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Geology of the Susa Shear Zone (Susa Valley, Western Alps)

Stefano Ghignone, Marco Gattiglio, Gianni Balestro and Alessandro Borghi

Department of Earth Sciences, University of Torino, Torino, Italy

ABSTRACT
The 1:10,000 scale geological map of the Susa Shear Zone (SSZ) in the inner sector of the Western Alps, aims to describe the geological setting and tectonic evolution of a first-order Alpine shear zone, which drove exhumation and juxtaposition of different oceanic and continental margin units (i.e. the blueschist-facies External Piedmont Zone in its hanging wall and the eclogite-facies Internal Piedmont Zone and Dora Maira Massif in its footwall). The SSZ corresponds to a tectonic mélange showing a block-in-matrix structure, wherein mylonitic calcschists embed blocks of different rock units. Geological mapping and structural analysis investigated overprinting relationships among shear planes and structures related to different deformation phases: they show that the SSZ evolved through two tectonic events, during which apparent reverse top-to-E shear planes were superposed by extensional top-to-W ones.

1. Introduction

The study of geodynamic evolution of orogenic belts often focuses on first-order shear zones, which drive stacking of tectonic units. Reconstructing the geometry, inner structure and polyphase kinematics of orogen-related shear zones is a key for better understanding subduction and exhumation processes. In the Western Alps, shear zones and tectonic mélanges bounding different tectonometamorphic units of both continental and oceanic origin, have been described within the axial sector of the belt (see Schmid, Kissling, Diehl, van Hinsbergen, & Molli, 2017, and references therein), and their detailed structural characterization as well as their role in multistage exhumation of tectonic units is an up to date topic (see e.g. Balestro, Festa, & Tartarotti, 2015; Federico, Crispini, Malatesta, Torchio, & Capponi, 2015; Gasco, Gattiglio, & Borghi, 2013; Kirst & Leiss, 2017; Manzotti, Zucali, Ballèvre, Robyr, & Engi, 2014; Roda, De Salvo, Zucali, & Spalla, 2018).

In this paper, the polyphase tectonic evolution of a shear zone, the Susa Shear Zone (SSZ hereafter), exposed in the inner sector of the Western Alps (Susa Valley, NW of Italy; Figure 1), is described. The SSZ juxtaposed and exhumed different oceanic and continental margin units, which are characterized by different Alpine metamorphic P-T peaks. Together with their former northern and southern analogs (i.e. the Combin fault and the West Viso Detachment, respectively; Balestro et al., 2018; Ballevre & Merle, 1993; Tricart, Schwartz, Sue, & Lardeaux, 2004), it represents a first-order shear zone separating two orogen-scale domains,

which have been distinguished within the Alpine accretionary wedge (i.e. the 'eclogite belt' and 'frontal wedge' of Malusà, Faccenna, Garzanti, & Polino, 2011). Our geological map at 1:10,000 scale (see Main Map), aims to describe in detail the kinematics of the SSZ and the structural and lithostratigraphic setting of its footwall and hanging-wall blocks.

