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Geological Setting of the Lyon-Turin Cross-Border Section (Italian Side)

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The planned railway line from Lyon (France) to Turin (Italy) is part of the developing Trans-European Transport Network. The line, on the Italian side, starts in the Turin plain and follows the Susa Valley up to the Ambin Massif in the Western Alps, where a new cross-border tunnel will connect the Susa area to Saint-Jean-de-Maurienne (France) (fig. 1 a).

The railway line crosses a part of the axial sector of the Alps, a collisional orogen consisting of tectonic units derived from the European and African paleomargins and from the interposed Tethys oceanic basin (Piedmont zone) (fig. 1 b). The geology of the Susa Valley is described by a very abundant literature, and is represented by a few geological maps in scale 1:50.000 realized by the official *project* of cartography of Italy (CARG).

The Susa Valley transect includes units ascribed to the oceanic External (EPZ) and Internal (IPZ) Piedmont Zones (distinguished on the basis of their metamorphic peak developed under blueschist-facies and eclogite-facies conditions respectively), and the continental Dora Maira Unit (DM) and Ambin Massif (AM) (fig. 1 c)[1]. As shown in fig. 1 c, the EPZ lies on the uppermost structural levels.

Based on published papers and new original data, the aim of this paper is to describe the main features of the Susa Valley transect.

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[1] G.V. Dal Piaz, *The Austroalpine-Piedmont Nappe Stack and the Puzzle of Alpine Tethys*, in G. Gosso *et al.* (eds.), *Third Meeting on Alpine Geological Studies*, in «Memorie di Scienze Geologiche», 51, 1999, pp. 155-176; S.M. Schmid, E. Kissling, T. Diehl, D.J.J. van Hinsbergen, G. Molli, *Ivrea Mantle Wedge, Arc of the Western Alps, and Kinematic Evolution of the Alps-Apennines Orogenic System*, in «Swiss Journal of Geosciences», 110, 2017, pp. 581-612.

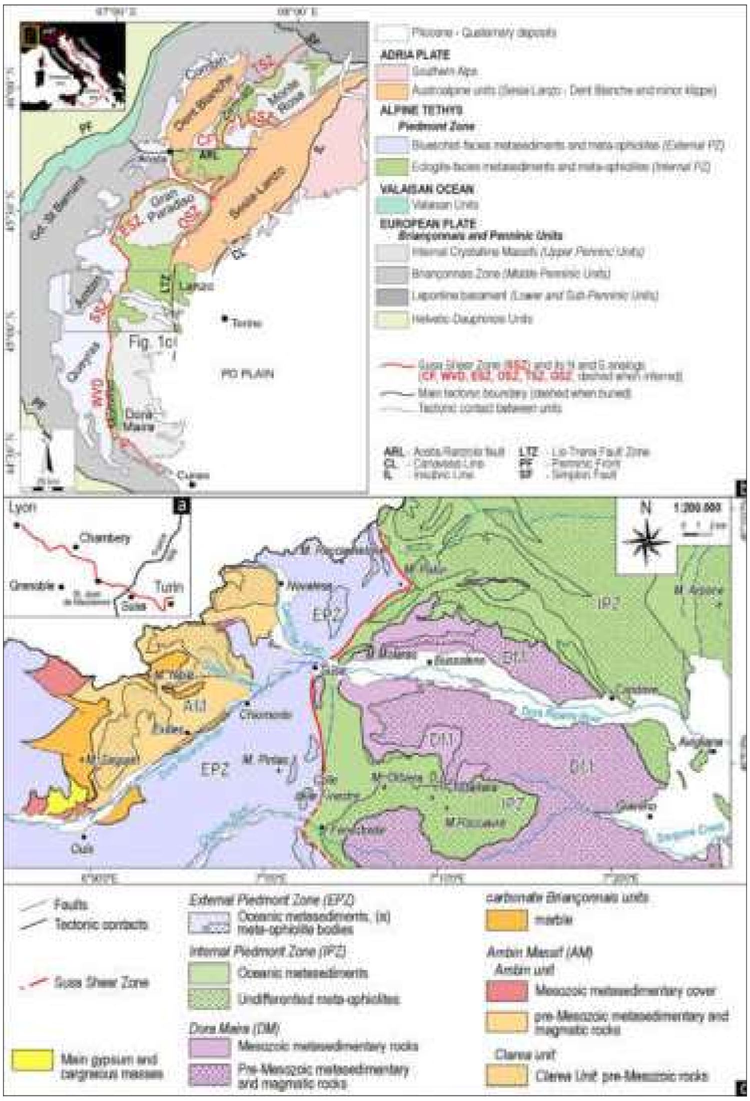

Fig. 1. Geological regional context of the planned railway Lyon-Turin line on the Italian side: a) Railway line route plan (in red) between Lyon and Turin; b) Simplified tectonic sketch-map of the Western Alps, modified after S. Ghignone, G. Balestro, M. Gattiglio, A. Borghi, *Structural evolution along the Susa Shear Zone: the role of a first-order shear zone in the exhumation of meta-ophiolite units (Western Alps)*, in «Swiss Journal of Geosciences», 113 (1), 2020a, 17, https://dx.doi.org/10.1186/s00015-020-00370-6. Black square indicates the considered area. SSZ Susa Shear Zone, CF Combin Fault, WVD West Viso Detachement, ESZ Entrelor Shear Zone, OSZ Orco Shear Zone, TSZ Täschalp Shear Zone, GSZ Gressoney Shear Zone; c) Simplified geological map of the axial sector of the Western Alps along the middle and lower Susa Valley.

Minerals abbreviations in the text are given according with the *Abbreviations for names of rock-forming minerals* in «American Mineralogist»[2].

1. Lithostratigraphic features

External Piedmont Zone

In the Susa Valley, the EPZ lies above the AM and the IPZ in the western and eastern sectors, respectively (fig. 1 c). It consists of a very thick sequence (fig. 2 a) of fine-grained calcschists (fig. 2 b, c) with bodies of meta-ophiolites and siliciclastic meta-sediments in-bedded. The ophiolitic bodies consist of metabasite, serpentinite and serpentine schist (fig. 2 d, e).

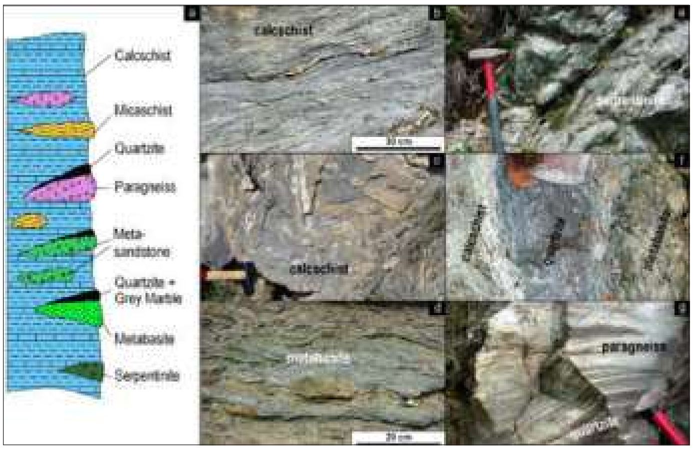

Fig. 2. Field photographs of the EPZ main lithotypes, preserved primary stratigraphic contacts in the considered area: a) Lithostratigraphic column of the EPZ (not to scale); b) Phyllosilicate-rich calcschist with quartz veins; c) Carbonate-rich calcschist where thin carbonate veins draw ductile folds; d) Metabasite consisting of alternating thin chlorite – and epidote – rich and albite-rich layers; e) Massive to discretely foliated serpentinite body; f) quartzite and calcschist in stratigraphic contact above metabasite; g) Charbonnel Gneiss consisting of quartzite and paragneiss alternating layers.

