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Taking advantage of petrostructural heterogeneities in subduction-collisional orogens, and effect on the scale of analysis

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Abstract

Since the beginning of the last century, tectonic history of polyphase metamorphic tectonites of orogenic basement complexes is often related to primary links with metasediments, of presumably known origin, and location of their original basins. However such history is worth to be compared with results of an alternative and independent investigation that pursues: i) an objective reconstruction of the evolutionary steps modifying the lithostratigraphic setting and of its deformation-metamorphism interactions during plate-scale events and ii) a privileged reconstruction of the rock memory for the structural and metamorphic correlation of crystalline basement units. Interpretative merging of data gathered from these affine rock properties made interpretations of orogenic zones more actualistic and based on recognition of tectonic trajectories of units through evolving geodynamic contexts. In this account a refinement of the analytical approach to inferring deformation and metamorphic paths and constructing geological histories of basements in axial zones of orogenic belts is presented and examples are synthesised from the Western Alps and the Canadian Cordillera, based on detailed structural and lithostratigraphic mapping in harmony with macro- and micro-structural techniques of analysis, are reported from the two belts.

Key words: multiscale structural analysis; fabric gradients; deformation-metamorphism interaction; rock memory; tectono-metamorphic units.

Introduction

Paleo-thermal gradients recorded in metamorphic tectonites of orogenic belts are signatures encrypted in rock units that were involved in major lithospheric events as rifting, subduction, collision and orogenic collapse that may be revealed by detecting the related series of mineral re-equilibration steps that took place along with tectonic fabric reorganizations, at any scale. However, in old continental crusts petrologic and structural transformations are inevitably to be discriminated within complex lithostratigraphic configurations, reworked by deformations at various lithospheric depths; therefore a convenient initial task is to analyse the structural history and obtain valid relative chronology between meso- micro-structural fabrics, mineral equilibria and lithologic association changes (Turner and Weiss, 1963; Ramsay, 1967; Hobbs et al., 1976; Passchier et al., 1990; Passchier and Trouw, 2005). The investigation quality ensuring reproducible results depends much on determination, before laboratory work, of such time-related sequence, valid in the range of the structural map volume. The areal check of the kinematic internal compatibility of fabric sets (meso-micro) individuates zones of local preservation of relict strain states constituting heterogeneities in the total strain field. Such zones are the fossil textural and metamorphic evolutionary steps necessary to reconstruct the full petrostructural history. The mosaic of preserved zones leads to broader scale patterns by map-tracing the records of superposed fabric sets; the time-related adjacent imprints of the structural history are valid to collect the samples of successive deformation stages. The resulting approach aims at establishing a relative structural chronology and at contouring the rock volumes that display the same structural and petrogenetic evolution (tectono-metamorphic units TMU), building, with the petrological support, geologic units bearing significance in the tectonic history. Such procedure and type of units have been proposed for the first time in the central Southalpine basement of the European Alps (Spalla et al., 2000), demonstrating that the dominant metamorphic imprint of each TMU coincides with that of the most pervasive fabric at the regional scale, not reflecting necessarily the T_{max}-P_{Tmax} conditions as suggested by the metamorphic field gradient model (e.g. England and Richardson, 1977; Spear, 1993). In the latter the prominent factor controlling reaction kinetics and the dominant metamorphic imprint of each unit should develop under T_{max}-P_{Tmax} experienced during each P-T loop, considering temperature as the prevailing factor controlling reaction kinetics. Results gained with the same approach in other domains of the Alpine chain (Austroalpine) carrying metamorphic evolutions under contrasted P/T ratios, showed the same valid relations between degree of fabric evolution and progress of metamorphic reactions; this leads to conclude that, in terrains of axial orogenic belts, use of the metamorphic field gradient concept should be abandoned to discriminate units that experienced the same history (i.e. TMU), and replaced by investigations that consider jointly the areal distribution of superposed syn-metamorphic fabrics (e.g. Zucali et al., 2002; Spalla et al., 2005). Aim of the paper is to demonstrate how integration of quality mapping of complex lithostratigraphies, superposed tectonic structures, and of strain-related petrologic heterogeneities is of high support to tracing tectonic histories, and to relate them with a better confidence to plate scale evolution. Application experiences of this productive, though apparently time-consuming, procedure to Alpine and Cordilleran orogens display the constraints supporting the interpretative results in contrasting tectonic contexts of convergent and divergent lithospheres.

