Structural evolution along the Susa Shear Zone: the role of a first-order shear zone in the exhumation of meta-ophiolite units (Western Alps)

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Abstract

In the Western Alps, different shear zones acting at different depths have been investigated for explaining multistage exhumation of (U)HP units, and several exhumation models have been proposed for explaining present-day stacking of different tectonometamorphic units. This study aims to reconstruct the tectonic evolution of the Susa Shear Zone (SSZ), a polyphasic first-order shear zone, outcropping in the Susa Valley. The SSZ consists of a thick mylonitic zone, along which units characterized by different Alpine metamorphic P–T peaks are coupled. In the study area, the footwall of the SSZ mostly consists of oceanic units (i.e., Internal Piedmont Zone), which record eclogitic conditions, whereas the hanging wall consists of oceanic units (i.e., External Piedmont Zone), which record blueschist-facies conditions. These tectonic units were deformed during subduction- and exhumation-related Alpine history, throughout four main regional deformation phases (from D1 to D4), and were coupled along the SSZ, wherein two shearing events have been distinguished (T1 and T2). T1 occurred during early exhumation and was characterized by "apparent reverse" Top-to-E kinematics, whereas T2 occurred during late exhumation and was characterized by Top-to-W kinematics. Detailed fieldwork and structural analysis allowed us to describe the main features of the different deformation stages and define the deformation relative timing. As final result, we propose a four-step geodynamic model, focused on the different stages developed along the SSZ, from pre-T1 to syn-T2, showing the geometrical relationships between the tectonic units involved in the exhumation. The model aims at explaining the role of the SSZ in the axial sector of the Western Alps.

Keywords: Western Alps, Structural evolution, Susa valley, Susa Shear Zone, Exhumation

1 Introduction

Understanding the building of collisional orogenic belts, and related subduction and exhumation processes, is a much-debated topic. The reconstruction of various evolution stages, recorded by tectonic units during their paths into the orogenic wedge, provides precise information about architecture and geodynamic of orogenic belts. In the Western Alps, several models have been proposed (see e.g., Butler et al. 2013) to explain the present-day stacking order of crustal units. The study of terranes coupled during exhumation focused on first-order shear zones that shaped the nappe stack and wherein polyphasic kinematics are recorded. Different Alpine shear zones acting at different depths have been investigated for explaining exhumation of (U)HP units in the axial sector of the Western Alps (see Platt 1993; Kurz and Froitzheim 2002 as reviews).

In this study, the polyphasic tectonic evolution of a first-order shear zone (i.e., the Susa Shear Zone, SSZ; see...
Ghignone et al. 2020a and references therein), outcropping in the inner sector of the Western Alps, is presented. The SSZ is a thick mylonitic zone, along which different shearing events occurred. Oceanic units are coupled along the SSZ, belonging to the Internal Piedmont Zone (IPZ hereafter) in the footwall, and to the External Piedmont Zone (EPZ hereafter) in the hanging wall.

The two units are characterized by different Alpine metamorphic P–T peaks: the footwall units record eclogite-facies conditions, whereas the hanging wall units record blueschist-facies conditions. The metamorphic jump in P between the two units is about 10 kbar: ~10–12 kbar between Zermatt-Saas (\(P \approx 25–30\) kbar, \(T = 550–600\) °C, Bucher et al. 2005; Angiboust et al. 2009) and Combin (\(P = 12–13\) kbar, \(T = 425–475\) °C, Cartwright and Barnicoat 2002; Negro et al. 2013) units, ~10 kbar between Monviso (roughly \(P \approx 25\) kbar and \(T = 550\) °C, Balestro et al. 2014; Groppo and Castelli 2010) and Queyras (\(P = 8–14\) kbar, \(T = 300–475\) °C, Michard et al. 2003; Tricart and Schwartz 2006) units. In the study area, the metamorphic jump in P between the IPZ and EPZ is >5 kbar (Agard et al. 2001, 2002; Angiboust and Glodny 2020; Ghignone et al. 2020b).

The occurrence of (i) polyphasic kinematic indicators and of (ii) a metamorphic jump from the eclogite-facies footwall to the blueschist-facies hanging wall, are the main characteristics of the SSZ. Similar features were reported in other sectors of the Western Alpine axial belt, as described by Phillipot (1990), and Ballèvre et al. (1990) (i.e., the West Viso Detachment), and by Ballèvre and Merle (1993), and Pleuger et al. (2007) (i.e., the Combin Fault). These shear zones can be considered the southern and northern equivalents of the SSZ (Ghignone et al. 2020a).