Metabasite occurs in few meters to about ten meters thick bodies, showing massive aspect, fine-grained and greenish color. Locally, the metabasite preserves their stratigraphic cover represented by impure quartzite and gray marble (fig. 2 f). Levels of serpentine schist mainly crop out along faults and tectonic contacts.

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[2] D.L. Whitney, B.W. Evans, *Abbreviations for names of rock-forming minerals*, in «American Mineralogist», 95, 2010, pp. 185-187, https://doi.org/10.2138/am.2010.3371.

The siliciclastic meta-sediments occur in up to hundreds of meters thick bodies, and consist of paragneiss, micaschist and impure quartzite (Charbonnel Gneiss *Auct.*)[3] (fig. 2 g). These meta-sedimentary bodies have lenticular geometry, scarce lateral continuity and variations in thickness.

Paragneiss is mainly exposed in the northern slope of the Susa Valley (especially at the confluence with the Cenischia Valley). This rock is whitish in color and massive, and is characterized by mm- to cm-sized K-feldspar porphyroclasts in quartz-mica matrix.

Locally, paragneiss preserves a meta-sedimentary cover constituted by impure quartzite (metachert[4]) and grey marble in primary contact.

Micaschist in decametric to hectometric bodies, mainly occur in the southern slope of the Susa Valley, showing primary layering defined by quartz-rich and phyllosilicate-rich layers.

Internal Piedmont Zone

The IPZ lies above the DM (fig. 1 c) and it is formed by an oceanic basement with its Jurassic to Cretaceous sedimentary cover (fig. 3 a). The oceanic basement is represented by serpentinite with sporadic bodies of metagabbro.

Serpentinite forms bodies of green-to-black color and several hundred meters thick (e.g. Sacra di S. Michele relief), with massive to foliate appearance (fig. 3 b). Deformation and recrystallization completely erased the previous mantle texture of the serpentinite, while along faults and tectonic contacts it occurs as serpentine schist. Locally, at the top of serpentinite thin levels of meta-ophicarbonate are present. Metagabbro occurs in few meters to tens of metres thick bodies (fig. 3 c), showing two main chemical composition: i) Fe-Ti metagabbro[5], and ii) Mg-Al metagabbro[6]. Fe-Ti metagabbro presents dark colour, massive aspect and usually preserves eclogitic relicts, while Mg-Al

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[3] U. Pognante, *Les intercalations gneissiques dans une unité des «schistes lustrés» de la valleé de Suse (Alpes Occidentales): Témoins d'une marge continentale subductée?*, in «Comptes Rendus de l'Académie des Sciences Paris», 296 (2), 1983, pp. 379-382.

[4] *Ibidem*.

[5] U. Pognante, J.R. Kienast, *Blueschist and Eclogite Transformations in Fe-Ti Gabbros: A case from the Western Alps Ophiolites*, in «Journal of Petrology», 28, 1987, pp. 271-292, https://doi.org/10.1093/petrology/28.2.271; G.C. Bortolami, G.V. Dal Piaz, *Il substrato cristallino dell'anfiteatro morenico di Rivoli-Avigliana (prov. Torino)*, in «Memorie Società Italiana Scienze Naturali Milano», 18, 1970, pp. 125-169.

[6] P. Cadoppi, M. Castelletto, R. Sacchi, P. Baggio, F. Carraro, V. Giraud, G. Bellardone, *Note illustrative alla Carta Geologica d'Italia alla scala 1:50.000, Foglio 154 Susa*, Servizio Geologico d'Italia, Litografica Geda, Torino 2002.

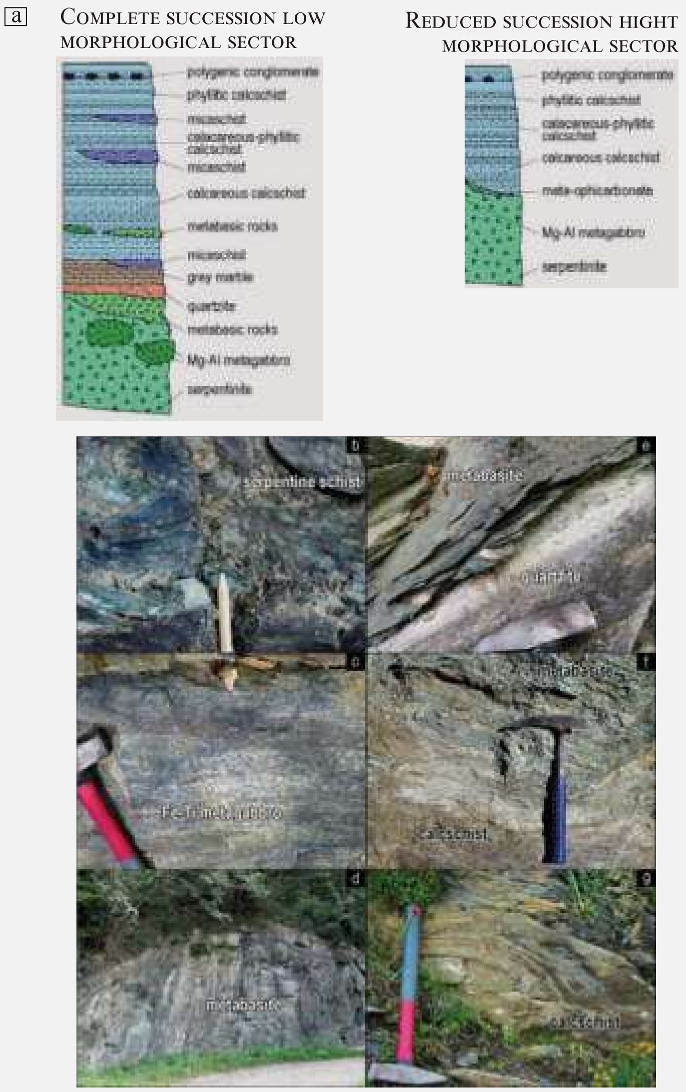

Fig. 3. Field photographs of the IPZ main lithotypes, preserved primary stratigraphic contacts in the considered area. a) Lithostratigraphic columns of the IPZ referred to Jurassic low and high morphological sectors (not to scale); b) Strongly foliated serpentinite (serpentine schist); c) Fe-Ti metagabbro showing abundant alpine garnet porphyroclasts (reddish spots); d) Massive metabasite outcrop deformed by open- to close- folds; e) Overturned stratigraphic contact between metabasite and its stratigraphic cover of quartzite; f) Overturned stratigraphic contact between metabasite and calcschist; g) Calcschist consisting of centimetric homogeneous carbonate levels (yellowish in color) and thin phyllosilicates levels (dark in color).

metagabbro is leucocratic, due to green mineral aggregates within a whitish matrix, locally preserving magmatic relicts.

The oceanic basement is covered by laterally discontinues bodies of metabasic rocks (meta-sandstone, meta-breccia and meta-conglomerate), representing the first dismantling products of the ocean floor. These lithotypes are fine to medium grained, from massive to locally banded, alternating whitish and greenish layers of different mineralogical composition and grain size (fig. 3 d).

The overlying pelagic meta-sedimentary succession includes quartzite (fig. 3 e) and grey marble with local thin levels of Grt+Cld micaschist.