Method of Analysis

Mapping polydeformed rock associations of orogenic zones implies absolute adherence to the geometry of the finite lithostratigraphic structure, which is the only reference for objective reconstructions of the pre-tectonic setting; indulgence to extrapolation beyond field-scale observables may heavily affect interpretation of stratigraphy. One of the first structural maps objectively displaying two superposed fold sets, leading to reconstruction of pre-deformational lithostratigraphy, is by Weiss and McIntyre (1957) (Figure 1); their map does not include other mesoscopic fabrics than lithologic layering.

Since regional folding is hardly possible without even poor granular scale deformation, connection of any tectonic imprint, from large- to grain-scale structures, is therefore necessary when aiming at modern petrologic studies; such link is to be established primarily in the field and suggestions for lithostratigraphic and structural mapping are exposed in chapters 5, 7 and 8 of Hobbs et al. (1976). Where fabric elements are numerous, mapping the foliation trace grid will locate the compatible strain domains and the kinematically coherent mosaic of time-related fold sets and its mineral-scale foliations necessary to establish changes in the equilibrium assemblages (idealised in Figure 2A). Populations of significant measurements may then be discriminated chronologically within sub-areas. On this type of quality map, reporting effects of several deformation episodes, a time-related sample selection is facilitated by the location of relatively less deformed ("fossil") strain domains and by following intensity variations of planar/linear fabrics. An enlightening and spectacular early report on a 150 km-scale gradient of fabric intensity and orientation is the description of the progressive gneissification of the Kangâmiut dike swarm in southwestern Greenland, within a progressive megashear zone (Escher et al., 1975; and Figure 1 in Mayborn and Lesher, 2006). As for lithologic boundaries, the foliation trajectories that better display on maps the superposition effects of deformation episodes are well evident at Glenelg (Figure 10.34 in Ramsay, 1967), close to the SW Caledonian front of the Scottish Highlands. Though of different scale, both examples report deformed lithostratigraphies on which fabric elements related to time may be objectively sampled for petrologic work within several bulk chemical lithologic types.

Individuation of pre-tectonic geological settings of lithotypes is actually a primary scope, mainly for ore prospecting. Mapped variations of foliation intensity, penetrativity and grade of differentiation of new planar foliations, or other grain scale fabrics, and progressively tightening fold systems express strain gradients that guide to locate zones of frequent loss of continuity of lithologic layers, or beds, of an original stratigraphy. Natural construction of false stratigraphies (re-foliation, or transposition in Hobbs et al., 1976) is a well known process, progressive in space (Figure 2 from Turner and Weiss, 1963, and in Ashgirei, 1963), in which the evident, chrono-structurally misleading, local pattern is that of a newly formed mineralogical layering parallelised to remnants of original lithologic horizons and lenses, repositioned by rotation and internal strain. Because of lithologic layering being parallel in fold limbs to a mineral foliation that is younger, the resulting mesoscopic fabric that reworks the lithostratigraphy is said to be chronologically composite (Hobbs et al., 1976). Severe disruption of layer sets over wide regions may happen and determination of the scale of this process is a target when aiming to decrypt the pre-deformational stratigraphic setting. In Figure 2B, the reality of an outcrop-scale double transposition (repeated in time) is displayed in a set of carbonate-chert layers.

