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Geology of the southern Dora-Maira Massif: insights from a sector with mixed ophiolitic and continental rocks (Valmala tectonic unit, Western Alps)

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ABSTRACT

In the Valmala sector of the southern Dora Maira Massif (Western Alps), two different eclogite- and blueschist-facies units (i.e. the Rocca Solei and Dronero units, respectively), are separated by a shear zone (i.e. the Valmala Tectonic Unit), which peculiarly consists of mixed slices of ophiolitic and continental rocks. A detailed geological map at 1:10,000 scale allowed to point out that the tectonic slices within the Valmala Tectonic Unit consist of 'native' rock slices wrested from the overlying Dronero Unit, and 'exotic' rocks likely sourced from other units of the Dora Maira and from a continental margin and an oceanic basin. On the contrary, rock slices sourced from the underlying Rocca Solei Unit are lacking. The overall tectonic stack results after an early subduction-related deformation phase (i.e. the D1), and the pervasive overprinting of two subsequent exhumation-related deformation phases (i.e. the D2 and D3). The Valmala Tectonic Unit is inferred to have played a role in decoupling the southern Dora Maira Massif during subduction, and/or in driving exhumation of the ultra-high pressure rocks occurring in the adjoining Brossasco-Isasca Unit.

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1. Introduction

The Western Alps represent one of the more studied orogens in the world. Nevertheless, a large part of this orogen lacks of detailed geological maps and the official Geological Maps of Italy at 1:100,000 scale are older than 50 years.

During the last tens of years, several works based on a detailed geological mapping, clearly documented that the Western Alps are characterized by complex structural and tectono-stratigraphic settings, part of which results from pre-orogenic structural inheritances (see e.g. Ballèvre et al., 2018; Bell & Butler, 2017; Festa et al., 2020; Mohn et al., 2011; Tartarotti et al., 2017, and reference therein), superposition of subduction- and exhumation-related deformation stages (see e.g. Federico et al., 2015; Manzotti et al., 2014; Roda et al., 2018, and reference therein) and late strike-slip to extensional tectonics (see e.g. Balestro et al., 2009; Perrone et al., 2010, and reference therein). This is the case of the Dora-Maira Massif (DM hereafter), a terrane of continental crust, worldwide known for the first discovery of coesite-bearing ultra-high pressure mineral assemblages (Chopin, 1984). Despite several metamorphic and petrological studies focused on the ultra-high pressure Brossasco-Isasca Unit (see e.g. Compagnoni et al., 2012; Ferrando et al., 2017, and reference therein), published data about the tectono-

stratigraphic and structural setting of the whole DM are scattered and actually not exhaustive.

Throughout a detailed geological map at 1:10,000 scale (see Main Map), this paper provides new detailed information about the geology of a poorly known tectonic stack in the southern DM (i.e. the Valmala sector; Figure 1), which lies above the coesite-eclogite bearing Brossasco-Isasca Unit (Chopin et al., 1991; Kienast et al., 1991). In this sector, two different DM units (i.e. the eclogite-facies Rocca Solei Unit and the blueschist-facies Dronero Unit) are separated by a tectonic unit (i.e. the here defined Valmala Tectonic Unit), which peculiarly consists of mixed slices of ophiolitic and continental rocks.

2. Regional setting

The Western Alpine orogenic belt developed as a result of the collision between Adria, in the upper plate, and Europe, in the lower plate, after the closure of the interposed Ligurian-Piedmont oceanic basin (see e.g. Coward & Dietrich, 1989; Rosenbaum & Lister, 2005; Schmid et al., 2017, and references therein). The belt evolved through the (i) Late Cretaceous to Middle Eocene subduction, (ii) Late Eocene to Early Oligocene continental collision, and (iii) Late Oligocene to Neogene deep crust/mantle indentation (see e.g. Solarino et al., 2018, and references therein). The DM represents

