Query Details

Back to Main Page

1. Author names: Please confirm if the author names are presented accurately and in the correct sequence (Spalla Maria Iole). Also, kindly confirm the details in the metadata are correct.

As indicated in the metadata and on the first page, for all the authors the Family Name are reversed with the Given Name.

2. Roda et al. (2019) has been changed to Roda et al. (2019a, b) so that this citation matches the list.

The correct citation is Roda et al. (2019b)

3. Reference: Reference (Pognate et al (1980), Stuenitz (1989)) was mentioned in the manuscript; however, this was not included in the reference list. As a rule, all mentioned references should be present in the reference list. Please provide the reference details to be inserted in the reference list.

The references are:

Pognante, U., Compagnoni, R., Gosso, G. (1980): Micro- mesostructural relationships in the continental eclogitic rocks of the Sesia-Lanzo zone (Italian Western Alps): a record of subduction cycle. Rend. Soc. Ital. Mineral. Petrol., 36, 169-186.

Stünitz, H., 1989. Partitioning of metamorphism and deformation in the boundary region of the "Seconda Zona Diorito-Kinzigitica", Sesia Zone, Western Alps. Ph.D. Thesis ETH, Zuerich.

4. Please confirm the section headings are correctly identified.

Yes, they are correctly identified.

5. Author names: Please check and confirm the layout of table 2 and amend if necessary.

Yes, we confirm the layout of table 2.

3D reconstruction of fabric and metamorphic domains in a slice of continental crust involved in the Alpine subduction system: the example of Mt. Mucrone (Sesia–Lanzo Zone, Western Alps)

Michele Zucali, [1,2]

Luca Corti, [1]

Email: luca.corti@unimi.it

Francesco Delleani, [1]

Davide Zanoni, [1]

Maria Iole Spalla, [1]

[1] Dipartimento di Scienze della Terra "Ardito Desio", Università degli Studi di Milano, Via Mangiagalli 34, 20133 Milan, Italy

[2] Department of Earth and Atmospheric Sciences, University of Houston, Houston, TX, USA

Received: 9 May 2019 / Accepted: 14 December 2019

Abstract

Geological mapping, multiscale structural analysis, and estimations of the degree of fabric evolution and of reaction progress allow the construction of a 3D quantitative model of structural and metamorphic gradients in a portion of continental crust deeply involved in the Alpine subduction system and mainly structured under eclogite-facies conditions before the continental collision. The investigated and modelled rocks outcrop in the surroundings of Mt. Mucrone, in the central Sesia–Lanzo Zone. The Geomodeller® software allowed a quantitative 3D estimation of domains characterized by homogeneous fabric evolution and metamorphic reaction progress (DFE and DRP, respectively) for two of the seven structural and metamorphic imprints detected in this area: the D2-eclogitic and D5-greenschist stages, which are the most pervasive at km scale. Such a 3D modelling clarifies mutual relationships between fabric and metamorphic gradients and indicates that: (i) DFE and DRP are closely related regardless of the rock type; (ii) the syn-deformational thermal regime can influence the degree of metamorphic transformation, if DFE remains below the 60% threshold; (iii) the phase transitions can not be properly implemented in quantitative geodynamic modelling without considering the heterogeneity of reaction progress and fabric evolution.

AQ1

Keywords

Strain partitioning
Metamorphic reaction progress
Eclogitized granitoids
Austroalpine domain

Introduction

The relationship between deformation and metamorphism in basements has long been studied (Turner and Weiss 1963; Park 1969; Hobbs et al. 1976), and it is currently generally accepted that the single use of geometric criteria during structural correlation turns out to be poorly reliable in order to shed light on tectono-metamorphic evolution (Spalla et al. 2000), mainly due to deformation partitioning commonly affecting crystalline basements (e.g. Myers 1970; Mørk 1985). Similarly, reconstructions of metamorphic evolutions without structural constrains are unconvincing, because strain partitioning may influence the heterogeneous distribution of metamorphic assemblages and, moreover, it can cause gaps in the metamorphic memory of rocks (Spalla et al. 2005; Pearce and Wheeler 2010). These gaps are thought to be due to the catalysing effect of deformation on the metamorphic reaction progress (e.g. Spalla et al. 2000, 2005; Hobbs et al. 2010; Chapman et al. 2019) or to local instabilities due to diffusion processes (e.g. Pearce and Wheeler 2010) or stress-driven reaction heterogeneities (Schmalholz 2014; Tajčmanová et al. 2014; Zhong et al. 2017). Detailed multiscale correlation among superposed fabric elements and metamorphic assemblages is known to be of first-order importance to infer relationship between fabric and metamorphic gradients (e.g. Williams 1985; Stünitz 1989; Lardeaux and Spalla 1990; Passchier et al. 1990; Johnson and Vernon 1995; Spalla et al. 1999; Zucali et al. 2002; Spalla and Zucali 2004; Gosso et al. 2010; Salvi et al. 2010; Hobbs et al. 2011; Delleani et al. 2012; Gosso et al. 2015; Rebay et al. 2015; Cantù et al. 2016; Corti et al. 2017, 2018; Delleani et al. 2018).

Indeed, syn-metamorphic finite strain gradients from domains that completely escaped deformation (coronite) or that partially (tectonite) or pervasively (mylonite) record deformation are common in adjacent rock volumes (e.g. Bell and Rubenach 1983; Lardeaux and Spalla 1990; Bell and Hayward 1991; Spalla and Zucali 2004; Salvi et al. 2010). In coronitic domains, metamorphic reactions take place without the development of a new oriented fabric. In contrast, where the strain is accumulated, tectonitic and mylonitic fabrics develop and the new metamorphic assemblages define the new fabrics (Spalla et al. 2005; Salvi et al. 2010; Gosso et al. 2015). Heterogeneities accompanying fabric evolution also characterize metamorphic reaction progress facilitating the reconstruction of structural and metamorphic evolution back in time. The resulting distribution of the superposed fabrics elements and metamorphic assemblages allows the evaluation of the percentage of the mechanically and chemically reacting volume during the successive tectono-metamorphic re-equilibrations. The correlation between degree of fabric evolution (DFE) and degree of metamorphic reaction progress (DRP) of superposed tectono-metamorphic imprints can be used for quantifying the size of rock volumes affected by such structural and metamorphic heterogeneities in crustal portions implicated in convergent dynamics (e.g. Salvi et al. 2010; Gosso et al. 2015). Estimates of the DFE and DRP relationships in rock volumes reworked during successive structural and metamorphic re-equilibrations show that the dominant tectono-metamorphic imprint is related to the high degree of fabric evolution and metamorphic reaction progress (e.g. in the Alps, Southalpine domain: Spalla et al. 2000; Sesia–Lanzo Zone: Zucali et al. 2002; Delleani et al. 2012, 2013; Corti et al. 2017; Dent Blanche nappe: Roda and Zucali 2008; Baletti et al. 2012; Languard-Tonale unit: Salvi et al. 2010; Roda et al. 2018b).

The Sesia–Lanzo Zone, and in particular the Monte Mucrone area, has long been a training area for multiscale structural analysis and for studying in detail the correlation between deformation and metamorphism, thanks to the remarkable fabric and metamorphic partitioning from micro- to km scale (Hy 1984; Koons et al. 1987; Ridley 1989; Ildefonse et al. 1990; Zucali et al. 2002; Babist et al. 2006; Cenki-Tok et al. 2011; Delleani et al. 2013; Corti et al. 2019). This area offers the opportunity to investigate the relationships between DFE and DRP. 2D representations of the fabric gradients and the metamorphic transformation have already been performed (Zucali et al. 2002; Delleani et al. 2012). For these reasons, this area can be an ideal place to develop a 3D model that allows a quantitative evaluation of the interaction between the fabric evolution and the metamorphic reaction progress.

In this contribution, we integrate geological mapping, multiscale structural analysis, DFE and DRP estimations of Zucali et al. (2002) and Delleani et al. (2012, 2013) with new original field data to construct a 3D quantitative DFE and DRP models of the area between Mombarone, Mt. Mucrone, and Mt. Mars. HP-LT metamorphic rocks derived from pre-Alpine continental protoliths ~~are~~were poly-deformed when involved in the Alpine subduction–collision system, and pre-Alpine igneous and HT metamorphic relicts are preserved in heterogeneously deformed and eclogitized meta-granitoids and meta-pelites, respectively. Multiscale structural analysis revealed seven groups of superposed Alpine structures developed under eclogite-facies conditions (D1 to D3) during subduction and successively under blueschist (D4) to greenschist-facies conditions (D5 to D6) during the exhumation. D2 structures are dominant at the regional scale and are characterized by isoclinal folding associated with a pervasive foliation. We synthesize the multiscale data, defining syn-D2 (HP-LT) and syn-D5 (LP-LT) structural and metamorphic heterogeneities, on maps showing the degree of fabric evolution and metamorphic reaction progress. We apply the GeoModeller ® software that allows to build a 3D model, that allow discriminating the percentage and spatial distribution of volumes, in which it is possible to discriminate the volumes characterized by different degrees of fabric evolution and metamorphic reaction progress developed during D2 and D5 stages and their quantitative estimation in volume percentage together with their spatial distribution.

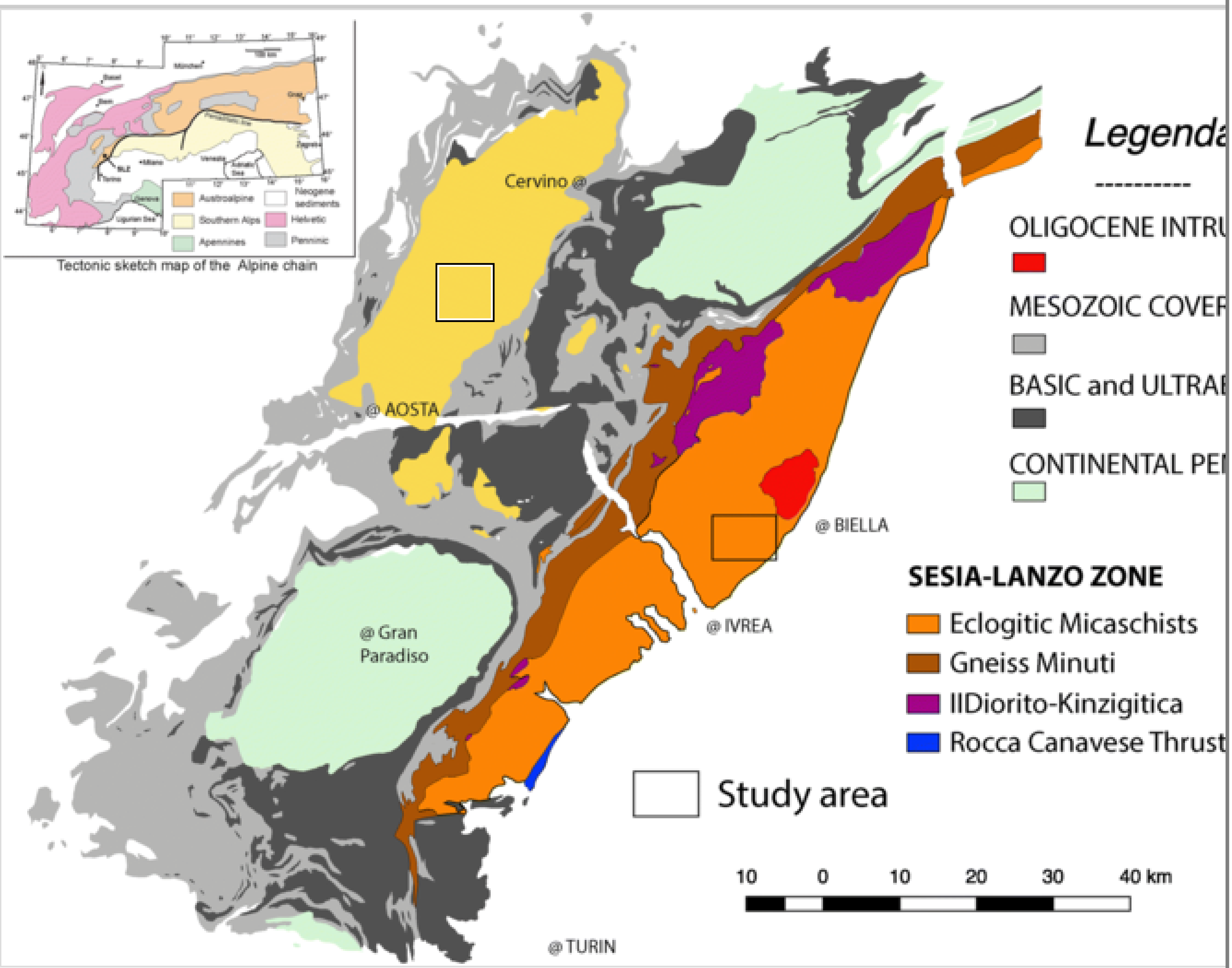
The 3D modelling allows a quantitative comparison between volumes preserving textural and mineral relicts during incomplete accomplishment of structural and/or metamorphic re-equilibrations, regardless of the possible influence of fluids. Moreover, the proposed 3D model quantifies structural and metamorphic evolutions in rock volumes that have re-equilibrated—texturally and/or mineralogically—several times through different structural levels, in which evolving thermomechanical regimes drive the change of dominant active deformation mechanisms.

