



Tectono-metamorphic map of the Mont Morion Permian metaintrusives (Mont Morion - Mont Collon - Matterhorn Complex, Dent Blanche Unit), Valpelline - Western Italian Alps

MANUEL RODA¹ and MICHELE ZUCALI²

¹ Università degli Studi di Milano, Dipartimento di Scienze della Terra "A. Desio", Sezione di Geofisica, Via L. Cicognara 7, 20129 Milano, ITALY; jediroda@gmail.com.

² Università degli Studi di Milano, Dipartimento di Scienze della Terra "A. Desio" Sezione di Geologia, Via Mangiagalli, 34, 20133, Milano, ITALY.

Abstract

The presented map displays the structural and metamorphic evolution of lithotypes from pre-Permian to present. We distinguish pre-Permian rocks (e.g., amphibolite, biotite-bearing gneiss and acid granulite) preserved as roof pendants (i.e., xenoliths) within Permian intrusives. Permian intrusives and hosted xenoliths are then re-equilibrated during Alpine evolution, producing coronitic to mylonitic metaintrusives, due to meter to kilometer-scale fabric gradients, and associated white mica-, glaucophane-bearing gneiss. The map also shows the traces of the superimposed foliations and the fold axial planes. The traces are distinguished on the basis of their relative chronology and mineralogical support. This information, reported on a single map, allows us to reconstruct the successive stages of this fragment belonging to the African plate continental crust, from the pre-Alpine extension, recorded by granulite- to amphibolite-facies xenoliths, to the Permian intrusive phase (e.g., Mont Morion, Mont Collon and Matterhorn intrusives) lasting with the Alpine subduction-collision related evolution. The Mont Morion, part of the Mont Morion-Mont Collon-Matterhorn Complex of the Dent Blanche unit, may be interpreted as a multi-stadial Alpine km-scale shear zone, where Permian intrusive rocks are transformed into white mica chlorite-bearing or glaucophane-bearing gneisses along high-strain horizons (100 m-thick), while within low-strain cores (100- to 1000 m-thick), meta-intrusives preserve igneous features and xenoliths of amphibolites, acid granulites and biotite-bearing gneisses. In this paper, an outcrop tectono-metamorphic map (1:10,000 scale) is presented, based upon fieldwork at 1:5,000 together with an interpretative map (1:15,000 scale), in which three dimensional relationships are described, and micro- to mesoscopic fabric types are shown, corresponding to finite strain states recorded by rocks.

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1. Introduction

Structural-geological mapping of metamorphic basements is an important task to reconstruct the tectono-metamorphic evolution and the relationships between deformation, localization of metamorphic transformations, protolith chemistry, textures and mineral compositions. Modern mapping of metamorphic basements include the description of mesoscopic fabrics with respect to the mineralogical support, which testify to the metamorphic conditions under which they developed (Zucali et al., 2002; Spalla and Zucali, 2004). The reconstruction of the complex network of superimposed strain states display the mosaic of rocks that homogeneously record deformation and metamorphic reactions in certain time intervals, the tectono-metamorphic units (Spalla et al., 2005). In this contribution we investigate the Permian intrusives of the Mont Morion-Mont Collon-Matterhorn Complex from igneous stages to the subsequent Alpine evolution, under greenschist- to blueschist-facies conditions. We map the partitioning of deformation and the degree of metamorphic reactions starting from the preserved primary features of the intrusive body. The map covers an area of 20 km² where strain partitioning led to the preservation of the undeformed core, dominated by coronitic metamorphic textures affecting the igneous minerals with no or little deformation associated, while the more external parts of the Mont Morion record the Alpine metamorphic evolution along with pervasive deformational imprints (Roda and Zucali, 2008). The Mont Morion is located within the Arolla Series, which is constituted by Permian intrusives of various compositions and their gneissic host rocks (Bussy et al., 1998). The rocks were re-equilibrated and reworked during the Alpine orogeny producing greenschist-facies mylonitic gneisses with scanty relicts of blueschist-facies mineral assemblages or single minerals (Roda and Zucali, 2008; Hellwig, 2003; Pennacchioni and Guermani, 1993; Canepa et al., 1990; Ayrton et al., 1982; Manzotti, 2011). The Mont Morion preserves primary igneous textures, wrapped by km-thick mylonitic horizons, which separate meta-intrusive rocks from the regularly layered Valpelline Series and Combin Zone (Regional frameworks B in the outcrop map) (Roda and Zucali, 2008; Pennacchioni and Guermani, 1993). The presented map shows, at the map scale, the relations between pre-Permian, Permian and Alpine structures and metamorphism allowing the separation of volumes where each of these evolutionary stages are more dominant.

2. Methods

The map is characterized by the synoptic representation of tectonic and metamorphic data integrated with microstructural analysis. The relative chronology was inferred from structural correlation criteria, widely used in various terrains (Ramsay and Huber, 1983; Williams, 1985; Passchier and Trouw, 2005; Turner and Weiss, 1963; Pollard and

Fletcher, 2005; Twiss and Moore, 1992). All rocks are described and mapped considering their mineral composition, the type of planar and linear structural elements (e.g., foliation, lineation, etc.) and their corresponding mineral support. These data are represented in the map as colored foliation traces, superimposed on standard lithological information. Each chronologic family of foliations is attributed to a relative time class (S1, S2, etc.) characterized by the metamorphic conditions in which it developed. Lithologic subdivisions are based and revised starting from previous detailed fieldwork on the Valpelline rocks (Diehl et al., 1952; Pennacchioni and Guermani, 1993).

In the case of the igneous rocks, three classes of fabrics are mapped, allowing the identification of finite strain states and fabric gradients:

1. CORONITIC: weak syn-metamorphic foliation, preserving 80-100% of the textural igneous features;
2. TECTONITIC: syn-metamorphic foliation preserving 20-80% of the textural igneous features;
3. MYLONITIC: syn-metamorphic foliation preserving 0-20% of the textural igneous features (Zucali, 2002; Spalla et al., 1998; 2003; Spalla and Zucali, 2004; Spalla et al., 2005; Salvi et al., 2010).

The resulting map is based on lithotectonic criteria and represents a lithostratigraphy which is structurally and petrologically constrained; it is a mosaic of superimposed foliation traces, which includes representation of: i) rotation, dislocation and overprinting of structures; ii) area where contrasting metamorphic assemblages are present; iii) map-scale finite strain states (e.g., rocks with coronitic, tectonitic, mylonitic structures) achieved during a given metamorphic stage; iv) identification of areas preserving contrasted stages of structural and metamorphic re-equilibrations.

In this contribution we specifically focus on localization of the volumes preserving primary igneous features and on the m- to km-scale distribution of fabrics and finite strain. The correlation between fabric evolution and degree of evolution of metamorphic transformations is inferred by microstructural analysis and tectono-metamorphic reconstruction on selected samples.

The outcrop tectono-metamorphic map displays the outcrops distribution at a scale of 1:10,000 and the mesostructures, such as foliations (S_n), fold axial planes (PA_n) fault and shear zones, chronologically divided into different evolutive stages. Quaternary deposits are also reported. Stereonets synoptically display the spatial orientation of mesoscopic fabrics. Three panoramic views of the mapped area show some litho-structural boundaries identified in the field. The interpretative map (scale 1:15,000) correlates

macroscopic and microscopic structural, lithological and petrographic data. Furthermore, a table of pictures showing the fabric evolution in terms of meso and micro-scale tectono-metamorphic structures is presented for the two main igneous lithologies and relative main deformation stages. Finally, four interpretative cross-section are shown in a prospective view, in order to represent the 3D mesoscopic relations between fabric and rocks evolutions. The topographic base map is the Carta Tecnica Regionale Regione Valle d'Aosta, scale 1:10,000, UTM ED 1950 coordinate system: t7082, t7086, t7482, t7486, t7882, t7886.

3. Geological Setting

The main tectonic domains of the Western Alps (MAP, insets A and B) are, from north-west to south-east: i) the Helvetic-Dauphinoise-Briançonnais domain, ii) the Penninic domain, separated by the Penninic Front thrust system, iii) the Austroalpine domain, iv) the South Alpine domain (see Map) separated by the Insubric Line steep transpressive fault system (Bigi, 1990). The Austroalpine domain of Western Alps consists of poly-metamorphic tectonic slices of the Paleozoic African continental crust and monometamorphic Mesozoic sedimentary covers; various authors (De Giusti et al., 2003; Dal Piaz et al., 2001; Caby et al., 1978; Balleve and Kienast, 1987; Canepa et al., 1990) divided the Austroalpine domain into an Upper and a Lower Unit: the Upper unit is non-eclogitic, dominated by Alpine greenschist to blueschist-facies metamorphic imprints and includes the Dent Blanche, Mont Mary and Pillonet. The Lower Unit is eclogitic and includes Sesia-Lanzo Zone, Monte Emilius, Glacier-Rafray, Torre Ponton and Etirol-Levaz outliers, which record an eclogite facies Alpine metamorphic imprint (Bigi, 1990; Cortiana, 1999; Compagnoni, 1977; Dal Piaz, 1999; Dal Piaz et al., 2001; Castelli et al., 2007; Polino et al., 1990; Spalla et al., 1996).

