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A new petro-structural map of the Monte Mucrone metagranitoids (Sesia-Lanzo Zone, Western Alps)

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The Mt. Mucrone metagranitoid is an extensively investigated intrusive Permian body, located in the Eclogitic Micaschists Complex of the Sesia-Lanzo Zone, within the high-pressure metamorphic belt of the Western Alps formed during the Alpine plate convergence. The structure of the northwestern sector of Mt. Mucrone, including both the metagranitoids and country rocks, has been mapped, although an integrated structural and petrological analysis is still lacking in its southwestern sector, a topic investigated in this contribution. During the field structural analysis, six groups of ductile structures were recognized to have evolved as follows: the D1 and D2 fabrics took place under eclogite-facies, D3 under blueschist-facies and D4 to D6 under greenschist-facies conditions, respectively. Foliation trajectories revealing the chronology of the superposed structures are represented in the analytical (drift and solid) and interpretative (solid) maps, both at a 1:10,000 scale, and a panel of structural cross-sections allows the 3D representation of the poly-deformed lithostratigraphy. The related metamorphism indicates the changes within the subduction-collision tectonic frame.

Keywords: structural mapping; petrological mapping; multiscale analysis; deformation evolution; metamorphic evolution; Sesia-Lanzo Zone

1. Introduction

The petrology and geochemistry of the Mt. Mucrone metagranitoids have been widely investigated (e.g. Cenki-Tok et al., 2011; Compagnoni, 1977; Oberhänsli, Hunziker, Martinotti, & Stern, 1985; Rubbo, Borghi, & Compagnoni, 1999; with refs.), but an integrated structural and petrological analysis of the southern slope of Mt. Mucrone was needed to reconstruct the superposed grid of foliation trajectories by taking into account the degree of fabric evolution and the associated mineral assemblages. The purpose of this work is to infer the deformation history of this area and correlate it with the structural and metamorphic history deduced in the nearby Mombarone-Mt. Mars-Mt. Mucrone sector to the NW (Zucali, Spalla, & Gosso, 2002). The results are summarized for these new objectives using interpretative structural maps constructed at a 1:10,000 scale (original analysis at a 1:2500 scale) and two sets of cross-sections that assist in visualizing the 3D structure. Details of the metamorphic evolution are also summarized in the

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legend, and symbols are used to highlight the metamorphic environment of the successive steps of the fabric development.

2. Geologic outline

The Sesia-Lanzo Zone (SLZ) represents the largest portion (~90 × 20 km) of the western Austroalpine region, the topmost sheet of continental crust overriding the Alpine oceanic suture, and has been eclogitized during the Alpine subduction (Figure 1). This portion is elongated parallel to its eastern tectonic boundary (Periadriatic Lineament), which separates the SLZ from the Southalpine domain. Two structural elements are traditionally described (e.g. Dal Piaz et al., 1972): an upper element or the 'II Zona Diorito-Kinzigitica' (IIDK), and a lower element divided in two main metamorphic complexes, i.e. the Eclogitic Micaschists Complex (EMC) and the Gneiss Minuti Complex (GMC). More recently, another tectonic unit has been identified in the southern SLZ: the Rocca Canavese Thrust Sheet (RC of Pognante 1989a, 1989b). A redefinition of these metamorphic complexes has been proposed by Babist, Handy, Konrad-Schmolke, and Hammerschmidt 2006.

The IIDK was not re-equilibrated under eclogite-facies conditions during the Alpine convergence and widely preserves the pre-Alpine high temperature-low pressure (HT-LP) metamorphic imprints. The IIDK is principally composed of metapelites and metabasites characterized by a dominant pre-Alpine metamorphic imprint under amphibolite/granulite-facies conditions (the so-called kinzigitic complex, e.g. Compagnoni et al., 1977) with minor metagranitoids and a few slices of mantle peridotite (Beccaluva, Dal Piaz, Macciotta, & Zeda, 1978). The Alpine metamorphic evolution is polyphase and displays a pervasive