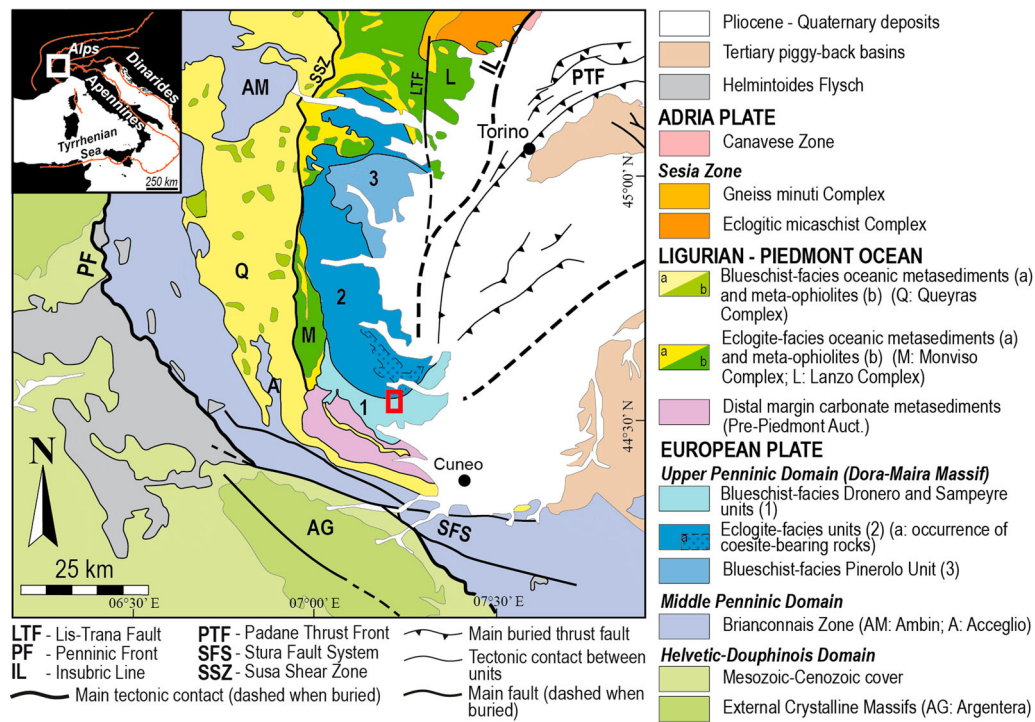


Figure 1. Tectonic map of the Western Alps (modified after Balestro et al., 2015). The red square indicates the study area.

a slab of the paleo-European continental margin, which was deeply involved in the subduction- and exhumation-related Alpine tectonometamorphic processes. It is now stacked in the inner sector of the Western Alps (i.e. the Upper Penninic Domain; Dal Piaz et al., 2003), and tectonically overlain by different meta-ophiolite complexes (see e.g. Balestro et al., 2014, 2018).

The DM consists of different tectonic units (i.e. the different ‘Ensembles’ of Vialon, 1966, and lithostratigraphic units of Sandrone et al., 1993), which differ from each other for both their lithostratigraphy, Alpine metamorphic P-T peaks and structural positions (Figure 1). The lowermost DM tectonic unit corresponds to the Pinerolo Unit, a tectonic window occurring in the central sector of the DM. It was metamorphosed under blueschist-facies peak conditions (Avigad et al., 2003; Borghi et al., 1984), and it consists of Upper Carboniferous metasediments, which were intruded by Lower Permian dioritic and granitic melts (Bussy & Cadoppi, 1996; Manzotti et al., 2016; Perrone et al., 2011). The Pinerolo Unit is tectonically overlain by different eclogite-facies tectonic units (see e.g. Compagnoni & Rolfo, 2003; Gasco et al., 2011), consisting of a composite polymetamorphic basement, intruded by Lower Permian granitoid bodies, and of discontinuous monometamorphic successions of siliciclastic and carbonate metasediments, Permian to Triassic in age (Bussy & Cadoppi, 1996; Sandrone et al., 1993). In the southern sector of the DM, these units correspond from bottom to top to the eclogite-facies San Chiaffredo Unit, the coesite-eclogite facies Brossasco-Isasca Unit and the eclogite-facies Rocca Solei Unit (Compagnoni et al., 2012). These eclogite-facies units are in turn tectonically overlain by the blueschist-facies Dronero and