The Dent Blanche unit is believed to correspond to the Ivrea Palaeozoic basement (Southern Alps) dismembered and involved in the Alpine subduction and collision (Carraro et al., 1970). The Dent Blanche unit includes lenses of mylonitized pre-Alpine and Mesozoic metasedimentary cover (i.e., Roisan Zone Manzotti, 2011) and pre-Alpine basement slices as the Valpelline Series and Arolla Series. The Valpelline Series is constituted by pre-Permian amphibolite to granulite facies rocks such as basic and acid granulites, amphibolites, and amphibolite-facies gneisses and marbles. The pre-Alpine re-equilibration under granulite-facies conditions ($P = 0.9-1.0$ GPa and $T = 700^{\circ}-750^{\circ}\text{C}$) is followed by a decrease in pressure ($P = 0.4-0.6$ GPa) and by an increase in temperature ($T = 750^{\circ}-800^{\circ}\text{C}$), while the Alpine re-equilibration (Hunziker, 1974; Gardien et al., 1994; Splendore et al., 2006) is localized and represented by greenschist facies re-equilibration, related to the development of an Alpine foliation (De Leo et al., 1987; Diehl et al., 1952) where kyanite-chloritoid parageneses have been described (Kienast and Nicot, 1971).

The Arolla Series granites have an age of 289 ± 2 My for igneous protholiths (Bussy et al., 1998). The Arolla Series is affected by greenschist-facies re-equilibration with local occurrence of high to intermediate pressure and low temperature minerals, during the Alpine evolution (Dal Piaz et al., 1969; Ballevre and Kienast, 1987; Canepa et al., 1990; Pennacchioni and Guermani, 1993; Hellwig, 2003; Roda and Zucali, 2008; Malaspina et al., 2010).

Permian igneous rocks of the Arolla Series are granites, diorites, gabbros transformed into ortho-gneisses, chlorite-white mica-bearing gneisses and schists during the Alpine history. Metric-sized lenses of pre-Permian biotite-bearing gneisses and amphibolites occur within igneous rocks (Diehl et al., 1952; Ayrton et al., 1982; Ayrton and Ramsay, 1974; Pennacchioni and Guermani, 1993). Alpine km-scale greenschist-facies mylonites and m-scale cataclasites underline the contacts between Arolla, Valpelline and Combin Zone (Mazurek, 1986; De Leo et al., 1987; Pennacchioni and Guermani, 1993; Diehl et al., 1952; Ayrton et al., 1982; Hellwig, 2003). Radiometric estimates on phengitic micas of the Pillonet unit (Cortiana et al., 1998) is used to define a Cretaceous age (75-74 Ma) for the Alpine re-equilibration.

4. Lithologic Types

In Figure 1 a megascale distribution of main structural features is shown. The Mont Morion complex (MMC) consists of a granitic to quartz-dioritic core, associated with gneiss and amphibolite lenses as roof pendants. The Mont Morion Complex shows a low-strain igneous core, in which granites and quartz-diorites preserve igneous textures (Figure 2c and d) and where intrusive relations with biotite-bearing gneisses and amphibolites with pre-Alpine high temperature metamorphic imprints are preserved (Figure 2a); the preserved core is surrounded by medium to high-strain domains defined by tectonic to mylonitic white mica/chlorite-bearing gneisses and glaucophane-bearing gneisses (Figures 1 and 2f).

4.1 Pre-Permian Protoliths

Biotite-bearing gneiss consists of plagioclase and K-feldspar (30-50%), quartz (25-45%), biotite (5-25%), garnet (0-20%), white mica (0-15%), chlorite (0-15%), epidote (0-10%) and amphibole (0-10%). Plagioclase is in lenticular aggregates (5 mm-thick) defining foliations (S1 and S2) together with mm-thick films, marked by biotite-rich layers, and mm- to cm-thick quartz-bearing lithons (Figure 2a).

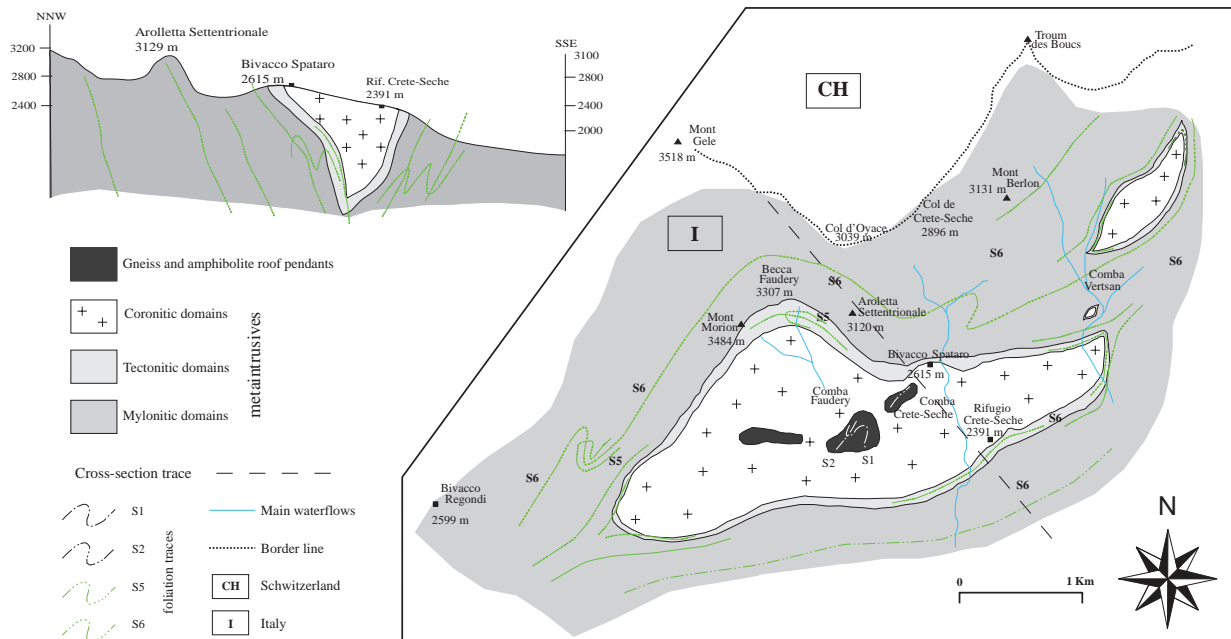


Figure 1. Structural sketch of the investigated area, showing km-scale relationships between coronitic-tectonic-mylonitic domains of the preserved lithologies and superimposed structures.

Amphibolites consist of amphibole (35-40%), plagioclase (20-45%), epidote (10-15%), biotite (0-15%) and quartz (0-10%). Plagioclase and dark-green amphibole alternate layers define the main foliation (mm to cm- thick) (Figure 2b). They occur as metric lenticular bodies within intrusive rocks, displaying elongated shape boundaries; they are interpreted as roof pendants of intrusive host rocks.

4.2 Permian Protoliths

Granite consists of quartz (20-30%), white mica (15- 25%), epidote (10-20%), alkali feldspar (5-15%), plagioclase (5-15%), chlorite (0-15%), hornblende amphibole (0-5%), biotite (0-5%) and opaques (0-5%) (Figure 2c); **amphibole-bearing granite** consists of quartz (20-30%), hornblende amphibole (10-25%), white mica (15-20%), epidote (10-20%), plagioclase (5-10%), chlorite (5-10%), alkali feldspar (0-15%), biotite (0-10%) and opaques (0-5%). Amphibole-bearing granites crop out as decametric to hectometric bodies with irregular or lenticular shape (Figure 2d). The contact of amphibole-bearing granites with granites may vary from place to place, from straight to wavy or without a discrete limit. The mineralogy of **quartz-diorite** consists of amphibole (20-25%), plagioclase (20-25%), white mica (15-25%), quartz (15-20%), epidote (10-15%), biotite (5-10%) and opaques (0-5%). Within quartz-diorites and amphibole-bearing granites, K-feldspar and amphibole SPO (Shape Preferred Orientation) defines an igneous S-L fabric (Figure 2e).