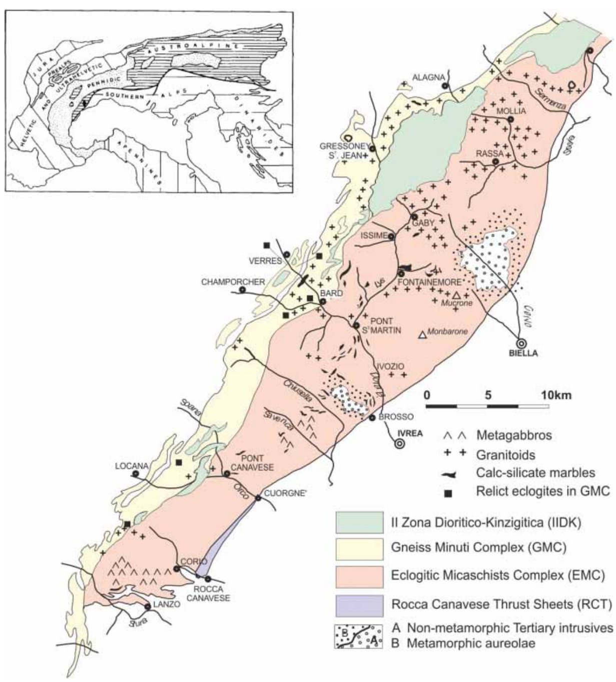

Figure 1. Tectonic sketch of the Sesia-Lanzo Zone redrawn after Compagnoni et al. (1977), Passchier et al. (1981), Spalla & Zulbati (2003) and location of the SLZ in the Alpine chain (inset).

re-equilibration under greenschist-facies conditions that partly obliterates the blueschist-facies mineral assemblages.

The EMC and the GMC complexes have been eclogitized during Alpine times, but only the first preserves the eclogitic imprint as dominant, whereas the second shows a pervasive Alpine retrogression under greenschist-facies conditions (Spalla, De Maria, Gosso, Miletto, & Pognante, 1983). The EMC and GMC rocks include metapelites, paragneisses, metagranitoids, metabasites and impure marbles with an Alpine polyphasic deformation under eclogite-facies conditions, followed by retrogression under blueschist- to greenschist-facies conditions (e.g. Castelli, 1991; Compagnoni et al., 1977; Lardeaux, Gosso, Kienast, & Lombardo, 1982; Pognante, 1991; Pognante et al., 1980; Zucali & Spalla, 2011).

High-pressure (HP) assemblages in the metapelites consist of Ky, Gln, Grt, Ph, Zo and Cld, yielding temperature estimates that do not exceed 650°C (e.g. Compagnoni et al., 1977; Dal Piaz, Gosso, & Martinotti, 1971; Gosso, 1977; Lardeaux et al., 1982; Roda, Spalla, & Marotta, 2012; Vuichard, 1987; Zucali & Spalla, 2011).

The pre-Alpine evolution of the SLZ is characterized by a granulite facies imprint followed by successive re-equilibrations under amphibolite and greenschist-facies conditions (e.g. Lardeaux & Spalla, 1991). The pre-Alpine ages of 280 and 240 Ma (e.g. Hunziker, Desmons, & Hurford, 1992) have been interpreted as dating the granulite- and amphibolite-facies imprints, respectively (Lardeaux & Spalla, 1991) whereas the early Alpine metamorphism has been dated to 60–70 Ma or older (e.g. Cenki-Tok et al., 2011; Rubatto, Gebauer, & Compagnoni, 1999). The exhumation of this portion of SLZ to shallow structural levels (low-pressure, greenschist-facies conditions) was accomplished before the emplacement of the Tertiary intrusive bodies of Biella and Traversella, as evidenced by the development of HT-LP contact mineral assemblages that overprint the greenschist-facies and late-Alpine parageneses (e.g. Zanoni et al., 2010).

Permian metaintrusives, of felsic to mafic bulk chemical compositions, variably re-equilibrated under HP conditions during the Alpine convergence (i.e. the Mt. Mucrone metagranitoids or the Sermenza and Corio and Monastero metagabbros) are embodied in the metasediments of the SLZ (e.g. Bertolani, 1971; Bussy, Venturini, Hunziker, & Martinotti, 1998; Castelli, Compagnoni, & Nieto, 1994; Compagnoni & Maffeo, 1973; Compagnoni et al., 1977; Koons, 1982; Oberhänsli et al., 1985; Rebay & Spalla, 2001; Zucali et al., 2002).

3. Mapping technique

The present work describes the correlation of the structural fabric and metamorphic assemblages in the subducted-exhumed polyphased tectonites and a consequent effort to distinguish the pre-Alpine protoliths of both the meta-intrusives and of their country rocks on a more convincing base.