2. Geological setting

The Western Alps resulted from convergence of the Adria plate and European plate, with closing of the interposed Ligurian–Piedmont oceanic basin (see e.g. Butler, Beaumont, & Jamieson, 2013, and references therein), through (*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. Festa, Balestro, Borghi, De Caroli, & Succo, 2019; Polino, Dal Piaz, & Gosso, 1990; Rosenbaum & Lister, 2005, and references therein). Remnants of the Ligurian–Piedmont oceanic basin correspond to different meta-ophiolite units (i.e. the Piedmont Zone; Balestro, Festa, & Dilek, 2019; Dal Piaz, Bistacchi & Massironi, 2003), which tectonically overlie the European continental margin units (Figure 1) and can be separated into an eclogite-facies Internal Piedmont Zone (IPZ hereafter) and a blueschist-facies External Piedmont Zone (EPZ hereafter) (see e.g. Martin, Tartarotti, & Dal Piaz, 1994; Tartarotti, Festa, Benciolini, & Balestro, 2017; Tricart & Lemoine, 1991).
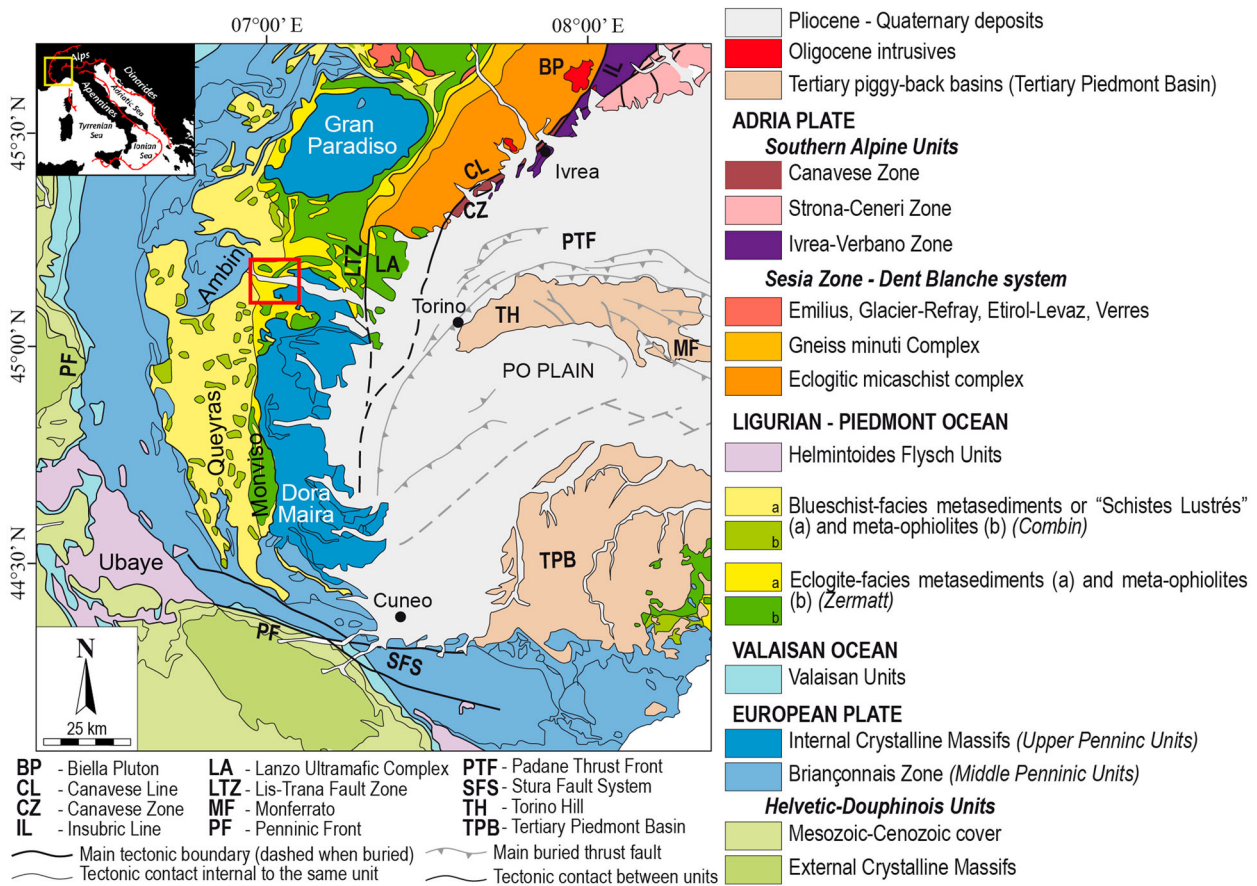
Figure 1. Tectonic map of the Western Alps (modified after Balestro, Festa, Dilek, & Tartarotti, 2015). The red square indicates the study area.

In the Susa Valley, the IPZ is bounded by the SSZ to the W and by the Col del Lis-Trana Deformation Zone to the E (Balestro, Cadoppi, Perrone, & Tallone, 2009; Ghignone & Gattiglio, 2013), and it consists of serpentinite, metagabbro, metabasalt and metasediments (Pognante, 1979, 1980), which tectonically overlie the Dora Maira Massif (DM hereafter). The DM is a remnant of the thinned European continental margin and its lithostratigraphy comprises a composite Variscan basement, post-Variscan meta-intrusives, Permian metavolcanics and siliciclastic metasediments, and Mesozoic carbonate metasediments (Cadoppi et al., 2002; Gasco, Gattiglio, & Borghi, 2011; Sandrone, Cadoppi, Sacchi, & Vialon, 1993; Vialon, 1966). The EPZ consists of a thick succession of oceanic metasediments embedding blocks of meta-ophiolite and it tectonically overlies the IPZ (Deville, Fudral, Lagabrielle, Marthaler, & Sartori, 1992; Pognante, 1983).

