New detailed maps of two key areas of the Southalpine basement unravel the superposition of pre-Alpine deformation stages associated with different metamorphic imprints, and distinguish Alpine thrust and fold structures involving basement and Permian-Mesozoic sedimentary cover. Basement rocks consist of metasediments (micaschists, quartzites and paragneisses) and metagranitoids and cover rocks comprise Permian volcanics and sediments. The boundaries between two tectono-metamorphic units have been distinguished at the map scale, thanks to the integrated use of structural and petrological analyses, on the basis of foliation trajectories supported by metamorphic assemblages. Two different pre-Alpine metamorphic evolutions characterise a basement portion that seemingly appears as a monotonous sequence dominantly affected by a greenschist-facies imprint. The volcano-sedimentary sequence of Permian age has been used as the time marker that separates Alpine from pre-Alpine superposed structures; Alpine deformation consists of two superposed groups of structures, the first of which is locally associated with a very low-grade metamorphic imprint and related at the regional scale to a south-verging thrust system.

Keywords: foliation trajectory maps; multi-scale structural analysis; Variscan basement; pre-Alpine – Alpine tectonics; Southern Alps; Italy

1. Introduction

The aim of field mapping of metamorphic basement of orogenic belts is the individuation of tectonic units that requires, in addition to the classical structural and lithostratigraphic tools useful to unravel, for example, basement–cover relationships, to decipher the deformation–metamorphism relationships at the regional scale. Such an investigation is useful to discriminate basement portions that underwent different structural and metamorphic histories and therefore representing separated tectono-metamorphic units (= TMUs; e.g. Spalla, Siletto, Di Paola, & Gosso, 2000; Zucali, Spalla, & Gosso, 2002). The evolution of analytical tools for correlation methods in orogenic belts (Hobbs, Means, & Williams, 1976; Lardeaux & Spalla, 1990; Passchier, Myers, & Kröner, 1990; Roda & Zucali 2008; Spalla, Zucali, Di Paola, & Gosso, 2005; Turner & Weiss, 2014).
Williams, 1985) highlights that the more effective approach to infer an accurate tectonic and metamorphic evolution in polydeformed terrains is the contemporaneous regional correlation of meso- and micro-structures and the associated metamorphic phase assemblages. Detailed structural mapping that validates the sequence of superposed structural and metamorphic imprints at the regional scale must support an accurate correlation. This integrated petrological and structural analysis generates high-precision Pressure–Temperature–relative time of deformation evolutions (P–T–d–t paths), that, in the central part of the Southalpine domain, highlighted adjacent portions of the pre-Alpine basement, recording structural and metamorphic imprints related to contrasted and diachronous tectonic histories (Spalla & Gosso, 1999; Spalla et al., 2014). These contrasted records have been inferred within single lithostratigraphic units, making necessary the distinction of tectonic units on the basis of their structural and metamorphic memory (TMUs). In spite of the accurate definition of the P–T–d–t histories, boundaries between TMUs are only locally precisely mapped and the two maps presented here regard a region where contrasted P–T–d–t evolution has been inferred. The integrated use of petrographic and multi-scale structural analysis can reveal the geometry of the tectonic boundary and shed light on the structural level of tectonic units coupling. The two maps presented in this contribution were made in key areas of the easternmost sector of the Orobic Alps, where different P–T–d–t evolutions have been inferred in rocks attributed to the same lithostratigraphic unit (Spalla & Gosso, 1999; Spalla, Carminati, Ceriani, Oliva, & Battaglia, 1999). Here, the occurrence of Permian cover rocks allows the separation of structures affecting exclusively the pre-Permian basement, and therefore developed during the pre-Alpine evolution, from structures affecting both the basement and the sedimentary cover, and therefore of Alpine age (Albini et al., 1994; Gosso et al., 2012; Spalla et al., 1999).