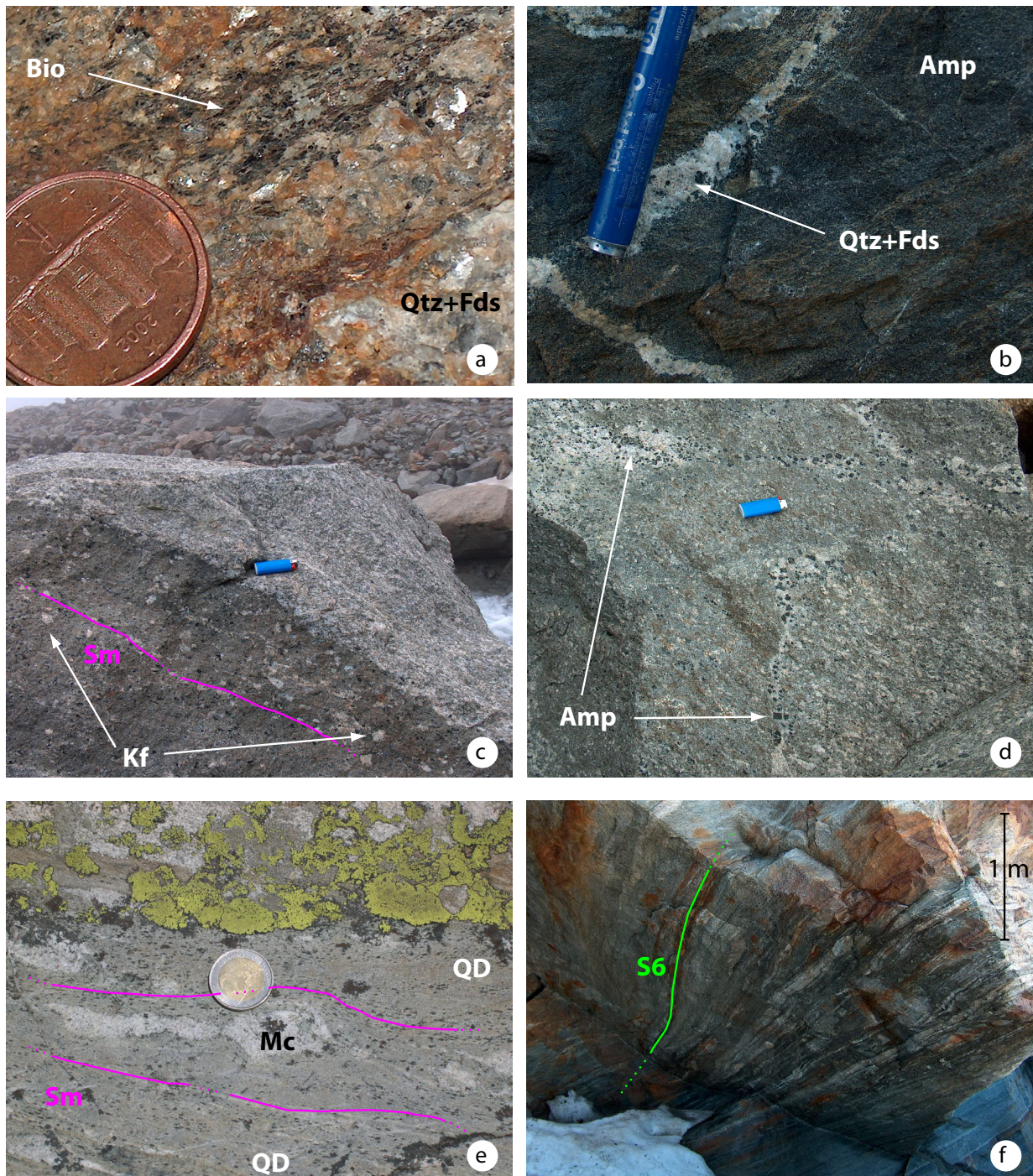


Figure 2. a) Biotite-bearing gneiss with alternate of Bt-rich layers (dark) and Qtz-Fds-rich layers (light); b) Amphibolite: Amp SPO defines the main foliation together with Pl + Bt-rich layers; c) Coronitic metagranite (Mc) with magmatic foliation (Sm) marked by SPO of Kf; d) Coronitic Amp-bearing metagranite; e) Coronitic quartz-diorite (QD) with magmatic flow structures (Sm): the magmatic lineation is marked by SPO of Amp and by the alignment of Qtz-Fds-rich boudins (Mc); f) Mylonitic metagranite: the mylonitic foliation is marked by layering of Qtz + Fds and Bt + Amp levels.

White mica/chlorite-bearing gneiss consists of white mica (15-45%), quartz (15-25%), chlorite (10-20%), feldspar (0-20%), epidote (0-15%) and opaques (0-5%) and form ten to hundred meter thick bands within mylonitic zones; this penetrative mylonitic foliation is marked by the SPO and the LPO (Lattice Preferred Orientation) of white mica, quartz and epidote-rich layers.

Glaucophane-bearing ortho-gneiss is characterized by quartz (35-40%), plagioclase (10-15%), glaucophane (10-15%), white mica (10-15%), epidote (5-10%), chlorite (5-7%) and opaques (5-7%). The SPO of glaucophane and white mica mark the main mylonitic foliation.

5. Mesostructures and Related Geologic History

A sequence of geologic events (stages) has been reconstructed by the investigation of the cross-cutting relationships between magmatic (Mag), metamorphic (Met) or deformational (D) signatures; microstructural analysis has been used to correlate mesoscopic fabrics and metamorphic mineral growth, and infer a crustal scale tectonic history (Roda and Zucali, 2008).

1. **Stage 1** is characterized by foliations preserved in biotite-bearing gneisses and amphibolites. In biotite-bearing gneisses D1 is defined by a spaced and discontinuous foliation (S1) marked by alternate biotite, rare amphiboles and light granoblastic (quartz and feldspar) mm- to cm-thick bands (Figures 2a, 3a and 4a). In amphibolites the S1 foliation is defined by layers of amphibole and rare biotites alternate with plagioclase-rich layers (Figures 2b and 4b). Amphibolites may also occur with granoblastic structure where large individuals of amphibole define the framework and plagioclase is generally interstitial.
2. **Stage 2** develops the S2 axial plane foliation associated with migmatitic structures. In biotite-bearing gneisses, the S2 foliation, axial plane to D2 folds, is discontinuous and marked by alternate biotite-rich layers (melanosomes) and quartz-feldspar-rich layers (leucosomes); leucosomes, parallel to S2, display mm-sized granoblastic textures of quartz and feldspar aggregates, while biotite within melanosomes shows SPO parallel to the S2 foliation (Figure 3b). Within amphibolites the S2 is marked by alternating amphibole-rich levels and granoblastic plagioclase-rich layers, where plagioclase crystals are about 5 mm in size. Biotite-bearing gneisses and amphibolites are also characterized by ptygmatic folds (D2) and boudins. D2 folds are from close to isoclinal in shape and with wave-length of about 20-30 cm. D2 axial plane dip direction (PA2) ranges from 70° to 180°, with a

dip angle between 45° and 70°. D2 axes trend 10° to 270°. S2 has a SE dip direction with dip angles of 55°-75°.

3. **Stage 3** corresponds to granitic-quartz-dioritic igneous intrusions (Mag3) that cross-cut D1 and D2 structures. Granites and amphibole-bearing granites have a subidiomorphic texture with an igneous assemblage including subhedral-anhedral quartz, subhedral plagioclase, euhedral alkali-feldspar, biotite and amphibole (Figures 2c, 2d, 4c and 4d). In places, alkali feldspars and amphiboles display a macroscopic SPO marking the igneous foliation surface (Sm3; Sm=planar fabric of magmatic origin) (Paterson et al., 1989) (Figures 2c, 2d and 2e); boundaries between volumes characterized by different textures and mineral abundances are however not mappable, because they merge one into the other (Figure 3c). Quartz-diorites have a subidiomorphic texture with original mineralogical assemblage characterized by euhedral amphiboles, subhedral-anhedral plagioclase, rare quartz and biotite. Quartz-diorites may display isotropic or anisotropic fabrics; the macroscopic fabric is commonly characterized by SPO of amphiboles and rare biotites, well representing the igneous foliation (Sm3). Metric-scale granitic dykes intrude quartz-diorites; where quartz-diorites are foliated, dykes are folded and boudinaged with the maximum elongation direction parallel to Sm3. Quartz-diorite occurs as sheet dykes or lenticular bodies within the metagranites or amphibole-bearing metagranites. Sheeted dykes, with straight boundaries, vary in thickness from 10 to 40 cm and 10-20 m in length. The lenticular bodies (1 to several tens of meters thickness) display wavy or lobate-cusped contacts, evidence of lower viscosity of the quartz-diorite with respect to that of the wall rock (Figures 3d and 3e). The Sm3 dips 70°-80° towards the SE.
4. During **stage 4** a S4 foliation occurred, associated with the growth of new metamorphic minerals (D4 contemporaneous to Met4). S4 is visible only in the micro-scale samples, within small S-tectonic domains and is marked by alternate white mica, chlorite and rare biotite-rich layers (20-30 cm thick) and alkali feldspar and plagioclase-rich layers (10-15 cm thick); Met4 is characterized by coronitic textures defined by newly formed minerals at the rims of igneous minerals.
5. **Stage 5** is represented by close to tight folds systems (i.e., D5 deformation imprint), with gently curved limbs and metric wavelength, which give rise to S-tectonic domains defining 100 m-size narrow bands. Fold axes trend around 250° or 90° and the axial planes dip 70° towards the NE. D5 is also associated with a spaced and discontinuous axial plane foliation (S5) dipping 60° towards the NE. The S5 foliation consists of alternate white mica, chlorite and rare biotite-rich layers (about 2 mm of thickness) and quartz and feldspar-rich layers in gneisses. The S5 foliation is present only in a single outcrop and it is not widespread throughout the entire field area. Both D4 and D5 occurred under greenschist facies conditions.