Then, upsection, a thick sequence of calcschist rests unconformable on the serpentinite and the lower terms of meta-sedimentary succession[7] (fig. 3 a, f). The calcschist preserves an original compositional layering defined by cm- to m-thick carbonate-rich and phyllosilicates-rich domains (fig. 3 g). In-bedded thin layers of grey marble, Grt-micaschist bodies and polygenic conglomerate also occur. The polygenic conglomerate consist of mm- to dm in size metabasic rocks, micaschist and marble rounded clasts in carbonate-phyllitic matrix.

Stratigraphic relationships between oceanic basement and cover are strongly variable. Serpentinite basement is locally topped directly by calcschist and locally by a complete metasedimentary sequence (metabasic rocks, quartzite, grey marble and calcschist, (fig. 3 a). These different lithostratigraphic successions were referred to different paleogeographic environments of high and low morphological framework respectively, formed during middle/upper Jurassic rifting and spreading phases[8].

The observed stratigraphic relationships between the oceanic basement and the different terms of the overlying sediments define an articulate paleo-morphology of the ocean floor (with topographic highs and lows) due to middle/upper Jurassic rifting and spreading phases.

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[7] S. Ghignone, G. Balestro, M. Gattiglio, A. Borghi, *Structural Evolution Along the Susa Shear Zone: the Role of a First-Order Shear Zone in the Exhumation of Meta-Ophiolite Units (Western Alps),* in «Swiss Journal of Geosciences», 113, 17, 2020, https://link.springer.com/article/10.1186/s00015-020-00370-6.

[8] M. Lemoine, P. Tricart, G. Boillot, *Ultramafic and Gabbroic Ocean Floor of the Ligurian Tethys (Alps, Corsica, Apennines): Insearch of a Genetic Model*, in «Geology», 15, 1987, pp. 622-625; Y. Lagabrielle, *Ophiolites of the southwestern Alps and the Structure of the Tethyan Oceanis Lithosphere*, in «Ofioliti», 19, 1994, pp. 413-434; G. Principi, V. Bortolotti, M. Chiari, L. Cortesogno, L. Gaggero, M. Marcucci, E. Saccani, B. Treves, *The Pre-Orogenic Volcano-Sedimentary Covers of the Western Tethys Ocean Basin: a Review*, in «Ofioliti», 29, 2004, pp. 177-211; M. De Togni, M. Gattiglio, S. Ghignone, A. Festa, *Pre-Alpine Tectono-Stratigraphic Reconstruction of the Jurassic Tethys in the High-Pressure Internal Piedmont Zone (Stura di Viù Valley, Western Alps)*, in «Minerals», 11, 361, 2021, https://doi.org/10.3390/min11040361.

Dora Maira Unit

Dora Maira Unit (DM) is one of the Internal Crystalline Massifs and forms a north-plunging regional dome. It crops out along the two sides of the Susa Valley between Susa and Condove (fig. 1 c). In this section, the DM consists of pre-Triassic micaschist (with local Grt and Cld enrichments), paragneiss («Pietra di Luserna» type) and Borgone metagranit (not reported in fig. 4 a), covered by a discontinuous Mesozoic meta-sedimentary succession (fig. 4 a).

Fig. 4. Field photographs of the DM main lithotypes in the considered area. a) Lithostratigraphic column of the DM (not to scale); b) Gneiss containing evident K-feldspar porphyroclasts (Gneiss *Pietra di Luserna* type); c) Borgone porphyric metagranit with tabular K-feldspar porphyroclasts and centimetric xenolitic bodies; d) Icaschist containing thin quartz veins deformed by isoclinal folds; e) Massive white dolomitic marble, black dashed lines indicate primary sedimentary layers.

The paragneiss «Pietra di Luserna» type is a phengitic gneiss, massive in aspect, largely outcropping in the southern slope of the Susa Valley where it forms continuous bodies up to some hectometer thick. Cm-sized quartz and K-feldspar porphyroclasts in fine quartz-white mica matrix define the gneissic texture (fig. 4 b). Inside this, cm- to dm-thick layers of quartz-phengitic micaschist are also present[9].

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[9] Silvery micaschist by P. Vialon, *Etude géologique du Massif cristalin Dora-Maira (Alpes cottiennes internes-Italie)*, Thèse d'état, Université de Grenoble, 1966, pp. 1-293; G. Barisone, G. Bottino, V. Coccolo, R. Compagnoni, O. Del Greco, F. Mastrangelo, R. Sandrone, S. Zucchetti, *Il bacino estrattivo della «Pietra di Luserna» (Alpi Cozie)*, in «Notiziario Associazione Mineraria Subalpina», 5, 1979, pp. 35-50.

The Borgone metagranit mainly crops out in the northern slope of Susa Valley and consists of a porphyric metagranite with idiomorphic K-feldspar megacrystals (up to 5-6 cm) (fig. 4 c). Fine-grained melanocratic and haplitic dikes intruded the main granitic body.

Micaschist, up to a hundred meters thick and medium- to fine-grained, consisting of a fine white mica and quartz matrix, wherein mm-sized garnet and cm-sized chlorithoid porphyroblasts occur (fig. 4 d). Locally, at the base of the micaschist succession, decimetric to metric thick grey quartzite bands are present, while thin carbonate-rich layers occur at the top. In addition, several bodies of massive fine-grained metabasite characterize this succession.

The lowermost terms of the Mesozoic meta-sedimentary succession are identified by discontinuous whitish homogeneous quartzite and overlying layers of carbonate micaschist (meter-to few hundred-meters thick).

Upward, a grey and white dolomitic marble occurs, with thickness ranging from few meters to 300-500 meters. This lithotype has a massive to banded aspect, homogeneous saccharoid texture and fine grain size (fig. 4 e). The uppermost terms, of the DM Mesozoic meta-sedimentary succession, are represented by sporadic layers of calcschist. It is important outline that large part of the calcschists previously considered as metasedimentary cover of DM[10] has been ascribed to the overlying IPZ: this is derived from the recognition of an important ductile tectonic contact between the dolomitic marble and the calcschist[11].

The reconstruction of the pre-Alpine stratigraphic setting of the DM in the Susa Valley[12] was based on the interpretation reported in the Susa Geological Sheet[13]. This interpretation was used to realize the geological map of the Lyon-Turin cross-border area (Italian side)[14].

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[10] *Servizio Geologico d'Italia. Foglio 154 Susa alla scala 1:50.000*, Litografica Geda, Torino 2002.

[11] I. Gasco, M. Gattiglio, A. Borghi, *Lithostratigraphic Setting and P–T Metamorphic Evolution for the Dora Maira Massif along the Piedmont Zone Boundary (middle Susa Valley, NW Alps)*, in «International Journal of Earth Sciences», 100, 2011, pp. 1065-1085.

[12] M. Gattiglio, R. Sacchi, *Lineamenti geologici della Val di Susa lungo il tracciato del progetto TAV Torino-Lione, Atti di due convegni su Amianto e Uranio in Val di Susa*, in «Rendiconti Società Geologica Italiana», 3, 2006, pp. 13-19.

[13] *Servizio Geologico d'Italia. Foglio 154 Susa alla scala 1:50.000*, cit.

[14] R. Sacchi, G. Balestro, P. Cadoppi, F. Carraro, L. Delle Piane, L. Di Martino, M. Enrietti, F. Gallarà, M. Gattiglio, G. Martinotti, P. Perello, *Studi geologici in Val di Susa finalizzati ad un nuovo collegamento ferroviario Torino-Lione*, Museo Regionale di Scienze Naturali, Regione Piemonte, Monografie XLI, 2004, pp. 1-117.