Geological outline

The Sesia–Lanzo Zone (SLZ, Fig. 1) represents the widest portion of continental crust in the Western Alps that underwent high-pressure (HP) metamorphism during the Alpine subduction (e.g. Dal Piaz et al. 1972; Compagnoni et al. 1977; Pognante 1991; Babist et al. 2006; Meda et al. 2010; Roda et al. 2012; Regis et al. 2014). This tectonic slice was the first demonstration of the concept of continental subduction in the Alps (Dal Piaz 1971, 2001; Dal Piaz et al. 1972; Hunziker 1974; Dal Piaz and Gosso 1984; Hunziker et al. 1992). The Alpine metamorphic history of the SLZ comprises the record of a prograde blueschist-facies imprint, overprinted by eclogite-facies imprint, and followed by blueschist- and greenschist-facies re-equilibrations (e.g. Compagnoni and Maffeo 1973; Compagnoni 1977; Gosso 1977; Reinsch 1979; Pognate et al. 1980; Lardeaux 1981; Lardeaux et al. 1982a, 1983; Spalla et al. 1983; Pognante 1989a; Venturini et al. 1994; Castelli and Rubatto 2002; Zucali et al. 2004; Babist et al. 2006; Rebay and Messiga 2007; Zanoni 2010; Zucali and Spalla 2011; Giuntoli and Engi 2016; Giuntoli et al. 2018a; Roda et al. 2018a, 2019a, b). Mineral ages ranging between 90 and 65 have been related to the Alpine eclogite-facies peak (Oberhänsli et al. 1985; Duchêne et al. 1997; Rubatto et al. 1999; Cenki-Tok et al. 2011; Regis et al. 2014; Giuntoli et al. 2018b; Halama et al. 2018). The very low *T*/*P* ratio characterizing this evolution assists the preservation of the prograde Alpine structures and metamorphism as well as pre-Alpine igneous and metamorphic relics in rocks with an Alpine polyphasic recrystallization. *P*–*T* conditions for the early Alpine HP imprints range between 500 and 625 °C and 1.3 and 2.5 GPa (see Roda et al. 2012 for a review of available PT estimates). The external margin of the SLZ is bounded by eclogitized ophiolitic relics of the Liguria–Piedmont Ocean, the ~~Piedmont~~Piemonte Zone. The SLZ internal margin is a thick mylonitic belt (the Canavese Line), separating it from the lower crustal rocks of the Southalpine Ivrea Zone, which escaped the Alpine HP evolution (e.g. Bigi et al. 1990; Spalla et al. 2010; Rebay et al. 2018; Balestro et al. 2019).

Fig. 1

Tectonic map of the Western Alps with the different metamorphic complexes of the Sesia–Lanzo Zone. Black rectangle locates the studied area



AQ2

A pre-Alpine polyphasic metamorphic evolution, from granulite- to amphibolite- and greenschist-facies conditions, is still preserved in marbles, meta-pelites, meta-granitoids, and meta-basics (Compagnoni et al. 1977; Lardeaux et al. 1982b; Castelli 1991; Lardeaux and Spalla 1991; Rebay and Spalla 2001; Roda et al. 2019a): the pre-Alpine T-climax has been constrained at $T = 730$–830 °C and P = 0.7–0.9 GPa (Lardeaux and Spalla 1991). Granulite- and amphibolite-facies imprints have been interpreted as the result of an extension-related uplift of a portion of the Variscan crust, occurred in Permian–Triassic times during the lithospheric thinning leading to the Tethys opening (e.g. Lardeaux and Spalla 1991; Marotta et al. 2009; Roda et al. 2019a). This pre-Alpine tectono-metamorphic evolution is preserved in the metamorphic complexes forming the SLZ: the Eclogitic Micaschist Complex (EMC), the Gneiss Minuti Complex (GMC), the II Dioritic–Kinzigitic Zone (IIDK), and the Rocca Canavese Thrust Sheets (RCT) (e.g. Compagnoni et al. 1977; Pognante 1989a, 1989b; Spalla et al. 1991; Cantù et al. 2016; Roda et al. 2018a, 2019b). The IIDK, lying between EMC and GMC, consists of kilometric lenses in which Alpine eclogitic assemblages are not described, even if in the Vogna Valley the tectonic contact underlying the margin between IIDK and EMC is marked by eclogite-facies mylonites (Lardeaux 1981; Lardeaux et al. 1982b). On the other hand, eclogitic parageneses are widely described both in EMC and GMC, even though the GMC, which lies along the tectonic boundary with the ~~Piedmont~~Piemonte Zone, is widely re-equilibrated under greenschist-facies conditions, whereas the EMC, constituting the internal part of the SLZ, records the greenschist-facies re-equilibration mainly along discrete shear zones and shows a dominant metamorphic imprint under eclogite-facies conditions (e.g. Spalla et al. 1983; Stuenitz 1989; Spalla et al. 1991; Giuntoli and Engi 2016; Cantù et al. 2016).

The EMC protoliths are high-grade paragneisses, granulites, amphibolites, and minor marbles and quartzites, which are the country rocks of Permian granitoids and gabbros (Compagnoni and Maffeo 1973; Callegari et al. 1976; Compagnoni et al. 1977; Lardeaux 1981; Oberhaensli et al. 1985; Castelli 1987; Bussy et al. 1998; Cenki-Tok et al. 2011; Zucali 2011) and from which the Mt. Mucrone body is the most renown. In this area, the deformation history of EMC comprises four generations of Alpine folds, two of which are associated with the high-pressure (HP) mineral assemblages and ~~two generations~~ the other two consist of shear zones synchronous with blue- and greenschist-facies re-equilibrations, respectively (Hy 1984; Zucali et al. 2002; Delleani et al. 2012, 2013). According to Zucali (2002), D1 and D2 groups of folds are generally associated with axial plane foliations marked by Ph, ± Pg, Na-Cpx, Grt, Rt, and Zo (mineral abbreviations according to Whitney and Evans 2010); the same mineral assemblage is stable during D3 folding. Consequently, D1, D2, and D3 represent three recognizable increments during progressive deformation developed under eclogite-facies conditions. D4 is accompanied by a widespread re-equilibration under blueschist-facies conditions confined along metre-wide mylonitic shear zones, which locally developed at the boundary between meta-granitoids and country rocks. D5 mega-scale folds and D6 centimetre-thick mylonitic shear zones and gentle folding, overprinting blueschist mylonites and the eclogitic foliations, are synchronous with the formation of the greenschist-facies paragenesis Qtz, Ab, Wm, Ep, Ttn, and green-Amp.

AQ3

Lithostratigraphy and mesostructures

The interpretative map reported in Fig. 2 shows the distribution of the main lithotypes and structures in the area from the Mt. Mucrone, to the east, and Mombarone–Mt. Mars ridge, to the west. Here, the main lithologic types are: (1) meta-intrusives, comprising meta-granites, meta-quartzdiorites, and meta-diorites; (2) meta-aplites; (3) eclogites and glaucophanites; (4) micaschists; (5) gneisses; (6) marbles and quartzites; (7) zoisites; and (8) andesitic dykes. The interpretative map in Fig. 2 and the 3D modelling have been built grouping lithotypes with structural and lithostratigraphic affinities to increase readability and modelling. Five groups have been defined: (1) micaschists; (2) gneisses; 3) metabasites; (4) meta-intrusives; and (5) marbles and “quartzites” (Figs. 2 and 3; Table 1). Mineral assemblages marking coronitic, tectonitic, and mylonitic fabrics, which are developed during successive deformation stages (D1 to D6) in the different lithologic groups, are summarized in Table 1. Below, a brief description of each group is given; more details can be found in Zucali (2002), Zucali et al. (2002), and Delleani et al. (2012, 2013).

Fig. 2

Petrostructural map with foliation and axial plane trajectories (S: foliation; AP: fold axial plane), synthesized by Zucali (2002), Zucali et al. (2002), Delleani et al. (2012), and Delleani et al. (2013) integrated with original field data

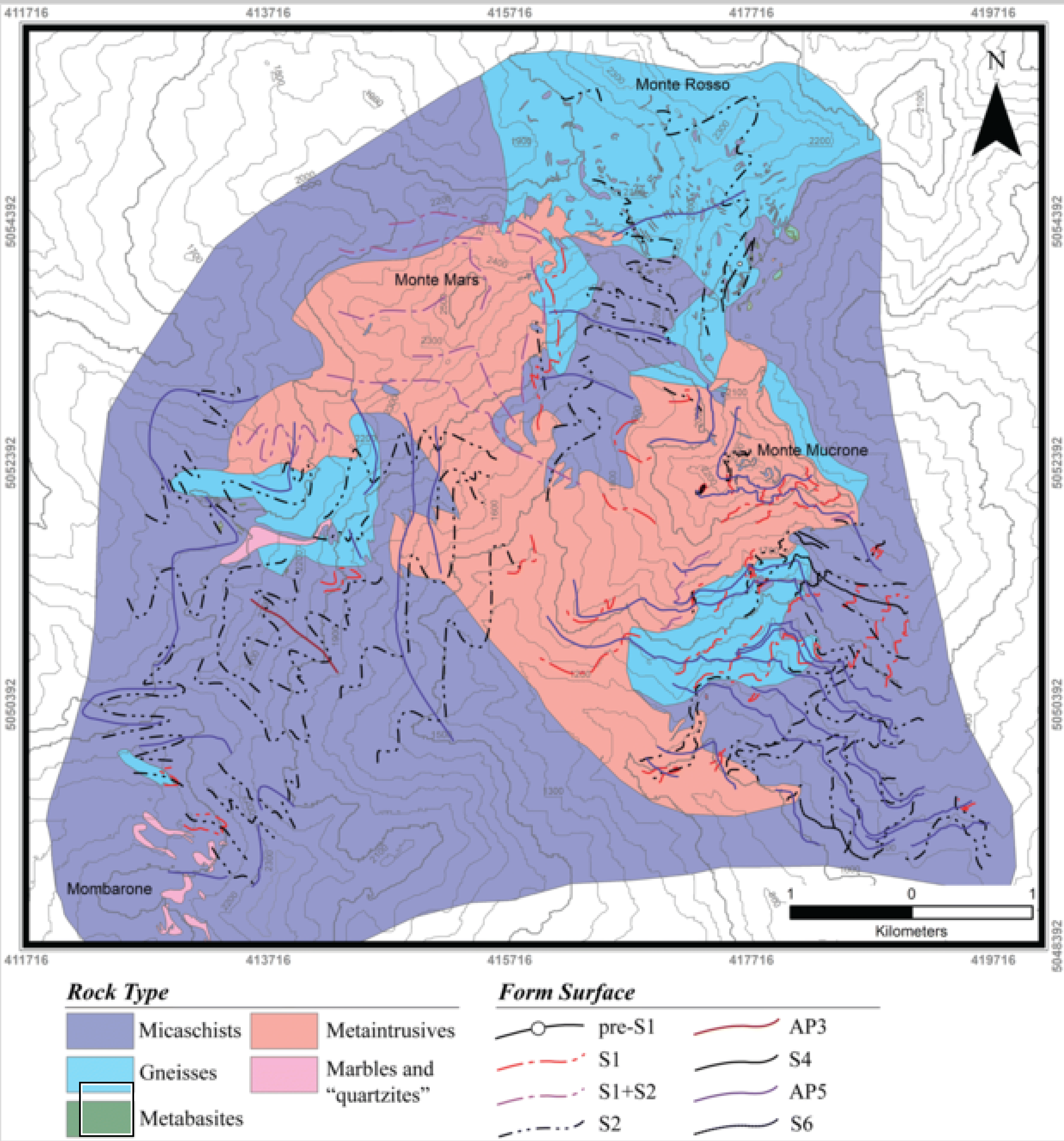
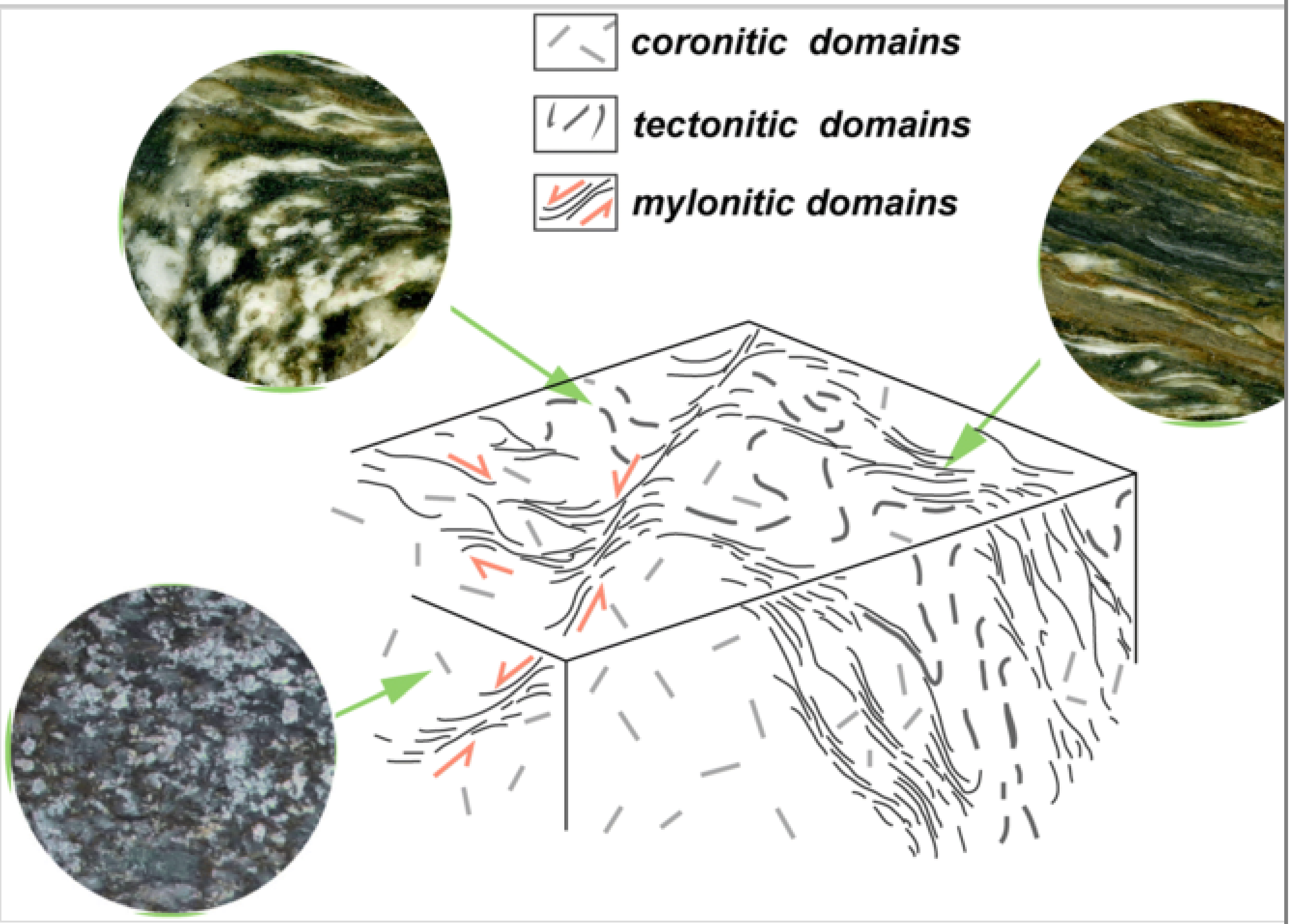