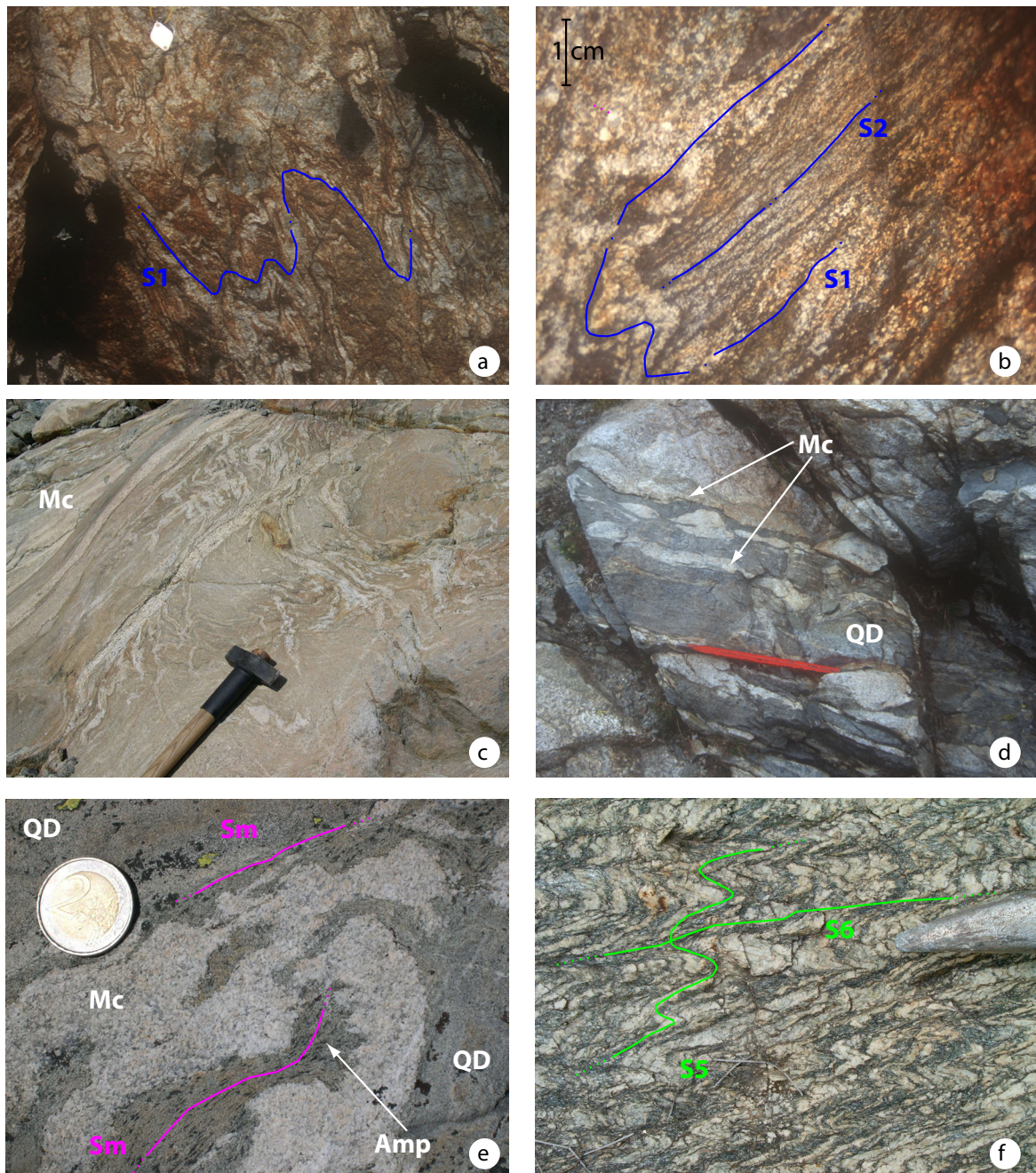


Figure 3. a) Migmatitic structures in Bt-bearing gneiss: alternate leucosomes (white) and melanosomes (black) mark the S1 foliation folded during D2; b) Migmatitic structures in Bt-bearing gneiss: alternate leucosomes (white) and melanosomes (black) mark S1 foliation folded during D2; the S2 foliation is marked by alternate leucosomes and melanosomes; c) Irregular structures which characterize the coronitic metagranite (Mc) with different intrusion phases of aplitic layers; d) Irregular contact between coronitic quartz-diorite (QD) and coronitic metagranite (Mc) with boudins of metagranite in quartz-diorite; e) Lobate-cusate boundary between coronitic quartz-diorite (QD) and coronitic metagranite (Mc) with folded Qtz + Fds layers within quartz-diorite; f) Mylonitic metagranite: folding of foliation S5 with centimeter wavelength and development of S6 axial plane foliation.

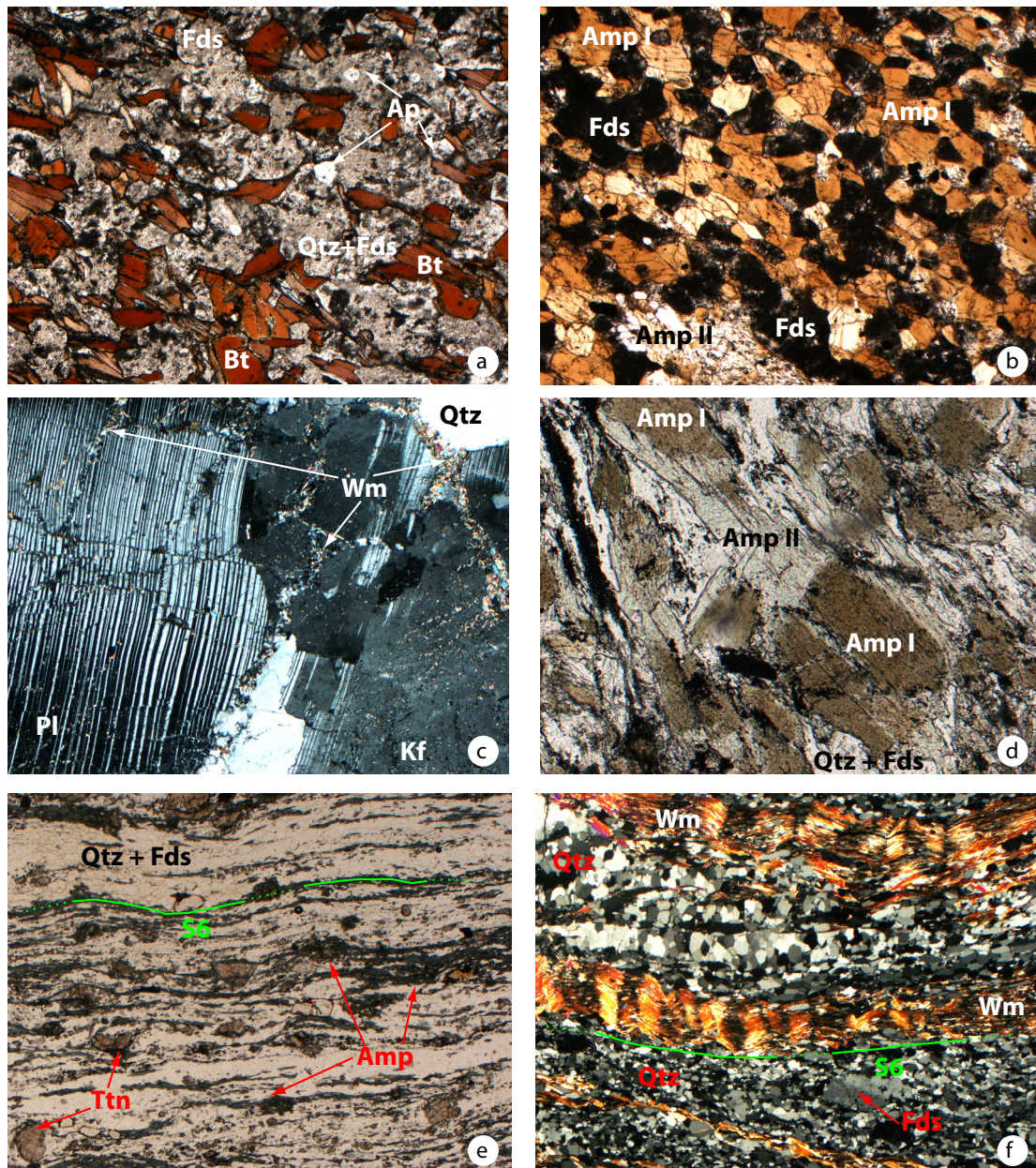


Figure 4. a) Microstructures of Biotite-bearing gneiss: feldspar domains (Fds) are strongly affected by recrystallization (Ep + Pl) (Plane-polarized light, base of the photo 0.9 mm); b) Microstructures of Amphibolite: two primary amphiboles are preserved (AmpI-brown and AmpII-white) and feldspar domains are strongly affected by recrystallization (Ep + Pl) (Plane-polarized light, base of the photo 0.9 mm); c) Igneous textures in coronitic metagranite: igneous Pl, Qtz and Kfs boundary is locally underlined by thin aggregates of alpine WmIII (crossed polars, base of photo 0.9 mm); d) Amp-bearing coronitic metagranite: AmpI (dark green) is rimmed by AmpII (light blue - light green) during D6 (Plane-polarized light, base of the photo 0.9 mm); e) Mylonitic metagranite: the S6 foliation is marked by layering of white (Qtz + Fds) and dark (Amp + Ttn) levels and by SPO of alpine Amp (black and dark blue) (Plane-polarized light, base of the photo 0.9 mm); f) Mylonitic metagranite: the S6 foliation is marked by layering of Qtz + Fds and Wm. Alpine Wm is characterized by SPO, LPO and syn-D7 crenulation (Crossed polars, base photo 0.9 mm). Legend: Qtz=quartz, Bt=biotite, Fds=feldspars, Amp=amphibole, Pl=plagioclase, Kf=K-feldspar, Wm=white mica, Ttn=titanite, Ap=apatite.