Micaschist in the Susa Geological Sheet was interpreted as poly-metamorphic, although in the notes of the map this interpretation is questioned, asserting that the succession may be of probable Permian age, and therefore resulting as mono-metamorphic, as previously proposed by P. Vialon *et alii*[15]. While the paragneiss «Pietra di Luserna» type were interpreted as a volcano-sedimentary complex[16], or as metagranitic bodies[17].

Ambin Massif

In the tectonic framework of the Western Alps, the AM corresponds to a fragment of continental crust cropping out in form of large antiform under different units of the EPZ and of successions of Briançonnais affinity with presence of masses of anhydrite (fig. 1 c)[18].

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[15] P. Vialon, *Etude géologique du Massif cristalin Dora-Maira (Alpes cottiennes internes-Italie)*, cit.; R. Sandrone, P. Cadoppi, R. Sacchi, P. Vialon, *The Dora-Maira massif*, in J.F. von Raumer and F. Neubauer (eds.), *Pre-Mesozoic Geology in the Alps*, Springer-Verlag, Berlin, 1993, pp. 317-325.

[16] P. Vialon, *Etude géologique du Massif cristalin Dora-Maira*, cit.

[17] G.C. Bortolami, G.V. Dal Piaz, *Il substrato cristallino dell'anfiteatro morenico di Rivoli-Avigliana (prov. Torino)*, in «Memorie Società Italiana Scienze Naturali Milano», 18, 1970, pp. 125-169; P. Cadoppi, *Geologia del basamento cristallino nel settore settentrionale del Massiccio Dora-Maira (Alpi Occidentali)*, Tesi di Dottorato, Università di Torino, 1990, 208 pp.

[18] For the knowledge of the geology of the AM are fundamental, among the others, the studies performed by R. Michel, *Premiers résultats de l'étude pétrographique des schistes cristallins du massif d'Ambin (Alpes Franco-Italiennes)*, in «Compte rendu sommaire des séances de la Société Géologique de France», 6, 1956, pp. 121-123; Id., *Les faciès à glaucophane dans le massif d'Ambin (Alpes franco-italiennes)*, in «Compte rendu sommaire des séances de la Société Géologique de France», 6, 1957, pp. 130-131; J. Goguel, *Présence des conglomérats à la base du «groupe d'Ambin» dans les schistes cristallins du massif d'Ambin (Savoie)*, in «Compte rendu sommaire des séances de la Société Géologique de France», 11, 1958, pp. 229-231; S. Lorenzoni, *Studio geo-petrografico del versante italiano del massiccio d'Ambin*, in «Memorie dell'Istituto Geologia e Mineralogia Università Padova», 25, 1965, pp. 1-88; Id., *Étude pétrographique du versant italien du massif d'Ambin (Alpes franco-italiennes)*, in «Schweizerische Mineralogische. Petrographische Mitteilungen», 48/1, 1968, pp. 428-436; M. Gay, *Le massif d'Ambin et son cadre de Schistes Lustrés (Alpes franco-italiennes)*, Thèse, 1971, pp. 1-296; Id., *Le massif d'Ambin et son cadre de Schistes lustrés (Alpes franco-italiennes). Evolution métamorphique*, in «Arc. Sci. Genève», 25 (1), 1972, pp. 5-100; Id., *Le massif d'Ambin et son cadre de Schistes lustrés (Alpes franco-italiennes). Evolution structurale*, in «Arc. Sci. Genève», 25 (2), 1972, pp. 165-214; S. Fudral, E. Deville, G. Nicoud, U. Pognante, P.L. Giullot, E. Jaillard, *Notice explicative, Carte géol. France (1/50.000), feuille Lanslebourg-Mont d'Ambin (776)*, BRGM, Orléans 1994, pp. 1-94; S. Fudral, E. Deville, U. Pognante, M. Gay, G. Fregolent, S. Lorenzoni, D. Robert, G. Nicoud, C. Blake, A.

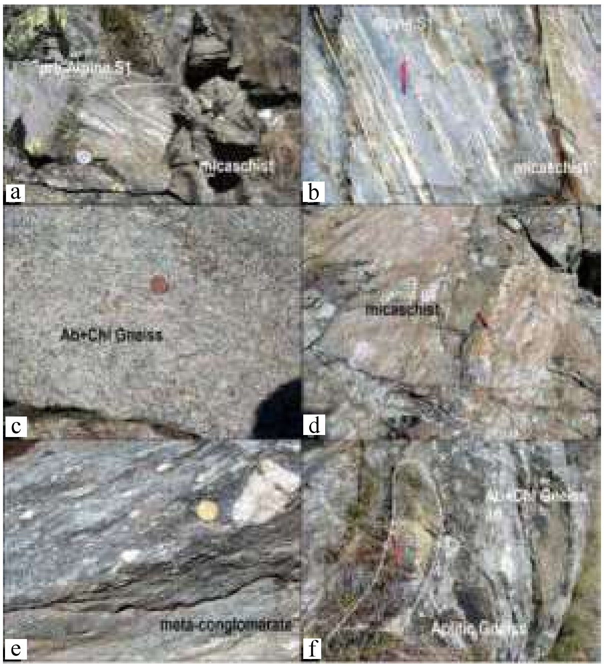

Fig. 5. Field photographs of the AM main lithotypes. a) Folded pre-alpine foliation in micaschist of the Clarea Unit; b) HP/LP foliation developed in micaschist of the Clarea Unit; c) Meso-scale texture of the Ab-Chl gneiss of the Ambin Unit; d) Different facies of micaschist of the Ambin Unit; e) Metaconglomerate in-bedded within micaschist of the Ambin Unit; f) Aplitic gneiss intruded in Ab-Chl gneiss of the Ambin Unit.

Jayko, E. Jaillard, J.M. Bertrand, M.G. Forno, G. Massazza, *Carte Géol. France (1/50.000), feuille Lanslebourg-Mont d'Ambin (776)*, BRGM, Orléans 1994; R. Polino, F. Dela Pierre, A. Borghi, G. Fioraso, M. Giardino, F. Carraro, G. Bellardone, M. Gattiglio, M. Malusà, P. Mosca, *Note illustrative al Foglio 153 (132-152) Bardonecchia. Carta Geologica d'Italia alla scala 1:50.000*, Serv. Geol. It., Litografia Geda, Torino 2002; *Servizio Geologico d'Italia. Foglio 132-152-153 Bardonecchia alla scala 1:50.000*, cit.; A. Borghi, M. Gattiglio, F. Mondino, G. Zaccone, *Structural and Metamorphic Evidence of Pre-Alpine Basement in the Ambin Nappe (Cottian Alps, Italy)*, in «Memorie Scienze Geologiche Padova», 51, 1999, pp. 205-220; M.G. Malusà, P. Mosca, A. Borghi, F. Dela Pierre, R. Polino, *Approccio multidisciplinare per la ricostruzione dell'assetto tettono-stratigrafico e dell'evoluzione metamorfico-strutturale di un settore di catena orogenica: l'esempio dell'Alta Valle di Susa (Alpi Occidentali)*, in «Bollettino della Società Geologica Italiana», 57, 2002, pp. 249-257; J. Ganne, *Multi-stage Garnet in the Internal Briançonnais Basement (Ambin Massif, Savoy): New Petrological Constraints on the Blueschist-facies Metamorphism in the Western Alps and Tectonic Implications*, in «Journal of Petrology», 44 (7), 2003, pp. 1281-1308, https://doi.org/10.1093/petrology/44.7.1281; J. Ganne, The AM comprises two tectonic basement units, i.e. the Clarea and Ambin units, resting at the lower and upper structural levels respectively and whose rocks has been also correlated in literature with those of the South Vanoise.