2. Geological setting

The two maps have been realised in the Eastern end of the Orobic Alps, representing the central portion of the Southalpine Domain (Figure 1) that is separated from the axial portion of the Alpine belt (Penninic and Austroalpine domain) by the Periadric Lineament. The Variscan metamorphic basement mainly constitutes its northern portion, whereas Upper Palaeozoic to Tertiary cover dominates the southern part.

The Southern Alps architecture results from crustal thickening, involving a shallow portion of the Variscan metamorphic basement and the Palaeozoic to Tertiary volcano-sedimentary sequences, developed during Alpine convergence (Brack, 1983; Cassinis et al., 1986; Castellarin, 1979; Castellarin et al., 1992; Doglioni & Bosellini, 1987; Gaetani & Jadoul, 1979; Laubscher, 1985; Schönborn, 1992) from Late Cretaceous to Tertiary and that generated a thick-skinned south-verging thrust system (Figure A in the Main Map). The main ENE-WSW tectonic boundaries are cut by the Tertiary Adamello intrusion, dated between 42 and 35 Ma (Callegari & Brack, 2002; Del Moro, Pardini, Quercioli, Villa, & Callegari, 1983; Mayer et al., 2003; Schaltegger et al., 2009; Schoene et al., 2012), and by the associated dyke swarms (Brack, 1981, 1983; Cassinis & Castellarin, 1988; D’Adda et al., 2011; Fantoni et al., 1999). Alpine structures have been recently interpreted as the effect of a convergent lithosphere dynamics inducing gravitational effects at the shallowest structural level (Carminati & Siletto, 1997; Carminati, Siletto, & Battaglia, 1997 and refs. therein).

The detailed structural analysis at the boundary between Permian cover and Variscan metamorphic basement in the central Orobic Alps allowed the distinction of Alpine and pre-Alpine structures and the individuation of N50 striking extensional faults, bounding Permian basins (Cadel, Cosi, Pennacchioni, & Spalla, 1996; Cassinis et al., 1986; Milano, Pennacchioni, & Spalla, 1988).
The Pre-Alpine structural evolution, consisting of at least two superposed deformation stages, is accompanied by polyphase metamorphic histories mainly recorded during a retrograde P–T evolution (Bertotti, Siletto, & Spalla, 1993; Diella, Spalla, & Tunesi, 1992; Gosso, Siletto, &
Structural and metamorphic evolutions inferred in different portions of Southalpine Orobic basement allow the individuation of five different types (Figure 1) of TMUs (Spalla et al., 2014 and refs. therein), but tectonic contacts are accurately traced only locally. Type I consists of metamorphic rocks displaying an evolution from amphibolite- to greenschist-facies conditions, indicating the exhumation of deep-seated continental crust from nearly 30 km depth; type II metamorphic rocks preserve part of a P–T prograde evolution pre-dating an amphibolite-facies, and successively a greenschist-facies imprint similar to those characterising type I; type III consists of metapelites transformed exclusively under greenschist-facies conditions, in which black phyllites containing Silurian-Ordovician microfossils have been described (Gansser & Pantik, 1988); type IV includes metamorphic rocks characterised by the transition from amphibolite- to Permian-Mesozoic amphibolite/granulite-facies conditions of low pressure, followed by an isobaric T-decrease up to greenschist-facies conditions; finally, type V consists of continental crust that escaped the Varrovian metamorphic imprint related to the Variscan collision and it is characterised by a sequence of two syn-metamorphic deformation phases developed under epidote–amphibolite and greenschist-facies conditions (Spalla et al., 2009 and refs. therein).

Such contrasted tectonic and metamorphic histories account for a complex pre-Alpine geodynamic evolution (Diella et al., 1992; Siletto, Spalla, Tunesi, Lardeaux, & Colombo, 1993; Zanoni et al., 2010) responsible for: (i) the tectonic thickening consequent to the Variscan subduction and collision; (ii) late orogenic extension; and (iii) lithospheric continental thinning postdating the Variscan gravitational evolution and heralding the Jurassic oceanisation (Marotta, Spalla & Gosso 2009).