Sampeyre units (Chopin et al., 1991; Groppo et al., 2019), consisting of polymetamorphic mica schists, monometamorphic meta-intrusive bodies, Permian metasediments locally with interlayered metavolcanic rocks and Lower Triassic siliciclastic metasediments (Bonoli et al., 1992; Michard & Vialon, 1966). In between the eclogite-facies units and the blueschist-facies Dronero and Sampeyre units, meta-ophiolitic rocks consisting of serpentinite, metabasite and calcschist discontinuously occur (i.e. the ‘ophiolitiferous band’ of Henry et al., 1993; see also Carraro et al., 1971). In the southernmost sector of the DM, the Dronero and Sampeyre units are tectonically overlain by a succession of carbonate metasediments (pre-Piedmont Auct.; Michard, 1967), which was detached from the European distal margin (Figure 1). This succession mainly consists of Middle-Late Triassic platform-derived dolomitic marble, and of Early-Jurassic syn-rift marble and carbonate-rich calcschist with layers of carbonate metabreccia.

The structural setting and tectonic evolution of the southern DM is related to three main stages (see e.g. Henry et al., 1993), which correspond to the D1, D2 and D3 phases. The subduction-related D1 was coeval to the high-pressure and ultra-high pressure metamorphism, whereas the exhumation-related D2 and D3 were coeval to the widespread greenschist-facies retrograde recrystallization (see e.g. Groppo et al., 2007; Henry et al., 1993).

3. Methods

The here presented map (Main map) is the result of fieldwork carried out at 1:10,000 scale and

encompasses an area of around 10 km² south of the Varaita River (i.e. the Valmala Valley). Data were stored in a GIS database (coordinate system WGS 84 UTM Zone 32N) and represented on a vector topographic map compiled from the Carta Tecnica Regionale Vettoriale of the Regione Piemonte (vector_10 series, Edition 1991-2005). Lithostratigraphic analyses have been supported by microscope thin section observations. The structural setting is also documented in a NNW-SSE striking cross section. Regional deformation phases have been distinguished through overprinting relationships among structures, which are represented through stereographic projections (equal-area lower-hemisphere). The geological map is part of a wider project, which aims to produce detailed geological maps in tectonically meaningful sectors of the Western Alps (Balestro et al., 2011, 2013; Barbero et al., 2017; Cadoppi, Camanni, Balestro & Perrone, 2016; Fioraso, Balestro, Festa & Lanteri, 2019; Ghignone et al., 2020).

4. Lithostratigraphy

The map includes two DM units, which correspond to the Rocca Solei Unit and the Dronero Unit, and the interposed Valmala Tectonic Unit. These units are locally covered by Quaternary alluvial, landslide and debris flow deposits (see Main Map).

4.1. Rocca Solei Unit

The RSU occurs in the northern sector of the study area (see Main Map) and consists of massive coarse-grained augen gneiss (Rg in the Main Map), with centimeters-sized K-feldspar porphyroclasts. The augen gneiss locally preserves microstructural relics of a granitic protolith and it is similar to the Early Permian metagranite (275 Ma; Gebauer et al., 1997), occurring further north the study area in the Brosasco-Isasca Unit (Biino & Compagnoni, 1991). Toward the top of the Unit (i.e. at the tectonic contact with the Valmala Tectonic Unit), the augen gneiss is gradually transformed into mylonitic gneiss (Figure 2(a)), which is several meters to few tens of meters thick.

4.2. Dronero Unit

The DU consists of mica schist, metabasite and gneiss. The garnet- and chloritoid-bearing mica schist (Dm in the Main Map; see also Figure 2(b)), shows a characteristic texture defined by alternating quartz-rich and phengite-rich centimeters-thick domains (Figure 3(a)), and it is locally interbedded (NE of Santuario di Valmala) by garnet-bearing quartzite layers, up to few meters in thickness. Two lines of evidence suggest that these mica schists

are polymetamorphic rocks (i.e. rocks metamorphosed during the Variscan and Alpine orogenic cycles): (i) the occurrence of at least two different generations of garnet, either porphyroblastic or neoblastic, with neoblastic garnet growing at the rim of the porphyroblasts and in the matrix; (ii) the occurrence of sagenitic rutile included in the neoblastic garnets, which suggests a garnet growth at the expense of high-temperature Ti-rich biotite (e.g. Spiess et al., 2007). The rare occurrence of Variscan staurolite in the mineral assemblage of these mica schists, was described by Chopin et al. (1991), further supporting the hypothesis of a polymetamorphic nature for this lithological unit.