Through detailed fieldwork, geological mapping and structural analysis, we describe here the tectonic evolution that occurred along the SSZ. We detected distinct stages in the evolution of the SSZ and of its footwall and hanging wall blocks, disclosing some key steps of the building of this sector of the Western Alpine belt.

### 2 Regional geology

The Western Alps (Fig. 1) are a collisional belt that originated from convergence between the Adria upper plate and the European lower plate, and the interposed Alpine Tethys, which developed during Middle to Late Jurassic spreading of oceanic crust (Lemoine and Tritapepe 1986; Michard et al. 1996; Vissers et al. 2013; Balestro et al. 2019). The axial sector of the Western Alpine belt, consisting of the most deformed (U)HP tectonometamorphic units, corresponds to an exhumed fossil subduction-complex, which was overthrust on the European and Adriatic forelands to the NW and to the SE, respectively (Ricou and Siddans 1986; Rosenbaum and Lister 2005; Schmid et al. 2017). The present-day architecture of the axial sector resulted from three main tectonic stages developed during the (i) Late Cretaceous to Middle Eocene subduction and HP metamorphism, (ii) Late Eocene to Early Oligocene collision-related NW-verging accretion and metamorphic re-equilibration, and (iii) Late Oligocene to Neogene deep Adriatic crust/mantle indentation and shallow crustal tectonic (e.g., Le Bayon and Ballèvre 2006; Lardeaux et al. 2006; Manzotti et al. 2014; Balestro et al. 2015b; Festa et al. 2020).

Remnants of the Alpine Tethys (i.e., the Piedmont Zone; see e.g., Martin et al. 1994), were tectonically sandwiched between the overlying Adriatic continental margin units and the underlying European ones (Dal Piaz et al. 2003 and references therein). Based on different tectonic position, metamorphic evolution and lithostratigraphy, meta-ophiolite units of the Western Alps have been historically distinguished into Internal Piedmont Zone (IPZ) and External Piedmont Zone (EPZ), i.e., Zermatt-Saas-like units and Combin-like units of Bearth (1967), respectively. The IPZ was metamorphosed under eclogite-facies P–T peak conditions and consists of meta-ophiolite covered by thin metasedimentary successions (see e.g., Balestro et al. 2014, 2018; Tartarotti et al. 2017, and references therein), whereas the EPZ was metamorphosed under blueschist-facies P–T peak conditions, and consist of meta-ophiolite bodies scattered within thick metasedimentary successions (see e.g., Agard et al. 2001; Schwartz et al. 2009).

The IPZ units tectonically overlie the Internal Crystalline Massifs (ICM: Monte Rosa, MR, Gran Paradiso, GP, and Dora-Maira, DM; see e.g., Gasco et al. 2013 and references therein). These massifs consist of composite polytectonic metamorphic basements intruded by post-Variscan metagranite and metadiorite bodies, and covered by discontinuous Permian metavolcanic rocks, Permian to Early Triassic siliciclastic metasediments and Middle to Late Triassic carbonate metasediments. The ICM and IPZ units record an Alpine metamorphic evolution characterized by a first main eclogite-facies stage, usually regarded as Eocene (see e.g., Rosenbaum and Lister 2005; Weber et al. 2015 and references therein), and a low-P greenschist to amphibolite facies re-equilibration of Upper Eocene to Lower Oligocene age (see Beltrando et al. 2010; Gauthiez-Putallaz et al. 2016; Manzotti et al. 2018). The EPZ units tectonically lie above both the IPZ and Middle Penninic units, which were metamorphosed under blueschist-facies P–T peaks conditions (Ganne et al. 2003, 2006, 2007). The Middle Penninic units consist of composite polytectonic metamorphic basements, post-Variscan meta-intrusives, widespread Carboniferous to Permian metasediments and thick Mesozoic carbonate
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successions (i.e., the Gran San Bernardo System and the Briançonnais Zone; see e.g., Malusà et al. 2005; Strzerzynski et al. 2012 and references therein).

Tectonic contacts separating the IPZ and the overlying EPZ units, have been recognized all along the Western Alpine belt as polyphasic first-order shear zones. These shear zones are characterized by (i) a metamorphic gap between footwall (eclogite facies) and hangingwall (blueschist and greenschist facies), (ii) the occurrence of opposite kinematic indicators along similarly dipping shear planes, (iii) development under greenschist-facies metamorphic conditions and (iv) Eocene age of shearing (Ring 1995; Freeman et al. 1997; Reddy et al. 1999; Schmid and Kissling 2000; Cartwright and Barnicoat 2002; Ganne et al. 2006; Rosenbaum et al. 2012).