Fig. 3

Idealized block diagram showing the heterogenous fabric evolution due to the multiscale strain partitioning (modified after Lardeaux and Spalla 1990; Baletti et al. 2012). In the loops, coronitic, tectonic, and mylonitic fabrics of the eclogitized meta-granitoid surfacing at the base of NE slope of Mt. Mucrone


coronitic domains
tectonitic domains
mylonitic domains

Synoptic view of the main evolutionary stages in the three main lythological groups

C=coronite; T=tectonite; M=mylonite

Stage	Micaschists+Gneisses+Quartzites	Metabasites	Metaintrusives	P-T estimates	DRP (%)
pre-D1	S-pre1 in gneisses Bt+Sill+Grt+Pl+Wm	no planar fabric preserved Ti-rich Amp	igneous texture Ti-rich Amp Bt+Kfs	Granulite facies condition 0.3 ± 0.05 GPa 720 ± 48 °C	100
D1	M Qz+Wm+Omp+Grt+Amp+Ky+Rt	T-M Wm+Amp+Grt+Rt+Omp	S1 M Omp+Wm+Amp Grt+Qz+Zo	Eclogite facies condition 1.95 ± 0.24 GPa 490 ± 40 °C	90-100
D2	S2 T-M Qz+Wm+Grt+Omp+Amp+Rt	S2 T-M Wm+Omp+Amp+Grt+Czo+Zo+Rt	S1+S2 or S2 C-T-M Qz+Omp+Grt+Amp+Wm+Rt+Czo	Eclogite facies condition 2.31 ± 0.16 GPa 520 ± 45 °C	
D3	T AP3-S3 Omp+Wm+Amp+Qz	C not found	AP3-S3 C Omp+Wm+Amp+Qz	Eclogite facies condition 2.02 ± 0.48 GPa 550 ± 50 °C	
D4	S4 C localized shear zones Wm+Qz+Czo+Gln+Grt+Ttn	C Wm+Amp+Czo+Grt+Ttn+Qz	S4 T diffuse foliation reactivation Wm+Amp+Grt+Ttn+Qz+Czo	Blueschist facies condition 1.33 ± 0.20 GPa 480 ± 60°C	<5
D5	AP5-S5 C-T Wm+Chl+Ab+Act Qz+Czo+Ttn	AP5 C Wm+Act+Ab+Czo+Chl+Ttn	AP5 C Wm+Act+Ab+Ttn+Czo+Qtz+Chl	Greenschist facies condition 0.64 ± 0.16 GPa 400 ± 50°C	15-20
D6	S6 C localized shear zones Qz+Ab+Chl+Wm+Ep	not found	C Qz+Ab+Chl+Wm+Ep	Greenschist facies condition 0.30 ± 0.15 GPa 300 ± 50°C	

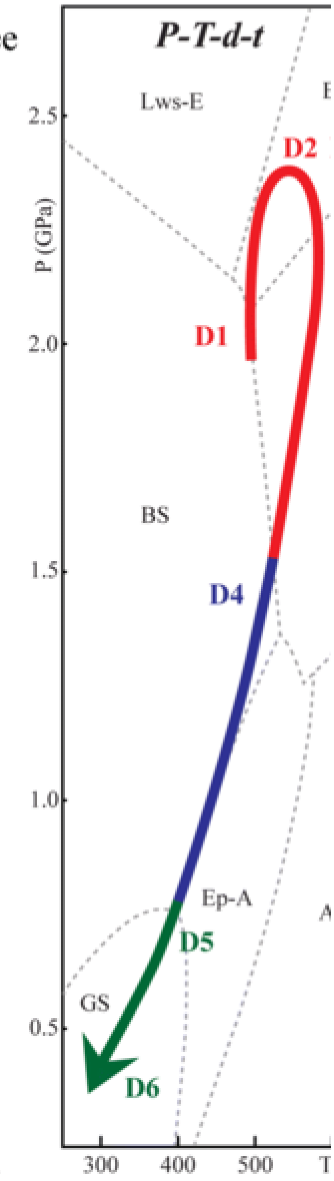


Table 1

Summary of the structures developed in each rock type during pre-Alpine and Alpine polyphase tectonic evolution

The degree of fabric evolution (C: coronite; T: tectonite; M: mylonite) and degree of metamorphic reaction progress (DRP: percentage of syn-metamorphic minerals) have been quantified for each deformation stage. The pressure–temperature estimated for successive structural and metamorphic stages and the inferred P–T-d-t path are also reported (modified after Zucali et al. 2002; Delleani et al. 2012)

AQ4

Meta-intrusives

Protoliths consist of granitoids that occur as 10-m to -km-sized bodies, including minor metre- to 30-m-sized granodioritic lenses. The meta-granitic complex ("grey-type" meta-granitoids and "green-type" meta-granitoids according to Delleani et al. 2012, 2013) forms the upper part of Mt. Mucrone and Mt. Mars and derives from Permian intrusive rocks (Oberhänsli et al. 1985; Bussy et al. 1998; Cenki-Tok et al. 2011), locally in primary contact with meta-sedimentary country rocks (Compagnoni and Maffeo 1973; Hurford and Hunziker 1985; Delleani et al. 2013) that preserve the pre-Alpine HT-LP metamorphic imprint (Zucali et al. 2002).

Meta-granitoids comprise medium- to coarse-grained lithotypes, showing a well-preserved isotropic and hypidiomorphic igneous texture, with igneous relics as biotite, allanite, and K-feldspar, which are only partially replaced by Alpine jadeite, garnet, zoisite, and phengite; meta-quartzdiorites consist of fine- to medium-grained rocks, showing a dominant foliation marked by omphacite, garnet, white mica, glaucophane, and clinozoisite. In the meta-intrusives, the partitioning of Alpine deformation is responsible for the preservation of igneous texture in low-strain volumes that are wrapped by finely foliated domains (mylonitic textures) defined by dominant Alpine eclogite-facies assemblages. Blueschist- and greenschist-facies assemblages are poorly developed, being associated with localized deformation bands, shear zones, or large-scale recumbent folds.

Zoisites layers may occur as 1- to 10-m-sized enclaves in meta-granitoids at Mt. Mars and Mt. Mucrone; these rocks are characterized by garnet grains up to 10 cm in size associated with epidotes.

Metre- to 10-m-thick meta-aplite dikes show a well-developed foliation, marked by the shape preferred orientation (SPO) of phengitic mica, quartz, feldspar, and omphacite. The foliation and the lithological boundaries commonly are parallelized with the D2 eclogitic foliation within micaschists, gneisses, and large meta-intrusives bodies.

Micaschists

Coarse- to fine-grained micaschists show S2 pervasive foliation with millimetre-scale spacing, marked by Qz + Omp + Gln + Grt and Wm-rich layers. They can be characterized by mm- to cm-sized rootless folds, generally marked by Qz-rich veins or layers. Omp and/or Gln SPO is common and generally lying parallel to the most penetrative D2 eclogitic foliation.

Gneisses

Gneisses are structured as Qtz- and Grt-bearing layers alternating with more mafic layers, primarily consisting of Omp, Grt, and Gln with minor Qtz and

Wm; this layering marks the gneissic penetrative D2 eclogitic foliation. Metre-thick layers of porphyric gneiss and coarse-grained Kfs crystals occur. In agreement with the observations of adjacent areas (Compagnoni et al. 1977; Zucali 2002), these rocks are interpreted as derived from pre-Alpine partially melted paragneisses, named kinzigites (high-grade Bt + Grt + Kfs + Sil-bearing gneisses) in the Alpine literature. Micaschists and gneisses may generally bear metre-sized lenses or boudins of mafic rocks, such as eclogites and glaucophanites, or, alternatively, marbles, quartzites, or meta-aplitic layers.

Metabasites (eclogites and glaucophanites)

Eclogites mainly consist of omphacite and garnet with minor glaucophane, white mica, and carbonates. They locally display a foliation, commonly marked by the SPO of omphacite. Eclogite boudins within micaschists or gneisses may have a reaction rim rich in glaucophane and white mica. Glaucophanites may have a spaced foliation marked by glaucophane, whereas omphacite is normally randomly oriented.

Marbles and “quartzites”

Metre- to 10-m-thick marbles and quartzites occur in layers or boudins in micaschists and gneisses. Pure and silicate-rich marbles (Pognante et al. 1980; Castelli 1991; Zucali 2002) are characterized by penetrative foliation generally marked by compositional layering in marbles and by mineral white mica SPO in impure marbles. “Quartzites” ~~correspond to~~consist of quartz-rich micaschists and occur as few-metre-sized boudins characterized by the D2 dominant foliation, generally marked by white mica, chloritoid, garnet, and kyanite (Pognante et al. 1980; Zucali 2002; Gatta et al. 2009; Regis et al. 2014) indicating eclogite-facies conditions (Zucali et al. 2002).

Structural and metamorphic evolution

Seven groups of structures were recognized (Table 1), from pre-Alpine to Alpine in age, named as follows: D1 to D3 took place under eclogite-facies, D4 under blueschist-facies, and D5–D6 under greenschist-facies conditions, respectively (Zucali et al. 2002; Delleani et al. 2012, 2013). A pre-D1 foliation has also been recognized in paragneisses and is marked by relicts of the pre-Alpine high-temperature fabric (Zucali 2001).

D1 and D2 are the most pervasive fabrics developed under eclogite-facies conditions, as testified by SPO of white mica, omphacite, and garnet ± glaucophane: S1 and S2 foliations developed in all lithotypes (Table 1; Fig. 2). In meta-intrusives, S1 can be distinguished from S2 only in the Mt. Mucrone area, while in Mt. Mars a S1 + 2 composite fabric occurs (Fig. 2). D3 isoclinal folding is locally associated with an S3 axial plane foliation, marked by omphacite SPO only in micaschists and gneisses (Table 1; Fig. 2). In D4, m-thick shear zones SPO of glaucophane, white mica, and clinozoisite mark the new planar fabric S4 (Table 1). D5 and D6 are tight to open fold systems, associated with white mica, chlorite, albite, and actinolite growth (Table 1). D6 consists of centimetre- to 10-cm-thick shear zones in which chlorite marks the localized S6 foliation (Table 1).

3D reconstruction method

3D geological modelling in metamorphic basements has proved to be an excellent tool for quantitative estimates of rock volumes that recorded different fabric evolution and metamorphic transformation during a polyphase structural and metamorphic history (Salvi et al. 2010). To verify the effectiveness of this approach also in rocks forged in a subduction complex, we perform a quantitative 3D representation of domains characterized by homogeneous degree of fabric evolution (DFE) and degree of metamorphic reaction progress (DRP) for D2 eclogite-facies and D5 greenschist-facies stages, associated with the most pervasive tectono-metamorphic imprints at km scale in the area.