Meters-thick massive bodies of garnet-bearing blue amphibole- metabasite (Db in the Main Map), discontinuously occur along the contact between the polymetamorphic mica schist and the gneiss (see below). The fine-grained texture of the metabasite, its stratigraphic position and relationships with the mica schist (Figure 2(b)), and the lack of any Variscan-related mineral or textural relics, suggest an origin from aphyric mafic to intermediate volcanic rocks of post-Variscan (Early Permian?) age.

The gneiss (Dg in the Main Map), up to hundreds of meters in thickness, consists of (i) micro-augen gneiss with millimeter-sized K-feldspar porphyroclasts, (ii) fine-grained K-feldspar bearing leucogneiss (Figures 2(c) and 3(b)), (iii) layers of quartz- and phengite-bearing mylonitic schist and (iv) masses of coarse-grained augen gneiss with centimeter-sized K-feldspar porphyroclasts. The heterogeneity of this gneissic succession and the partially preserved primary textures suggest an origin from both volcanic, subvolcanic and plutonic acidic rocks, which can be related to the Early Permian magmatic activity which occurred throughout the paleo-European crust of the Western Alps (see e.g. Dallagiovanna et al., 2009). The occurrence of coarse-grained augen gneiss particularly suggests that part of the gneiss succession derive from granite bodies. Metagranitoid rocks and orthogneiss of subvolcanic origin emplaced at shallow levels, have been described further south of the study area by Balestro et al. (1995) and by Vialon (1966), respectively.

4.3. Valmala Tectonic Unit

The VTU represents a shear zone, consisting of tectonically juxtaposed slices of different lithologies, both 'exotic' and 'native' in origin (see below), ranging in size from few tens of meters to several hundreds of meters and lenticular in shape. According to the terminology used for mélangé rock units (see Festa et al., 2019 and reference therein), we use the term