3 Geological setting of the Susa Valley

The different tectonic units exposed in the study area (Fig. 2a), from lower to higher structural levels, correspond to (i) the northern sector of the DM continental margin unit, (ii) the IPZ meta-ophiolite units, and (iii) the EPZ meta-ophiolite units. In the Susa Valley, the DM and the overlying IPZ were folded together during an early exhumation-related deformation phase and are separated from the EPZ by the SSZ, as shown in Fig. 2b. A panoramic view of the left slope of the Susa Valley is shown in Fig. 3, wherein different tectonic units and their geometrical relationships are highlighted.

3.1 Dora Maira unit

In the Susa Valley, the uppermost subunit of the DM occurs as defined by Vialon (1966), and Borghi et al. (1984), metamorphosed under eclogite-facies P–T peak conditions (i.e., P = 19 kbar and T = 510 °C; Gasco et al. 2011) and subsequently re-equilibrated under greenschist-to amphibolite-facies conditions, and its structural evolution was characterized by four main deformation phases (Gasco et al. 2011). The DM consists of a polymetamorphic basement (not exposed along the SSZ) and a metasedimentary Permo-Mesozoic cover (Sandrone et al. 1993; Cadoppi et al. 2002). The latter consists of a siliciclastic succession, which shows an upward transition
to a carbonate one. Only the upper part of the metasedimentary Permo-Mesozoic cover (i.e., blocks of dolomitic marble) has been involved in the SSZ-related deformation (see Ghignone et al. 2020a).

### 3.2 Internal Piedmont Zone

The IPZ tectonically overlies the DM and, in the study area, consists of meta-ophiolites and related metasedimentary cover (i.e., the Orsiera-Rocciavrè Complex of Pognante 1979, and the Bassa Val di Susa-Valli di Lanzo-Monte Orsiera Unit of Cadoppi et al. 2002) and was metamorphosed under eclogite-facies P–T peak conditions (i.e., \( P = 25–29 \) kbar and \( T = 460–510 \) °C, Ghignone et al. 2020b) and during exhumation were re-equilibrated under greenschist-to-amphibolite facies conditions. The IPZ consists of serpentinized

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**Fig. 2** a) Simplified geological map of the axial sector of the Western Alps along the Susa Valley, b) cross-section through the Susa Valley, showing the geometrical relationships between different tectonic units.
metaperidotite, metagabbro, metabasalt and metasediments (Nicolas 1966). Metaperidotite is of lherzolitic origin and was intruded by bodies of Mg–Al metagabbro and Fe–Ti metagabbro (Leardi and Rossetti 1985), whereas metabasalt locally shows relics of breccia- and pillow-lava structures. The metasedimentary cover mainly consists of calcschist of supposed Late Cretaceous age (Marthaler et al. 1986). Serpentinite usually shows a massive structure but appears as strongly foliated serpentinite schist along tectonic contacts and particularly along the SSZ, whereas metagabbro and metabasalt are generally less deformed.

3.3 External Piedmont Zone (EPZ)

In the Susa Valley, the EPZ consists of different tectonic units (e.g., the Puys-Venaus Unit of Polino et al. 2002), made up of metasediments of oceanic origin (i.e., the Schistes Lustrés; Deville et al. 1992, and references therein) which embed bodies of meta-ophiolite. The EPZ records a metamorphic evolution defined by a P–T peak under blueschist-facies conditions and a subsequent re-equilibration under greenschist-facies conditions (P = 12–13 kbar and T = 350 °C, Agard et al. 2001 and references therein).

The meta-ophiolite consists of serpentinitized metaperidotite, serpentinite schist, metagabbro and metabasalt. The metasedimentary cover is mainly made up of a thick calc schist succession. The latter is interbedded by paragneiss, micaschist and quartzite (i.e., the Charbonnel Gneiss of Michel 1953; Pognante 1983), ranging from meter- to hundred-of-meter thick lenticular bodies. In the study area, the EPZ tectonically overlies both the IPZ and the Ambin Massif (see Lorenzoni 1968; Borghi and Gattiglio 1997; Borghi et al. 1999 and references therein), a Briançonnais-like continental margin unit.

4 Structural evolution

The tectonic units outcropping in the study area were deformed during subduction- and exhumation-related Alpine history, recording four main regional deformation phases, from D1 to D4. The polyphasic Susa Shear Zone (SSZ), was characterized by two distinct shearing events (T1 and T2 hereafter). Some outcrop-scale structures related to the main deformation stages are reported in Fig. 4 (details below), while the orientation of the different structural elements characterizing the deformation stages are shown in Fig. 5 (see details below). As shown in Fig. 6f, the shearing events in the SSZ (T1 and T2) were nearly coeval with regional folding and weaker shearing in the neighbouring rocks (D2 and D4).