The mapped structural elements include the lithologic boundaries, differentiated mineral layerings (foliations) and lineations or fold systems axial plane traces distinguished by means of overprinting relationships. The mineralogical support of the new grain-scale planar and linear fabrics is the primary reference to select mineral compatibilities marking each successive foliation (Hobbs, Means, & Williams, 1976; Passchier & Trouw, 2005; Spalla, Siletto, Di Paola, & Gosso, 2000; Spalla, Zucali, Di Paola, & Gosso, 2005; Turner & Weiss, 1963; Williams, 1985). The inferred lithostratigraphic configuration has been represented on the 'drift and solid' map (in which surfacing rocks are separated by drift cover), and the full pattern of the superposed structures has been reported on the 'solid' map and on the cross-section grid. The terms 'solid' and 'drift and solid' conceptually refer to the mapping and representation techniques in use at the Geological Survey of Great Britain, which concisely convey to readers the extent of lithostratigraphic and structural interpretation inherent to the map document (e.g. Sheet 62 W Loch Quoich, 1:50,000 scale solid edition) by means of displaying either the extent of the Quaternary cover (incoherent deposits = drift) or an indication of the fully interpreted lithostratigraphic configuration below it (solid map) or a synthetic combination of both representations (drift and solid). Such objectivity in displaying mapping results has also been attempted in the German (bedekte-covered and unbedekte-uncovered maps), American (Kupfer, 1966) and Italian (carta oggettiva-covered and interpretativa-uncovered maps) geological mapping literature (Rau & Tongiorgi, 1972a,b; Spalla et al., 1983; Spalla, Di Paola, Gosso, Siletto, & Bistacchi, 2002). Note that the meta-sediments and meta-granitoids, which are distinguished as different varieties in the 'drift and solid' map, are undistinguished in the lithologic legend of the sub-outcropping map. The results of the 1:2500 scale survey of the outcrop contours and structural elements have been drawn using Adobe Illustrator CS6 at a 1:10,000 scale. The curves and polylines have been exported in a GIS system as polyline geo-referencing locations using common landmarks between the topography and the reproduced elements.

The orientation of structural elements, such as axial plane foliations, axial surface traces and fold axes, are reported on the outcrop map together with their relative chronology. The orientation data have been elaborated with the StereoWin 1.2 software to generate equal area Schmidt diagrams grouped according to their relative chronology. On the interpretative form surface map, the traces of the foliation trajectories are grouped based on relative age, and the metamorphic minerals marking successive fabrics are specified. This representation technique conveys evolutionary visualizations in complex structural frameworks together with an immediate perception of the paleo-thermal regimes that characterize the deformation history.

4. Field data

Metagranitoids, paragneisses, micaschists and certain leucocratic metagranitoids are the main lithotypes in the mapped area, with minor occurrences of eclogites, glaucophanites and zoisitites.

In all of these rocks, the Alpine eclogitization obliterated most of the previous metamorphic mineral assemblages. The HP metamorphic imprint is dominant and is pervasively replaced only locally by the subsequent blueschist and greenschist-facies re-equilibrations. Structural relics dominate on mineralogical relics of pre-Alpine age, with the exception of certain low strain domains of metagranitoids in which more than 40% in volume of the igneous minerals is preserved.

The lithologic types are distinguished as follows: (1) metagranitoids of Mt. Mucrone subdivided into (a) 'grey-type' metagranitoids comprising medium- to coarse-grained rocks showing a well-preserved isotropic and hypidiomorphic igneous structure with igneous relics Bt, Aln, and Kfs only partially replaced by Alpine Jd, Grt, Zo and Ph (photo A in the 'lithologic types' of the map plate; mineral abbreviations after Whitney and Evans 2010 plus Wm for white mica); metaquartzdiorite; metaaplite; metapegmatoid; (b) 'green-type' metagranitoids consisting of fine- to medium-grained rocks showing a deformed igneous texture with a dominant foliation marked by Jd (or Omp), Grt, Wm, Gln and Czo (photo B in 'lithologic types' of the map plate); (2) leucocratic metagranitoids; (3) eclogites; (4) micaschists; (5) paragneisses; (6) porphyric gneisses; (7) zoisitites; and (8) glaucophanites. All of these lithotypes contain Qz-dominated high-pressure veins (HP veins). The last two rock types and the HP veins are marked on the map using colored diamonds because they occur as unmappable meter-sized lenses. The mineral associations and dominant textures of these lithotypes are detailed in Table 1.