In the Susa Valley, eclogite-facies and blueschist-facies units occur (Pognante, 1984; Pognante & Sandrone, 1989), and different P-T peaks were calculated for the DM (i.e. $P = 19$ kbar and $T = 510°C$; Gasco et al., 2011), IPZ (i.e. $P = 18–20$ kbar and $T = 450–520°C$; Agard, Monie, Jolivet, & Goffe, 2002) and EPZ (i.e. $P = 12–13$ kbar and $T = 350°C$, Agard et al., 2002). The DM, IPZ and EPZ lithostratigraphic successions were folded and sheared during four ductile deformation phases (D1, D2, D3 and D4 hereafter), and then faulted during post-metamorphic brittle deformation (Gasco et al., 2013; Perrone et al., 2010; Perrone, Cadoppi, Tallone, & Balestro, 2011). D3 and D4 were roughly coeval to the development, within the DM, of an exhumation-related dome-like structure, which caused a large scale westward tilting of the overlying IPZ and EPZ (Lardeaux et al., 2006).

3. Methods

The geological and structural data were collected at 1:5000 scale, stored in a GIS database and represented on a topographic map compiled from the Carta Tecnica Regionale Vettoriale of the Regione Piemonte (vector_10 series, Edition 1991–2005). In the geological map (see Main Map), encompassing an area of almost 30 km², geological and structural data have been generalized at 1:10,000 scale. The structural architecture and geological setting of the SSZ are given in three cross sections and in a tectonic sketch map. Regional deformation phases have been distinguished through overprinting relationships among structures. Orientation of structural elements has been analyzed by equal-area lower-hemisphere stereographic projections. The geological map presented here is part of a wider project, which aims to produce detailed geological maps

in tectonically meaningful sectors of the Western Alps (Balestro, Fioraso, & Lombardo, 2011, 2013; Cadoppi, Camanni, Balestro, & Perrone, 2016; Fioraso, Balestro, Festa, & Lanteri, 2019; Gasco & Gattiglio, 2010; Gasco & Gattiglio, 2011).

4. Lithostratigraphy

In the study area, the SSZ involves different rock units of the DM, IPZ and EPZ (see Main Map).

The DM consists of older siliciclastic metasediments and younger carbonate rocks. The siliciclastic metasediments are up to one hundred meters thick and correspond to coarse-grained massive paragneisses and medium- to fine-grained mica schists, both embedding rare lenticular bodies of metabasite. The paragneisses are interbedded with levels of quartzite and show transitional contacts with the mica schists which, in their stratigraphically upper part, are characterized by levels of quartzite and of carbonate-bearing mica schist. The carbonate metasediments are roughly one hundred meters thick and mainly consist of massive dolomitic marbles and metadolostones, which have been considered of Middle Triassic to Late Triassic age (Franchi, 1897). Medium-grained calcschists and fine-grained carbonate-rich calcschists discontinuously occur at the bottom and at the top of marbles, respectively.

The IPZ corresponds to a hundreds of meters thick meta-ophiolite and metasedimentary succession, mainly consisting of serpentinites, metabasites and calcschists. The ultrabasic rocks correspond both to massive serpentinites and serpentine schists, and locally embed meter-sized elongated bodies of metagabbro which are both of Mg-Al-rich and Fe-Ti-rich compositions. Metagabbros are massive, poorly rodingitized, and locally retain eclogitic mineral assemblages. The metabasites are rather massive and medium-grained, and derive from pillow lavas and volcanic breccia. The calcschists represent the metasedimentary cover of the meta-ophiolites; they have been attribuited to the lower part of the Late Cretaceous (Marthaler, Fudral, Deville, & Rampnoux, 1986). The calcschists are interbedded with levels of grey micaceous marble and are locally characterized by centimeter- to meter-sized horizons of impure quartzite, carbonate-bearing quartz schist and metabasite. Levels of metabreccia with clasts of dolomitic marble also occur.