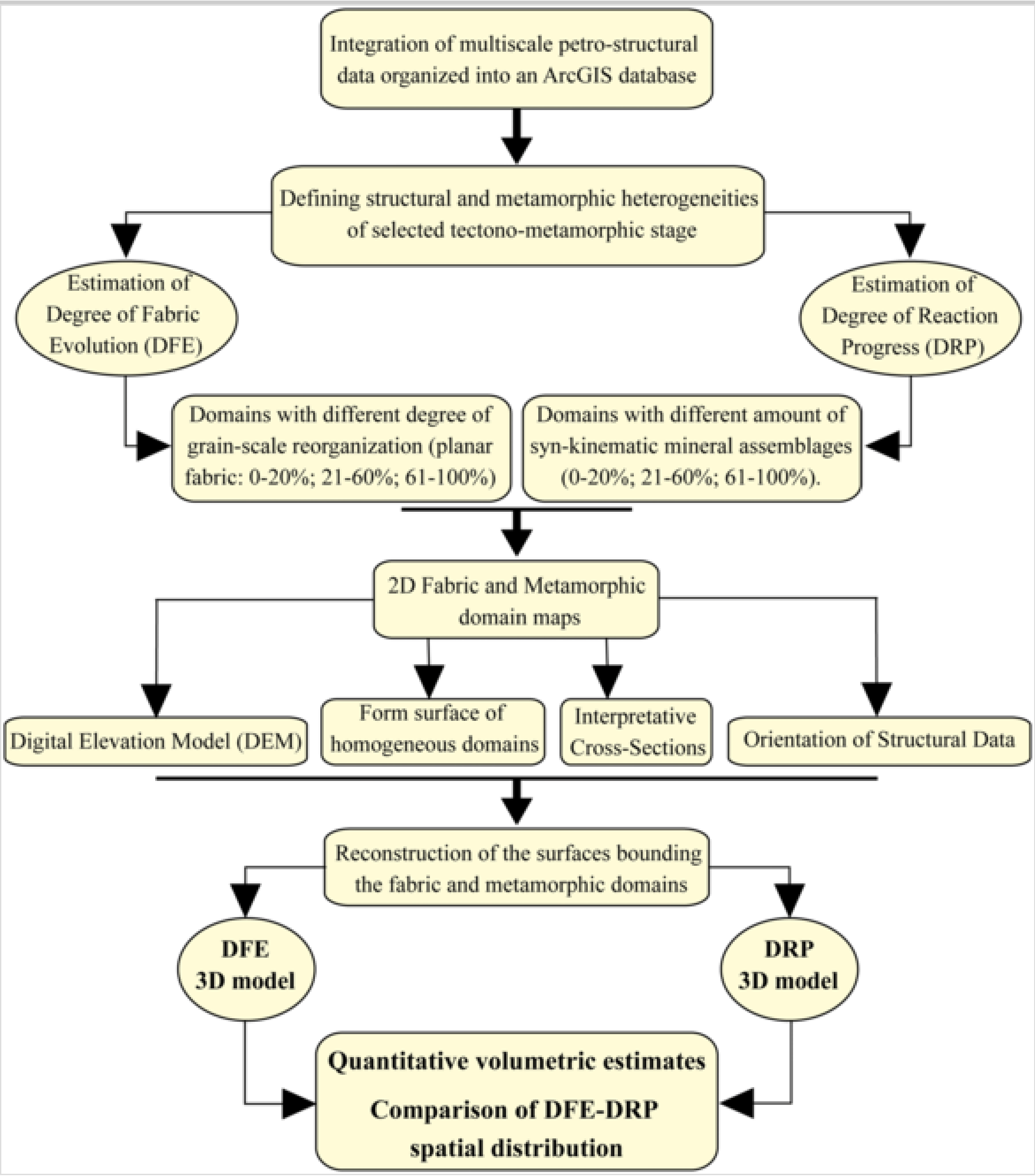
The contouring of domains that show homogeneous fabric development and metamorphic transformation is facilitated by integrating meso- with micro-scale structural analysis to estimate the DFE and DRP in volume percentage (Salvi et al. 2010; Delleani et al. 2012; Gosso et al. 2015; Corti et al. 2017). During incremental deformation related to a specific tectono-metamorphic stage, rock volumes may escape deformation in coronitic domains or may be partially or pervasively deformed in tectonitic and mylonitic domains (Fig. 3), respectively. In the coronitic domains, metamorphic reactions take place without the formation of a new oriented fabric. Where the strain is accumulated, tectonitic and mylonitic fabric develop planar/linear tectonites or mylonites, marked by metamorphic assemblages peculiar of PT conditions under which the strain is accumulated (Bell and Rubenach 1983; Lardeaux and Spalla 1990; Passchier and Trouw 2005). Microstructural analysis was performed on 175 thin sections, strategically distributed throughout the area (≈ 52 km^2). The DFE is estimated on the basis of the amount of newly formed fabric compared to relic fabrics, following the method of Salvi et al. (2010). The DFE is made explicit into three groups: coronite (C) 0–20%; tectonite (T) 21–60%; and mylonite (*M*) > 60% (Fig. 3; Table 1). The DPR reflects the modal proportion of mineral phases produced by new mineral growth and recrystallization related to a specific deformation phase, as inferred using the modal analysis at optical microscope.

Three classes of DRP domains have been individuated: low (*L*) 0–20%; medium (*M*) 21–60%; and high (*H*) > 60%.

The flowchart shown in Fig. 4 summarizes the main method steps combining both field-based structural and petrographic analyses with software-based modelling.

Fig. 4

Flowchart for the 3D model set-up



2D interpolation

The whole multiscale dataset was georeferenced and stored in a GIS (Geographic Information System) database. The GIS environment allows rapid data management, representation, querying, and manipulation to predispose the multiscale structural and metamorphic dataset to 3D modelling by interfacing GIS to the GeoModeller® software.

The topography shape file was acquired on the Geoportal of Piemonte Region administration (http://www.geoportale.piemonte.it/cms/) and the digital elevation model DEM20 on SINAnet (ISPRAmbiente website). The multiscale DFE and DRP punctual data combined with the foliation trajectory map are the starting point to constrain the area and the shape of the D2- and D5-related homogenous fabric evolution and metamorphic transformation domains. The results are synthetized in DFE and DRP thematic maps representing strain and metamorphic gradients in categorized domains as outlined in Figs. 5 and 6. The maps of fabric evolution and metamorphic transformation domains linked to digital elevation model, together with eight interpretative cross sections, foliation trajectory map, and orientation data of the structural elements are used to constrain volumes during the 3D modelling with Geomodeller®.

Fig. 5

Domains of homogeneous degrees of fabric evolution and metamorphic reaction progress reconstructed for D2 stage (inferred from Zucali 2002; Zucali et al. 2002; Delleani et al. 2012; Delleani et al. 2013 integrated with original field data)

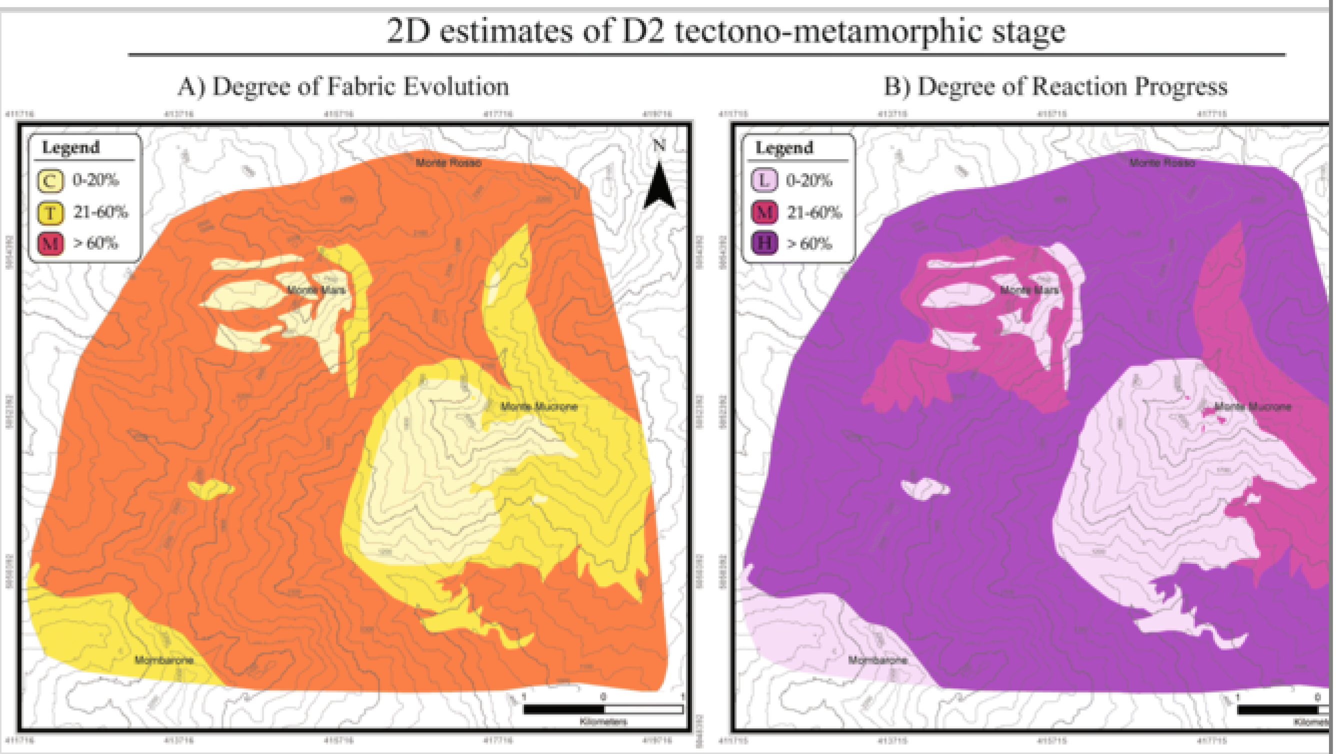
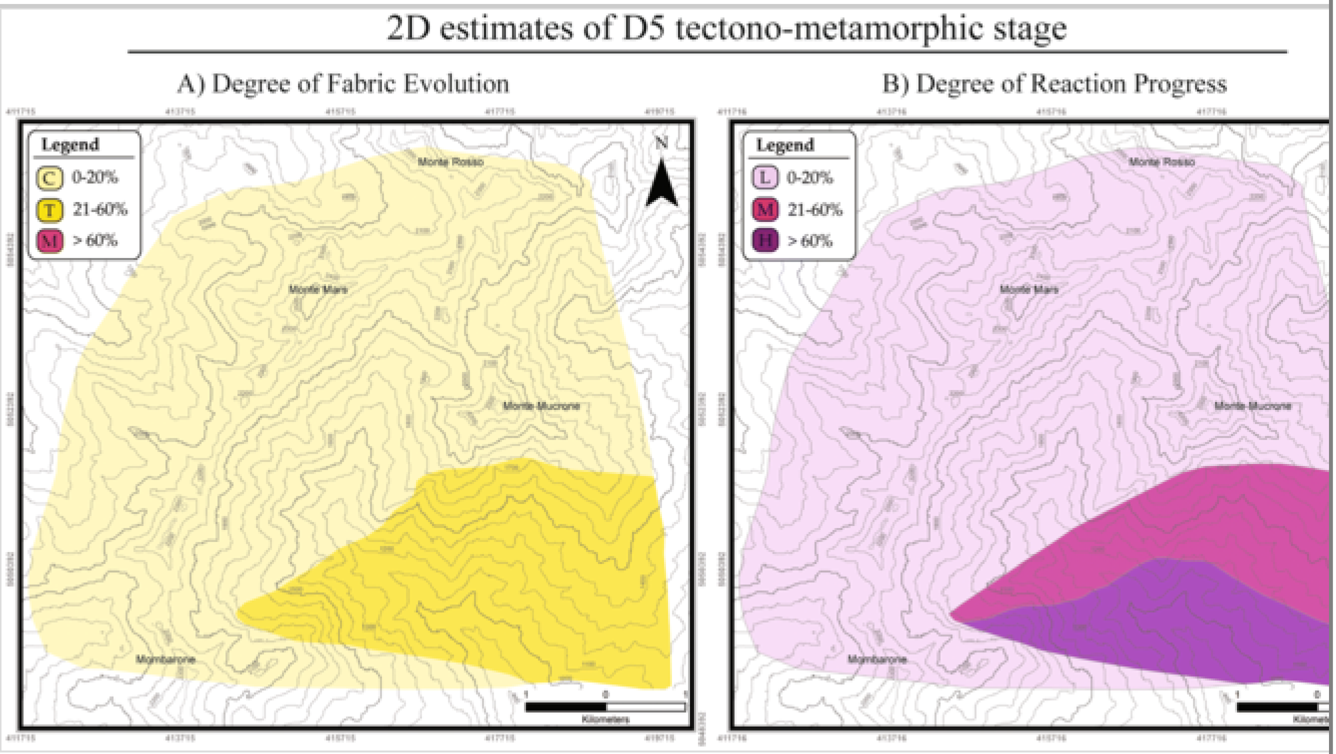


Fig. 6

Domains of homogeneous degrees of fabric evolution and metamorphic reaction progress reconstructed for D5 stage (inferred from Zucali 2002; Zucali et al. 2002; Delleani et al. 2012; Delleani et al. 2013 integrated with original field data)



3D modelling

Geomodeller® is based on the surface potential-field method to build 3D geological models using geological maps, DEM, and structural orientations as data input (Chilès et al. 2004). Each geological interface is treated as an iso-potential surface of a potential field defined in 3D space. The potential-field interpolation is based on a co-kriging statistical analysis defining the correlation between geological and structural data values as a function of the distances between data points. These distances are calculated using a system of parametric coordinates defined internally to the potential field (Lajaunie et al. 1997). The software takes into account the iso-potential surfaces (i.e. geological interfaces) and computes those distances through an implicit method based on a system of potential-field functions (Calcagno et al. 2008). In detail, geological bodies are modelled integrating the location of geological interfaces (iso-potential data), used as spatial distribution parameters with their structural data orientation (potential gradients), used as anisotropy shape parameters. The combination of these functions allows a full spatial and volumetric description of shapes of geological bodies (Guillen et al. 2011).