4.1. *Metaintrusives*

The intrusive protoliths consist principally of granitoids that occur as 10-m to km-sized bodies, including minor meter-sized granodioritic lenses. The first metagranitic complex ('grey-type'

Table 1. Mineral associations and dominant textures in metagranitoids and surrounding rocks of Monte Mucrone southern slope.

	Rock-type	Modal composition	Coronitic texture	Tectonitic texture	Mylonitic texture
Metaintrusives	Green-type metagranitoid: Jd or Omp, Grt, Wm and Gln fine to medium grained bearing metagranitoid	Qz 30–50%, Cpx (Jd/Omp) 20–30%, Wm 15–20%, Grt 15–20%, Zo 5% and Gln 5%		green colored rock medium grained with gneissic spaced foliation evidenced by Wm and Cpx SPO	fine grained mm spaced foliation evidenced by Wm and Cpx SPO
	Grey-type metagranitoid: Jd, Grt and Wm bearing medium to coarse grained metagranitoid with relics of igneous Bt, Ksp and Aln	Qz 50%, Jd 25%, Wm 15%, Grt 5% and Zo 5%. Estimated igneous composition: Qz 40%, Pl 40%, Ksp 20% and Bt 10%	grey colored rock with preserved hypidiomorphic igneous texture, with withish aggregates of Jd + Qz and Grt rimming Bt microsites		localized mm thick shear zones marked by Act, Wm and Ep SPO
	Metaquartzdiorite: Omp, Grt, Wm and Gln medium to coarse grained bearing metaquartzdiorite	Omp 30%, Grt 25%, Qz 20%, Wm 10% and Gln 10%. Igneous composition: Pl 30%, Qz 20%, Ksp 10% and mafic minerals 40%	medium to coarse grained rock with randomly oriented Omp, Ph and Gln	tectonitic to mylonitic textures occur at the boundaries of metaquartzdiorite lenses with foliation marked by Gln, Grt and Ph SPO	
	Metaaplite-metapegmatoid: Jd-bearing fine grained metaaplite and Jd, Wm and Grt bearing coarse grained metapegmatoid	Qz 50%, Jd 25%, Wm 15%, Grt 5% and Zo 5%	same of grey-type metagranitoid s.s.	gneissic texture with foliation marked by Ph and elongated Qz-rich domains	
	Leucocratic metagranitoid: Ab, Wm and Gln medium to fine grained leucocratic metagranitoid	Qz 40%, Ab 40% and Wm 20%		spaced to continuous tectonitic to mylonitic foliation, medium to fine grained, marked by Ph SPO and elongated Qz domains	
	Eclogite: Gln, Wm and Zo bearing fine grained eclogite	Omp 35%, Grt 25%, Gln 20%, Wm 10% and Zo 10%	massive to very poorly foliated rock with S2 foliation marked by Gln		localized mm thick shear zones marked by Act, Wm and Ep SPO

Paraderivates	Micaschist: Wm, Grt, Gln, Cpx (Jd/Omp) and Zo bearing fine grained micaschist	Wm (15–40%), Qz (15–50%), Gln (5–25%), Grt 15%, Cpx 10% and Zo 5%		micaschist always have a tectonitic to mylonitic pervasive texture, with mm spaced continuous foliation marked by Qz, Cpx, Gln, Wm and Zo. Foliation can be reactivated as slip plane by successive deformation stages	
	Paragneiss: alternances of Qz and Grt bearing layers and mafic layers	Qz and Grt bearing layers: Qz 65%, Grt 15%, Wm 15% and Gln 5%; mafic layers: Gln 50%, Omp 25%, Grt 15%, Qz 5% and Wm 5%	gneissic texture inhereted by pre-Alpine metasediments is marked by alternating layers	in less developed tectonitic texture the tectonitic fabrics are concentrated in Qz and Grt layers marked by Wm SPO. In more developed tectonite and in mylonitic texture a mm spaced foliation occurs in all layers marked by Qz, Wm, Cpx and Gln SPO	
	Porphyric gneiss: Qz, Ab, Wm and Ksp fine to medium grained rock with coarse grained Ksp crystals	Qz 35%, Ab 25%, Wm 20% and Ksp 20%		gneissic texture with foliation marked by Wm SPO and by elongation of Qz and Ksp-rich domains	
	Zoisitite: Zo, Qz, Wm and Gln bearing fine grained zoisitite with Grt	matrix (70% volume) composed of Zo 35%, Qz 15%, Wm 10%, Gln 5% and Omp 5%, with ten cm sized Grt blast 30%	granoblastic texture		mylonitic foliation marked by Zo, Wm and Gln enveloping Grt blasts
	Glaucophanite: Omp, Grt and Wm bearing porphiric fine grained glaucophanite	Gln 50%, Omp 20%, Grt 20% and Wm 10%. Locally Qz occurs		foliation marked by Gln and Wm SPO with randomly oriented Omp and Grt	
	Quartz-dominated high-pressure vein: Wm, Grt, Zo and Gln bearing coarse grained quartzite	Qz 90–95% with Wm, Grt, Gln and Zo accessories		spaced foliation marked by Wm and Zo SPO	