The EPZ mainly consists of hundreds of meters carbonate metasediments, which vary from phyllosilicate-rich calcschists to carbonate-rich schists and embed up to few decameter-sized stretched bodies of serpentinite, metabasite, prasinite and paragneiss. The ultrabasic rocks occur both as massive serpentines and serpentine schists. The metabasites are fine- to medium-grained and, along the contact with the calcschists, are characterized by discontinuous centimeter- to decimeter-

thick horizons of quartzite, mica schist and marble. These horizons locally occur also along the contact between calcschists and siliciclastic metasediments, which are up to few decameters thick and consist of quartz-rich paragneisses (i.e. Charbonnel Gneisses Auct.; Michel, 1953) and mica schists. The paragneisses are massive and leucocratic, and are characterized by centimeters-sized porphyroclasts of K-feldspar. Their occurrence in the oceanic succession of the EPZ likely documents a significant terrigenous input into the basin, sourced from a continental margin area.

5. Regional deformation phases

In the study area, four regional deformation phases (from D1 to D4) have been distinguished (see Main Map). The D1 phase is mainly defined by an early foliation (i.e. the S1), which is preserved as a structural relic in more massive rocks such as the dolomitic marbles, metagabbros and paragneisses. In the DM and IPZ, the S1 is scattered but on average it dips toward W at medium angle (Figure 2(a)); in the EPZ the S1 dips both to the N and S at high angle (Figure 2(b)). The S1 is characterized by a N-S trending stretching lineation. At the map scale, the main D1 structure corresponds to the tectonic contact between the DM and IPZ.

The regional foliation (i.e. the S2) developed during the D2 phase and it mainly dips at low to medium angle to the W (Figure 2(c–d)). The S2 corresponds to the axial plane of non-cylindrical closed-to-isoclinal folds, which occur at all scales and pervasively deform and reorient both the tectonic contact between the DM and IPZ and the stratigraphic contacts within the DM, IPZ and EPZ. Fold axes are on average W-plunging at a low angle and are about parallel to a stretching lineation. As highlighted by related kinematic indicators (Figure 3(a)), the D2 was characterized by a westward tectonic transport.