The 3D quantification of the relationships between the DFE and DRP during polyphasic tectono-metamorphic evolution is obtained through the reconstruction of the boundaries between homogeneous domains using the foliation trajectory map (Fig. 2) and several cross sections as structural guides. The location precision of these boundaries varies between 5 and 50 m, depending on the density of the input petro-structural data. Taking advantage of the rapidity of the Geomodeller® elaborations, 3D modelling is performed for D2 and D5 stages (i.e. for eclogite- and greenschist-facies main finite structures). The first step consists in merging the digital elevation model with the 2D maps of DFE and DRP, locating the cross sections and structural orientation data to constrain the boundaries between homogeneous domains in three dimensions (Fig. 4). The modelled volume of 61.54 km^3 is voxelized into a regular and orthogonal 3D triangular mesh, and geological properties are attributed to each cell. In the *x*–*y*–*z* directions the voxel dimension is 50–50–25 m and the entire volume is discretized in 3.534*e6 voxels. The consistency of the 3D results has been verified by visual inspection, to check the geologically coherent geometries and intersection relationships, plotting the modelled surfaces on the 2D maps and cross sections in order to verify the model reliability with respect to the input data. The model allows defining the size, shape, and spatial relations of rock volumes showing homogeneous DFE and DRP for the two selected tectono-metamorphic stages. Comparing the DFE and DRP models for each analysed stage, it is possible to calculate the volumetric misfit between the corresponding homogeneous DFE and DRP volumes.

Results

The degree of fabric evolution does not necessarily correspond to the degree of metamorphic reaction progress during each tectono-metamorphic stage, as qualitatively suggested by Zucali et al. (2002) and, quantitatively, by Salvi et al. (2010). The DFE and DRP can evolve independently at different rates, but from DFE above 60% the degree of mechanical and chemical transformation increases at the same rate (Salvi et al. 2010). To investigate this heterogeneity at the km scale, the DFE and DRP models are built separately. The 2D contouring of the fabric and metamorphic gradient is performed for D2 (Fig. 5) and for D5 stages (Fig. 6). As already pointed out, these maps of fabric and metamorphic domains include also data from Zucali (2002), Zucali et al. (2002), and Delleani et al. (2012, 2013), integrated with original structural and petrologic data.

The quantitative results of 3D modelling on syn-D2 and syn-D5 structural and metamorphic heterogeneities are compared in Fig. 7, where the volumetric estimates for D2 fabric domains (coronitic domain: 5.83%; tectonitic domain: 8.51%; mylonitic domain: 85.66%) and for metamorphic domains (low-transformation domain: 5.93%; medium-transformation domain: 11.13%; high-transformation domain: 82.95%) are shown. Accordingly, Fig. 8 shows the D5 volumes for the fabric domains (88.62% for the coronitic domain and 11.38% for the tectonitic domain) and for the metamorphic domains (86.77% for the low-transformation domain; 9.42% for the medium-transformation domain; and 3.81% for the high-transformation domain). In general, the dominant D2 stage is characterized by the highest DFE values, and the tectonitic–mylonitic domains correspond to the 94.17% of the modelled rock volume. The D2-related syn-kinematic mineral assemblage reaches the DRP of 100% only above the 60% DFE threshold. Regardless of the spatial distribution, the DFE-DRP relations are proportional and the absolute volumetric misfit between the corresponding DFE-DRP domains is lower than 4% for D2 and D5 (Figs. 7, 8). The comparison of the tectono-metamorphic map (Fig. 2) with the DFE-DRP map (Figs. 5, 6) and the 3D models (Figs. 7, 8) of the considered stages clearly shows that the distribution of the high- and low-strain domains is not controlled by lithology, as high-strain domains intersect lithological boundaries.

Fig. 7

3D models of DFE and DRP for the D2 stage. Volumetric estimation and misfit between DFE and DRP domains are reported

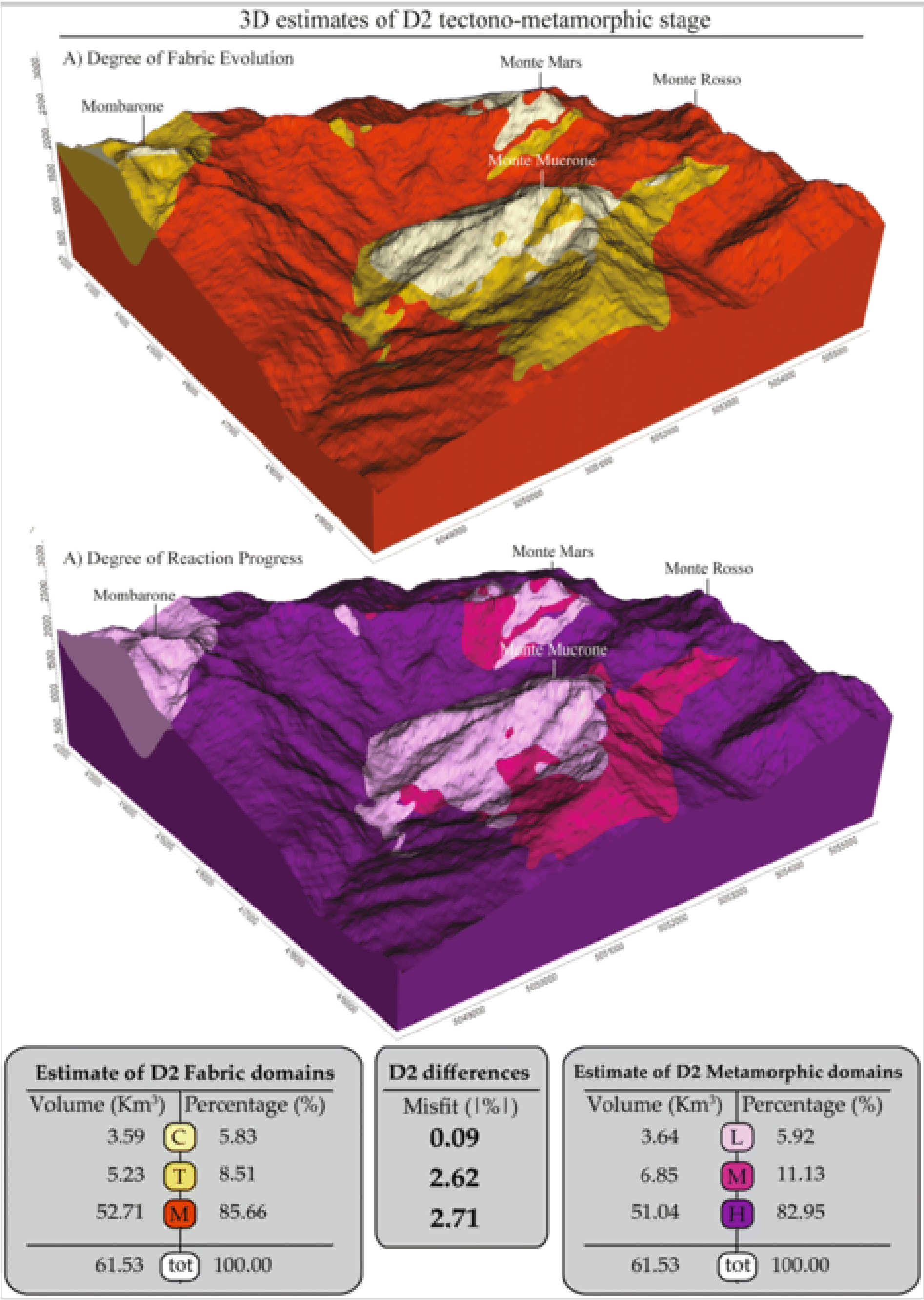
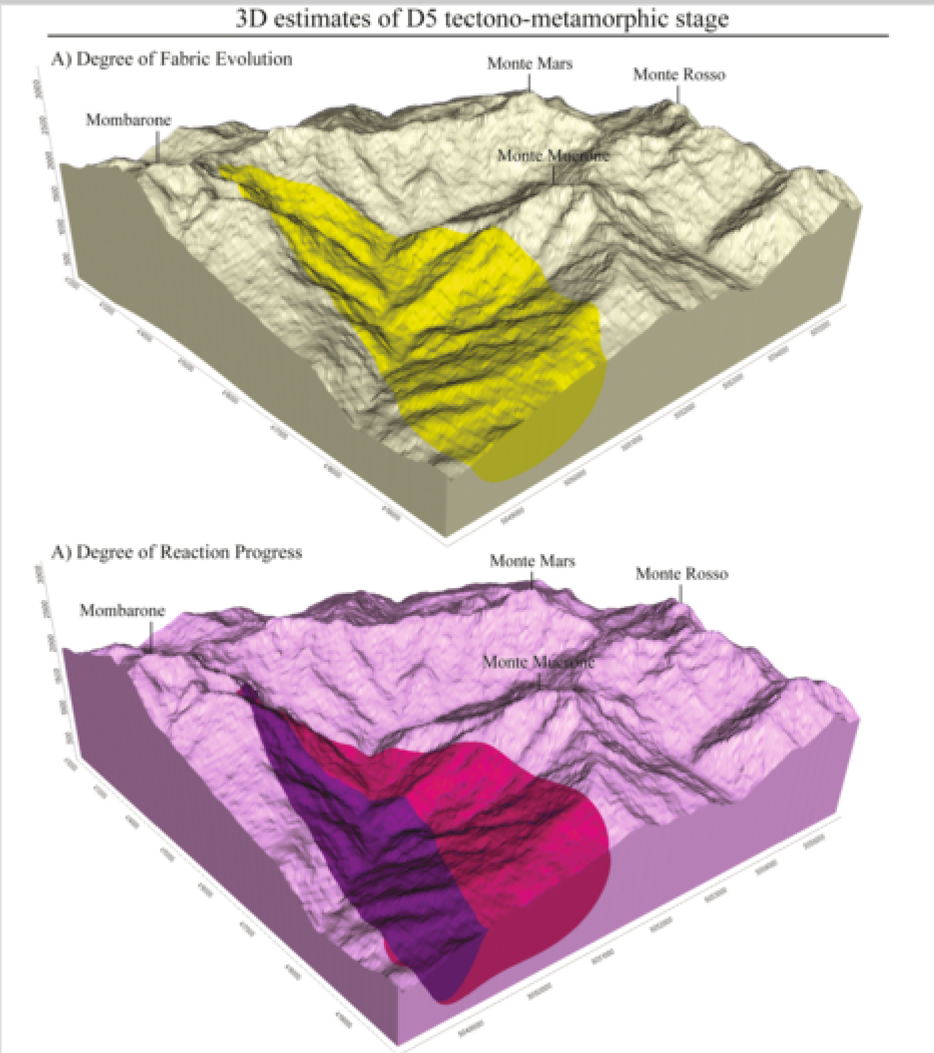


Fig. 8

3D models of DFE and DRP for the D5 stage. Volumetric estimation and misfit between DFE and DRP domains are reported



Estimate of D5 Fabric domains		
Volume (Km³)		Percentage (%)
54.53	C	88.62
7.00	T	11.38
0.00	M	0.00
61.53	tot	100.00

D5 differences
Misfit (|%|)
1.85
1.96
3.81

Estimate of D5 Metamorphic domains		
Volume (Km³)		Percentage (%)
53.39	L	86.77
5.80	M	9.42
2.34	H	3.81
61.53	tot	100.00

During eclogite-facies metamorphism, high variation rate of the DFE and DRP occurred. Large rock volumes totally escaped deformation and metamorphic re-equilibration effects. In the Mars, meta-granitoids' larger undeformed volumes are preserved during D1 stage, contrary to the Mucrone meta-granitoids. This fact influences the different D2 structural and metamorphic evolution: in the Mars meta-granitoids the transition between mylonitic-DFE to coronitic-DFE domains is sharp with narrow or absent tectonitic domains, whereas in Mucrone meta-granitoids the transition from coronitic to mylonitic domains is gradual (Fig. 7). The low- to medium-DRP domains show a spatial mismatch with respect to the corresponding coronitic- to tectonitic-DFE domains, especially along the Mars–Mombarone ridge and along the Elvo Valley, where the transition from mylonitic- to coronitic domains is sharp. The DFE does not show drastic changes for greenschist-facies stage, showing a gradual transition from coronitic- to tectonitic domains. The 60% DFE threshold is never reached for the D5 stage, and the tectonitic fabric is developed with high-DRP accumulation. The highest DFE and DRP volumes are localized in the southeastern part of the 3D model (Fig. 8).