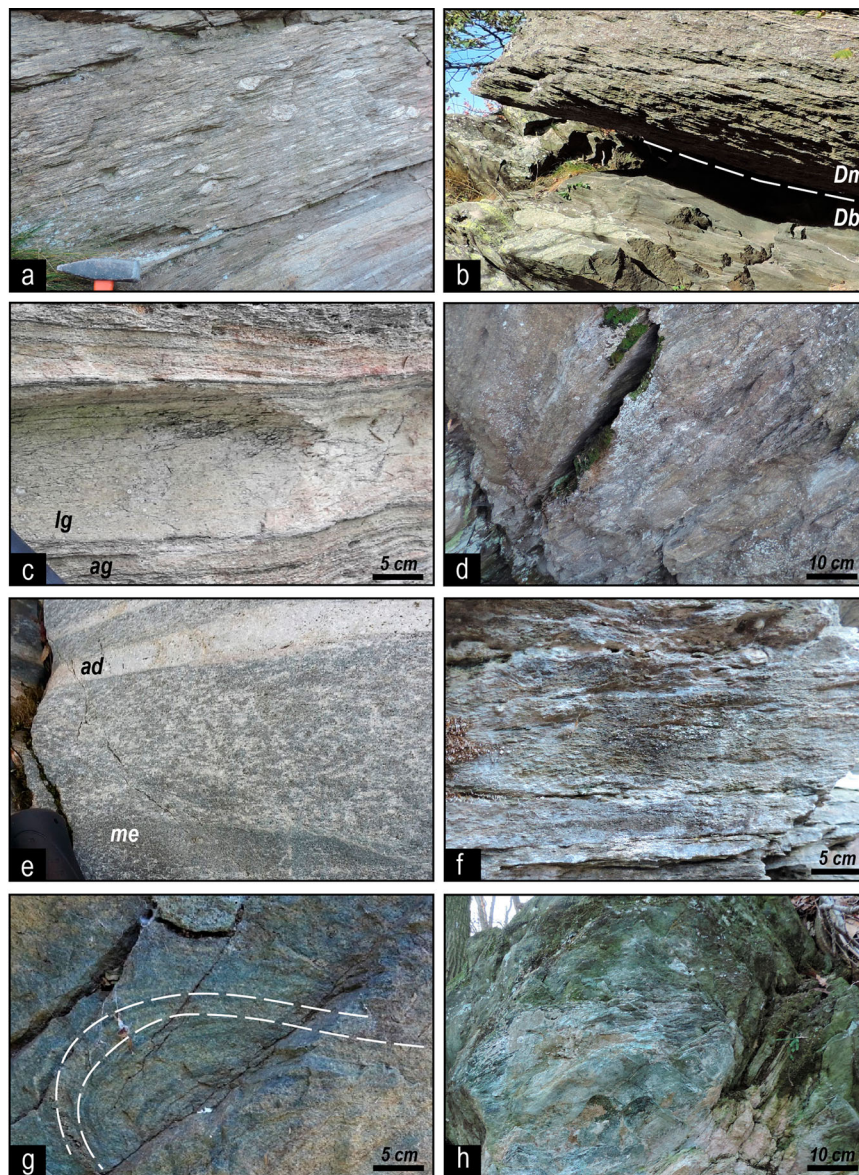


Figure 2. Field images of different lithologies exposed in Valmala: (a) mylonitic augen gneiss (Rocca Solei Unit, N of Vacot, $44^{\circ}33'33''$, $7^{\circ}21'22''$); (b) stratigraphic contact relationships (dashed white line) between the garnet- and chloritoid-bearing mica schist (Dm) and the fine-grained massive metabasite (Db) (Dronero Unit, N of Santuario di Valmala, $44^{\circ}31'7''$, $7^{\circ}20'31''$); (c) layer of leucogneiss (lg) interbedded in micro-augen gneiss (ag) (Dronero Unit, S of Chiot del Bosco, $44^{\circ}31'57''$, $7^{\circ}20'46''$); (d) grayish mica schist with millimeters-thick quartz veins (Valmala Tectonic Unit, Bric Guardia, $44^{\circ}32'50''$, $7^{\circ}19'35''$); (e) massive meta-quartzdiorite with centimeters-thick mafic enclave (me) and acidic dyke (ad) (Valmala Tectonic Unit, Comba di Valmala, $44^{\circ}32'54''$, $7^{\circ}20'27''$); (f) carbonate-rich calcschist (Valmala Tectonic Unit, W of Perotto, $44^{\circ}32'34''$, $7^{\circ}20'17''$); (g) banded metabasite showing the S1 foliation (dashed white lines) deformed by D2 folds (Valmala Tectonic Unit, E of Rora, $44^{\circ}32'56''$, $7^{\circ}20'54''$); (h) carbonate-bearing serpentinite (Valmala Tectonic Unit, W of Botto, $44^{\circ}32'53''$, $7^{\circ}19'52''$).

‘native’ and ‘exotic’ to indicate the lithology of rock slices whose source is present or not in the units surrounding the VTU (i.e. the RSU and DU), respectively.

‘Native’ rock slices, which show a close lithological affinity with the DU, consist of the following lithologies:

- garnet- and chloritoid-bearing mylonitic mica schist (Vm in the Main Map), which are texturally and compositionally similar to the polymetamorphic mica schist of the DU, although pervasively deformed and recrystallized;
- fine-grained mylonitic gneiss and micro-augen gneiss (Vg in the Main Map) with peculiar dark grayish pervasively fractured K-feldspar porphyroclasts. These blocks closely resemble the gneiss of the DU, potentially Early Permian in age;
- grayish mica schist (Vt in the Main Map) with widespread quartz veins (Figure 2(d)), chloritoid-bearing mica schist and garnet-bearing mica schist, with local layers of garnet- and white mica-bearing metabasite, decimeters- to few meters in thickness. This mica schist is locally associated with ankerite-bearing mica schist and reddish mylonitic schist (Vn in the Main Map), and lithologically resembles

