows) shear planes (BDSZ; ENE of Foresto, $45^{\circ}8'44''\text{N}$, $7^{\circ}7'22''\text{E}$). (e) Block of whitish metadolostone (Fd) embedded in mylonitic calcschist (Fc) of FSZ (the red dashed line mark the boundary of the block; ESE of Piani, $45^{\circ}8'39''\text{N}$, $7^{\circ}6'30''\text{E}$). (f) Carbonate tectonic breccia (Fd) and mylonitic to cataclastic calcschist (Fc) separated by the Falcemagna fault (the dashed blue line mark the main fault plane; FSZ; Campobenello, $45^{\circ}9'20''\text{N}$, $7^{\circ}8'26''\text{E}$).

The A2 fold axes are scattered but predominantly plunge toward WSW and ENE at low to medium angle, whereas the L2 mineral stretching lineations primarily plunge westward at low angle. This suggests a lower degree of non-cylindrical folding compared to the D1 phase.

Regarding the D2 shearing deformation, the S2 is mylonitic along both the BDSZ and FSZ, with related shear planes exhibiting S–C fabrics mainly indicative of reverse top-to-E senses of shearing. The D1 and D2 structures are partially reoriented by widespread open to close folds (Figure 2(b)) and by localized

gentle folds (Figure 2(d)) related to the D3 and D4 phase, respectively. The A3 axes mostly plunge westward at very low angles, with their axial planes clustering in a medium-angle NNW-dipping orientation. In both the monocyclic and polycyclic micaschists, D3 folds locally developed a new foliation corresponding to a crenulation cleavage. The A4 axes plunge both NNW and SSE at low angles, while D4 axial planes are mainly steeply dipping toward the ENE.

5.2. Map scale structures

The map scale geological setting of the study area (see cross sections in the Main Map), is dominated by two major D2 folds, corresponding to an antiform and a synform. These folds have at their cores the DMM Paleozoic basement and the FSZ, respectively. As a result, the Paleozoic basement thins westward and closes near the Piani locality, where the BDSZ and the Mesozoic cover succession are also folded. Conversely, the FSZ thins eastward and closes SE of Truc San Martino within the Mesozoic cover succession. Due to D2 shearing deformation, the northern limb of the antiform and the southern limb of the synform are strongly delaminated along the major tectonic contacts. These contacts are pervasive within the FSZ and the BDSZ, and they also extend into the Mesozoic cover succession (Figure 3(c)), dismembering it into three elongated, kilometres-scale bodies. The above described structures indicate that the geological setting of the study area is significantly shaped by D2 deformation. However, the fact that D2 folds deform both the BDSZ and the Mesozoic cover bodies suggests that D1 deformation, though largely overprinted, played an early role in the current tectonic setting.

The nearly E-W striking D1 + D2 lithostratigraphic and tectonic contacts were subsequently deformed during the D3 and D4 folding stages. The D3 phase resulted in a main pair of antiform/synform folds occurring in the central and eastern sectors of the study area, deforming the Paleozoic basement, the BDSZ, and the detached Mesozoic cover. In contrast, the main D4 folds occur in the western sector, where the contacts are partly deflected from an E-W to a NE-SW orientation. The final phase of deformation is mainly characterized by the NNW-dipping Falce-magna fault (Figure 3(f)), which extends across the study area. This fault separates the DMM basement from the FSZ and represents an extensional fault.