metagranitoids and 'green-type' metagranitoids) occupies the upper part of Mt. Mucrone and derives from Permian intrusive rocks (287−293 Ma) in primary contact with metasedimentary country rocks (Bussy et al., 1998; Cenki-Tok et al., 2011; Oberhänsli et al., 1985) that preserve some HT-LP pre-Alpine metamorphic imprints. The second is a 100-m thick leucocratic metagranitoid occurring in the lower part of the southeastern ridge of Mt. Mucrone; it is embodied in eclogitized micaschists.

In the first metagranitic complex, the partitioning of Alpine syn-metamorphic deformation is responsible for the differentiation of the two main types: part of the metagranitoids underwent Alpine metamorphism and preserve the igneous texture, i.e. the 'grey-type' metagranitoids and part of the metagranitoids also display an intense Alpine deformation locally associated with the development of a mylonitic fabric (the 'green-type' metagranitoids). The 'grey-type' metagranitoid is smaller (approximately one-tenth) than the entire metagranitic complex.

Both portions are poorly affected by the metamorphic re-equilibrations under blueschist or greenschist-facies conditions, which are mainly concentrated along centimeter- to meter-thick mylonitic shear zones.

4.2. *Metasediments*

The metasediments consist mostly of paragneisses and micaschists with minor gneisses, glaucophanites and zoisitites. The paragneisses are structured as Qz- and Grt-bearing mineral layers alternating with mafic layers primarily consisting of Omp, Grt and Gln with interstitial Qz and Wm; this alternance marks the gneissic S1 foliation. Meter-thick layers of porphyric gneiss and coarse-grained Ksp crystals occur in the paragneisses. In agreement with the observations of adjacent areas (Zucali, 2002), these materials are interpreted as derived from pre-Alpine partial melting of the kinzigites (high-grade Bt, Sil-bearing gneisses). The micaschists are fine-grained rocks with a pervasive foliation with millimeter-scale spacing marked by alternating Qz- and Wm-rich layers. The boundary with the paragneisses is not sharp because the latters are Wm-rich and shade into the micaschists in the high-strain domains. Minor bodies of glaucophanites (1 m to 10 m in size) and HP Qz-dominated veins occur within the micaschists. The glaucophanites display a spaced foliation marked by a shape preferred orientation (SPO) of Gln and are overgrown by randomly oriented Omp crystals. The zoisitites occur as enclaves with a thickness of 10 m in the 'green-type' metagranitoid; these rocks are characterized by Grt blasts 10 cm in size.

5. Structural analysis

The mesoscale structural analysis is aimed at recognition of strain gradients that aid in individuating the protoliths and revealing the superposition of tectonic structures. Six groups of superposed structures (D1 to D6) are defined, mainly consisting of fold systems, foliations and shear zones (cross-sections and solid map of the map plate) developed during the Alpine subduction-exhumation cycle. As detailed in Table 2, the relationships between the superposed fabrics and successive mineral assemblages lead us to infer the following metamorphic and structural evolution:

- D1 folding, with the formation of a S1 eclogite-facies foliation;
- D2 folding, with the formation of a S2 eclogite-facies foliation;
- D3 shear zones, with the formation of a S3 blueschist-facies foliation;

Table 2. Mineral assemblages marking fabrics related to successive deformation stages (D1, D2 . . .) in metaintrusives and metasediments of Monte Mucrone southern slope.