6. During **stage 6** open to isoclinal folds developed, associated to S6 foliations and lineations, overprinting the S5 foliation. D6 folds display planar limbs, curved hinges and mm to dm wavelength. Fold axes trend horizontally S-SE, axial planes dip SE of 50°. The S6 foliation may be mylonitic; in the metagranitoids the S6 tectonic foliation is spaced and discontinuous, in places anastomosing and is marked by alternate white mica layers (about 2 mm thick) and quartz, alkali feldspar, plagioclase, epidote and amphibole-rich layers (2-5 mm thick). Mylonitic foliation is spaced to continuous, and is marked by alternate white mica films (about 2 mm thick) and quartz, feldspar, epidote; amphibole-rich (glaucophane) lithons also develop within amphibole-bearing rocks (Figures 3f, 4e). Within coronitic domains epidote occurs at plagioclase rims, white mica surrounds biotite crystals and blue amphibole overgrows igneous amphiboles. The L6 stretching lineation is marked by SPO of white mica and amphibole and quartz ribbons on the foliation plane and strikes 250°. The S6 foliation dips 45° to 90° towards the SSE. D6 deformation zones are coherent up to the km-scale with the zones of straight trend of lithological boundaries; D6 occurred under blueschist facies conditions (Roda and Zucali, 2008).
7. **Stage 7** is associated with deformation under greenschist facies conditions, D7, and is represented by gentle to close folds, which bend the S6 foliation; D7 fold system displays straight limbs, curved hinges and 10 m to 1 km-wavelength. Axial surfaces display attitudes ranging between dip of 60°-90° towards 345°-20°; fold axes have ENE and SW direction and commonly low dipping plunge. The associated L7 intersection lineation is marked by SPO of white mica and quartz with 90°N trend, gently dipping.
8. **Stage 8** corresponds to development of 1 to 10 m-size shear zones D8; they display straight boundaries and the well foliated volumes are marked by alternate quartz, feldspar and epidote-rich lithons and by white mica and chlorite-rich mm-thick films. They are characterized by a top-to-SE kinematics and greenschist facies conditions.
9. **Stage 9** is characterized by the intrusion of granodioritic dykes with porphyritic texture (D9 fracturing and Mag9 dykes intrusion). They may reach about 50 cm thickness, with boundaries parallel to the main mineralogical foliation of the country rock.
10. During **stage 10**, widespread dip-slip faulting occurs, associated with cohesive cataclases (D10 faulting) and pseudotachylites. Stage 10 faults crosscut the porphyritic D9 dykes, the S5 and S6 foliation planes and the lithological boundaries. Along fault planes, slickenside structures occur as calcite fibrous striae and chlorite-rich planes and striae. Meter-scale fracture zones also occur as cataclases and foliated cataclases; away from fracture zones the rocks (generally meta-intrusives) are almost undeformed, with only local, isolated fractures.

6. Conclusions

Detailed lithological, structural and petrographic mapping of the Mont Morion allowed to reproduce, at the map scale, the network of superimposed fabrics produced by the polycyclic evolution and associated with evolving metamorphic mineral associations. The strain distribution is also visible at various scales and within different lithotypes, showing volumes of rocks with different rock memories at the map scale. The Mont Morion Complex shows a low-strain igneous core, in which granites and quartz-diorites preserve igneous textures and where intrusive relations with biotite-bearing gneisses preserving pre-Alpine HT metamorphic relicts and amphibolites are well preserved (D3-Mag3 stage); these decameter- to kilometer-thick cores are surrounded by medium to high-strain domains, from decameter- to hectometer-thick, defined by tectonic to mylonitic white mica/chlorite-bearing gneisses and glaucophane-bearing gneisses. This km-scale partitioning of fabrics and the metamorphic reactions are related to the Alpine prograde (D6 stage) and retrograde (D7 stage) evolution in a depressed geothermal regime (e.g., blueschists facies conditions, Roda and Zucali, 2008), which follows the pre-Alpine (i.e., Permian) granitic and quartz-dioritic intrusions within a thinned continental crust.

Software

The geological map was compiled using Quantum GIS ([Quantum GIS Development Team, 2009](#)), ESRI ArcGIS and refined using Adobe Illustrator. Stereonet plots were produced using Stereonet ([Allmendinger, 2011](#)).

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References

ALLMENDINGER, R. (2011) Stereonet 7 for Windows [Online]. Available from: <http://www.geo>.

- cornell.edu/geology/faculty/RWA/programs/stereonet-7-for-windows.html, [Last accessed: 12 September, 2011].
- AYRTON, S., BUGNON, C., HAARPAINTER, T., WEIDMANN, M. and FRANK, E. (1982) Geologie du front de la nappe de la Dent Blanche dans la region des Monts-Dolins, Valais, *Eclogae Geologicae Helveticae*, 75, 269–285.
- AYRTON, S. and RAMSAY, J. G. (1974) Tectonic and Metamorphic Events in the Alps, *Schweizerische Mineralogische Und Petrographische Mitteilungen*, 54, 609.
- BALLEVRE, M. and KIENAST, J. R. (1987) Decouverte et signification de parageneses a grenat-amphibole bleu dans la couverture mesozoique de la nalle de la Dent-Blanche (Alpes-Occidentales), *Compte Rendu Academie des Sciences Paris*, 305, 43.
- BIGI, G. E. A. (1990) Structural Model of Italy, sheets 1-2: CNR, Progetto Finalizzato Geodinamica, Quaderni de "La ricerca scientifica", 114.
- BUSSY, F., VENTURINI, G., HUNZIKER, J. and MARTINOTTI, G. (1998) U-Pb ages of magmatic rocks of the western Austroalpine Dent-Blanche-Sesia Unit, *Schweizerische Mineralogische Und Petrographische Mitteilungen*, 78, 163.
- CABY, R., KIENAST, J. R. and SALIOT, P. (1978) Structure, métamorphisme et modèle d'évolution tectonique des Alpes occidentales, *Revue de Géologie Dynamique et de Géographie Physique*, 20, 307.
- CANEPA, A., CASTELLETTO, M., CESARE, B., MARTIN, S. and ZAGGIA, L. (1990) The Austroalpine Mont Mary nappe (Italian Western Alps), *Memorie Scienze Geologiche*, 42, 1.
- CARRARO, F., DAL PIAZ, G. and SACCHI, R. (1970) Serie di Valpelline e Il Diorito-kinzigitica sono i relitti di un ricoprimento proveniente della zona Ivrea-Verbano, *Memorie della Società Geologica Italiana*, 9, 197–224.
- CASTELLI, D., GOSSO, G., ROSSETTI, P., SPALLA, M. I., ZANONI, D. and ZUCALI, M. (2007) Guide-book to the DRT 2007 Workshop Field Excursion on the subducted continental crust of the Sesia-Lanzo Zone (Monte Camino-Monte Mucrone; Oropa-Biella, Western Italian Alps), In GOSSO, G., MAROTTA, A. M., SABADINI, R. and SPALLA, M. I., (eds.) XVI DRT programs and field guides of Conference, pre-Conference Excursion and post-Conference Workshop, *Quaderni di Geodinamica Alpina e Quaternaria*, Milano, pp. 35–70.
- COMPAGNONI, R. (1977) The Sesia-Lanzo zone: high-pressure low-temperature metamorphism in the Austroalpine continental margin, *Rendiconti della Società Italiana di Mineralogia e Petrologia*, 33, 335–374.
- CORTIANA, G., DAL PIAZ, G. V., DEL MORO, A. and HUNZIKER, J. C. (1998) ⁴⁰Ar-³⁹Ar and Rb-Sr dating of the Pillonet klippe and Sesia-Lanzo basal slice in the Ayas valley and evolution of the Austroalpine-Piedmont nappe stack, *Memorie Scienze Geologiche*, 50, 177.
- CORTIANA, G. E. A. (1999) Eocene eclogitic imprint in the lower Austroalpine outliers and underlying Zermatt-Saas ophiolites across the Aosta Valley, Western Alps., *Tuebinger Geowissenschaftliche Arbeiten Reihe A Geologie Palaeontologie Stratigraphie*, 52, 24–25.
- DAL PIAZ, G. (1999) The Austroalpine-Piedmont nappe stack and the puzzle of Alpine Tethys, *Memorie di Scienze Geologiche*, 51, 155–176.