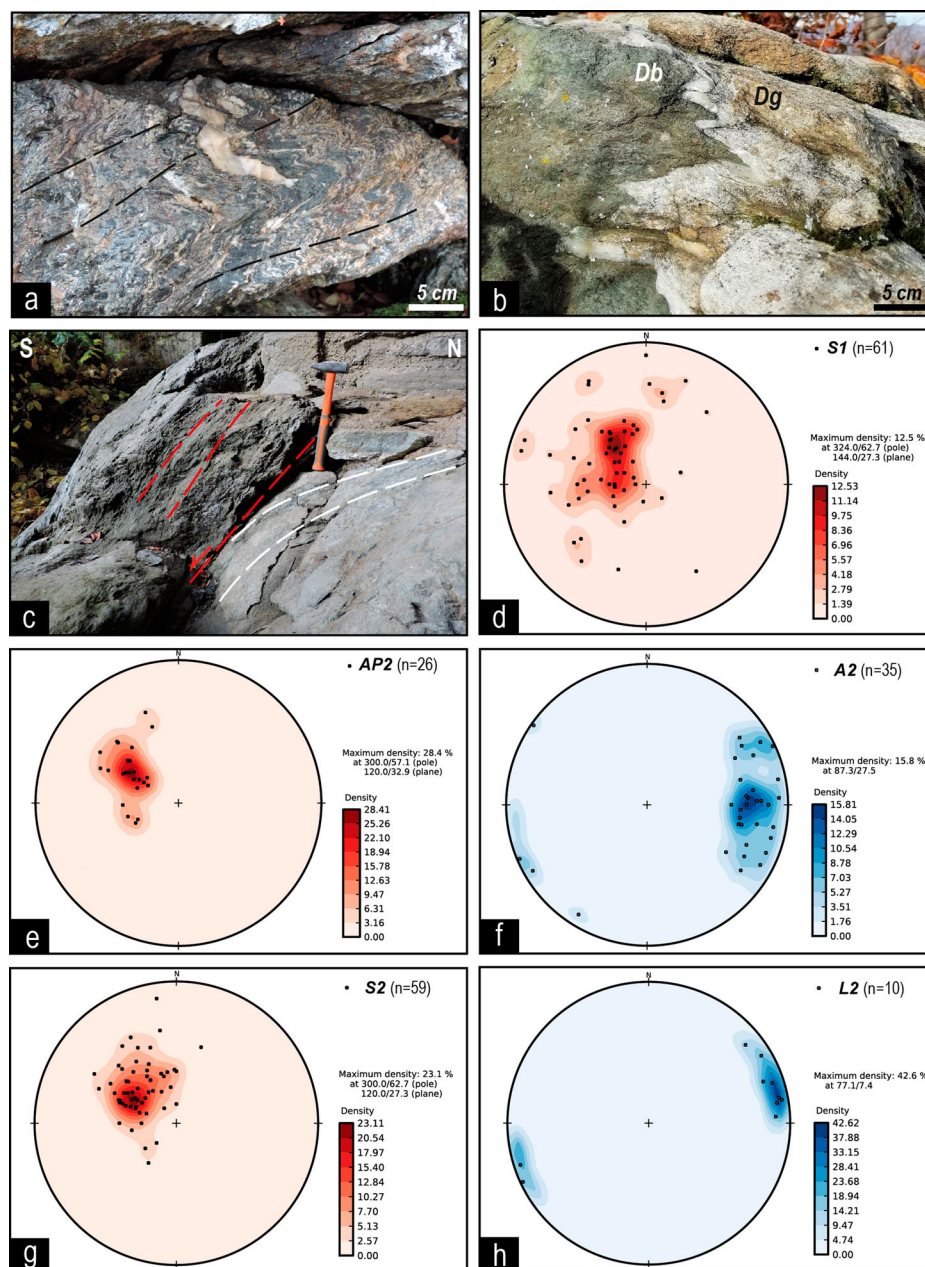


Figure 3. Images of different field-scale structures: (a) D2 crenulation cleavage (dashed black lines) in garnet- and chloritoid-bearing mica schist (Dronero Unit, N of Santuario di Valmala, 44°31'7, 7°20'35); (b) D2 folds deforming the contact between metabasite (Db) and leucogneiss (Dg) (Dronero Unit, E of Santuario di Valmala, 44°30'48, 7°21'2); (c) D3 extensional shear planes (dashed red lines) dragging the S2 foliation (dashed white lines) in mylonitic dioritic gneiss (Valmala Tectonic Unit, Comba di Valmala, 44°32'48, 7°20'30). (d–h) Equal-area lower-hemisphere stereographic projections of different structures (n: number of data; counting method: Fisher distribution): (d) poles of S1 foliation; (e) poles of D2 axial plane (AP2); (f) D2 axes (A2); (g) poles of S2 foliation; (h) D2 stretching lineations (L2).

the Permian monometamorphic metasediments described in the southernmost sector of the DU by [Michard and Vialon \(1966\)](#).