4.1 Regional deformation phases

It should be emphasized that the pre-coupling structural evolution may have been different between the tectonic units (DM, IPZ and EPZ), while the post-coupling deformation history was common. Therefore the older tectonic phases (D1 and early D2), although presenting similar deformation and kinematic features, likely developed at different crustal levels, metamorphic and tectonic conditions.
Fig. 4 Images of different field-scale structures. Interference relationships between S1 (dashed black lines) and S2 (dashed white lines) folds in a calcschist + paragneiss in EPZ and in b metagabbro + serpentinite in IPZ. c D3 box-folds (conjugated S3 axial planes dashed red lines) deforming Sm1 mylonitic foliation (dashed white lines) in the mylonitic calcschist of the SSZ. d A3 (dashed red lines) crenulation lineations in metabasalt. e D4 folds (S4 axial planes dashed orange lines) deforming S2 regional foliation (dashed white lines) in calcschist of the IPZ. f T1-related Top-to-E shear sense marked by a sigma-shaped exotic block wrapped by the Sm1 mylonitic foliation (dashed white lines) in the mylonitic calcschist of the SSZ. g T1-related kinematic indicators (Top-to-E C-planes in red, Sm1 dashed white lines) in mylonitic calcschist. h T2-related S–C structures (C-planes in orange) showing Top-to-W kinematism deforming S2 regional foliation (dashed white lines), in calcschist of the IPZ.
4.1.1 D1

D1 phase is only discontinuously preserved, and testified by mesoscopic relics of different structural elements. This deformation phase developed under HP conditions, in particular the DM and IPZ record D1 during eclogite-facies conditions as reported by Ghignone et al. (2020b), while the EPZ was affected by D1 deformation phase under blueschist-facies conditions (Agard et al. 2001).

S1 metamorphic foliation is the most pervasive foliation in each tectonic unit, but its fabric, almost completely overprinted by S2 regional foliation, is preserved only locally (e.g., marble of the DM, metagabbro of the IPZ and paragneiss of the EPZ), or it is identifiable as deformed surface in D2 fold hinges (Fig. 4a, b). Locally, especially in the IPZ, S1 is developed as a metamorphic layering. D1 folds are rootless structures showing elongated isoclinal limbs, sharp hinges and asymmetric geometry (in both the IPZ and EPZ). In the whole study area, A1 fold axes are mainly defined by intersection lineations, while Le1 stretching lineations are defined by elongated metamorphic minerals (e.g., phyllosilicates in marbles, chloritoid in metapelites). A1 and Le1, are about N-S trending and parallel to each other in both the IPZ and EPZ. This is in line with the presence of D1 sheath folds exposed with typical anvil- or eye-shaped sections on rock surfaces (Mies 1993), in both the IPZ and EPZ. In the IPZ, S1 is almost N–S striking and W dipping (Fig. 5a); in the EPZ, S1 is E–W striking, dipping both to N and to S (Fig. 5b). This different S1 orientation in the two tectonic units could be due to its different
development between the tectonic units, or to different development of the subsequent D2 deformation, which re-oriented D1 structural elements.

At the bottom of the IPZ, relics of the tectonic contact responsible for the early coupling with the DM (not detailed in this work; see Gasco et al. 2011 for further details) are present. This tectonic contact is marked by an almost fully recrystallized shear zone, along which several tectonic blocks, belonging to both adjacent tectonic units, are preserved. This tectonic contact was folded by D2 folds and developed between D1 and D2 (Gasco et al. 2011).

4.1.2 D2

The main structures developed in the study area are due to D2 deformation phase. The latter developed under greenschist-facies re-equilibration in the IPZ, as also reported by Gasco et al. (2011) for the DM Massif, coupled with the IPZ. Also in the EPZ, D2 developed under greenschist-facies conditions (Agard et al. 2001).

D2 folds show isoclinal profile in the IPZ, whereas close to tight geometry is common in the EPZ. D2 folds developed inside the units, as shown in Fig. 6a, b, away from the boundary of the units. In both tectonic units, D2 re-fold previous structural elements, developing a pervasive S2 axial plane foliation, which represents the regional foliation in the study area. In detail, S2 developed well in lithologies where phyllosilicate content is abundant, whereas in other lithologies, such as metagabbro and marble, S2 is represented by discrete surfaces, developed in the D2 fold hinges. S2 dips to W (mainly to NW-SW in marble, S2 is represented by discrete surfaces, developed where in other lithologies, such as metagabbro and micaschist and serpentine schist. These features include common cusps and lobes morphology. D3 folds are generally characterized by asymmetric geometry, with long and short limbs, locally overturned, and D3 folds occur at all scales, re-orienting previous structures. Box-folds related to D3 also occur, with conjugated axial planes mostly dipping to N and less often to S (Fig. 4c). Along mesoscopic hinges, A3 axes are well developed as pervasive crenulation lineations (Fig. 4d), mainly WSW-ENE trending and west-plunging at low to medium angle. Due to the partly different orientation of the box-folds, minor A3 axes oriented WNW-ESE are present (Fig. 5e).