- DAL PIAZ, G., CORTIANA, G., DEL MORO, A., MARTIN, S., PENNACCHIONI, G. and TARTAROTTI, P. (2001) Tertiary age and paleostructural inferences of the eclogitic imprint in the Austroalpine outliers and Zermatt-Saas ophiolite, Western Alps, *International Journal of Earth Sciences*, 90, 668–684, doi: [10.1007/s005310000177](https://doi.org/10.1007/s005310000177).
- DAL PIAZ, G. V., DE VECCHI, G. and HUNZIKER, J. C. (1969) Osservazioni geologiche sul lembo di ricoprimento del Pillonet (Dent Blanche l.s.), *Memorie della Società Geologica Italiana*, 8, 835.
- DE GIUSTI, F., DAL PIAZ, G. V., MASSIRONI, M. and SCHIAVO, A. (2003) Carta Geotettonica della Valle d'Aosta, *Memorie Scienze Geologiche*, 55, 129.
- DE LEO, S., BIINO, G. and COMPAGNONI, R. (1987) Riequilibrazioni metamorfiche alpine nella serie di Valpelline e di Arolla a nord di Bionaz (Valpelline-Aosta), *Rendiconti della Società Italiana di Mineralogia e Petrologia*, 42, 181.
- DIEHL, E. A., MASSON, R. and STUTZ, A. H. (1952) Contributo alla conoscenza del ricoprimento Dent Blanche, *Memorie degli Istituti di Geologia e Mineralogia dell'Università di Padova*, 17, 5.
- GARDIEN, V., REUSSER, E. and MARQUER, D. (1994) Pre-Alpine metamorphic evolution of the gneisses from the Valpelline series (Western Alps, Italy), *Schweizerische Mineralogische Und Petrographische Mitteilungen*, 74, 489.
- HELLWIG, D. (2003) Die Mobilisierung der austroalpinen Dent Blanche Decke auf Fluid-induzierten Scherzonen während alpiner Hochdruckmetamorphose, Unpublished PhD Thesis, Fachbereich Geowissenschaften der Philipps-Universität Marburg.
- HUNZIKER, J. C. (1974) Rb/Sr and K/Ar age determination and the Alpine tectonic history of the Western Alps, *Memorie degli Istituti di Geologia e Mineralogia dell'Università di Padova*, 31, 1.
- KIENAST, J. R. and NICOT, E. (1971) Presence d'une paragenese a disthene et chloritoide (d'age alpin probable) dans les gneiss a sillimanite, grenat et cordierite de Valpelline (Val d'Aoste, Italie), *Compte Rendu Academie des Sciences Paris*, D 272, 1836.
- MALASPINA, N., SCAMBELLURI, M., PENNACCHIONI, G. and SPAGNOLO, C. (2010) Fluid-induced plastic deformation in the crustal Austroalpine system (Western Italian Alps): a petrologic and fluid inclusion analysis, *Italian Journal of Geosciences*, 129.
- MANZOTTI, P. (2011) Petro-structural map of the Dent Blanche tectonic system between Valpelline and Valtouranche valleys, Western Italian Alps, *Journal of Maps*, v2011, 340–352.
- MAZUREK, M. (1986) Structural evolution and metamorphism of the Dent Blanche Nappe and the Combin Zone West of Zermatt (Switzerland), *Eclogae Geologicae Helvetiae*, 79, 41.
- PASSCHIER, C. W. and TROUW, R. A. J. (2005) *Microtectonics*, Springer, Verlag Berlin Heidelberg, 366 pp.
- PATERSON, S. R., VERNON, R. H. and TOBISCH, O. T. (1989) A review of criteria for the identification of magmatic and tectonic foliations in granitoids, *Journal of Structural Geology*, 11, 349.
- PENNACCHIONI, G. and GUERMANI, A. (1993) The mylonites of the Austroalpine Dent Blanche Nappe along the northwestern side of the Valpelline Valley (Italian Western Alps), *Memorie Scienze Geologiche*, 45, 37.

- POLINO, R., DAL PIAZ, G. and GOSSO, G. (1990) Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny of the Alps, *Mémoires de la Société Géologique de France*, 156, 345–367.
- POLLARD, D. D. and FLETCHER, R. C. (2005) *Fundamentals of Structural Geology*, Cambridge University Press, Cambridge, 500 pp.
- QUANTUM GIS DEVELOPMENT TEAM (2009) Quantum GIS Geographic Information system [Online]. Available from: <http://qgis.osgeo.org>, [Last accessed: 12 September, 2011].
- RAMSAY, J. G. and HUBER, M. I. (1983) *The Techniques of Modern Structural Geology*, Academic Press, London, 307 pp.
- RODA, M. and ZUCALI, M. (2008) Meso and microstructural evolution of the Mont Morion metaintrusive complex (Dent Blanche nappe, Austroalpine domain, Valpelline, Western Italian Alps), *Bollettino della Società Geologica Italiana*, 127, 105–123.
- SALVI, F., SPALLA, M. I., ZUCALI, M. and GOSSO, G. (2010) Three-dimensional evaluation of fabric evolution and metamorphic reaction progress in polycyclic and polymetamorphic terrains: a case from the Central Italian Alps, *Geological Society, London, Special Publications*, 332, 173–187, doi: 10.1144/SP332.11.
- SPALLA, M., LARDEAUX, J., DAL PIAZ, G., GOSSO, G. and MESSIGA, B. (1996) Tectonic significance of the Alpine eclogites, *Journal of Geodynamics*, 21, 257–285.
- SPALLA, M. I., GOSSO, G., SILETTO, G. B., DI PAOLA, S. and MAGISTRONI, C. (1998) Strumenti per individuare unità tettono-metamorfiche nel rilevamento geologico del basamento cristallino, *Memorie della Società Geologica Italiana*, 50, 155–164.
- SPALLA, M. I. and ZUCALI, M. (2004) Deformation vs. metamorphic re-equilibration heterogeneities in polymetamorphic rocks: a key to infer quality P-T-d-t path, *Rivista Italiana di Mineralogia e Petrologia*, 73, 249.
- SPALLA, M. I., ZUCALI, M., DI PAOLA, S. and GOSSO, G. (2005) A critical assessment of the tectonothermal memory of rocks and definition of the tectonometamorphic units: evidence from fabric and degree of metamorphic transformations, In GAPAIS, D., BRUN, J. P. and COBBOLD, P., (eds.) *Deformation Mechanisms, Rheology and Tectonics: from Minerals to the Lithosphere*, Geological Society Special Publications, London, pp. 227–247.
- SPALLA, M. I., ZUCALI, M., SALVI, F., GOSSO, G. and GAZZOLA, D. (2003) Tectono-metamorphic map of the Languard-Campo, Serie del Tonale Nappes between upper Val Camonica and Valtellina (Central Italian Alps, Austroalpine Domain), *Memorie Scienze Geologiche*, 55, 105.
- SPLENDORE, R., ZUCALI, M., GIORDANO, G. and RODA, M. (2006) Struttura e metamorfismo Alpino di una zona di taglio crostale: analisi meso e microstrutturale del Complesso del Mont Morion (Falda Dent Blanche, Alpi Occidentali, Italia), *Rendiconti della Società Geologica Italiana*, 2.
- TURNER, F. J. and WEISS, L. E. (1963) *Structural analysis of metamorphic tectonites*, 545, McGraw-Hill, New York.
- TWISS, R. J. and MOORE, C. H. (1992) *Structural Geology*, W.H. Freeman, New York, 2nd ed., 532 pp.
- WILLIAMS, P. F. (1985) Multiply deformed terrains - problem of correlation, *Journal of Structural Geology*, 7, 269–280.

ZUCALI, M. (2002) Foliation map of the "Eclogitic Micaschists Complex" (Monte Mucrone – Monte Mars – Mombarone, Sesia-Lanzo Zone, Italy), *Memorie Scienze Geologiche*, 54, 86–100.

ZUCALI, M., SPALLA, I. and GOSSO, G. (2002) Strain partitioning and fabric evolution as a correlation tool: the example of the Eclogitic Micaschists Complex in the Sesia-Lanzo Zone (Monte Mucrone-Monte Mars, Western Alps, Italy), *Schweizerische Mineralogische Und Petrographische Mitteilungen*, 82, 429–454.