‘Exotic’ rock slices, which do not show any lithological affinity with units directly surrounding the VTU, consist of the following lithologies:

- garnet- and blue amphibole-bearing meta-quartz-diorite (Vg in the Main Map), which is mostly massive ([Figure 2\(e\)](#)), but transformed into carbonate-bearing mylonitic gneiss at its top ([Figure 3\(c\)](#)).

This lithology shows widespread mafic enclaves and acidic dykes, several centimeters in thickness, and it can be tentatively compared to the metadiorite exposed in central-northern sector of the DM ([Sandrone et al., 1988](#));

- quartz-rich schist (Vq in the Main Map) mainly shows a mylonitic structure but locally preserves layers of white to pale green quartzite. The latter is quite similar to the Early Triassic quartzite (Werfenian *Auct.*) widespread in the succession of the DM Sampeyre Unit ([Vialon, 1966](#));

- marble cropping out W of Chiarreri locality (Vd in the Main Map), and mostly transformed into tectonic carbonate breccia;
- carbonate-rich calcschist (Vc in the Main Map; see [Figure 2\(f\)](#)) and graphite-rich mylonitic schist;
- pervasively sheared carbonate-bearing serpentinite and talc-bearing serpentine schist (Vs in the Main Map, see [Figure 2\(g\)](#)), cropping out in the Botto, Perotto, Rora and Vacot localities;
- banded and massive metabasite (Vb in the Main Map, see [Figure 2\(h\)](#)), which includes garnet- and blue amphibole in its mineral assemblage, and it is locally transformed into carbonate-bearing greenschist and coarse-grained recrystallized metabasite. This metabasite does not retain textural or mineralogical relics of its protolith. However, its spatial relationship with the serpentinite suggests an origin from gabbro.

Part of the ‘native’ rock slices (i.e. the garnet- and chloritoid-bearing mica schist and the gneiss) are mostly distributed in the uppermost part of the VTU, along the tectonic boundary with the DU. Calcschist, serpentinite and metabasite ‘exotic’ slices are mainly aligned in the central sector of the VTU, whereas slices of meta-quartzdiorite are clearly localized in its lowermost part, along the tectonic boundary with the RSU.

5. Structures

Three main deformation phases (i.e. D1, D2 and D3) have been distinguished (see Main Map).

The D1 phase is defined by an early foliation (i.e. the S1), which is preserved in more massive rocks such as the metabasite ([Figure 2\(h\)](#)) and meta-quartzdiorite of the VTU (Vt and Vr in the Main Map), and the metabasite and coarse-grained augen gneiss of the DU (Db and Dg in the Main Map). The S1 is scattered along a NNE-striking best fit great circle ([Figure 3\(d\)](#)), which is roughly coherent with reorientations related to the D2 phase. The latter is characterized by the development of tight to close folds ([Figure 3\(b,c\)](#)), which deformed S1, and a pervasive axial plane foliation (i.e. the S2) in less massive rocks such as mica schist and calcschist of the VTU (Vt and Vn in the Main Map) as well as mica schist of the DU (Dm in the Main Map). D2 axial planes dips toward ESE at low to medium angle ([Figure 3\(e\)](#)), whereas D2 axes are on average E-plunging at a low angle ([Figure 3\(f\)](#)). Because of refraction along fold limbs, the distribution of S2 ([Figure 3\(f\)](#)) is more scattered than that of D2 axial planes. Stretching lineations on S2 are almost ENE-plunging at low angle ([Figure 3\(h\)](#)), highlighting that D2 folds are geometrically non-cylindrical. At the map scale, the effect of D2 folds is more evident in the DU, wherein the originally S1-parallel contact

between the polymetamorphic mica schist and meta-volcanic rocks (Dm and Dg in the Main Map) is clearly deformed and overturned in the sector between two major fold hinges (i.e. between Chiot Martin and Santuario di Valmala). D2 folds also occur within the VTU ([Figure 2\(h\)](#)), although, in this unit, the D2 is mainly characterized by the occurrence of related tectonic contacts. The latter bounds both the VTU and the embedded ‘native’ and ‘exotic’ slices.