3. Mapping technique and software

The maps represent the lithological associations and the regional grid of overprinting foliations, associated with the indications of the metamorphic environment in which they developed. The chosen representation allows the visualisation of different episodes of the thermomechanical evolution through the use of different symbols and colours. Following methods used in mineral prospections (Johnson & Duncan, 1992) and already used in metamorphic terrains in the Alps (Baletti, Zanoni, Spalla, & Gosso 2012; Delleani, Spalla, Castelli, & Gosso, 2013; Di Paola & Spalla, 2004; Spalla et al., 2000; Zucali et al., 2002), it is therefore possible to recognise tectonic contacts, even when they are partially obliterated, sutured and polydeformed, individuating also the structural level at which coupling between tectonic units took place, thanks to the information on the metamorphic environment of fabrics development.

In summary, such kind of mapping represents an integrated report of the field and laboratory analytical work carried out in order to reconstruct the relationships between finite deformation field, metamorphic evolution and different lithological settings. The relative chronology of overprinting planar fabrics is shown on the maps by the number of dots along trajectory traces for Variscan structures; D3 Alpine trajectories are represented by solid black lines. Mineral assemblages related to successive fabrics in each rock type are added in the legend, and represent the basic elements used to identify the metamorphic environment in which the successive fabric groups developed (indicated by differently coloured trajectories). In this way, information regarding the relative chronology of structural imprints and the metamorphic environment in which they developed is synthesised and spatially located.

The geographical location and a tectonic map (with a related legend) introduce the main maps at a 1:10,000 scale with a related legend. The projection coordinate system is UTM ED50. The map presents a synthesis of the whole data set on a redrawn original topographic base (the
Technical Regional Topography, provided by the Lombardia Regional Administration). The geological cross-sections are shown in two perpendicular sets of panels to give, together with a block-diagram, a 3D visualisation. Stereographic projections summarise the structural data represented on the maps. Structural data analysis was performed using the computer software stereonet (Cardozo & Allmendinger, 2013). Final map layout and geological cross-sections have been drawn using the commercial computer software Adobe Illustrator.

4. Structural and petrographic data

Multiscale structural analysis, performed since the end of 1980s in central Southern Alps, allowed the separation of Alpine tectonic history from the pre-Alpine, which affected exclusively the metamorphic basement rocks. In a recent synthesis of the field and laboratory data, Gosso et al. (2012) individuated three TMUs at the eastern end of the Orobi Alps, on the basis of their thermal and deformational histories (Figure A in the Main Map). The two maps presented in this contribution (Map A and Map B in the Main Map) have been carried out in a region where two TMUs crop out, namely Passo Cavalcafiche and Aprica TMU, corresponding to NEOB-A and NEOB-B/C described by Spalla et al. (2009), (Figure 1).

4.1. Lithotypes

Basement rocks belonging to the two tectonic units were grouped in the ‘Edolo Micaschists’ formal formation’ of the ancient literature (Salomon, 1901), which consists of metapelites, with lenses of quartzites and minor marbles. The only distinguishing lithological character of Passo Cavalcafiche TMU is the occurrence of widespread metagranitoids (Figures 2 and 3) and minor amphibolites (Figure 3(a)), lacking in the Aprica TMU (Figure 3(b) and 3(c)). Layers of grey-pink quartzites, with thin layers of white mica and chlorite and biotite and garnet relics, with at places gradational transition to the enclosing rocks, and fine-grained plagioclase-white mica and quartz paragneisses (Figure 3(d)) are interlayered in the generally chlorite-rich micaschists, containing diffused relics of biotite and only locally of garnet, which can occur concentrated in thin layers (Figure 2(a)–(c)). Metagranitoids (Figure 2(d)) are mainly chlorite and white mica-bearing flaser gneisses, locally with a discrete lineation marked by elongated aggregates of quartz and feldspars. Relics of red-brown biotite and of minor garnet are still saved by diffused chlorite growth (Figure 3(e) and 3(f)). Igneous textures and mafic inclusions are only locally preserved. Finally, minor white mica- and chlorite-bearing amphibolite with relics of garnet, rutile and titanite occurs in up to metric lenses and bands.