6. Discussion and conclusions

Detailed geological mapping, combined with lithostratigraphic and structural analyses, highlights the tectonic relationships between the Paleozoic basement and the Mesozoic cover succession in the northernmost sector of DMM. The original basement-cover

stratigraphic contact has been extensively reworked along the BDSZ, which incorporates material from the Paleozoic basement, the Mesozoic cover, and additional lithologies not present in these successions. These additional lithologies are likely derived from a composite stratigraphic horizon at the former basement-cover interface. The latter, due to its position between the top of the Paleozoic basement and the base of the overlying Middle to Late Triassic carbonate platform, is considered Early Triassic in age, and it likely consisted of very different sediments, including siliciclastic arenites, alternating pelite and limestone layers, and dolostones. The relatively weak metasediments occurring along this interface may have played a significant role in localizing the basement-cover décollement and in developing the BDSZ. Notably, no clear evidence of rocks derived from evaporate sediments have been found in the study area. However, anhydrites are present at the base and within the pre-rift successions of the adjoining Briançonnais Nappe System (Figure 1), where they act as an important décollement level (Michard et al., 2004; Barré et al., 2020). It is important to point out that, in the study area (*i.e.* the northern side of the lower Susa Valley), despite the tectonic nature of the basement-cover contact, the DMM Mesozoic cover is tectonically dismembered but remains closely associated with its basement. This contrasts with observations on the southern side of the lower Susa Valley and the western flank of the DMM dome (Balestro et al., 2011; Nosenzo et al., 2024), where the Mesozoic cover is either absent or extensively sliced, respectively.

Since D2 folds deform the BDSZ, as well as the Mesozoic and Paleozoic successions, this indicates that the current tectonic setting was initially established during the subduction-related D1 phase, which exhibited N-NW vergence on a regional scale (Dumont et al., 2022) and developed under eclogite-facies P-T peak conditions in the study area (Gasco et al., 2011). The cover and basement may have shared a common subduction history and could have detached at their P-T peak depth, forming the BDSZ. The D1 phase may also have caused large-scale boudinage and dismembering of the Mesozoic cover into the three main bodies. However, the occurrence of the BDSZ between these bodies suggests a more complex and polyphasic deformation history. Additionally, an early stage of shearing deformation, occurring between the D1 and D2 phases, has been documented in the study area (Gasco et al., 2011), specifically within the FSZ. This shear zone, which is deformed by map-scale D2 folds, extends well beyond the study area and is consistently interposed between the DMM and the overlying meta-ophiolite complexes (see the tectonic sketch map in the Main Map). The FSZ likely had an important tectonic role during plate convergence, and it is interpreted as a tectonic

mélange (*sensu* Festa et al., 2019), comprising metadolostone and marble blocks, up to kilometres in size, along with minor blocks of meta-ophiolites embedded within the Cretaceous calcschist.

The early D1 structures were, later overprinted by D2 W-verging, non-cylindrical folding (Gasco et al., 2011), and reactivated during D2 shearing deformation. Both the DMM and FSZ display widespread tectonic contacts that form a complex network of interconnected shear zones. The D2 shear planes exhibit reverse top-to-E kinematics, similar to those described just W of the study area along the Susa Shear Zone (*i.e.* the T1 event of Ghignone et al., 2020b). This kinematic pattern has been linked to the early exhumation path of both the DMM and the meta-ophiolite complexes, consistent with observations in other tectonic units of the Western Alps (Philipot, 1990; Ballèvre & Merle, 1993; Ganne et al., 2006; Pleuger et al., 2007). The DMM, BDSZ, and FSZ, along with their associated D1+D2 structures, were subsequently deformed by D3 folds, which are predominantly N-verging, and D4 folds, which are coeval with top-to-W extensional shearing (*i.e.* the T2 event along the Susa Shear Zone; Ghignone et al., 2020b).

In conclusion, the geological map highlights the tectonic relationships between the Paleozoic basement and the former Mesozoic cover succession in the northernmost sector of DMM. However, further investigations are ongoing to better constrain the timing and the metamorphic (P-T) and geodynamic conditions under which the BDSZ formed. The structural and geological data provided here aim to contribute to the study of basement-cover interfaces throughout the DMM and the other internal crystalline massifs.

Software

The geological map was edited with QGIS (v. 3.34.8-Prizren). Structural data have been projected using Stereonet v. 11 by Richard W. Allmendinger © 2020.

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Disclosure statement

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Data availability statement

The authors confirm that the geological data supporting the findings of this study are available within the article and its Supplementary materials.

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