TECTONO-METAMORPHIC MAP OF THE MONT MORION PERMIAN METAINTRUSIVES

MONT MORION - MONT COLLON - MATTERHORN COMPLEX

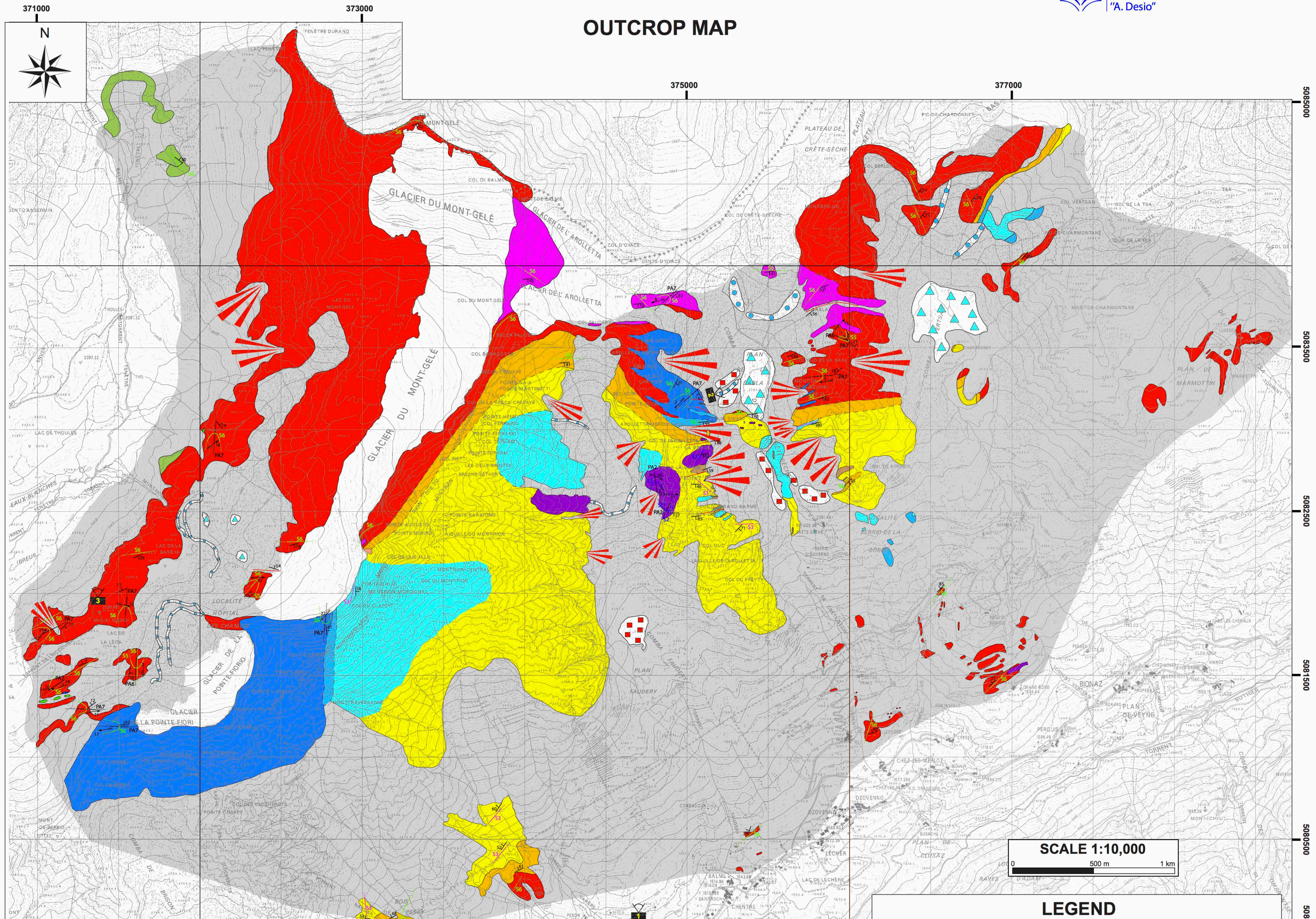
DENT-BLANCHE UNIT - VALPELLINE VALLEY - ITALY

MANUEL RODA and MICHELE ZUCALI

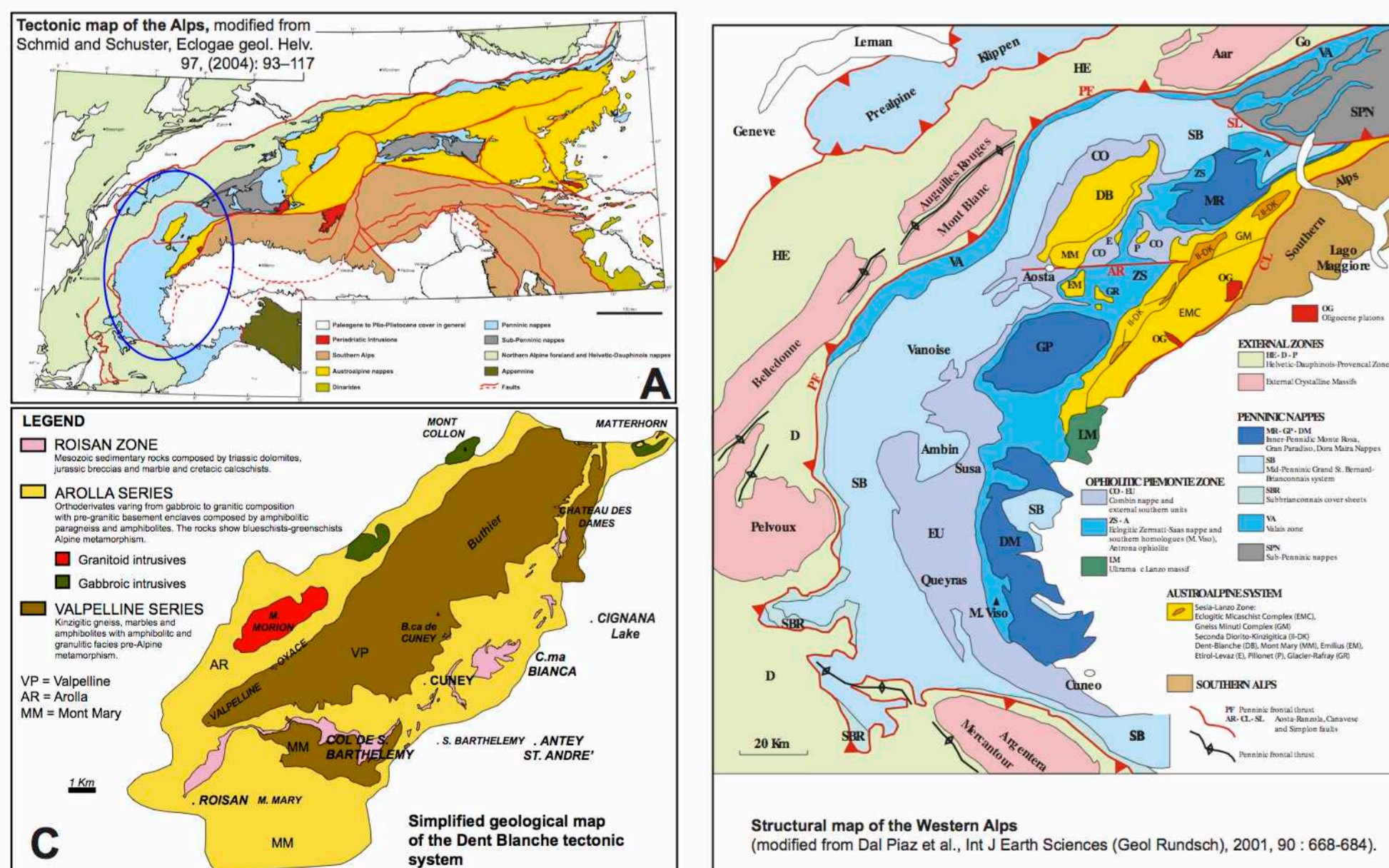
(Università degli Studi di Milano - Dipartimento di Scienze della Terra "A. Desio")



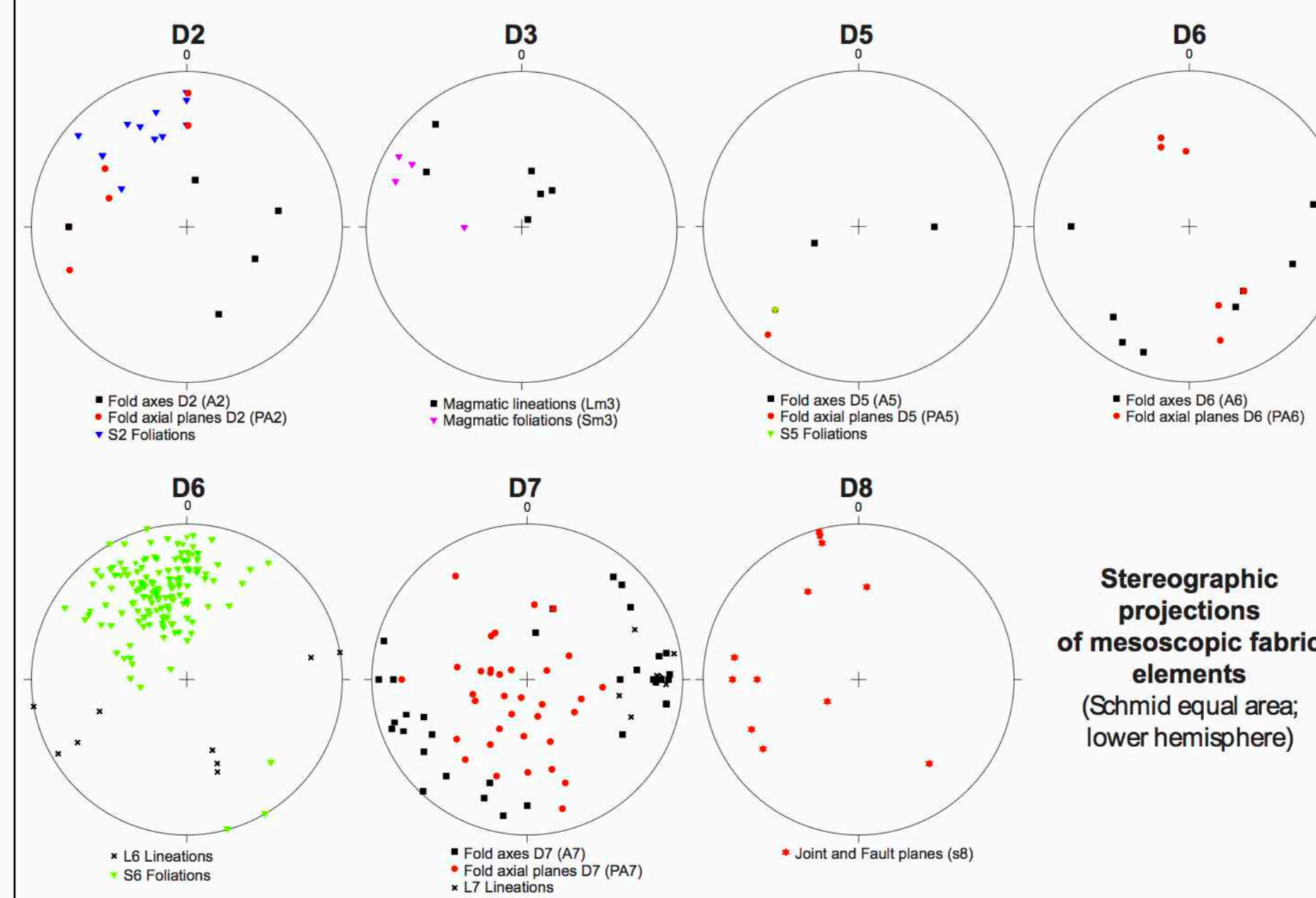
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REGIONAL GEOLOGICAL AND TECTONIC FRAMEWORKS