Permian cover rocks occur as small tectonic slices pinched in basement rocks, finely foliated and consisting of volcaniclastic deposits, conglomerates, sandstones and siltstones (Figure 2(d) and (2e)) probably belonging to Verrucano Lombardo and Collio Formations (Gosso et al., 2012). Sandstones and siltstones are very deformed and consist of a fine-grained sericitic matrix with a few quartz-feldspar and albite clasts. Some quartz clasts have gulf structures, indicating a volcaniclastic origin. Conglomerates have angular quartz and basement rocks clasts. Tourmalinites have been detected as levels in the sedimentary cover (Palone del Torsolazzo on map A) or as deformed lenses, crosscut by quartz veins, at the boundary between micaschists and metagranitoids (Val Moranda, Monte Palone on map A, Figure 3(g)). Different types of early and late dykes occur: the first type is coarse-grained, characterised by plagioclase, biotite, pyroxene, amphibole and opaques. Mafic minerals are partially to completely substituted by chlorite, and minor carbonates are observed at places. These dykes are sometimes affected by D3 foliation. The second group of fine-grained porphyric dykes contains plagioclase and amphibole, crosscuts
the Alpine structures and may show chilled margins and flow textures, normally with metric thickness, and intrudes both the basement and cover rocks.

5. Structures
In the following, the results of multiscale structural analysis are separately described for each inferred deformation stage: they were obtained by a synthesis of fieldwork results and microstructural analyses performed on samples representing the same relative age groups of structures in different rock types. Deformation–metamorphism relationships for the pre-Alpine syn-metamorphic structures in metapelites are reported in Table 1; orientations of all described successive groups of structures are shown in two synoptic tables on Schmidt projections, lower hemisphere, associated with the two maps (A and B) in the Main Map.
5.1. D1 and pre-D2

In the Passo Cavalcacifche TMU, D1 structures are mainly small, rootless, isoclinal folds preserved in the less deformed domains of S2, especially where micaschists have abundant quartz layers (Figure 2(b) and 2(c)). Polyphase relict foliations in S2 microlithons with chloritoid-bearing or staurolite-bearing assemblages have been described in adjacent areas (Spalla et al., 1999), as
synchronous with D1a and D1b, respectively. Staurolite relics detected in this area only at Piz Tri (North of Lago Lungo in map A) occur as isolated porphyroclasts, due to a more pervasive greenschist facies re-equilibration related to D2, making difficult the attribution to a specific ancient fabric, and therefore they are interpreted simply as pre-D2 remnants. S1 is defined by the shape preferred orientation (SPO) of biotite and white mica and garnet is mainly preserved in the microlithons. Garnet and biotite may occur in contact with rational boundaries, suggesting textural equilibrium during D1 (Figure 3(e)). Well-preserved garnets have an internal foliation marked by opaque and quartz trails (Figure 3(h)). Rutile, opaque minerals, plagioclase, apatite and rare epidote and tourmaline occur in quartz-feldspar-rich domains of S1 together with garnet, biotite and white mica. Where lithological markers such as metagranitoid layers are found, D1 folds are well preserved and recognisable at the meso- and mega-scales, with hinges that reach hundreds of metres in metagranitoids (E of M. Faeto, map B and block diagram). In

Table 1. Sequence of assemblages in the two tectonometamorphic units (rows) supporting the superposed fabrics (columns).