	Rock-type	pre-D1	D1	D2	D3	D4	D5	D6
Metaintrusives	Green-type metagranitoid	Ap, Aln and Zrn	S1 gneissic massive foliation marked by Qz, Omp/Jd, Ph, Grt, Zo and Rt	coronitic growth of Cpx, Ph, Czo and Qz mainly associated to crenulation	10 cm-thick shear zones producing lenticular Qz and Wm. Brs formation on boudinaged Omp	ten m scale open parallel folds. Ab, Act, Ep and Wm replacement on Cpx, Gln, Zo and Ph	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	gentle folds with axial plane disjunctive foliation marked by Ab, dark Amp, Kfs(Adl) and Pg replacing Jd
	Grey-type metagranitoid	igneous texture preserved with Bt, Aln, Ap and Zrn relics	coronitic substitution of Pl by Qz + Jd + Zo aggregates, Bt and Ksp partially replaced by Ph. Grt rims igneous Bt	ten m scale isoclinal folds, coronitic growth of Omp on Cpx. Ph recrystallization of older Wm	cm-thick shear zones. S3 marked by Ph, Brs, Czo and Ttn	ten m scale open parallel folds. Ab, Act, Ep and Wm replacement on Cpx, Gln, Zo and Ph	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	ten m scale gentle folds
	Metaquartzdiorite	igneous texture preserved with Bt, Aln, Ap and Zrn relics	granoblastic texture of Omp and Grt with interstitial Qz, Gln and Ph	ten m scale isoclinal folds, coronitic reaction forming Qz, Omp, Gln, Ph, Grt, Czo and Rt	m-thick shear zones on the lithologic boundaries. S3 marked by Qz, Ph, Brs, Grt, Czo, Mg-Chl and Ttn	ten m scale open parallel folds. Ab, Act, Ep and Wm replacement on Cpx, Gln, Zo and Ph	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	ten m scale gentle folds
	Metaaplite and metapegmatoid	igneous texture preserved with Bt, Aln, Ap and Zrn relics	coronitic substitution of Pl by Qz + Jd + Zo aggregates, Bt and Ksp partially replaced by Ph. Grt rims igneous Bt	ten m scale isoclinal folds, coronitic growth of Omp on Cpx. Ph recrystallization of older Wm	cm-thick shear zones. S3 marked by Ph, Brs, Czo and Ttn	ten m scale open parallel folds. Ab, Act, Ep and Wm replacement on Cpx, Gln, Zo and Ph	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	ten m scale gentle folds

(*Continued*)

Table 2. Continued.

	Rock-type	pre-D1	D1	D2	D3	D4	D5	D6
	Leucocratic metagranitoid	/	S1 cm spaced continuous foliation marked by Ph and elongated Qz domains	ten m scale isoclinal similar folds. Partial dynamic recrystallization of Ph and growth of Gln parallel to fold axes	/	open to tight folds, crenulation of hinge zones and dynamic ricrystallization of Qz, Ab, Act, Wm and Ep	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	ten m scale gentle folds
	Eclogite	/	granoblastic texture of Omp, Gln, Grt and Ph	coronitic growth of Omp, Gln, Grt and Ph	cm-thick shear zones. S3 marked by Ph, Brs, Czo and Ttn	ten m scale open parallel folds. Ab, Act, Ep and Wm replacement on Cpx, Gln, Zo and Ph	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	ten m scale gentle folds
Paraderivates	Micaschist	pre-Alpine Grt cores, Ap, Aln and Zrn	isoclinal similar folds. S1 marked by Qz, Cpx (Jd/Omp), Ph, Gln, Zo and Rt	m scale isoclinal similar folds, with associated S2 obliterating S1 marked by Qz, Omp, Ph, Gln, Grt, Czo and Rt	deformation distributed in all the volume with Qz, Ph and Brs grain size reduction	open to close folds with intense crenulation. Widespread growth of Ab, Wm, Qz, Act, Chl, Ep and Ttn	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	ten m scale gentle folds with minor kink folds
	Paragneiss	pre-Alpine layer alternation of metasediments and Grt cores, Ap, Aln and Zrn	coronitic growth of Omp, Grt, Gln, Ph, Zo and Rt. S1 marked by Qz, Cpx (Jd/Omp), Ph, Gln, Zo and Rt	m scale isoclinal folds. Coronitic growth of Qz, Omp, Ph, Gln, Czo and Rt	cm-thick shear zones. S3 marked by Ph, Brs, Czo and Ttn	ten m scale open parallel folds. Coronitic growth of Qz, Ab, Act, Chl, Ep and Wm	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	ten m scale gentle folds
	Porphyric gneiss	Ksp relics	isoclinal similar folds. S1 marked by Qz, Ksp, Ph, Gln, Zo and Rt	m scale isoclinal folds. Coronitic growth of Qz, Omp, Ph, Gln, Czo and Rt	cm-thick shear zones. S3 marked by Ph, Brs, Czo and Ttn	ten m scale open parallel folds. Coronitic growth of Qz, Ab, Act, Chl, Ep and Wm	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	ten m scale gentle folds