The Clarea unit consists of micaschist and paragneiss with widespread quartz veins and rods, embedding metric to decametric bodies of metabasite and pluri decametric masses of orthogneiss of dioritic composition[19]. The lower part of this unit preserves pre-Alpine amphibolite facies metamorphism highlighted by mineralogical assemblages of muscovite, biotite, garnet and staurolite[20] that define a mesoscopic foliation (fig. 5 a) progressively transposed by alpine deformation moving up-section (fig. 5 b).

The basement rocks of the Ambin unit are here ascribed to the Ab-Chl Gneiss complex and the Micaschist complex, both unconformable capped by an Upper Permian-Mesozoic succession[21].

The Ab-Chl Gneiss complex is formed by abundant gneiss (fig. 5 c) and subordinate quartz-micaschist derived from volcano-clastic protoliths, representing the lowermost terms of the pre-deformation lithostratigraphic setting of the Ambin unit. Numerous magmatic relics are recognizable in this complex, such as Ilm, Mag, Rt, allanitic core of epidote, sodium pyroxene grown on magmatic plagioclase, and chlorite grown on magmatic biotite. Trace elements suggest a dominant rhyodacitic composition for the photoliths, with low content in CaO, Na_2O and K_2O and high content of Al_2O_3 suggesting sub-aerial exposure[22].

The Micaschist complex groups different types of micaschist with variable content of Qz, Ab, Wm, Chl, Na-Amph, Cld, Bt and Grt. At the outcrop

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J.M. Bertrand, S. Fudral, *Geometry and kinematics of early Alpine nappes in a Briançonnais basement (Ambin Massif, Western Alps)*, in «Comptes Rendus Geoscience», 336 (13), 2004, pp. 1219-1226, https://doi.org/10.1016/j.crte.2004.06.006.

[19] A. Borghi, M. Gattiglio, *Osservazioni geologico-petrografiche nel settore occidentale del Massiccio d'Ambin*, in «Atti Ticinesi di Scienze della Terra», 5, 1997, pp. 64-84.

[20] A. Borghi, M. Gattiglio, F. Mondino, G. Zaccone, *Structural and metamorphic evidence of pre-Alpine basement in the Ambin nappe (Cottian Alps, Italy)*, in «Memorie Scienze Geologiche Padova», 51, 1999, pp. 205-220; P. Monié, *Preservation of Hercynian 40Ar/39Ar ages through high-pressure low-temperature Alpine metamorphism in the Western Alps*, in «European Journal Mineralogist», 2, 1990, pp. 343-361.

[21] P. Mosca, A. Borghi, M. Gattiglio, *Storia pre-alpina ed alpina nel Massiccio di Ambin (Alpi Occidentali)*, in «Rendiconti della Società Geologica Italiana», 6, 2008, pp. 129-131.

[22] A. Boldrin, A. Borghi, P. Cadoppi, M. Gattiglio, R. Ruffini, R. Torri, *Caratterizzazione del magmatismo di unità di crosta continentale coinvolte nell'orogenesi alpina: un esempio dall'unità tettonostratigrafica d'Ambin (Alpi occidentali)*, 80° Congresso nazionale SIMP, in «Plinius», 24, 2000, pp. 46-48.

scale, an irregular compositional banding is often recognizable by Qz+Ab and Wm+Chl rich domains (fig. 5 d). The micaschists contain discontinuous masses of metaconglomerate (fig. 5 e), levels of graphite–bearing micaschist, of quartzite and of rare marble with silicates (dm-thick), and bodies of metabasite. Protoliths for this complex are identifiable in alternations of dominant arenaceous and pelitic sediments.

At the contact with the Ab-Chl gneiss, the Micaschist complex contains discontinuous levels of quartzite enriched in U (low radioactivity levels detected), and from those a progressive reduction of quartz content coupled by an increasing in phyllosilicate content occurs up-section.

Both the Ab-Chl Gneiss and the Micaschist complexes are intruded by Aplitic Gneiss of Late Cambrian age[23] (fig. 5 f), interpreted as a meta-granophyre[24]. The principal masse of this intrusive is exposed at the confluence of the Clarea valley with the Susa Valley. It is important to outline that, although their (at least) Early Paleozoic age, the two basement complexes of this unit lack of pre-alpine mineralogical relicts.

The stratigraphic contact between the magmatic and metasedimentary complexes is cut by the tectonic contact between Clarea and Ambin units, marked by phyllite and quartz-rich micaschist[25]. With respect to this tectonic contact, the polarity between magmatic and metasedimentary complexes of the Ambin unit is not constant, resulting locally inverted. Similar relationships with opposite polarity between magmatic and metasedimentary complexes also occur at the base of Mesozoic cover. Therefore, the Ambin Unit recorded an earliest folding phase pre-juxtaposition with Clarea Unit and pre-deposition of Mesozoic cover[26]. The Clarea-Ambin contact cannot be a stratigraphic unconformity, as previously stated by[27], but represents a pre-alpine shear zone. The

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[23] J.M. Bertrand, R.T. Pidgeon, J. Leterrier, F. Guillot, D. Gasquet and M. Gattiglio, *SHRIMP and IDTIMS U-Pb zircon ages of the pre-Alpine basement in the Internal Western Alps (Savoy and Piemont)*, in «Schweiz Mineral. Petrogr. Mitt.», 80, 2000, pp. 225-248.

[24] E. Callegari, R. Sacchi, S. Bovo, G. Torassa, *Osservazioni strutturali sul versante italiano del Massiccio di Ambin (Alpi Graie)*, in «Bollettino Società Geologica Italiana», 99, 1980, pp. 395-404.

[25] P. Mosca, A. Borghi, M. Gattiglio, *Storia pre-alpina ed alpina nel Massiccio di Ambin (Alpi Occidentali)*, cit.

[26] *Ibidem.*

[27] J. Goguel, *Présence des conglomérats à la base du «groupe d'Ambin» dans les schistes cristallins du massif d'Ambin (Savoie)*, cit.; S. Lorenzoni, *Studio geo-petrografico del versante italiano del massiccio d'Ambin*, cit.; Id., *Étude pétrographique du versant italien du massif d'Ambin (Alpes franco-italiennes)*, cit.; M. Gay, *Le massif d'Ambin et son cadre de Schistes Lustrés (Alpes franco-italiennes)*, cit.; Id., *Le massif d'Ambin et son cadre de Schistes lustrés (Alpes franco-italiennes). Evolution structurale*, cit.; A. Borghi, M. Gattiglio, *Osservazioni*

Upper Cambrian age of the Aplitic Gneiss allows us to correlate the deformation of the Ambin unit to the pre-Alpine tectonics. In Variscan orogeny, Ambin and Clarea units were then at two different crustal levels: i) the Clarea Unit was at deep level within the chain (as recorded by amphibolite facies metamorphism); ii) the Ambin Unit, due to the occurrence of folding and not related metamorphic recrystallization, is thought located at higher crustal levels[28].