D1- and D2-related structures are partly reoriented by open-to-closed folds (Figure 3(b)), which characterize the D3 phase. These folds accommodated the exhumation-related doming of the DM and thus, in the study area (i.e. the northern to north-western flank of the DM), are northward verging. D3 fold axes are on average W-plunging at low to medium angle and axial planes mainly dip to the NNW at medium angle, although box folds with conjugated N- and S-dipping axial planes also occur. D3 folds did not develop a pervasive foliation but spaced cleavages and crenulation cleavages locally occur. Map-scale D3 axial planes have been detected both in the DM, IPZ, SSZ and EPZ. The D3 phase is also responsible for a major tectonic contact occurring within the DM and IPZ. This map-scale structure dips both toward NNW and NW at medium angle and it is defined by
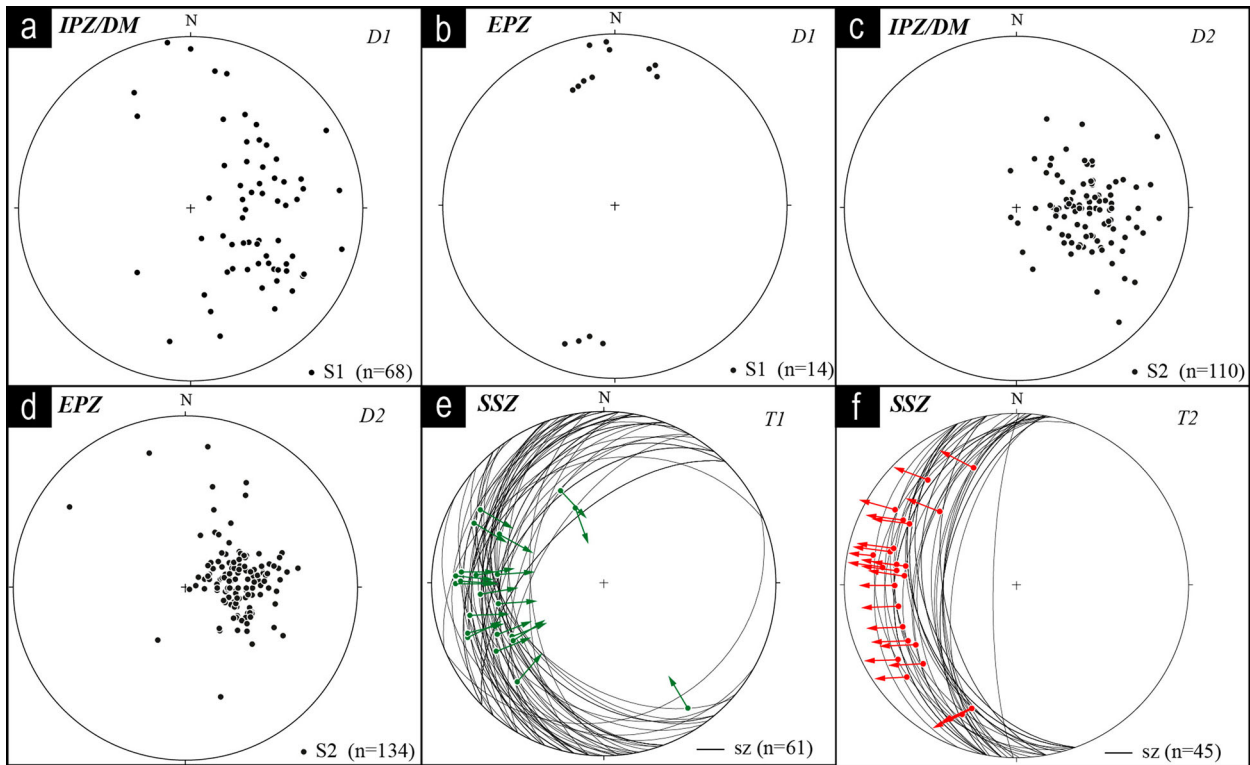
Figure 2. Equal-area lower-hemisphere stereographic projections of different structures (n: number of data): (a) poles of S1 foliations from the IPZ and DM, and (b) from the EPZ; (c) poles of S2 foliations from the IPZ and DM, and (d) from the EPZ; (e) great circles of T1-related and (f) T2-related shear planes (sz) from the SSZ (green and red arrows indicate T1- and T2-shear senses, respectively).

mesoscale discrete shear zones, which on average indicate top-to-NNW extensional shear senses.

The D4 is the latest deformation phase and is characterized by open folds, which occur at all scales in each units. D4 fold axes are both N- and S-plunging at low angle, and axial planes are steeply dipping and roughly NNW-SSE striking. Long-short D4 fold limbs highlight westward tectonic transport. Post-D4 brittle deformation was characterized by the development of different fault systems, which mainly correspond to N-S striking normal faults, and to conjugate WSW-ENE and NW-SE directed strike-slip faults showing right-lateral and left-lateral movements, respectively.