Zoisitite	Aln	S1 cm spaced foliation marked by Ph, Zo, Gln and Qz	m scale isoclinal similar folds, with associated S2 marked by rotation of Ph and Gln	cm-thick shear zones. S3 marked by Ph, Brs, Czo and Ttn	open to close folds with crenulation between hinge zones. Abundant formation of Ep, Act, Wm, Qz, Chl and Ttn	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	ten m scale gentle folds
Glaucophanite	/	S1 mm spaced foliation marked by Gln with granoblastic texture of Omp and Grt	/	cm-thick shear zones. S3 marked by Ph, Brs, Czo and Ttn	/	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	ten m scale gentle folds
HP quartz vein	/	S1 cm spaced foliation marked by Ph, Zo, Gln and Grt trails	m scale isoclinal similar folds, S2 marked by Ph, Gln and Czo SPO	large deformed Qz crystals	/	mm-thick shear zones with widespred growth of Chl, Wm, Ab, Act, Bt, Ep and Ttn	ten m scale gentle folds

- D4 folding, associated with a greenschist-facies partial re-equilibration, but not accompanied by a new mesoscopic foliation;
- D5 shear zones occurring under greenschist-facies conditions;
- D6 gentle folding, without a new foliation development and occurring under greenschist- to sub-greenschist-facies conditions.

The orientation of the structural elements is shown on the map plate. D1 is the main pervasive deformation, which, together with the development of contemporary eclogite-facies mineral assemblages, extensively obliterates all of the previous textures, structures and mineralogical associations.

Structural and mineralogical pre-Alpine relics: Selected portions of the metagranitoids and metasediments of Mt. Mucrone escaped the granular scale deformation during D1, maintaining the igneous contacts and internal structures between 'grey-type' metagranitoids and pre-Alpine lithological layering of the metasediments. Rare mineralogical relics escaped replacement by Alpine minerals, particularly in the metagranitoids, and retain igneous Bt and Aln crystals. Magmatic Kfs are preserved in the metagranitoids and in porphyric gneisses, and reddish Grt cores represent the pre-Alpine relics preserved in the micaschists and paragneisses.

D1: A geometrically coherent fold system with its related pervasive axial plane foliation, S1, overprints the lithologic boundaries and is attributed to the D1 deformation event. S1 is defined by Qz, Ph, Pg, Na-Cpx, Grt, Gln, Zo and Rt in the metasediments and metagranitoids. In addition, the same assemblage also occurs in the foliated eclogites, though in different component proportions. In the 'green-type' metagranitoid, the S1 is mainly marked by Wm, Amp, Omp and Qz lenticular domains (photo B in the 'syn-D1 microstructure' of the map plate).

During D1, only coronitic and/or pseudomorphic replacements occur in the poorly strained portions of the metagranitoids, paragneisses and eclogites:

- In the metagranitoids, the igneous Pl is replace by fine-grained aggregates of whitish Jd, Zo and Qz, and Bt is partially overgrown by fine-grained Ph and rimmed by Grt; fine-grained Ph replaces igneous Kfs (photo A in the 'syn-D1 microstructure' of the map plate);
- In the paragneisses and eclogites, randomly oriented Omp develops.

D2: Several shapes of the D2 folds (1–10 m in size) exist with wavelengths of 5–10 meters. An axial plane S2 foliation occurs only in the micaschists and is marked by Qz, Gln, Ph, Pg, Grt, Czo and Rt with SPO of the Wm, prismatic minerals, and lenticular or tabular Qz domains. In all lithologic types, Gln commonly displays the prismatic elongation parallel to the D2 fold axes. Locally, in the 'green-type' and leucocratic metagranitoids, S1 is partially reactivated and is oriented parallel to the D2 axial plane; it grades laterally into a continuous foliation associated with grain-size reduction (composite S1 + S2 fabric). In places where S2 is lacking, syn-D2 minerals are coronitic (Gln, Omp, Ph, Grt and Czo) growing over the previous mineral assemblages.