Discussion

The analysis of diffuse textural and metamorphic heterogeneities in the studied rock volume using 3D quantification of fabric and metamorphic gradients developed during a polyphasic tectono-metamorphic evolution shows that only ~ 15% of the total rock volume was mechanically and chemically re-equilibrated during the late stage developed under greenschist-facies condition (Fig. 8). Around 5% of the total volume preserves structural and metamorphic imprints related to the earlier stages (pre-D1 and D1 events) due to a poor mechanical reactivation during the subsequent events. Moreover, the eclogitic dominant tectono-metamorphic imprint shows the highest degree of fabric evolution and reaction progress (Fig. 7). The syn-eclogite-facies mylonitic and high-transformation domains (above the 60% DFE-DRP threshold) are about 85% of the modelled volume. Both D2 and D5 (Figs. 7 and 8) display differences when considering the DFE-DRP relations in terms of absolute volumetric estimation and spatial distribution.

The structural pattern (i.e. orientation data, foliation trajectories map, and intersection relationships) is used as a geometric constrain to interpolate the point of DFE estimates in volumetric domains. Conversely, the reconstruction of the boundaries of DRP domains can be attained through two different approaches: (1) contouring using co-kriging algorithm and (2) structural control on the co-kriging interpolation. To explain these two approaches, we performed a 3D modelling focused exclusively on the Mucrone volume (Fig. 9) where the highest concentration of points of D2-related DRP estimates is available (63 samples over 28.63 km^2). Regardless of the structural pattern, the first approach implies the contouring interpolation of the DRP point estimates through the co-kriging algorithm (Fig. 9a). In detail, the georeferenced DRP values are used as input data for the co-kriging statistical analysis in order to build the grid in 3D space. With these points as internal standard, Geomodeller® is able to classify all voxels as a function of the value distances between input data and thus contouring such voxels in the three chosen ranges. Figure 9b shows the reconstruction of those boundaries, using the orientation data, the intersection relationships (Table 1), and the foliation trajectory map (Fig. 2) as a structural discriminating tool. Integrating the foliation surfaces (iso-potential data) and related structural data orientation (potential gradients), Geomodeller® interpolates the DRP volumes using the co-kriging approach with the structural control. Figure 9 shows the volumetric misfit and the different geometries of the DRP domains modelled with the two approaches. Since the multiscale analysis shows that the metamorphism is strictly correlated with deformation, the structural control on the DRP volume contouring is fundamental for the correct interpolation and evaluation of DRP volume heterogeneities and in comparison with the corresponding DFE estimates. In this view, the second approach turns out to be more precise when analysing the DFE-DRP relationships. The 3D reconstruction shows that DFE and DRP are strictly correlated. The localization of the high-strain domains is not controlled by the lithological setting, because high-strain domains intersect the lithological boundaries. The relationships between DFE and DRP in different rock types suggest that differences in original mineral assemblages and fabrics (i.e. pre-Alpine originally foliated or isotropic) can exert an influence on the mechanical reworking and reaction progress when DFE remains lower than 60%. These results strongly stress the role of strain energy in catalysing metamorphic reactions (Hobbs et al. 2010, 2011). At low- and medium-strain conditions, originally isotropic meta-granitoids achieved a lower degree of metamorphic reaction progress than the originally foliated meta-pelites. At a high-strain condition, the deformational and metamorphic effects proportionally increase, up to the total replacement of pre-existing minerals, where new fabrics evolved up to the stage of a continuous foliation, in agreement with previous qualitative and quantitative observations (Zucali et al. 2002; Spalla et al. 2005; Roda and Zucali 2008; Salvi et al. 2010; Delleani et al. 2012; Corti et al. 2017). These differences may be related to strain softening that resulted from strain localization during successive deformation stages, making the originally competent rocks softer by grain-size reduction increasing the amount of reaction surfaces. Below the 60% DFE threshold, the thermal regime can significantly influence the degree of metamorphic transformation: for the same DFE, the metamorphic reaction progress is more evolved under eclogite-facies conditions (estimated at $T = 520 \pm 45$ °C) than under greenschist-facies conditions (estimated at $T = 400 \pm 50$ °C). This quantitative estimation of the directly proportional variation in DFE and DRP suggests that higher DFE promotes increase in rock densities under eclogite-facies conditions, while under greenschist-facies conditions high DFE will correspond to lower rock densities. Considering that density is one of the main factors controlling subduction dynamics, it is possible to obtain from the 3D modelling an evaluation of differences in densities consequent to incomplete metamorphic re-equilibration detected in the different DFE. Using an average density of 2.65 g/cm^3 for granitoids–gneiss and 3.10 g/cm^3 for eclogitized continental crust (Schön 2011), the incomplete eclogitic re-equilibration in the different DRP domains allows inferring a density that ranges between 2.81 and 3.06 g/cm^3. This density is lower than 3.10 g/cm^3 expected for a fully eclogitized continental crust (Table 2), over the studied area. The resulting difference up to 9% may be crucial to evaluate the potential influence that relict domains have on the choice of the density values for numerical simulations of subduction processes.

Fig. 9

Two different approaches discussed in the text for the DRP quantification and their shape and volume differences in the Mt. Mucrone area. **a** DRP domains contoured using co-kriging algorithm. **b** Structural control on the co-kriging interpolation

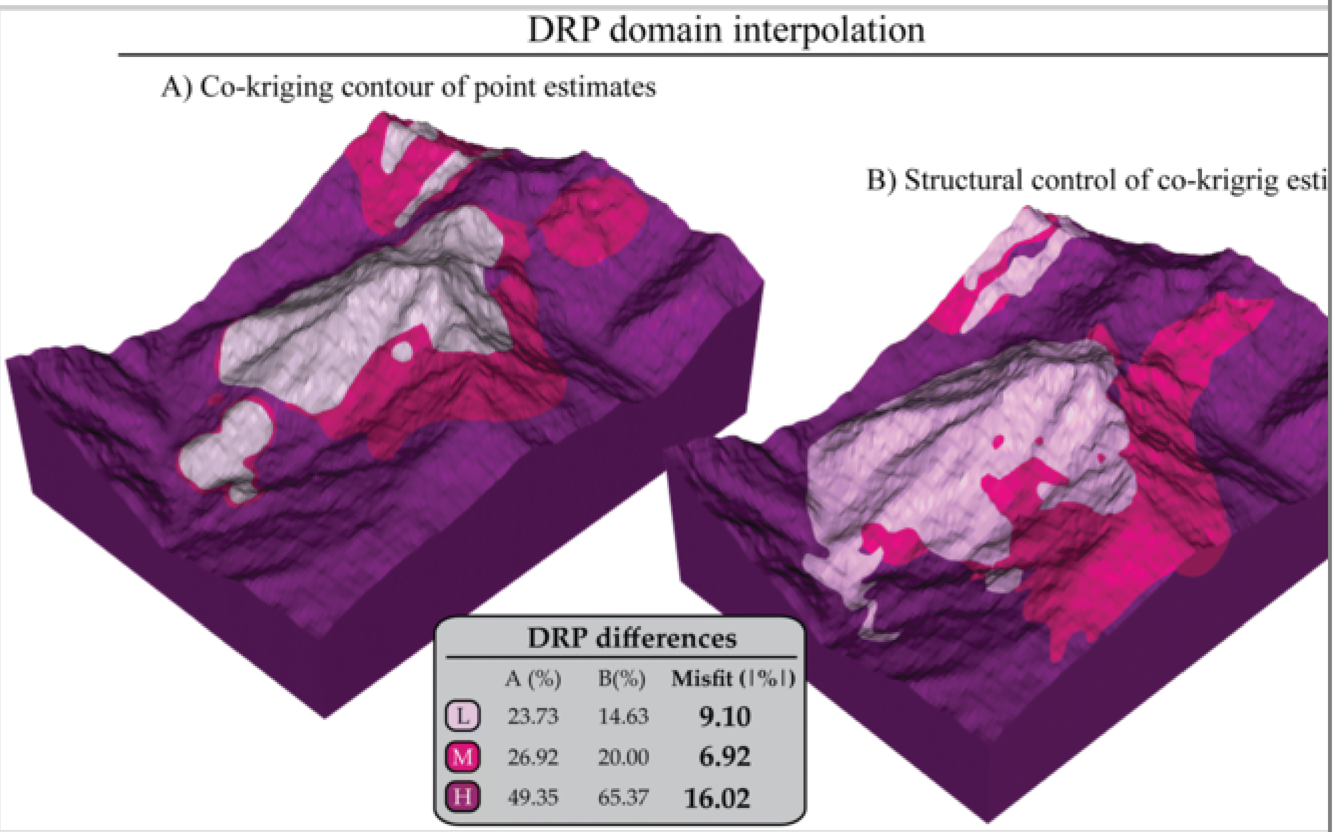


Table 2

Synoptic summary of differences in DFE, DRP, and density estimation in the modelled rock volume

Degree		DFE		DRP		Density estimation			
Min	Max	km^3	%	km^3	%	Min (g/cm^3)		Max (g/cm^3)	
0	20	3.59	5.83	3.64	5.92	2.65		2.74	
21	60	5.23	8.51	6.85	11.93	2.74	2.81	2.92	3.06
61	100	52.71	85.66	51.04	82.95	2.83		3.10	
Average density is 2.65 g/cm^3 for granitoids-gneiss and 3.10 g/cm^3 for eclogitized continental crust (Schön 2011)									

AQ5

Conclusions

Thanks to Geomodeller® software, a quantitative 3D estimation of domains characterized by homogeneous DFE and DRP has been performed for the D2-eclogitic and D5-greenschist stages, the two more pervasive tectono-metamorphic stages affecting the study area at km scale. The 3D geological model proves to be an excellent tool for the quantitative estimates of rock volumes that recorded different degrees of fabric evolution and metamorphic reaction progress during a polyphase tectono-metamorphic history, in this portion of continental crust deeply involved in the Alpine subduction system.

The multiscale analysis shows that metamorphic transformations are strongly controlled by deformation. Therefore, the structural control on the DRP reconstruction is fundamental for the correct evaluation of DRP domains and in comparison with the corresponding DFE volumes.

This analysis shows that the degree of metamorphic reaction progress is controlled by *bulk rock*, *mineral compositions*, *inherited textures*, and *degree of fabric evolution*. As a matter of fact, only 10% of the rock volume was mechanically and chemically re-equilibrated during D5-greenschist stage. Almost 5% of the volume preserves fabrics and mineral relics of pre-D1 and D1 events. The eclogitic D2 dominant tectono-metamorphic imprint shows the highest degree of fabric evolution and of metamorphic reaction progress (up to the 85% of the modelled volume). The DFE and DRP are strongly correlated, regardless of the rock type. The comparison between models and geological maps shows that the localization of the high-strain domains is *transversal to the lithological boundaries*. The relationships between DFE and DRP in different rock types suggest that differences in original mineral assemblages and fabrics can exert an influence on the mechanical reworking and reaction progress, especially when DFE is lower than 60%. At low- and medium-strain conditions (coronitic and tectonitic fabrics), meta-granitoids had a lower degree of metamorphic reaction progress than meta-pelites. On the contrary, at high-strain conditions the deformation and metamorphic transformations developed at the same rate up to the 100% of the considered volume, irrespective of the rock type.

The *thermal regime* can exert an additional influence on the degree of metamorphic transformation when the DFE remains below to the 60% threshold. The metamorphic reaction progress is more efficient during D2 that took place at $T = 520 \pm 45$ °C, than during D5 at $T = 400 \pm 50$ °C, for the same DFE values.

These results demonstrate that this approach is a powerful tool to unravel the variation in size of rock volumes that share a common subduction–collision–exhumation history, developed inhomogeneous structural and metamorphic records: the results from this 3D approach can therefore be usefully applied to improve the numerical modelling of geodynamic processes. Indeed, the estimation of volumes preserving textural and mineral relicts after phase transitions may shed light on the potential effects of incomplete metamorphic transformations on the rheology of rock volumes during their paths through different lithospheric depths along active margins: phase transitions cannot be properly implemented in numerical modelling of geodynamic processes without evaluating the heterogeneity of reaction progress and fabric evolution.

Acknowledgements

The authors acknowledge funding by University of Milano: Linea 2, Azione A—fondi giovani ricercatori "*Analisi strutturale delle catene collisionali*" (PSR2018_DZANONI). The results here presented have been developed in the frame of the MIUR Project "Dipartimenti di Eccellenza 2017—Le Geoscienze per la società: risorse e loro evoluzione (work package 3, tasks 3.3 and 3.4)". 3D modelling with Geomodeller® has been performed by LC. Suggestions and comments by G. Rebay and an anonymous reviewer greatly improved the original version.