| Tectono-metamorphic units | D1 in metapelite | D2 in metapelite |
|---------------------------|-----------------|-----------------|
| Passo cavalcafriche (PT estimates after Spalla et al., 1999; Gosso et al., 2012) | \( \text{syn-D1a} = \text{Cld, Blt, Ms1, Grt, Pl, Qtz} \) \((T = 480–540°C \text{ P} = 0.75–0.95 \text{ GPa})\) | \( \text{syn-D2} = \text{Ms1, Chi, Ab, Qtz, ±Ep} \) \((T < 400–550°C \text{ P} < 0.3–0.4 \text{ GPa})\) |
| Aprica (PT estimates after Spalla et al., 1999; Zanoni et al., 2010; Gosso et al., 2012) | \( \text{syn-D1b} = \text{St, Blt, Ms1, Grt, Pl, Qtz} \) \((T = 570–660°C \text{ P} = 0.85–1.15 \text{ GPa})\) | \( \text{syn-D2} = \text{Qtz, Ms, Chill, Bt, ±Grt} \) \((T < 300–350°C \text{ P} < 0.3 \text{ GPa})\) |

Notes: PT estimates from cited references. Mineral abbreviations Cld = Chloritoid, St = Staurolite, Bt = Biotite, Ms = Muscovite, Grt = Garnet, Pl = Plagioclase, Qtz = Quartz, Chl = Chlorite, Ab = Albite, Ep = Epidote. Roman numbers indicate timing of mineral growth.

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metagranitoids, the S1 is marked by biotite and white mica SPO, garnet porphyroblasts predate S2 and relict K-feldspar porphyroclasts are wrapped by S1 (Figure 3(i)).

In quartzites of the Aprica TMU D1 folds are well preserved as hundred metre scale structures (Figures 3(b) and 4(b) in the Main Map) and generally, in micaschists or phyllites, D1 structures consist of small, rootles, isoclinal folds preserved in the less deformed domains of S2. The mineral assemblage associated with S1 is muscovite, plagioclase, quartz, opaque minerals, biotite, chlorite, ± garnet, suggesting greenschist-facies conditions (Figure 3(b) and 3(c)). In phyllites from this unit, relics of palynomorphs and marine microplankton of Ordovician-Silurian age have been detected (Gansser & Pantic, 1988).

5.2. **D2**

In both TMUs, D2 folds are isoclinal, with thickened hinges and attenuated limbs (Figure 2(b)). S2, which is mainly defined by SPO of chlorite and white mica, is the most pervasive fabric element at the regional scale and is steeply dipping to the NNW. It consists of a well-differentiated crenulation cleavage often evolved up to a continuous foliation (Figure 3(a, c, f, g)). Biotite, which is usually aligned along S1, has lobate margins and is overgrown by chlorite and new white mica along the (001) cleavage, where it has been rotated parallel to S2, or replaced by sagenitic chlorite (Figure 3(e)). Garnet is wrapped by S2 and variably replaced by chlorite (Figure 3(h) and 3(i)). Biotite and white mica porphyroclasts (Figure 3(d)) show internal deformation and are partly replaced by chlorite and a second generation of fine-grained white mica along (001). Sphene and albite porphyroclasts including garnet, quartz, white mica, tourmaline and opaque minerals are syn-kinematic with S2. In micaschists, S2 locally becomes mylonitic, and is then enriched in chlorite, graphite and carbonates, giving rise to a black phyllonite. These mylonitic horizons, similar to those described as old folded mylonites by Lardelli (1981), are associated with anastomosed mm to cm thick quartz and carbonate veins, widespread in the metapelites of Aprica TMU and abundant at the contact with the Passo Cavalcaciche TMU. In metagranitoids, S2 is marked by chlorite and white mica films, sometimes comprising new green-biotite, alternate to quartz-albite rich domains containing garnet relics that are partially to totally replaced by chlorite (Figure 3(i)). In D2 mylonites, a fine-grained aggregate of chlorite and white mica is interlayered with ribbon quartz, and only feldspars and garnet porphyroclasts are locally preserved. Mylonitic bands are concentrated at the boundaries with micaschists where the mylonitic bands together with D1 and D2 superposed rootless folds are responsible for the gradational transition between these two rocks (near Passo Salina and further to the south in map A). Overprinting of D2 on D1 folds (Figure 2(b)) gives rise to type 3 interference patterns (Ramsay, 1967).