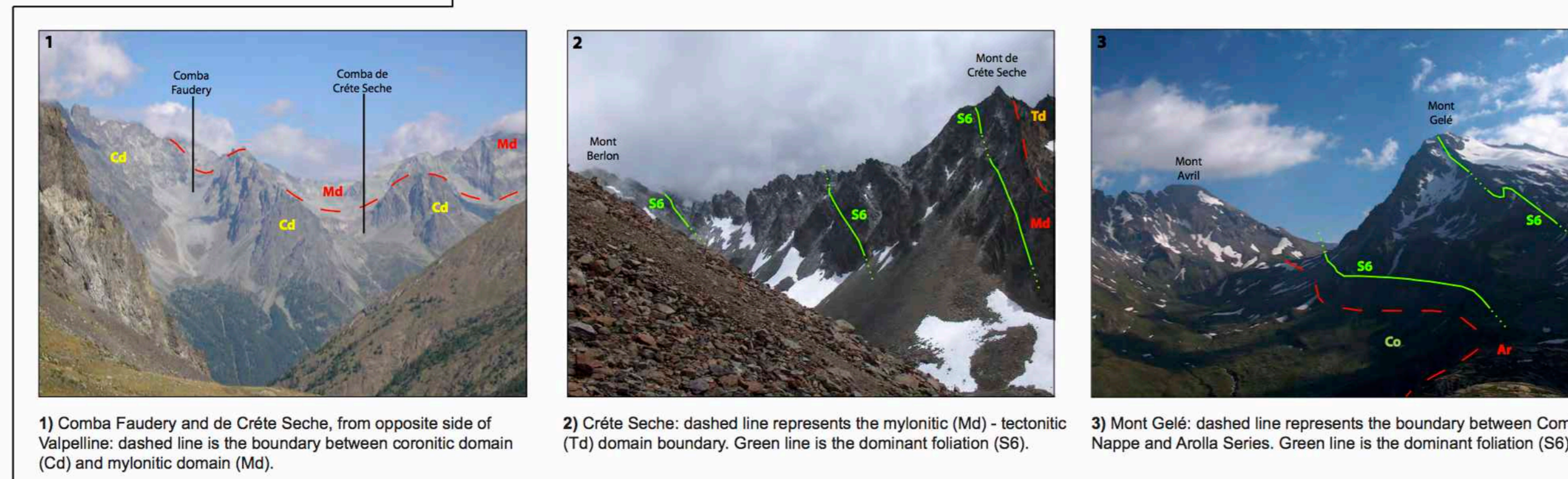


STEREONETS



PANORAMIC VIEWS

Location of viewpoints is indicated in the outcrop map



LEGEND

AUSTROALPINE BASEMENT OF THE WESTERN ALPS Dent-Blanche and Saio-Lanzo composite tectonic systems of paleoffrican provenance.		QUATERNARY DEPOSITS	
DENT-BLANCHE UNIT The DB tectonic system is characterised by a Palaeozoic basement, Permian intrusives and lenses of Mesozoic metasedimentary cover. It includes the Valpelline Series and Arolla Series distinguished on the basis of their lithological assemblage and metamorphic history.		<ul style="list-style-type: none"> Detrital fans Debris talus and debris ow Ruival and glacial deposits Landslides Moraines 	
AROLLA SERIES			
Protoliths of pre-Permian age			
Bottle-bearing gneiss: Qtz, Pl, B, Wm +/- Ep +/- Qt +/- Chl +/- Amp +/- Bk +/- Op. Compositional layering composed by B-rich levels with foliation marked by B, Amp and Wm and Qtz-Pl-Q-rich levels with granblastic texture.		<ul style="list-style-type: none"> S1 S2 S3 S4 S5 S6 	
Amphibolite: Pl, Amp, Ep +/- Qtz +/- Bk. Rocks with a foliation marked by compositional layering of Amp and Pl.		<ul style="list-style-type: none"> PA2 PA6 PA7 	
Protoliths of Permian age			
Coronitic metagranite: Qtz, Kf, R, Wm, Ep +/- Chl +/- Amp +/- Bk +/- Op. Holocrystalline rocks with magmatic foliation marked by Kf porphyroclasts.		<ul style="list-style-type: none"> Trace of successive foliations Trace of axial planes to fold systems 	
Tectonic metagranite: Qtz, Kf, R, Wm, Ep +/- Chl +/- Amp +/- Op. Rocks with discontinuous foliation marked by Wm +/- Chl.			
Mylonitic metagranite: Qtz, Kf, R, Wm, Ep +/- Chl +/- Amp +/- Bk +/- Op. Rocks with a mylonitic foliation marked by Wm, Act and Chl.			
Coronitic Amphibole-bearing metagranite: Qtz, Pl, Amp, Ep +/- Kf +/- Wm +/- Bk +/- Op. Holocrystalline rocks with magmatic foliation marked by Kf porphyroclasts.			
Tectonic Amphibole-bearing metagranite: Qtz, Pl, Amp, Ep +/- Kf +/- Wm +/- Bk +/- Op. Rocks with discontinuous foliation marked by Wm, Amp and Ep.			
Mylonitic Amphibole-bearing metagranite: Qtz, Pl, Amp, Ep, Wm +/- Act +/- Chl. Rocks with a mylonitic foliation marked by Wm, Act and Chl.			
Granodiorite: Pl, Amp, Qtz +/- Wm +/- Ep +/- Bk +/- Act +/- Op. Holocrystalline rocks with magmatic foliation marked by Amp porphyroclasts. Rimmed growth of Act on Amp.			
White mica-Chlorite-bearing gneiss: Qtz, Wm, Chl, Pl +/- Kf +/- Ep +/- Op. Rocks with a foliation marked by Wm and Chl.			
Glaucophane-bearing gneiss: Qtz, Pl, Kf, G, Wm, Ep +/- Chl +/- Op. Rocks with a foliation marked by G, Wm and Ep.			
OPHIOLITIC-PIEMONTE ZONE			
Tectonic systems derived from the closure of the Piemont-Ligurian basin, including oceanic lithosphere sections, cover units from the ocean facing continental edges and orogenic, yach units. Most of the truly oceanic units show a peculiar eclogite-blueschists-early-Alpine metamorphism.			
COMBIN UNIT			
Protoliths of Mesozoic age		<ul style="list-style-type: none"> Fold axes attitude (A2, A6, A7) Planes attitude Directly observed limit Inferred by indirect methods limit (panoramic view, pictures and orthophoto) Fault Supposed fault Viewpoint of photographs 	
Calcic schist: Qtz, Wm, Qt +/- Chl +/- Op. Rocks with a mylonitic foliation marked by Wm and Chl.			
Serpentine: Srp +/- Ep +/- R +/- Px +/- Chl. Rocks with a mylonitic foliation marked by Srp.			

NOTES

Redrawn after mapping by: Manuel Roda, Michele Zucali, Raffaele Splendore, Glauco Giordano, Marco Meda, Marta Senaldi, Marco Pesce, Marco Riboni, Andrea Marzorati

Topography from the 1:10,000 scale Carta Tecnica Regionale (CTR) of Valle d'Aosta; UTM 1950 coordinate system; files: t7082, t7086, t7482, t7486, t7882, t7886

Coordinate system UTM ED 1950, 32°N, meters