References

Babist J, Handy MR, Konrad-Schmolke M, Hammerschmidt K (2006) Precollisional, multistage exhumation of subducted continental crust: the Sesia Zone, western Alps. Tectonics 25:6008. https://doi.org/10.1029/2005TC001927

Balestro G, Festa A, Dilek Y (2019) Structural Architecture of the Western Alpine Ophiolites, and the Jurassic Seafloor Spreading Tectonics of the Alpine Tethys. J Geol Soc. https://doi.org/10.1144/jgs2018-099

Baletti L, Zanoni D, Spalla MI, Gosso G (2012) Structural and petrographic map of the Sassa metaintrusives (Dent Blanche nappe, Austroalpine tectonic system, Western Alps, Italy). J Maps 8(4):413–430. https://doi.org/10.1080/17445647.2012.745678

Bell TH, Hayward N (1991) Episodic metamorphic reactions during orogenesis: the control of deformation partitioning on reaction sites and reaction duration. J. Metamorp Geol 9:619–640. https://doi.org/10.1111/j.1525-1314.1991.tb00552.x

Bell TH, Rubenach MJ (1983) Sequential porphyroblast growth and crenulation cleavage development during progressive deformation. Tectonophysics 92:171–194. https://doi.org/10.1016/0040-1951(83)90089-6

Bigi G, Castellarin A, Coli M, Dal Piaz GV, Sartori R, Scandone P, Vai GB (1990) Structural Model of Italy, sheets 1-2. In: Progetto Finalizzato Geodinamica del CNR—SELCA, Florence

Bussy F, Venturini G, Hunziker J, Martinotti G (1998) U–Pb ages of magmatic rocks of the western Austroalpine Dent-Blanche-Sesia Unit. Schweitz Mineral Petrogr Mitt 78:163–168

Calcagno P, Chilès JP, Courrioux G, Guillen A (2008) Geological modelling from field data and geological knowledge: Part I. Modelling method coupling 3D potential-field interpolation and geological rules. Phys Earth Planet In 171:147–157. https://doi.org/10.1016/j.pepi.2008.06.013

Callegari E, Compagnoni R, Dal Piaz GV, Frisatto V, Gosso G, Lombardo B (1976) Nuovi affioramenti di metagranitoidi nella zona Sesia-Lanzo. Rend Soc Ital Miner Petrol 32:97–111

Cantù M, Spaggiari L, Zucali M, Zanoni D, Spalla MI (2016) Structural analysis of a subduction-related contact in southern Sesia-Lanzo Zone (Austroalpine Domain, Italian Western Alps). J Maps 12(1):22–35. https://doi.org/10.1080/17445647.2016.1155925

Castelli D (1987) Il metamorfismo alpino delle rocce carbonatiche della Zona Sesia-Lanzo (Alpi Occidentali). Consorzio Universitario di CA-GE-TO. PhD Thesis

Castelli D (1991) Eclogitic metamorphism in carbonate rocks: the example of impure marbles from the Sesia-Lanzo Zone, Italian Western Alps. J Metam Geol 9:61–77. https://doi.org/10.1111/j.1525-1314.1991.tb00504.x

Castelli D, Rubatto D (2002) Stability of Al- and F-rich titanite in metacarbonate: petrologic and isotopic constraints from a polymetamorphic eclogitic marble of the internal Sesia Zone (Western Alps). Contrib Miner Petrol 142:627–639. https://doi.org/10.1007/s00410-001-0317-6

Cenki-Tok B, Oliot E, Rubatto D, Berger A, Engi M, Janots E (2011) Preservation of Permian allanite within an Alpine eclogite facies shear zone at Mt Mucrone, Italy: mechanical and chemical behavior of allanite during mylonitization. Lithos 125:40–50. https://doi.org/10.1016/j.lithos.2011.01.005

Chapman T, Clarke GL, Piazolo S, Daczko NR (2019) Inefficient high-temperature metamorphism in orthogneiss. Am Miner 104:17–30. https://doi.org/10.2138/am-2019-6503

Chilès JP, Aug C, Guillen A, Lees T (2004) Modelling the geometry of geological units and its uncertainty in 3D from structural data: the potential-field method. In Proceedings of international symposium on orebody modelling and strategic mine planning, Perth, Australia vol 22, pp 313–320

Compagnoni R (1977) The Sesia-Lanzo zone: high-pressure low-temperature metamorphism in the Austroalpine continental margin. Ren Soc Ital Miner Petrol 33:335–374

Compagnoni R, Maffeo B (1973) Jadeite bearing metagranites ls. and related rocks in the Mount Mucrone Area (Sesia-Lanzo zone, Western Italian Alps). Schweiz Mineral Petrogr Mitt 53:355–378

Compagnoni R, Dal Piaz GV, Hunziker JC, Gosso G, Lombardo B, Williams PF (1977) The Sesia Lanzo zone, a slice of continental crust with alpine high pressure-low temperature assemblages in the Western Italian Alps. Rend Soc Ital Mineral Petrogr 33:281–334

Corti L, Alberelli G, Zanoni D, Zucali M (2017) Analysis of fabric evolution and metamorphic reaction progress at Lago della Vecchia-Valle d'Irogna, Sesia-Lanzo Zone, Western Alps. J Maps 13(2):521–533. https://doi.org/10.1080/17445647.2017.1331177

Corti L, Alberelli G, Zanoni D, Zucali M (2018) Tectonometamorphic evolution of the Lago della Vecchia metaintrusive and its country rocks, Sesia-Lanzo Zone, Western Alps. Ital J Geosci 137(2):188–207. https://doi.org/10.3301/IJG.2018.08

Corti L, Zucali M, Visalli R, Mancini L, Mohammad S (2019) Integrating X-ray computed tomography with chemical imaging to quantify mineral re-crystallization from granulite to eclogite metamorphism in the Western Italian

Alps (Sesia-Lanzo Zone). Front Earth Sci. 7:327. https://doi.org/10.3389/feart.2019.00327

Dal Piaz GV (1971) Alcune osservazioni sulla genesi delle ofioliti e dei giacimenti ad esse associati. Boll Ass Min Sudalpina 8:365–388

Dal Piaz GV (2001) History of tectonic interpretations of the Alps. J Geodyn 32:99–114. https://doi.org/10.1016/S0264-3707(01)00019-9

Dal Piaz GV, Gosso G (1984) Le moderne interpretazioni tettoniche delle Alpi. In: Cento anni di geologia italiana. I Centenario SGI, Vol giub, pp 95–112

Dal Piaz GV, Hunziker JC, Martinotti G (1972) La Zona Sesia-Lanzo e l'evoluzione tettonico-metamorfica delle Alpi Nord-occidentali interne. Mem Soc Geol ltal 11:433–460

Delleani F, Spalla MI, Castelli D, Gosso G (2012) Multiscale structural analysis in the subducted continental crust of the internal Sesia-Lanzo Zone (Monte Mucrone, Western Alps). J Virtual Explor 41(7):1–35. https://doi.org/10.3809/jvirtex.2011.00287

Delleani F, Spalla MI, Castelli D, Gosso G (2013) A new petro-structural map of the Monte Mucrone metagranitoids (Sesia-Lanzo Zone, Western Alps). J Maps 9(3):410–424. https://doi.org/10.1080/17445647.2013.800004

Delleani F, Rebay G, Zucali M, Tiepolo M, Spalla MI (2018) Insights on Variscan geodynamics from the structural and geochemical characterization of a Devonian-Carboniferous gabbro from the Austroalpine Domain (Western Alps). Ofioliti 43(1):23–39. https://doi.org/10.4454/ofioliti.v43i1.454

Duchêne S, Blichert-Toft J, Luais B, Télouk P, Lardeaux JM, Albarede F (1997) The Lu–Hf dating of garnets and the ages of the Alpine high-pressure metamorphism. Nature 387(6633):586–589

Gatta GD, Rotiroti N, Zucali M (2009) Plastic deformations in kyanites by tectonometamorphic processes: a single-crystal X-ray diffraction study. Min Magn 73(3):359–371. https://doi.org/10.1180/minmag.2009.073.3.359

Giuntoli F, Engi M (2016) Internal geometry of the central Sesia Zone (Aosta Valley, Italy): HP tectonic assembly of continental slices. Swiss J Geosci 109(3):445–471. https://doi.org/10.1007/s00015-016-0225-4

Giuntoli F, Lanari P, Engi M (2018a) Deeply subducted continental fragments – Part 1: fracturing, dissolution–precipitation, and diffusion processes recorded by garnet textures of the central Sesia Zone (western Italian Alps). Solid Earth 9:167–189. https://doi.org/10.5194/se-9-167-2018

Giuntoli F, Lanari P, Burn M, Kunz BE, Engi M (2018b) Deeply subducted continental fragments - Part 2: insight from petrochronology in the central Sesia Zone (western Italian Alps). Solid Earth 9(1):191–222. https://doi.org/10.5194/se-9-191-2018

Gosso G (1977) Metamorphic evolution and fold history in the eclogite micaschists of the upper Gressoney valley (Sesia-Lanzo zone, Western Alps). Rend Soc Ital Mineral Petrol 33:389–407

Gosso G, Messiga B, Rebay G, Spalla MI (2010) Interplay between deformation and metamorphism during eclogitization of amphibolites in the Sesia-Lanzo Zone of the Western Alps. Int Geol Rev 52(10):1193–1219. https://doi.org/10.1080/00206810903529646

Gosso G, Rebay G, Roda M, Spalla MI, Tarallo M, Zanoni D, Zucali M (2015) Taking advantage of petrostructural heterogeneities in subduction-collisional orogens, and effect on the scale of analysis. Per Miner 84(3B):779–825. https://doi.org/10.2451/2015PM0452

Guillen A, Courrioux G, Bourgine B (2011) 3D kriging using potential fields surfaces. In: IAMG Conference, Salzburg proceedings vol 1, pp 735–741

Halama R, Glodny J, Konrad-Schmolke M, Sudo M (2018) Rb-Sr and in situ $^{40}Ar/^{39}Ar$ dating of exhumation-related shearing and fluid-induced recrystallization in the Sesia zone (Western Alps, Italy). Geosphere 14(4):1425–1450. https://doi.org/10.1130/GES01521.1

Hobbs BE, Means WD, Williams PF (1976) An outline of structural geology. Wiley, Amsterdam, p 571

Hobbs BE, Ord A, Spalla MI, Gosso G, Zucali M (2010) The interaction of deformation and metamorphic reactions. Geol Soc Lond Spec Publ 332(1):189–223. https://doi.org/10.1144/SP332.12

Hobbs BE, Ord A, Regenauer-Lieb K (2011) The thermodynamics of deformed metamorphic rocks: a review. J Struct Geol 33:758–818. https://doi.org/10.1016/j.jsg.2011.01.013

Hunziker JC (1974) Rb–Sr and K–Ar age determination and the Alpine history of the Western Alps. Mem Ist Geol Min Univ Padova 31:1–54

Hunziker JC, Desmons J, Hurford AJ (1992) Thirty-two years of geochronological work in the Central and Western Alps: a review on seven maps. Mem Geol Lausanne 13:1–59

Hurford AJ, Hunziker JC (1985) Alpine cooling history of the Monte Mucrone eclogites (Sesia-Lanzo zone): fission track evidence. Schweiz Miner Petrogr Mitt 65:325–334

Hy C (1984) Métamorphisme polyphasé et evolution tectonique dans la croûte continentale éclogitisée: les series granitiques et pélitiques du Monte Mucrone (zone Sesia-Lanzo, Alpes italiennes). Université Paris VI. PhD thesis, p 200

Ildefonse B, Lardeaux JM, Caron JM (1990) The behavior of shape preferred orientations in the metamorphic rocks: amphiboles and jadeites from the Monte Mucrone Area (Sesia-Lanzo Zone, Italian Western Alps). J Struct Geol 12:1005–1011. https://doi.org/10.1016/0191-8141(90)90096-H

Johnson SE, Vernon RH (1995) Inferring the timing of porphyroblast growth in the absence of continuity between inclusion trails and matrix foliations; can it be reliably done? J Struct Geol 17:1203–1206. https://doi.org/10.1016/0191-8141(95)00021-5

Koons PO, Rubie DC, Frueh-Green G (1987) The effects of disequilibrium and deformation on the mineralogical evolution of quartz-diorite during metamorphism in the eclogite facies. J Petrol 28:679–700. https://doi.org/10.1093/petrology/28.4.679

Lajaunie C, Courrioux G, Manuel L (1997) Foliation fields and 3D cartography in Geology. Math Geol 29(4):571–584. https://doi.org/10.1007/BF02775087

Lardeaux JM (1981) Evolution tectono-métamorphique de la zone nord du Massif de Sesia-Lanzo (Alpes Occidentales): un exemple d'éclogitisation de croûte continentale. PhD Thesis, Université Paris VI, 226 p

Lardeaux JM, Spalla MI (1990) Tectonic significance of P–T-t paths in metamorphic rocks: examples from ancient and modern orogenic belts. Mem Soc Geol Ital 45:51–69