2. Tectono-metamorphic alpine evolution

The units presently juxtaposed along the Susa Valley transect recorded partially different Alpine tectono-metamorphic evolutions, reaching peaks under eclogite-facies (DM and IPZ) or blueschist-facies (AM and EPZ) conditions. Therefore, the earlier deformation phases preceding tectonic coupling, although can show similar deformation and kinematic features, were likely developed, for each units, at different crustal levels, metamorphic and tectonic conditions.

Taking into account present tectonic setting and the results of recent studies[29], this section describes first the tectono-metamorphic evolution of the DM, IPZ and EPZ, and then that of the AM. The next section deals with the features of tectonic contacts among the different units.

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geologico-petrografiche nel settore occidentale del Massiccio d'Ambin, cit.; J. Ganne, *Multi-stage Garnet in the Internal Briançonnais Basement (Ambin Massif, Savoy)*, cit.

[28] P. Mosca, A. Borghi, M. Gattiglio, *Storia pre-alpina ed alpina nel Massiccio di Ambin (Alpi Occidentali)*, cit.

[29] S. Ghignone, *Structural and Petrological constraints in the exhumation processes of the Western Alpine meta-ophiolite units*, Tesi di Dottorato, Università di Torino, 2019, 246 pp.; S. Ghignone, G. Balestro, M. Gattiglio, *et al.*, *Structural evolution along the Susa Shear Zone: the role of a first-order shear zone in the exhumation of meta-ophiolite units (Western Alps)*, cit.; S. Ghignone, M. Gattiglio, G. Balestro, A. Borghi, *Geology of the Susa Shear Zone (Susa Valley, Western Alps)*, in «Journal of Maps», 16 (2), 2020, pp. 79-86, https://doi.org/10.1080/17445647.2019.1698473; S. Ghignone, A. Borghi, G. Balestro, D. Castelli, M. Gattiglio, C. Groppo, *HP-tectono-metamorphic evolution of the Internal Piedmont Zone in Susa Valley (Western Alps): New petrologic insight from garnet+chloritoid – bearing micaschists and Fe-Ti metagabbro*, in «Journal Metamorphic Geology», 39 (4), 2021, pp. 391-416, https://doi.org/10.1111/jmg.12574; S. Ghignone, M. Sudo, G. Balestro, A. Borghi, M. Gattiglio, S. Ferrero, V. van Schijndel, *Timing of exhumation of meta-ophiolite units in the Western Alps: New tectonic implications from 40Ar/39Ar white mica ages from Piedmont Zone (Susa Valley)*, in «Lithos», 404-405, 2021, pp. 1-18, https://doi.org/10.1016/j.lithos.2021.106443.

Structural and Metamorphic Evolution of DM-IPZ and EPZ

In these tectonic units, four alpine deformation phases are well preserved[30]. D1 phase develops isoclinal folds and S_1 axial plane foliation (fig. 6 a). Remnants of S_1 foliation are only preserved in stiff lithologies (e.g., DM dolomitic marble, IPZ metagabbro and EPZ paragneiss). In other lithotypes, S_1 is locally preserved in D2 fold hinges. A_1 fold axis and L_1 stretching lineations are parallel to each other, resulting about N-S oriented.

The metamorphic peak reached during D1, although developed under HP/LT conditions, is different in these units and corresponding to different eclogite-facies conditions[31] for DM and IPZ, and to blueschist facies conditions for EPZ[32].

D2 phase led the development of the S_2 regional foliation deforming DM/IPZ tectonic contact after the coupling of the two units. S_2 is strongly pervasive in rheological weak lithologies, while in stiffer ones S_2 consists of discrete surfaces only developed in D2 fold hinges (fig. 6 b). In the DM dolomitic marble, S_1 was reoriented parallel to S_2 axial plane, without developing a proper S_2. D2 folds show isoclinal geometry in the IPZ and DM, while close-to-tight geometry in the EPZ. A_2 fold axis and L2 stretching lineation are parallel to each other, roughly E-W oriented. The non-cylindrical geometry of D2 folds is particularly evident around M. Molaras, where they appear as double-verging folds along their axial plane.

Kinematic indicators along S_2 show Top-to-W sense of shear, consistent with a general westward tectonic transport during D2 phase.

D2 phase developed at greenschist facies conditions in DM, IPZ and EPZ[33].

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[30] S. Ghignone, G. Balestro, M. Gattiglio, A. Borghi, *Structural evolution along the Susa Shear Zone: the role of a first-order shear zone in the exhumation of meta-ophiolite units (Western Alps)*, cit.; S. Ghignone, M. Gattiglio, G. Balestro, A. Borghi, *Geology of the Susa Shear Zone (Susa Valley, Western Alps)*, cit.

[31] S. Ghignone, M. Sudo, G. Balestro, A. Borghi, M. Gattiglio, S. Ferrero, V. van Schijndel, *Timing of exhumation of meta-ophiolite units in the Western Alps*, cit.; I. Gasco, M. Gattiglio, A. Borghi, *Lithostratigraphic setting and P–T metamorphic evolution for the Dora Maira Massif along the Piedmont Zone boundary (middle Susa Valley, NW Alps)*, cit.

[32] P. Agard, L. Jolivet, B. Goffe, *Tectonometamorphic evolution of the Schistes Lustrés complex: Implications for the exhumation of HP and UHP rocks in the western Alps*, in «Bulletin de la Société Géologique de France», 172, 2001, pp. 617-636.

[33] S. Ghignone, G. Balestro, M. Gattiglio, A. Borghi, S*tructural evolution along the Susa Shear Zone: the role of a first-order shear zone in the exhumation of meta-ophiolite units (Western Alps)*, cit.; S. Ghignone, M. Gattiglio, G. Balestro, A. Borghi, *Geology of the Susa Shear Zone (Susa Valley, Western Alps)*, cit.; I. Gasco, M. Gattiglio, A. Borghi, *Lithostratigraphic setting and P–T metamorphic evolution for the Dora Maira Massif along the Piedmont Zone bounda-*

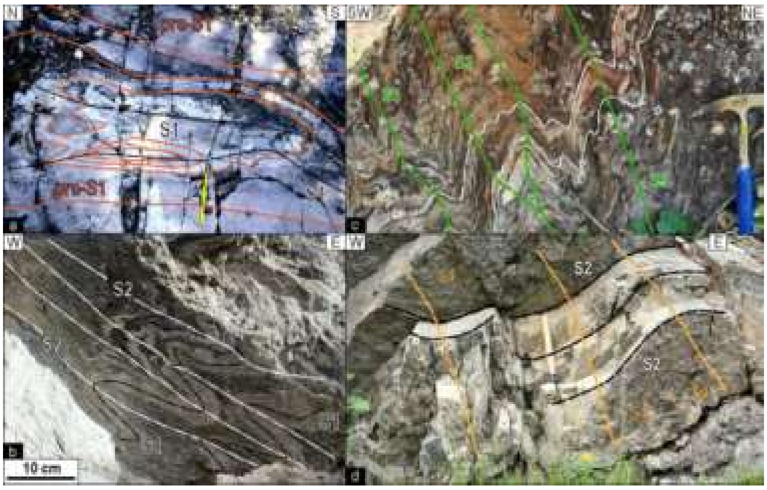

Fig. 6. Field photographs showing the features of the main deformation phases (IPZ+DM+EPZ). a) D1-related isoclinal non-cylindrical folding in DM dolomitic marble; b) D2-related isoclinal non-cylindrical folding in IPZ micaschist; c) D3-related fold hinges in EPZ micaschist: local box-folds occur; d) D4-related open asymmetric folds (long limb-short limb).