5.3. **D3**

This group of structures are comprehensive of meso- to mega-scale kink bands in metagranitoids (South of Passo Salina) and chevron folds in micaschists and quartzite. The interlimb angle of the kinks is 40°–60° and the axial plane steeply dips towards NNW (with a maximum at 340°/70°–80°). In metapelites and metagranitoids, D3 microtextures are micro chevron folds or crenulations. Chlorite and opaque minerals are concentrated in D3 microfold hinges. Overprint of D3 on previous folds generates types 2 and 3 interference patterns. D3 folds affect Permian cover rocks, exposed in the southernmost sector of map A (Figure 2(d)), and correspond to the regional southverging Alpine fold and thrust system (Albini et al., 1994). In the sedimentary rocks, D3 folds are open to isoclinal, with steep axial planes. S3 is a differentiated foliation (Figure 2(e)), with a few mm- to some cm-spacing, and defined by SPO of opaque minerals, fine-grained carbonates and sheet silicates. Detrital quartz, feldspar and white mica show internal deformation and
lobate margins and are re-oriented parallel to S3; elongated pebbles in conglomerates are flattened and aligned parallel to S3, acidic volcanic pebbles being distinctively more flattened than quartz ones. The D3 thrusts are evidenced by up to 300 m wide and up to few km long synforms of sedimentary rocks, locally boudinaged along cataclastic zones (SW portion of Map A, south of Palone del Torsolazzo). Folds are associated with thrusts, and the cover-basement contacts may be either primary or tectonic, being folded and thrust together.

5.4. **D4**

The last group of structures consists of cataclastic bands and subhorizontal shear planes ranging from 330/30 to 040/30, characterised by top to SE shear sense, both in the basement and in the cover rocks (Figure 3(j)), and which crenulate the S3 foliation when present. The shear planes are especially evident in the cover rocks. Open folds or gentle waving of pre-existing structures also occurs, and a crenulation cleavage rarely develops in the sedimentary rocks (see also Gosso et al., 2012). Folds and shear planes both belong to the D4 structures and could represent a different deformation stage or a late incremental stage of D3.

6. **Summary and conclusive remarks**

The representation technique used to illustrate results of the integrated structural and petrographic analysis here performed makes very effective the immediate perception of the distribution in space of the deformation history record by means of the superposed grid of foliations and the associated succession of mineral assemblages.

The inferred structural and metamorphic evolutions indicate that four generations of superposed folds affected this portion of Southalpine domain at the easternmost end of the Orobie Alps. The earlier two (D1 and D2) are syn-metamorphic. They affect exclusively the basement rocks and are responsible for the geometry of the lithological boundaries in the Variscan metamorphic basement. The two late groups of structures (D3 and D4), deforming together the Permian cover and the Variscan basement, developed during Alpine convergence, and consist of a grid of thrusts separating the pre-Alpine structural framework into detached slices.

Style of deformation, coherence of fabric orientation and of metamorphic assemblages allow to correlate the greenschist D2 structures of the two mapped TMUs and to relate them, at the regional scale, with the greenschist D2 structures described in surrounding areas (Gosso et al., 2012 and refs. therein). D2 structures actually affect also the boundary between Passo Cavalcafiche and Aprica TMUs that during D1 recorded different metamorphic imprints. Relationships between metamorphic assemblages and pre-D2 structures indicate that in Passo Cavalcafiche TMU, D1 developed under amphibolite-facies conditions, following an earlier epidote amphibolite-facies imprint, and that a retrograde Pressure–Temperature (PT) evolution accompanied the transition to the syn-D2 greenschist-facies retrogression. On the contrary, no traces of amphibolite-facies imprints have been detected in the Aprica TMU, where both D1 and D2 structures developed under greenschist facies conditions. The few relics pre-dating the greenschist facies re-equilibrations are Silurian-Ordovician microfossils. The Aprica TMU therefore represents a more superficial Variscan tectonic unit, coupled with Passo Cavalcafiche TMU at shallow crustal level, during the exhumation of the latter, under greenschist facies conditions, as coherently represented in these detailed structural and metamorphic maps.

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