(See figure on next page.)

Fig. 6. 2D-schematic sketches showing the geometry and relationships between deformation phases: a pre-coupling D1 and D2 folds geometry inside EPZ unit; b D2-related deformation of the IPZ/DM tectonic contact (blue line) and D2 folds geometry inside coupled IPZ and DM unit; c T1 coupling between IPZ + DM and EPZ, and related Top-to-E shear zones (green lines; see text); d D3 folds re-orienting previous T1 shear zone; e D4 folds and coeval T2 shear zones superposed T1 shear zones; f Summary of deformation relative timing, highlighting the nearly coeval development of the shearing events with D2 and D4 folding phases.
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Vergency of D3 folds is mainly northwards, even if, locally, parasitic folds of inverted D3 fold limbs have southward vergence. S3 axial plane foliation is not pervasive and mainly developed in calcschist and micaschist as a disjunctive crenulation cleavage, mostly dipping to NW. In addition, syn-D3 shear zones locally occur, defined by meter-thick mylonitic to cataclastic rocks. These shear zones accommodate the D3 deformation, showing Top-to-N shear sense, coherent with D3 vergency.

4.1.4 D4
D4 is the latest ductile regional phase, developed at shallow structural levels, as testified by the geometry of folds, which are variably open, without developing pervasive axial plane foliations or cleavages. These folds, never overturned, show asymmetric geometry (Fig. 4e) with NNW-SSE trending axes (A4), gently plunging northwards (5–10°, Fig. 5f). Their axial plane, always very steep, is directed approximately N–S and defined by spaced disjunctive cleavage (S4). These folds, recognizable from mesoscopic to map scale, show widespread Top-to-W vergency, causing a diffused westward lowering of all tectonic surfaces and lithological contacts. Locally, along D4 folds short limbs, discrete shear bands with Top-to-W shear sense occur.

4.2 Susa Shear Zone (SSZ)
As previously stated, the IPZ, EPZ and, in part, the DM were coupled through the SSZ, which developed during two distinct shearing events (T1 and T2). A mylonitic foliation (Sm1) developed during T1 event, whereas a disjunctive cleavage (Sm2) developed during T2 event. The inner tectonic architecture of the SSZ is arranged as a tectonic mélange (sensu Festa et al. 2019), mainly consisting of a calcschist matrix wrapping blocks sampled from the units in contact. The superposition of the two shearing events has progressively increased this block-in-matrix structure. The entire rock volume affected by the superposed T1 and T2 deformation varies in thickness from some hundreds of meters, in the northern slope of the Susa valley, to about one kilometer in the southern one. A pervasive mylonitic foliation developed in calcschist, micaschist and serpentinite schist, whereas metabasalt, metagabbro and paragneiss blocks are wrapped by this mylonitic foliation, and partly disrupted in domino structures (sensu Goscombe and Passchier 2003). Upper and lower boundaries of the shear zone appear commonly not sharp. In particular, moving toward the EPZ, the mylonitic foliation and the superposed shear bands are less and less pervasive, more spaced and often concentrated in discrete m-sized deformation bands. Moving toward the IPZ, the deformation also decreases, as testified by the occurrence of thinner shear bands in which deformation is concentrated. The geometric relationships between T1 and T2 are reported in Fig. 6e.

4.2.1 T1
The first shearing event (T1) gave rise to a thick shear zone, on average NNE-SSW striking, showing a block-in-matrix structure. The strongly deformed matrix (i.e., mylonitic calcschist) embeds blocks sliced from the IPZ, EPZ and, to a lesser degree, from the DM (e.g., metabasalt, massive serpentinite, paragneiss, dolomitic marble and metagabbro, Fig. 4f). Sm1 is strongly pervasive and transpositional, millimetre-spaced in the calcschist. Sm1 overprints previous lithological textures, giving the rocks a homogeneous appearance. This homogenization is particularly evident in calcschist (Fig. 4g), wherein the original carbonate-rich and phyllosilicate-rich layering, occurring in the non-mylonitic calcschist of both the IPZ and EPZ, disappears. The dip of Sm1 is quite scattered towards NW to SW (Fig. 5g), resulting on average about sub-parallel to S2 regional foliation. Geometrical field relationships between Sm1 and S2 are not always univocal: Sm1 was usually observed to cut S2 at low angle (< 10°), and locally the two foliations are parallel to each other, distinguished on the basis of a local strain increase. These structural relationships suggest that Sm1 and S2 developed nearly coeval, in different domains. Sm1 developed as mylonitic foliation at the boundary between the lower IPZ + DM and the upper EPZ during syn-to-late-D2 deformation event, while S2 developed as axial plane foliation inside the tectonic units.