6. The Susa Shear Zone

The SSZ separates the DM and IPZ (i.e. the footwall) from the EPZ (i.e. the hanging-wall) and it is about 500 meters thick (Figure 4). It corresponds to a tectonic mélange (sensu Festa, Pini, Ogata, & Dilek, 2019), showing a block-in-matrix structure, with mylonitic calcschists embedding elongated blocks of different rock units. Blocks are mainly meters- to decameters-sized and consist of paragneiss (Charbonnel Gneisses Auct.), metabasite, grey marbles and serpentinite, which were tectonically sampled from the EPZ and IPZ. A major hectometers-thick block of dolomitic

marbles sliced from the DM, occurs in the southern side of the Susa Valley (see Main Map).

The SSZ was characterized by a polyphase kinematic evolution and two superposed tectonic events (T1 and T2 hereafter) have been recognized. The T1 is defined by a pervasive mylonitic foliation, which dips at low angle both toward NW and SW (Figure 2(e)). T1-related stretching lineations are on average westward plunging and kinematic indicators (i.e. S–C fabrics and sigma-shaped porphyroclasts and quartz veins) provide reverse top-to-E sense of shears (Figure 2(e) and Figure 3(c–d)). The block-in-matrix structure of the SSZ mainly developed during the T1 and, at the map scale, T1 tectonic contacts correspond to the boundaries of the SSZ and of the embedded blocks (Figure 4). The occurrences of both T1 tectonic contacts and T1-related mylonitic foliation deformed by D3 folds (Figure 3(b)), highlight that the T1 occurred between the D2 and D3 regional deformation phases, which developed under greenschist-facies conditions (see Gasco et al., 2011).