Lardeaux JM, Spalla MI (1991) From granulites to eclogites in the Sesia zone (Italian western Alps): a record of the opening and closure of the Piedmont ocean. J Metam Geol 9:35–59. https://doi.org/10.1111/j.1525-1314.1991.tb00503.x

Lardeaux JM, Gosso G, Kienast JR, Lombardo B (1982a) Chemical variations in phengitic micas of successive foliations within the Eclogitic Micaschists complex, Sesia-Lanzo zone (Italy, Western Alps). Bull Minéral 106:673–689

Lardeaux JM, Gosso G, Kienast JR, Lombardo B (1982b) Relations entre le métamorphisme et la déformation dans la zone Sésia-Lanzo (Alpes Occidentales) et le problème de l'éclogitisation de la croûte continentale. Bull Soc Géol Fr 7 (XXIV): 793-800

Lardeaux JM, Lombardo B, Gosso G, Kienast JR (1983) Découverte de paragenèses à ferro-omphacites dans les orthogneiss de la zone Sesia-Lanzo septentrionale (Alpes Italiennes). C R Acad Sci Paris 296:453–456

Marotta AM, Spalla MI, Gosso G (2009) Upper and lower crustal evolution during lithospheric extension: numerical modelling and natural footprints from the European Alps. Geol Soc Lond Spec Publ 321:33–72. https://doi.org/10.1144/SP321.3

Meda M, Marotta AM, Spalla MI (2010) The role of mantle hydration into the continental crust recycling in the wedge region. Geol Soc Lond Spec Publ 332(1):149–172

Mørk MB (1985) A gabbro eclogite transition of Flemsoy, Suamore, western Norway. Chem Geol 50:283–310. https://doi.org/10.1016/0009-2541(85)90125-1

Myers JS (1970) Gneiss types and their significance in the repeatedly deformed and metamorphosed Lewisian complex of Western Harris, Outer Hebrides. Scot J Geol 6:186–199. https://doi.org/10.1144/sjg06020186

Oberhänsli R, Hunziker JC, Martinotti G, Stern WB (1985) Geochemistry, geochronology and petrology of Monte Mucrone: an example of Eo-Alpine eclogitization of Permian granitoids in the Sesia-Lanzo Zone, Western Alps, Italy. Chem Geol 52(2):165–184. https://doi.org/10.1016/0168-9622(85)90016-8

Park RG (1969) Structural correlations in metamorphic belts. Tectonophysics 7:323–338. https://doi.org/10.1016/0040-1951(69)90077-8

Passchier CW, Trouw RA (2005) Microtectonics. Springer, Berlin, p 366

Passchier CW, Myers JS, Kroner A (1990) Field geology of high-grade gneiss terrains. Springer, Berlin, p 150

Pearce MA, Wheeler J (2010) Modelling grain-recycling zoning during metamorphism. J Metam Geol 28:423–437. https://doi.org/10.1111/j.1525-1314.2010.00872.x

Pognante U (1989a) Lawsonite, blueschist and eclogite formation in the southern Sesia Zone (Western Alps, Italy). Eur J Miner 1:89–104. https://doi.org/10.1127/ejm/01/1/0089

Pognante U (1989b) Tectonic implications of lawsonite formation in the Sesia zone (Western Alps). Tectonophysics 162(3–4):219–227. https://doi.org/10.1016/0040-1951(89)90245-X

Pognante U (1991) Petrological constraints on the eclogite- and blueschist-facies metamorphism and P–T-t paths in the Western Alps. J Metam Geol 9:5–17. https://doi.org/10.1111/j.1525-1314.1991.tb00501.x

Pognante U, Compagnoni R, Gosso G (1980) Micro-meso-structural relationships in the continental eclogitic rocks of the Sesia-Lanzo zone: a record of a subduction cycle (Italian Western Alps). Rend Soc It Miner Petrol 36:169–186

Rebay G, Messiga B (2007) Prograde metamorphic evolution and development of chloritoid-bearing eclogitic assemblages in subcontinental metagabbro (Sesia-Lanzo Zone, Italy). Lithos 98:275–291. https://doi.org/10.1016/j.lithos.2007.04.002

Rebay G, Spalla MI (2001) Emplacement at granulite facies conditions of the Sesia-Lanzo metagabbros: an early record of Permian rifting? Lithos 58(3–4):85–104. https://doi.org/10.1016/S0024-4937(01)00046-9

Rebay G, Riccardi MP, Spalla MI (2015) Fluid rock interactions as recorded by Cl-rich amphiboles from continental and oceanic crust of Italian orogenic belts. Per Miner 84:751–777. https://doi.org/10.2451/2015PM0453

Rebay G, Zanoni D, Langone A, Luoni P, Tiepolo M, Spalla MI (2018) Dating of ultramafic rocks from the Western Alps ophiolites discloses Late Cretaceous subduction ages in the Zermatt-Saas Zone. Geol Magn 155:298–315. https://doi.org/10.1017/S0016756817000334

Regis D, Rubatto D, Darling J, Cenki-Tok B, Zucali M, Engi M (2014) Multiple metamorphic stages within an eclogite-facies terrane (Sesia Zone, Western Alps) revealed by Th–U–Pb petrochronology. J Petrol 55:1429–1456. https://doi.org/10.1093/petrology/egu029

Reinsch D (1979) Glaucophanites and eclogites from Val Chiusella, Sesia-Lanzo Zone (Italian Alps). Contrib Mineral Petrol 70:257–266

Ridley J (1989) Structural and metamorphic history of a segment of the Sesia-Lanzo Zone, and its bearing on the kinematics of Alpine deformation in the Western Alps. Geol Soc Lond Spec Publ 45:189–201. https://doi.org/10.1144/GSL.SP.1989.045.01.10

Roda M, Zucali M (2008) Meso and microstructural evolution of the Mont Morion metaintrusive complex (Dent Blanche nappe, Austroalpine Domain, Valpelline, Western Italian Alps). Boll Soc Geol It 127:105–123

Roda M, Spalla MI, Marotta AM (2012) Integration of natural data within a numerical model of ablative subduction: a possible interpretation for the Alpine dynamics of the Austroalpine crust. J Metam Geol 30(9):973–996. https://doi.org/10.1111/jmg.12000

Roda M, De Salvo F, Zucali M, Spalla MI (2018a) Structural and metamorphic evolution during tectonic mixing: is the Rocca Canavese Thrust Sheet (Italian Western Alps) a subduction-related melange? Ital J Geosci 137:311–329. https://doi.org/10.3301/IJG.2018.17

Roda M, Zucali M, Li Z-X, Spalla MI, Yao W (2018b) Pre-Alpine contrasting tectono-metamorphic evolutions within the Southern Steep Belt, Central Alps. Lithos 310–311:31–49. https://doi.org/10.1016/j.lithos.2018.03.025

Roda M, Regorda A, Spalla MI, Marotta AM (2019a) What drives Alpine Tethys opening? Clues from the review of geological data and model predictions. Geol J. https://doi.org/10.1002/gj.3316

Roda M, Zucali M, Regorda A, Spalla MI (2019b) Formation and evolution of a subduction-related mélange: The example of the Rocca Canavese Thrust

Sheets (Western Alps) Geol Soc Am Bull. https://doi.org/10.1130/B35213.1

Rubatto D, Gebauer D, Compagnoni R (1999) Dating of eclogite-facies zircons: the age of Alpine metamorphism in the Sesia-Lanzo zone (western Alps). Earth Planet Sci Lett 167:141–158. https://doi.org/10.1016/S0012-821X(99)00031-X

Salvi F, Spalla MI, Zucali M, 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. Geol Soc Lond Spec Publ 332:173–187. https://doi.org/10.1144/SP332.11

Schmalholz SM, Podladchikov Y (2014) Metamorphism under stress: the problem of relating minerals to depth. Geology 42(8):733–734. https://doi.org/10.1130/focus0822014.1

Schön JH (2011) Physical properties of rocks. A workbook. Elsevier, Oxford, p 481p

Spalla MI, Zucali M (2004) Deformation vs. metamorphic re-equilibration heterogeneities in polymetamorphic rocks: a key to infer quality PTdt path. Per. Mineral 73(2):249–257

Spalla MI, De Maria L, Gosso G, Miletto M, Pognante U (1983) Deformazione e metamorfismo della Zona Sesia-Lanzo meridionale al contatto con la falda piemontese e con il massiccio di Lanzo, Alpi occidentali. Mem Soc Geol Ital 26:499–514

Spalla MI, Lardeaux JM, Dal Piaz GV, Gosso G (1991) Metamorphisme et tectonique a la marge externe de la Zone Sesia - Lanzo (Alpes Occidentales). Mem Sci Geol Padova 43:361–369

Spalla MI, Carminati E, Ceriani S, Oliva A, Battaglia D (1999) Influence of deformation partitioning and metamorphic re-equilibration on P-T path reconstruction in the pre-Alpine basement of central Southern Alps (Northern Italy). J Metam Geol 17(3):319–336. https://doi.org/10.1046/j.1525-1314.1999.00199.x

Spalla MI, Siletto GB, di Paola S, Gosso G (2000) The role of structural and metamorphic memory in the distinction of tectonometamorphic units, the basement of the Como Lake in the Southern Alps. J Geodyn 30:191–204. https://doi.org/10.1016/S0264-3707(99)00033-2

Spalla MI, Zucali M, Di Paola S, Gosso G (2005) A critical assessment of tectono-thermal memory of rocks and definition of tectonometamorphic units: evidence from fabric and degree of metamorphic transformation. Geol Soc Lond Spec Publ 243(1):227–247. https://doi.org/10.1144/GSL.SP.2005.243.01.16

Spalla MI, Gosso G, Marotta AM, Zucali M, Salvi F (2010) Analysis of natural tectonic systems coupled with numerical modeling in the polycyclic continental lithosphere of the Alps. Int Geol Rev 52:1268–1302. https://doi.org/10.1080/00206814.2010.482737

Stünitz H (1989) Partitioning of metamorphism and deformation in the boundary region of the "Seconda Zona Diorito-Kinzigitica", Sesia Zone, Western Alps. Ph.D. thesis ETH, Zürich, p 248

Tajčmanová L, Podladchikov Y, Powell R, Moulas E, Vrijmoed JC, Connolly JAD (2014) Grain-scale pressure variations and chemical equilibrium in high-grade metamorphic rocks. J Met Geol 32:195–207. https://doi.org/10.1111/jmg.12066

Turner FJ, Weiss LE (1963) Structural analysis of metamorphic tectonites. MacGraw-Hill, New York, p 545

Venturini G, Martinotti G, Armando G, Barbero M, Hunziker JC (1994) The Central Sesia Lanzo Zone (western Italian Alps); new field observations and lithostratigraphic subdivisions. Schweiz Miner Petrogr Mitt 74:115–125

Whitney DL, Evans BW (2010) Abbreviations for names of rock-forming minerals. Am Mineral 95(1):185–187. https://doi.org/10.2138/am.2010.3371

Williams PF (1985) Multiply deformed terrains—problems of correlation. J Struct Geol 7:269–280. https://doi.org/10.1016/0191-8141(85)90035-5

Zanoni D (2010) Structural and petrographic analysis at the north-eastern margin of the Oligocene Traversella pluton (Internal Western Alps, Italy). Ital J Geosci 129:51–69. https://doi.org/10.3301/IJG.2009.04

Zhong X, Vrijmoed JC, Tajčmanová L (2017) Effect of grain-scale pressure variations on garnet growth: a numerical approach. J Metam Geol 35:19–33. https://doi.org/10.1111/jmg.12213

Zucali M (2001) La correlazione nei terreni metamorfici, due esempi dall'Austroalpino occidentale (Zona Sesia-Lanzo) e centrale (Falda Languard-Campo/Serie del Tonale). PhD thesis Università degli Studi di Milano, p 121

Zucali M (2002) Foliation map of the "Eclogitic Micascists Complex" (Monte Mucrone-Monte Mars–Mombarone, Sesia-Lanzo Zone, Italy). Mem Sci Geol Padova 54:87–100

Zucali M (2011) Coronitic microstructures in patchy eclogitised continental crust: the Lago della Vecchia Permian metagranite (Sesia-Lanzo Zone, Western Italian Alps). J Virtual Expl 38(5). https://doi.org/10.3809/jvirtex.2011.00286

Zucali M, Spalla MI (2011) Prograde lawsonite during the flow of continental crust in the Alpine subduction: strain vs. metamorphism partitioning, a field-analysis approach to infer tectonometamorphic evolutions (Sesia-Lanzo Zone, Western Italian Alps). J Struct Geol 33:381–398. https://doi.org/10.1016/j.jsg.2010.12.006

Zucali M, Spalla MI, 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). Schweiz Miner Petrogr Mitt 82(3):429–454

Zucali M, Spalla MI, Gosso G, Racchetti S, Zulbati F (2004) Prograde Lws-Ky transition during subduction of the Alpine continental crust of the Sesia-Lanzo Zone: the Ivozio Complex. J Virtual Expl 16(4):1–21. https://doi.org/10.3809/jvirtex.2004.00105