Kinematic indicators occurring within the Sm1 correspond to S–C (C′) fabric, δ- and σ-type mantled porphyroclasts and overturned folds. In particular, extensional crenulation cleavage (ECC) and C planes (sensu Platt and Vissers 1980) are the most abundant kinematic indicators (Fig. 4g), concentrated in sets of millimeters to meters-spaced discrete shear bands.

Kinematic indicators provide a “Top-to-E apparent reverse” sense of shear (Fig. 5i). C planes dip from NW to SW (Fig. 5g) showing dispersion similar to the mylonitic foliation. Stretching lineations underlined by elongated minerals and occurring on the C planes roughly plunge parallel to the dip of C planes (Fig. 5g). The long axis of the blocks (of every size) is parallel to the stretching lineations measured on the C planes.

All the structural elements related to T1 show the same dispersion, because of their re-orientation during the D3 regional folding phase (see Fig. 5e, g for comparison between D3 and T1 structural elements, and Fig. 4c field relationships).
4.2.2 T2
The second shearing event (T2) developed a hundred-meter-thick deformation zone, on average N–S striking and W-dipping, which crosscuts previous structures, giving rise to a reworked tectonic mélangé. Sm2 is a disjunctive cleavage, different from the previous Sm1, concentrated along discrete and spaced shear bands. These are defined by bands of ECC and occur more pervasive and less spaced closer to the IPZ, while, moving towards EPZ, these discrete shear bands becomes progressively more spaced and wrapping tectonic blocks of various size. Usually, T2-related blocks are bigger than the T1-related ones and more disrupted. Sm2-C kinematic indicators (Fig. 5h) dip both toward W, almost parallel, varying their angle of dip. T2-related shear bands show fairly constant dip values and orientations, while C-planes vary from subhorizontal to medium-angle dipping to SW and NW. This wide range of values can be related to different orientations of the C-planes around tectonic blocks, also explaining the wide dispersion of stretching lineation on these planes. T2 kinematic indicators (e.g., ECC, S–C structures and rotated porphyroclasts) are consistent with Top-to-W sense of shear (Fig. 5l). S–C planes of the two shearing events show relations of superposition and cross-cutting, T2-related C planes crosscut and reorient T1-related C planes. Sm2 wraps lithons containing T1 kinematic indicators, and locally, T2-related C planes overprint and completely erase previous structural elements (Fig. 6e). On outcrop and map scale, the relative movement of footwall and hanging wall causes the downward bending of previous contacts in the footwall (Fig. 4h). T2-related structural elements are not involved in the regional folding phases, suggesting their development coeval with D4 regional deformation phase. This is consistent with T2-related shear bands developed along short limbs of D4-related folds, as stated before.

T2-related kinematic indicators occur more pervasively along the N slope of the Susa Valley, with cm- to m-spaced ECC shear bands, while in the southern one the shear bands are more spaced (tens of m). This is likely due to the interference with the adjacent Ambin Massif, present only in the northern slope and absent in the southern one.

5 Discussion
5.1 Tectonic evolution of the SSZ
The tectonic history recorded along the SSZ consists of two superposed steps (i.e., T1 and T2), whose relative timing is given by the relationships with the regional structures (D1 to D4, see Fig. 6f). The S1 + S2 composite foliation of the IPZ (Fig. 6b), and the S2 foliation of the EPZ (Fig. 6a) are the main structural markers. T1 drove the coupling between the IPZ, already coupled with the DM (Gasco et al. 2011), and the EPZ (Fig. 6c). The geometrical relationships between S2 and Sm1, highlight that D2 and T1 were nearly coeval, developing different structures and related kinematics within the tectonic units or along their boundary. Inside the IPZ and EPZ, S2 developed as axial plane foliation, with Top-to-W shear sense, while, along their boundary (i.e., the SSZ) the strain increased, developing the nearly coeval Sm1 mylonitic foliation, with Top-to-E shear sense.