The D3 is defined only at the mesoscale by open folds, deforming the S2 within the mica schist of the VTU and DU (Vt, Vm and Dm in the Main Map). D3 axial planes are E to ENE dipping at a high angle and the D3 axes mainly plunge toward NE at low to medium angle. The D3 is also characterized by the development of discrete shear planes, about SSE-dipping at a high angle, showing SC fabrics consistent with extensional top-to-S and top-to-SE sense of shears ([Figure 3\(c\)](#)). The D3 shear planes mainly developed within the VTU, corresponding to major faults at the map scale. The D3 deformation regionally accommodated the development of exhumation-related dome-like structure of the DM ([Lardeaux et al., 2006](#)), during which pre-D3 structures were reoriented.

6. Conclusion

The southern DM consists of eclogite and coesite-eclogite facies units, which are tectonically overlain by blueschist-facies units. Our new geological map (see Main map) shows that this tectonometamorphic setting matches well with a complex inherited tectono-stratigraphic setting. The lithostratigraphy of the RSU and DU, which are tectonically separated through the VTU, is not comparable (see also [Compagnoni et al., 2012](#)). In the VTU, which consists of the tectonic mixing of different rock slices, ‘native’ rock slices of polymetamorphic mica schist, orthogneiss and, possibly, monometamorphic mica schist, seem to be wrenched from the overlying DU sequence. On the contrary, lithological analogs of the quartz-rich schist and meta-quartz diorite rock slices do not occur in the units surrounding the VTU (see [Sandrone et al., 1993](#)). Carbonate- and mafic-ultramafic rock slices, could be wrenched from tectonic units now overlying the DM (see [Balestro et al., 2019](#)), although different sources cannot be excluded. Further investigations are necessary to better constraints their origin and age.

The RSU, VTU and DU seem to share the same exhumation-related D2 and D3 deformation. On the contrary, subduction-related D1 deformation developed differently in the RSU and DU, which show different metamorphic P-T peaks ([Groppi et al., 2019](#)). Although detailed petrologic data on the VTU are currently lacking and most lithologies are strongly

retrogressed under greenschist-facies conditions, the high pressure mineral assemblages preserved as relics in the less retrograded lithologies seem to support blueschist-facies peak metamorphic conditions, while eclogite-facies mineral assemblages have not been observed so far. This suggests that the VTU may have shared part of the subduction path and related tectonic history with the DU. Tectonic wrenching of part of its lithostratigraphic sequence, probably occurred at this stage, forming the early VTU internal architecture. Subduction-related processes seem to represent the most suitable mechanism responsible for the wrenching of tectonic slices, as documented in other sectors of the Western Alps and Northern Apennines (see e.g. Barbero et al., 2020; Roda et al., 2020). However, the inner setting of the VTU was reorganized during D2 and D3 phases. The effect of this exhumation-related tectonics was particularly pervasive within the VTU, which likely marked the tectonic contact between eclogite- and blueschist-facies units. This type of tectonic contact corresponds to a first-order shear zone along the Western Alps, where it has been interpreted as the boundary between two orogen-scale domains (i.e. the ‘eclogite belt’ and ‘frontal wedge’ of Malusà et al., 2011).

Finally, it is worth noting that just to E of the studied sector, the RSU is not continuous, and rocks pertaining to the VTU seem to be directly juxtaposed to the ultra-high pressure Brossasco-Isasca Unit (see Compagnoni et al., 2012). The VTU may thus have had also a role in decoupling the southern DM during subduction and/or in driving exhumation of ultra-high pressure rocks.

Software

The topographic map and the geological map database were edited with QGIS (v. 3.12.1-București), while the final map layout was drawn with Adobe® Illustrator® CS5. Structural data have been projected using Open Stereo.

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Disclosure statement

No potential conflict of interest was reported by the author (s).

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