Only for D3 and D4 phases the orientation of structural elements and tectonic meaning are common in the DM, IPZ and EPZ, indicating, during these phases, the same deformation history after their coupling.

D3 phase is recorded by open to close folds, asymmetrical (long-limb, short-limb) and locally overturned (fig. 6 c). D3 fold axes plunge W to SW and axial planes dip gently towards N and S due to the development of box folds. The S_3 axial plane foliation appears often as disjunctive crenulation cleavage in less competent lithotypes. The vergence of D3 folds, considered often as toward the south in DM, recently was interpreted towards the north[34], according to syn-D3 shear zones in DM (outlined by metres-thick mylonitic to cataclastic rocks) showing a top-to-N sense of shear. D3 folding was related to the development of the DM doming.

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ry, cit.; S. Ghignone, A. Borghi, G. Balestro, D. Castelli, M. Gattiglio, C. Groppo, *HP-tectono-metamorphic evolution of the Internal Piedmont Zone in Susa Valley (Western Alps)*, cit.

[34] S. Ghignone, G. Balestro, M. Gattiglio, A. Borghi, *Structural evolution along the Susa Shear Zone: the role of a first-order shear zone in the exhumation of meta-ophiolite units (Western Alps)*, in «Swiss Journal of Geosciences», 113 (1), 2020, 17, pp. 1-16 https://dx.doi.org/10.1186/s00015-020-00370-6.

Variably open folds with asymmetric geometry (long-limb, short–limb) and widespread Top-to-W vergence characterize D4 phase (fig. 6 d). These folds, recognizable from meso- to macro-scale, in particular in DM and IPZ, show NNW-SSE trending A_4 axes and very steep N–S directed S_4 spaced disjunctive cleavage. D4 deformation developed at shallows structural levels during the final stage of DM doming.

Structural and Metamorphic Evolution of Ambin Massif

Four alpine deformation phases (D1 to D4) were recognized in both Clarea and Ambin Units[35].

D1 phase developed under Ep-blueschist facies conditions. Such conditions became more evident from the core of the AM dome toward higher structural levels in the Clarea Unit. A_1 axes are about NS to NNE-SSW trending. In the Ambin Unit S_1 is recognizable only in D2 meso-scale isoclinal fold hinges.

D2 phase developed at the blueschist-greenschist transition, and it is characterized by S_2 transpositive regional foliation. This phase developed isoclinal folds and a stretching lineation oblique with respect to the A_2 trending NE-SW fold axes.

Late D3 and D4 phases developed crenulation cleavage related to open, asymmetrical folding with centrifugal vergence toward the edges of the Massif with NNE-SSW and E-W trending axes respectively. These later phases were referred to the final stages of exhumation process and doming. D3 recorded greenschist metamorphic conditions[36].

Brittle-ductile extensional shear planes with top-to-W kinematics along the western edge of the Ambin dome and top-to-E in the eastern edge develop during the latest phases.

3. Features of the tectonic contacts

The DM-IPZ tectonic contact

The tectonic contact between DM and IPZ Units corresponds to a shear zone characterized by «block in matrix structure», a few tens of meters thick,

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[35] A. Borghi, M. Gattiglio, *Osservazioni geologico-petrografiche nel settore occidentale del Massiccio d'Ambin*, cit.; R. Polino, F. Dela Pierre, A. Borghi, *et al.*, *Note illustrative al Foglio 153 (132-152) Bardonecchia. Carta Geologica d'Italia alla scala 1:50.000*, cit.; M.G. Malusà, P. Mosca, A. Borghi, *et al.*, *Approccio multidisciplinare per la ricostruzione dell'assetto tettono-stratigrafico e dell'evoluzione metamorfico-strutturale di un settore di catena orogenica*, cit.

[36] J. Ganne, *Multi-stage Garnet in the Internal Briançonnais Basement (Ambin Massif, Savoy)*, cit.

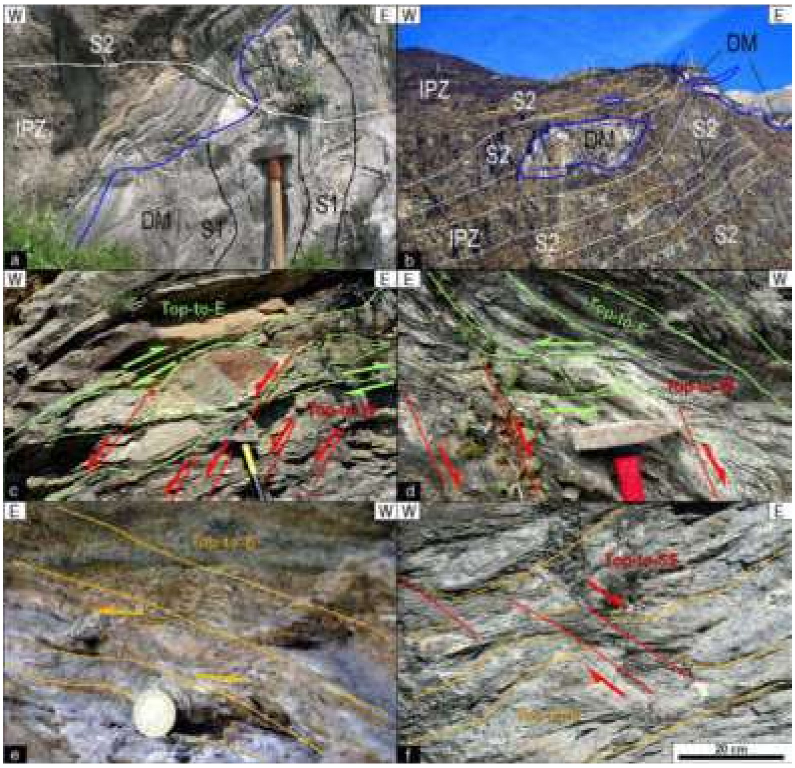

Fig. 7. Field photographs showing structures and their relationships along the main tectonic contacts. IPZ/DM pre-D2 tectonic contact: a) S_1 foliation (dashed black lines) is discordant respect to the tectonic contact (blue line), and deformed by D2 isoclinal folds; b) panorama view of the contact: D2-related non-cylindrical folding of the tectonic contact between DM dolomitic marble (white) and IPZ calcschist (brownish). S_2 foliation developed only in calcschist. SSZ (EPZ/IPZ tectonic contact) kinematics: c) T1 Top-to-E structural elements (green dashed lines) crosscutted by T2 Top-to-W C-planes (red lines); d) T1 Top-to-E mylonitic foliation and kinematic indicators (green dashed lines) crosscutted by T2 Top-to-W C-planes (red lines). EPZ/AM tectonic contact: e) Top-to-E early kinematics along the tectonic contact; f) Top-to-SE late kinematic indicators (S-C structures) crosscutting early Top-to-E-related mylonitic foliation.

in which a pervasive mylonitic foliation wraps DM- and IPZ-related stretched tectonic slices[37]. The mylonitic foliation cut and re-oriented S_1 foliation of the

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[37] I. Gasco, M. Gattiglio, A. Borghi, *Lithostratigraphic setting and P–T metamorphic evolution for the Dora Maira Massif along the Piedmont Zone boundary*, cit.

DM (fig. 7 a). This tectonic contact is folded by meter- to kilometer-scale D2 isoclinal folds[38] (fig. 7 b).