The T2 is defined by discrete shear bands, which are on average W-dipping at medium-angle (Figure 2(f)). T2-related SC fabrics are consistent with extensional top-to-W sense of shears (Figure 3(e–f)). Superposition between T1 and T2 structures is locally highlighted by T2 shear planes wrapping blocks containing T1-related structures, and by T2 C-planes crosscutting T1 C-planes.
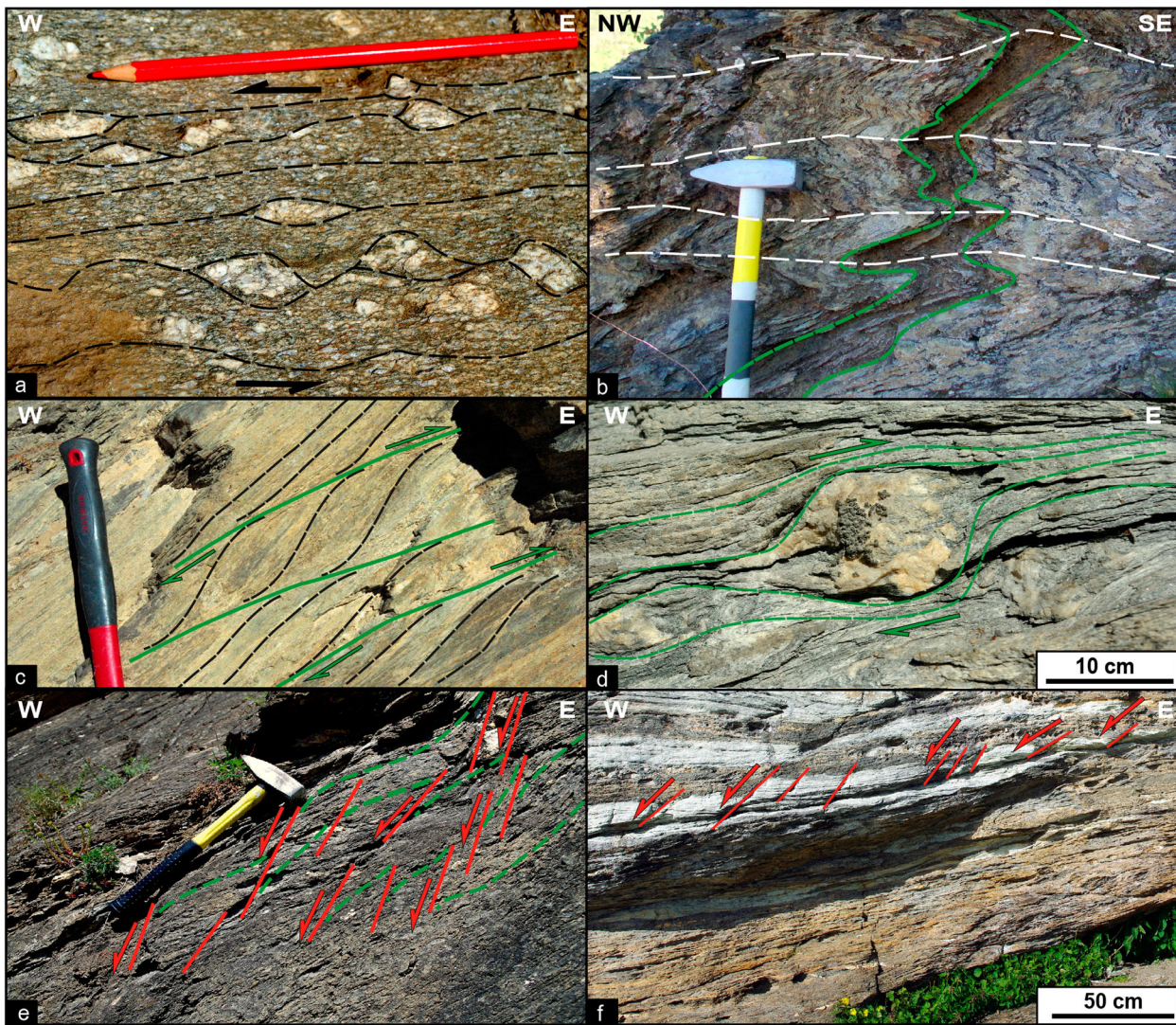
Figure 3. Images of different field-scale structures: (a) top-to-W shear sense marked by sigma-shaped K-feldspar porphyroclasts wrapped along the S2 foliation (dashed black lines) in the paragneiss of DM (E of Meana, 45°07′31″N, 7°04′22″E); (b) D3 folds deforming the T1 mylonitic foliation (dashed green lines) in the mylonitic calcschist of the SSZ (dashed white lines for D3 axial planes; N of Mompantero, 45°08′47″N, 7°04′00″E); (c) T1-related SC fabric with top-to-E shear planes (green lines) dragging the S2 foliation (dashed black lines) in the mylonitic calcschist of the SSZ (NW of Mad.na dell'Ecova, 45°08′53″ N, 7°04′20″ E); (d) top-to-E shear sense marked by a sigma-shaped quartz vein wrapped by the T1 mylonitic foliation (dashed green lines) in the mylonitic calcschist of the SSZ (NW of Susa, 45°08′23″ N, 7°02′38″ E); (e) T2-related top-to-W shear planes (red lines) dragging the T1 mylonitic foliation (green dashed lines) in the mylonitic calcschist of the SSZ (N of Mompantero, 45°09′00″ N, 7°04′28″ E); (f) top-to-W T2 shear planes (red lines) showing a domino-like structure (mylonitic calcschist of the SSZ; S of Susa, 45°07′36″ N, 7°02′37″ E).