After T1, the coupled tectonic elements suffered a regional folding (D3), tectonically linked with early development of a dome-like structure in the DM (see Gasco et al. 2013; Ghignone et al. 2020a). The original geometry of the T1 shear zones was then significantly re-oriented, as highlighted by the consistency between scattering of the Sm1 and orientation of D3 fold axes (Fig. 5e, g). D3 folds deformed, at the meso-scale, the T1 mylonites, tilting the original eastward plunging of the mylonites and the related kinematic indicators at the large scale, and giving the “apparent reverse” sense of shear. These structural relationships highlight that T1 tectonic developed before the D3 (Figs. 4c, 6d). Doming phases usually are related to folds with axes oriented concentric to the center of the dome and parallel to the border of the dome itself, with a centrifugal vergency (see e.g., Burg et al. 2004; Wang et al. 2015 and references therein).

In the study area, D3 fold axes orientation (and related vergency) are consistent with these assumptions, due to their location along the NW flank of the DM dome-like structure. It is to emphasize that “apparent reverse” shear sense is probably related to this dome-related tilting which reoriented the original plunging of the T1-related shear zone, maintaining the same shear sense (Top-to-E normal fault).

During exhumation of tectonic units at shallower crustal levels, T2 structures developed and crosscut T1 shear planes. T2 structures accommodated a later phase of dome-related uplift of the DM and IPZ in the footwall of the SSZ, and the relative downthrow of the EPZ in the hanging wall, with a westward kinematics. The relative timing of the T2 is inferred to be syn-D4. At the mesoscale, T2 shear zones developed along short limbs of D4 folds, and, at the macroscale, they are in turn associated with D4 drag folds (Fig. 6e).

It is noteworthy that the tectonic elision of the IPZ south of the study area (see Fig. 1) likely corresponds to a maximum of exhumation of the underlying DM.

The tectonic evolution of the SSZ through time has been represented in a step-model (Fig. 7). The different steps reconstruct the tectonic evolution of the axial sector of the Western Alps along the Susa Valley, highlighting the geometrical relationships between the different tectonic units. In Fig. 7a the geological setting at late-D1
stage is represented, prior to the development of the SSZ. The IPZ was coupled through a thrust above the DM still in HP conditions. The IPZ and EPZ were probably not already adjacent each other (see dashed line along their contact, Fig. 7a), but this point still remains unclear. After the IPZ and DM coupling, the eclogite-bearing units were coupled with the upper blueschist-bearing units (EPZ), through the east-plunging T1-related shear zone, displaying Top-to-E kinematics (Fig. 7b). Different exhumation rates of the eclogite-bearing units with respect to the blueschist-bearing ones are inferred from the kinematics of the nearly coeval deformation events (syn- to late-D2), as represented in Fig. 6c (arrows indicate the different relative exhumation velocity). The subsequent D3 folding was related to the development of the dome-like structure of the eclogite-bearing units (Fig. 7c), which reoriented the previous structures, rotating the orientations of the surfaces from east-dipping to west-dipping in the study sector. The T2-related shear zone (Fig. 7d, red line) allowed the final uplift.

Fig. 7 Tectonic model of the evolution of the axial sector of the Western Alps along the Susa Valley (see text for details)
5.2 Comparison with other first-order shear zones

The polyphasic tectonics and the kinematics of the SSZ are discussed in the following by comparison with other shear zones that coupled tectono-metamorphic units with different P–T metamorphic paths in the axial sector of the Alpine belt.

The occurrence of two distinct generations of kinematic indicators and of an important metamorphic jump from eclogite-facies footwalls to the greenschist- and blueschist-facies hanging walls has been widely reported along the Alpine belt (the Combin Fault by Ballèvre and Merle 1993; Ring 1995; Froitzheim et al. 2006; Pleuger et al. 2007; Kirst and Leiss 2017; the Susa Shear Zone by Gasco et al. 2013; Ghignone and Gattiglio 2013; Ghignone et al. 2020a; the Orco Shear Zone by Gasco et al. 2009; Gasco et al. 2013; the Gressoney shear zone by Reddy et al. 1999, 2003; Wheeler et al. 2001; Gasco et al. 2013; Savignano et al. 2016; the Täschalp shear zone by Barnicoat et al. 1995; Cartwright and Barnicoat 2002; the Entrelor shear zone by Butler and Freeman 1996; Rolland et al. 2000, Bucher et al. 2003; Malusà et al. 2005; Ganne et al. 2006; Rosenbaum et al. 2012; the West Viso Detachment by Ballèvre et al. 1990; Philippot 1990; Tricart et al. 2004).

All these cited shear zones are potential segments of one single coherent first-order regional-scale structure, because they are in the same tectonostratigraphic and tectono-metamorphic position, as reported in Fig. 1.

Geochronological data constrain the timing of deformation along the Combin, Täschalp, Gressoney and Entrelor Shear Zones as Eocene, around 33–45 Ma (Barnicoat et al. 1995; Ring 1995; Freeman et al. 1997; Reddy et al. 1999; Schmid and Kissling 2000; Cartwright and Barnicoat 2002; Malusà et al. 2005; Rosenbaum et al. 2012). These Eocene ages are suitable for the timing of the T1 in the SSZ, considering the nearly coeval age of the D2 deformation in the Western Alps (Reddy et al. 1999; Dal Piaz et al. 2001).