Eastwards, the IPZ is juxtaposed to DM along the Col del Lys-Trana Deformation Zone (LTZ)[39]. This zone is a significant brittle structure in the Cottian Alps, and is characterized by steep fault planes showing anastomosed geometry at the map scale. The activity of LTZ is related to two late-to post-metamorphic deformation phases. The first one led development of N-S trending major faults and NNW-SSE to NNE-SSW minor faults with right lateral shearing and minor reversal component. The subsequent phase developed E-W faults and reactivated previous faults inducing normal and left lateral shears.

The IPZ-EPZ tectonic contact

The boundary between IPZ and above EPZ Units is a tectonic contact named Susa Shear Zone (SSZ)[40].

This is a NNE-SSW directed and W-plunging polyphasic first-order shear zone coupling units with different metamorphic peak.

The SSZ is defined by mylonitic calcschist wrapping blocks sampled from the IPZ and EPZ units. Blocks are various sized, from meter up to one kilometer. An example is the large block of dolomitic marble (belonging to the DM cover) cropping out south of Susa, and previously reported as *Incertae Sedis* Unit[41]. This setting testifies that the SSZ involves both oceanic units (EPZ and IPZ) and the continental DM. The SSZ is mylonitic zone wherein two distinct shearing events (T1 and T2) occurred in two distinct moments of the alpine tectonic evolution[42].

The first shearing event (T1) develops mylonitic foliation (Sm_1), whose radiometric ages are nearly the same as those obtained for the S_2 regional

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[38] *Ibidem.*

[39] G. Balestro, P. Cadoppi, G. Perrone, S. Tallone, *Tectonic evolution along the Col del Lis-Trana Deformation Zone (internal Western Alps)*, in «Bollettino Società Geologica Italiana», 128 (2), 2009, pp. 331-339.

[40] I. Gasco, *Structural and metamorphic relationships between the Internal Crystalline Massifs and the Piedmont Zone, Western Italian Alps,* Tesi di Dottorato, Università di Torino, 2010, pp. 1-225; S. Ghignone, M. Gattiglio, *Late to post-metamorphic cross-section trough the Piedmont Zone in the lower Susa Valley (Western Alps)*, in «Rendiconti Online Società Geologica Italiana» 29, 2013, pp. 66-69; S. Ghignone, M. Gattiglio, G. Balestro, *et al.*, *Geology of the Susa Shear Zone (Susa Valley, Western Alps)*, cit.

[41] *Servizio Geologico d'Italia. Foglio 154 Susa alla scala 1:50.000*, cit.

[42] S. Ghignone, G. Balestro, M. Gattiglio, A. Borghi, *Structural evolution along the Susa Shear Zone*, cit.

foliation in the lower and upper units[43]. Sm_1 and S_2 developed in different domains: Sm_1 developed as mylonitic foliation at the boundary between the lower (IPZ + DM) and the upper (EPZ) units, during syn-to-late-D2 deformation event, while S_2 developed as axial plane foliation inside the tectonic units. Kinematic indicators occurring within the Sm_1 (S–C (C′) fabric, δ- and σ-type mantled porphyroclasts and overturned folds) provide Top-to-E *apparent reverse* sense of shear (fig. 7 c). Kinematic indicators along the S_2, both in EPZ and in IPZ+DM indicate Top-to-W sense of shear. The different metamorphic conditions in the IPZ and EPZ Units before their coupling indicates that they were at different crustal levels within the alpine accretion wedge. Coupling between IPZ and EPZ Units occurred during exhumation in greenschist-facies conditions, as recorded by the metamorphic conditions in which S_2 develops within the juxtaposed units[44].

The second shearing event (T2) along the SSZ developed a hundreds of meters-thick deformation zone, on average N–S striking and W-dipping, characterized by disjunctive cleavage, concentrated along discrete and spaced shear bands. T2 kinematic indicators (ECC, S–C structures and rotated porphyroclasts) are consistent with Top-to-W sense of shear (fig. 7 d). T2-related structural elements are coeval with D4 regional deformation phase[45].

The AM-EPZ tectonic contact

The tectonic contact between the AM and the overlying EPZ developed under HP/LT conditions[46] and with Top-to-E kinematics[47] (fig. 7 e). This contact, defined by mylonitic foliation, encompasses also tectonic slices of Triassic metadolomite.

In the eastern sectors of the Ambin dome (Cenischia Valley) the AM-EPZ tectonic contact is crosscut by "C" planes, steeply SE dipping[48] and marking

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[43] S. Ghignone, M. Sudo, G. Balestro, *et al.*, *Timing of exhumation of meta-ophiolite units in the Western Alps*, cit.

[44] *Ibidem*.

[45] S. Ghignone, G. Balestro, M. Gattiglio, *et al.*, *Structural evolution along the Susa Shear Zone*, cit.; S. Ghignone, M. Gattiglio, G. Balestro, *et al.*, *Geology of the Susa Shear Zone (Susa Valley, Western Alps)*, cit.

[46] M.G. Malusà, P. Mosca, A. Borghi, *et al.*, *Approccio multidisciplinare per la ricostruzione dell'assetto tettono-stratigrafico e dell'evoluzione metamorfico-strutturale di un settore di catena orogenica*, cit.

[47] *Ibidem*; J. Ganne, J.M. Bertrand, S. Fudral, *Geometry and kinematics of early Alpine nappes in a Briançonnais basement*, cit.

[48] S. Ghignone, M. Gattiglio, *Late to post-metamorphic cross-section trough the Piedmont Zone in the lower Susa Valley*, cit.

a top-to-SE extensional shear (fig. 7 f). The western sectors of Ambin dome have late West-dipping extensional shear planes. These extensional structures are interpreted as related to the AM doming development[49].

Subsequently, during its final uplift stages, the AM dome results bounded by a major fault zone roughly running parallel to the middle Susa Valley (N60 directed), and defined by normal to left-lateral strike-slip faults[50].

Conclusions

This paper aimed to describe principal geological features of the Susa Valley, where oceanic (IPZ and EPZ) and continental (DM and AM) units are exposed. Geological surveys performed in the last 20 years mainly confirmed the good lithotypes mapping reported in the geological map along the Lyon-Turin cross-border section, Italian side, realized by Department of Earth Sciences (University of Torino)[51].

Recent studies brought new data on the lithostratigraphic, structural and metamorphic evolution of the juxtaposed units, as well as on the nature, kinematic significance and age of their tectonic boundaries. In particular: i) a new lithostratigraphic setting has been defined for the DM; ii) new and more detailed structural features of the DM, IPZ and EPZ tectonic pile have been defined; iii) in the AM, the pre-alpine evolution of the Ambin unit has been recognized by field data. Moreover, deciphering the nature of tectonic contacts and their ages, both absolute (for some of them by geochronology) and relative, respect to the deformation history of each unit, as well as new data on metamorphic peaks, provide new constraints for the reconstruction of the alpine exhumation history in this chain sector.

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[49] J. Ganne, J.M. Bertrand, S. Fudral, *Geometry and Kinematics of Early Alpine Nappes in a Briançonnais Basement*, cit.

[50] R. Polino, F. Dela Pierre, A. Borghi, *et al.*, *Note illustrative al Foglio 153 (132-152) Bardonecchia. Carta Geologica d'Italia alla scala 1:50.000*, cit.; *Servizio Geologico d'Italia. Foglio 132-152-153 Bardonecchia alla scala 1:50.000*, cit.

[51] R. Sacchi, G. Balestro, P. Cadoppi, *et. al.*, *Studi geologici in Val di Susa finalizzati ad un nuovo collegamento ferroviario Torino-Lione*, cit.