At the map scale, T2 tectonic contacts occur within the SSZ or close to its boundaries, within the EPZ and IPZ (see Main Map), and their relative movements caused the downward bending of both previous structures and lithological contacts. The T2 was coeval to the D4 phase, whose folds accommodated the same westward tectonic transport. The latter was likely driven by a late stage of doming of the DM, during which pre-D4 structures were likely reoriented (Lardeaux et al., 2006). As a consequence, the top-to-E sense of shear of the T1 shear planes would correspond to an apparent reverse kinematic, and T1-related structures would have actually originated as extensional E-dipping structures (see also Ghignone & Gattiglio, 2013).

7. Conclusions

The here presented 1:10,000 scale geological map, describes in detail the structural architecture and tectonic evolution of the SSZ, as well as the tectonostratigraphic setting of its footwall and hanging-wall blocks. Our interpretation of the SSZ is that it had an important role in driving exhumation and juxtaposition of blueschist-facies units (i.e. the EPZ) onto eclogite-facies ones (i.e. the IPZ and DM), suggesting a plurikilometric throw. It is remarked that the DM and IPZ were coupled before the onset of the SSZ (i.e. during the D1) and, therefore, they experienced a common exhumation history.
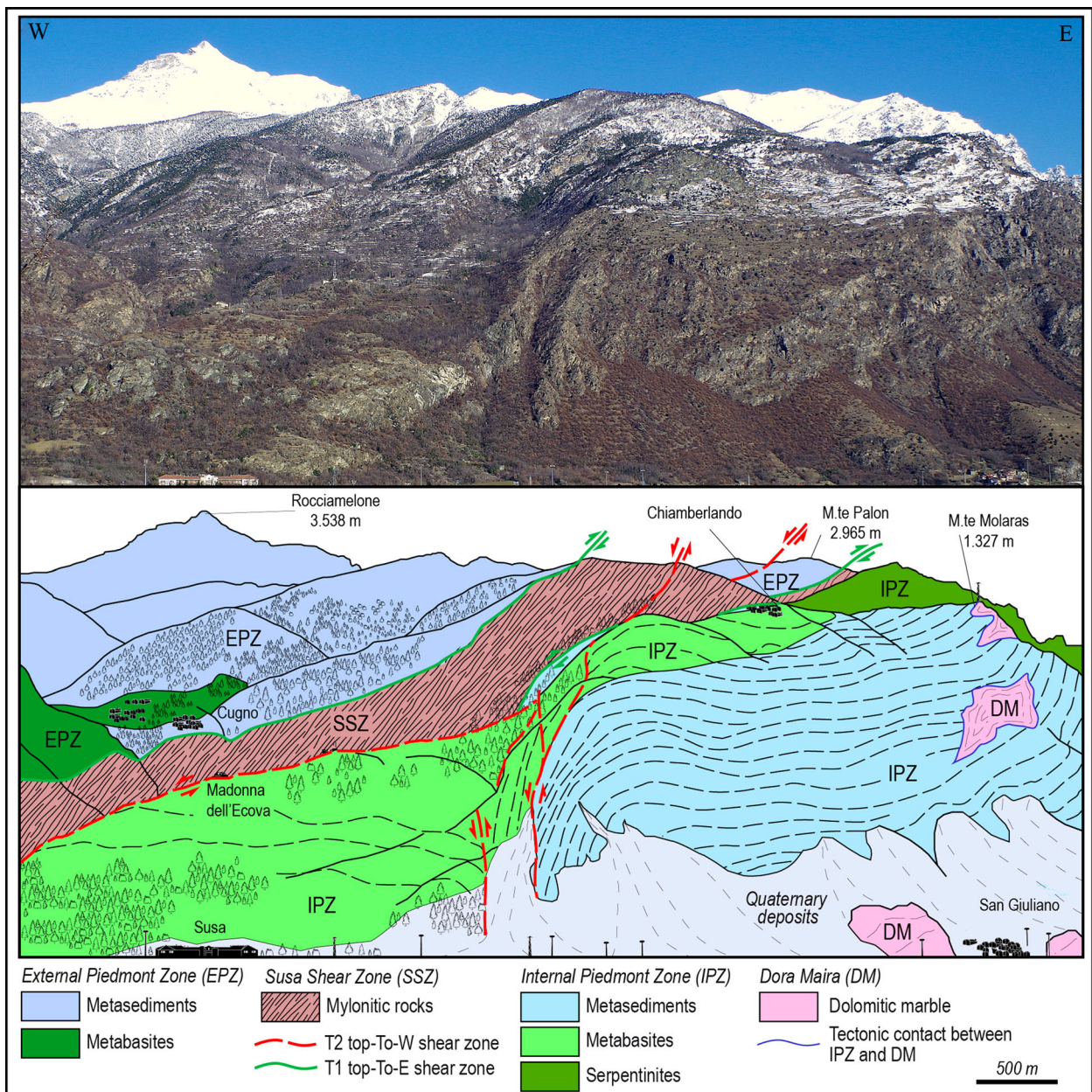
Figure 4. View and related geological sketch of the SSZ along the northern slope of the Susa Valley.

Geological mapping and structural analysis highlight that the SSZ evolved through two different tectonic events, over which early developed top-to-E shear planes (i.e. the T1) were superposed by late top-to-W ones (i.e. the T2). Along the former southern analog of the SSZ (i.e. the West Viso Detachment; Tricart et al., 2004), top-to-E shear zones have been described and interpreted either as conjugate sets of extensional top-to-W/E shear planes (Ballevre, Lagabrielle, & Merle, 1990) or as evidence of a large-scale buck-thrusting phase (Philippot, 1990). It is here pointed out that T1 structures developed between the D2 and D3 and thereby they can not be coeval to T2 structures, which developed during the D4. We also suggest that, as a result of D3- to D4-related regional doming of the DM and westward tilting of the overlying IPZ and EPZ, the top-to-E shear planes were likely reoriented giving apparent reverse kinematics.

Software

The map has been drawn using the software QGIS (v. 3.4.2-Madeira) and Adobe Illustrator® 10. Structural data have been projected with the software StereoNett©.

Acknowledgements

Disclosure statement

ORCID

Stefano Ghignone http://orcid.org/0000-0002-1295-6291
Marco Gattiglio http://orcid.org/0000-0002-1885-2872
Gianni Balestro http://orcid.org/0000-0001-5215-4659
Alessandro Borghi http://orcid.org/0000-0002-2545-0396

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