T2 deformation of the SSZ, coeval with D4 deformation phase, likely developed in the Oligocene, according to the ages proposed by Balestro et al. (2009), and Perrone et al. (2010) for the D4 deformation phase.

The polyphase activity of previously mentioned shear zones was described by several authors, who reported early Top-to-E (SE) kinematics superposed by widespread later Top-to-W kinematics along the same contacts (Malusà et al. 2005; Ganne et al. 2006; Savignano et al. 2016). Reddy et al. (2003) inferred that the Top-to-SE kinematics played a major role in the structural history, responsible for the exhumation of the eclogite-facies units in the footwall of the Gressoney Shear Zone. In the same work, it was also pointed out that shear zones with normal-fault kinematics may have been tilted into orientations with apparent thrust geometry by later folding and shearing phases (Wheeler and Butler 1993; Butler and Freeman 1996; Ring 1995; Ganne et al. 2006; Pleuger et al. 2007). The occurrence of the “apparent reverse” sense of shear (i.e., re-folded early shear zone) has been documented by Barnicoat et al. (1995), Bucher et al. (2003), Ganne et al. (2006), Gasco et al. (2009), Ghignone et al. (2020a), and related to the doming of the ICM.

Philippot (1990) also reported the presence of discrete shear bands, including both Top-to-E and Top-to-W kinematic indicators.

The former nature of early shear zones was interpreted either as folded normal faults or as folded thrusts. Rolland et al. (2000), Wheeler et al. (2001), and Tricart et al. (2004) interpreted the shear zones as characterized by a single event of normal faulting.

Philippot (1990), and Ballèvre et al. (1990) proposed the occurrence of backthrusting for the West Viso Detachment, wherein two opposite kinematic indicators were referred to a coeval deformation stage. Butler and Freeman (1996) also support the hypothesis of backthrusting along the Entrelor Shear Zone, which involves the Gran Paradiso Massif and the Piedmont Zone.

Furthermore, Froitzheim et al. (2006), and Pleuger et al. (2007) interpreted the Combin Fault as a normal fault that formed during downward extraction of a larger rock volume above the exhuming eclogite-bearing unit and subsequent out-of-sequence thrusting.

Ballèvre and Merle (1993) suggested that early Top-to-E kinematic developed along a normal fault (i.e., the Combin fault), which was reactivated during Top-to-W shearing.

6 Orogen scale implications and conclusions

As already inferred, SSZ is a first-order tectonic contact, mostly developed within the meta-ophiolitic units of the Piedmont Zone (i.e., the IPZ and EPZ), tectonically overlying the ICM (i.e., the DM in the study area) and the Gran San Bernardo nappe system (i.e., the Ambin Massif in the study area). During the T1 event, the already coupled DM and IPZ were exhumed below the EPZ in the form of an extruding wedge structure, bounded by a normal fault, such as the SSZ, at its top and a by thrust, at its base, likely deep-rooted and associated with the Frontal Pennidic Thrust.

We propose a general common evolution for the system of different shear zones, which drove exhumation of different tectonic units within the axial sector of the Western Alps. As a matter of fact, each of these shear zones was characterized by two shearing events. A first shearing event (Top-to-E, T1 of the SSZ) exhumed the already coupled ICM + IPZ units below the EPZ units, which were both moving away from the upper plate
towards the foreland during Late Eocene shortening. T1 shear zones were dipping towards the hinterland, displaying an exhumation-related “extensional” Top-to-the-foreland kinematics. “Extensional kinematics” would thus result from different exhumation rates, which should be higher for the IPZ+DM, and lower for the EPZ. In this interpretation, T1 shear zones are clearly part of an exhumation-related normal fault (Butler et al. 2013), in a system similar to the “pip” model proposed by Wheeler et al. (2001).

When the second shearing event occurred (T2 of the SSZ), during a main phase of doming, resulting shear zones then developed with a centrifugal kinematics with respect to the center of the dome-like structures. Accordingly, it is possible to suggest a later vertical motion of the composite eclogite-bearing continental-oceanic crust (ICM and IPZ) beneath the blueschist–greenschist-bearing one (EPZ). In this view, a HP–LT metamorphic dome occurred in the axial position of the Western Alps orogenic wedge: the ICM (and the IPZ, when present) behave as core complexes, and the shear zones developed along their flanks were the weak zones that accommodated the doming itself.

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Authors’ contributions
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