D3: These structures are a group of shear zones (1-cm to 1-m thick) marked by Qz, Ph, Pg, Grt, Mg-Chl, Czo and Ttn; they are generally located at a low angle to the pre-existing S1 and S2 that are therefore reactivated as slip planes giving rise to S1 + S3 and S2 + S3 composite fabrics, especially near the main lithologic boundaries. The S3 foliated zones display a 1-m to 10-m spacing, and in the metagranitoids and paragneisses, the deformation is localized in bands with a thickness of 1–2 cm, whereas in the other lithologic types the S3 is less localized and affects much larger volumes of the rock. Almost everywhere, the S3 foliation wraps around eclogite and metaquartzdiorite boudins with a size of 10 m. The syn-D3 minerals are coarse-grained where they are concentrated along discrete layerings, especially those consisting of Ph and Pg.

D4: These fold structures are not accompanied by a new foliation. Tight (30°) to open (120°) symmetric folds with 10 m wavelengths in the metagranitoids and paragneisses and 5 m in the micaschists and leucocratic metagranitoids. The syn-D4 fold systems and related granular scale fabric are associated with the growth of fine-grained Ab, Wm, Chl, Act, Ttn, Ksp (Adl), Ep and Bt, partially replacing the coarser-grained eclogite- and blueschist-facies mineral assemblages as coronitic aggregates. A penetrative crenulation develops locally in the micaschists, associated with the almost complete passive replacement of Cpx by Ab and Wm and Act aggregates.

D5: Mylonitic shear zone systems with a thickness of 0.5–1 cm formed during this deformation episode; the new grain-scale fabric is marked by Ab, Chl, Qz, Ep, Act and green Bt, with a 10-m spacing in the northern portion of the map and a narrower spacing in the southern portion, and increasing dynamic re-crystallization in the Qz grains of the micaschists. The shear zones are a few centimeters wide in all lithologic types, and the new mineral growth generated a grain-size reduction.

D6: The gentle folding of D6 imposes weak undulations of the previous structures. A centimeter-scale kinking of the mineral layering is associated with these folds. The major undulations display a 100-m wavelength responsible for the bimodal distribution of the previous fabric elements. The formation of a disjunctive cleavage is associated to the D6 axial planes with formation of Ab, Wm, Adl, dark Amp and Fe-oxides.

6. Conclusions

The petro-structural mapping and representation technique used in this work offers a powerful tool for modeling of the superposed grid of foliated textures and the deformation history in space together with the related succession of mineral assemblages shown in a time sequence. Both maps provide better insights into the sequence of metamorphic conditions under which different groups of structures were imprinted; they additionally provide a consistent visualization of the vertical displacements experienced during the tectonic evolution based on the pressure and thermal variations recorded by this portion of the Austroalpine basement during Alpine orogeny. Field data supported by microstructural results are therefore a coherent base from which to infer the tectonics steps of Alpine geodynamics.

In detail, the metamorphic and structural evolution indicates that: (1) the D1 and D2 stages are synchronous with mineral assemblages that widely testify to the persistence of HP metamorphic conditions under a low thermal regime and are compatible with active subduction, and (2) the metamorphic assemblages syn-kinematic with D3 to D6 suggest that these deformations took place during cooling and decompression, indicating tectonic exhumation to shallower structural levels. The latter occurred prior to 30 Ma, as indicated by the relationships with the Biella and Traversella intrusive body (e.g. Zanoni et al., 2010, with refs.). The structural and metamorphic outline is coherent with that inferred by Zucali, 2002a; Zucali et al., 2002b, in the northernmost sector, from Mombarone to Mt. Mars. The detailed multi-scale structural investigation demonstrates that the 'green- and grey-type' metagranitoids differ mainly in the degree of fabric evolution (highly deformed vs. poorly to undeformed, respectively) acquired during the eclogite-facies re-equilibration. This result supports the interpretation proposed for the metagranitoids of the eastern wall of Mt. Mucrone (Castelli et al., 1994).

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