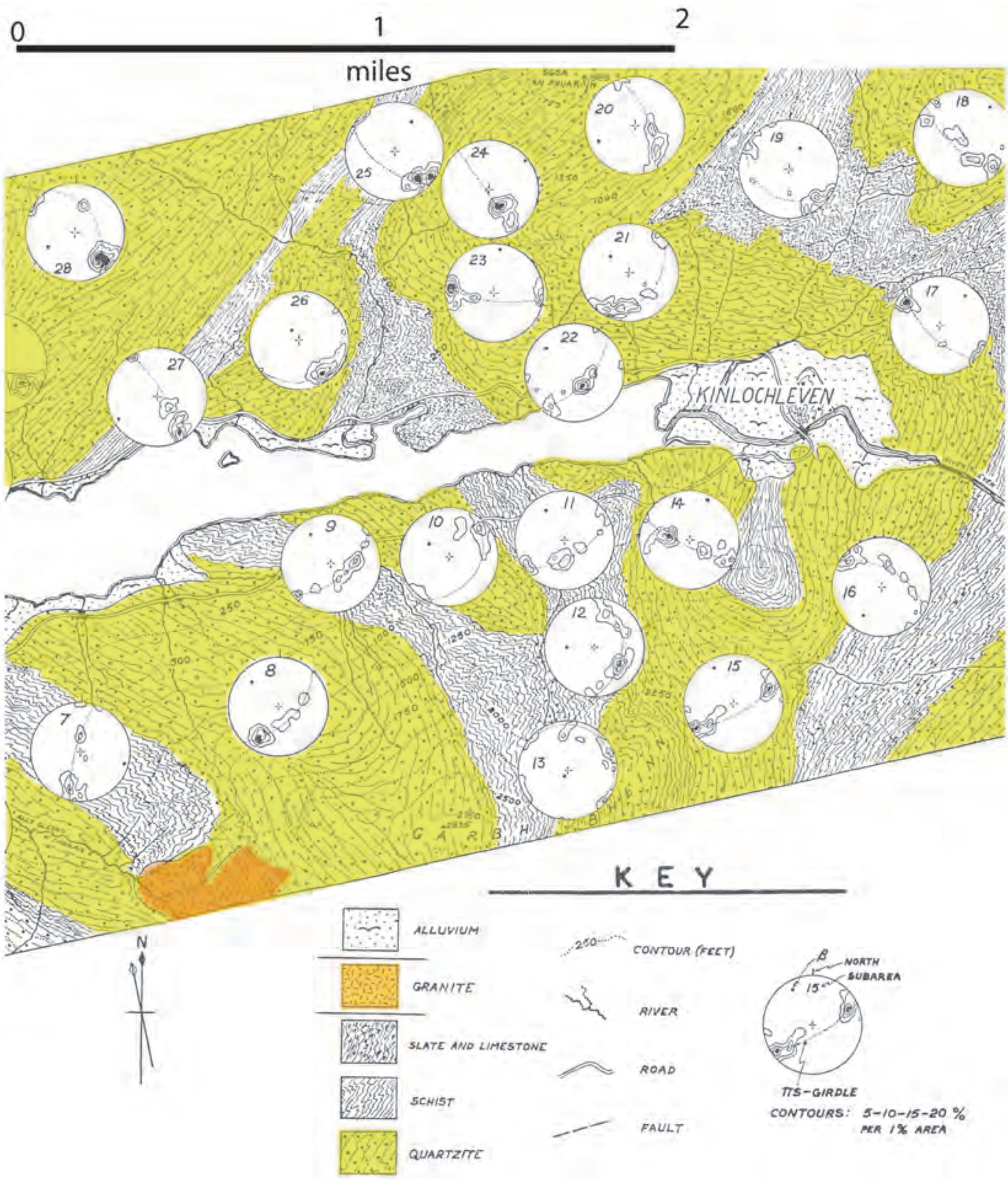


Figure 1. Geologic structure of the pretty well exposed Dalradian at Loch Leven (Scotland), presented by Weiss and McIntyre (1957) as a "solid" type of map (full interpretation, with no "drift" cover). The deformed lithostratigraphy, reported on map as traces of the lithologic boundaries, is sufficient to reveal the superposition of two folding episodes at the km-scale; no information on related mineral-scale deformation is reported. Topographic contour lines are dotted. For sake of clarity, colours are added to the original map.

Problems in recognition of the process derive from exposure rate, poorness of contrast in the multilayer, scarcity of differentiation in many horizons and confusion of boudinage with tight isoclinal rootless folds. The mechanism of full obliteration of stratigraphy was clarified by Williams (1967) at Little Broken Hill; the effect of deformational disruption and full loss of continuity of bedding (or lithologic layering), and of its stratigraphic order, happens where transposition of original layers, or of stratigraphy, has been imposed twice. The overcoming of difficulties in reconstructing stratigraphy, and the reasons for it, is as significant in mineral prospects, as it is for modern understanding of mountain building mechanisms (e.g. the lower Pennine Nappes, see Higgins, 1964; Hall, 1972, in Hobbs et al., 1976). Superposed folding may make recognition of previous lithostratigraphy extremely difficult, though being of much help in relating mineral-scale foliations to relative deformation time. Frequently, either transposition, or lenticularisation of lithologic types, occurs in association with formation of a new planar foliation by accumulation of grain scale deformation marking the finite strain of the XY plane of each structural stage (Figure 2A), and offering quality material to focus petrologically on the leading plate-scale major process (e.g. subduction zone or lithospheric extensional detachment). Localised overprint patterns of deformation (m - to km in scale) are being investigated since the seventies in modern terms, but surprisingly, application to solving tectonic problems sprang very much later than the enlightening work of Teall (1885) on the deformation and prograde metamorphism of dolerite dykes at Scourie Bay (Badcall, N-Scotland, Figure 3). Teall focused on unfoliated, ophitic dolerite dikes that are prograded into amphibolite facies gneisses confined within variably thick shear zones of Laxfordian age; contemporaneously, within the boundaries of the shear zone, their hosting Archean granulite gneisses are retrograded into amphibolite facies. A closer view reveals that the two metamorphic changes are not exclusively related to the newly foliated shear zone: corona-textured reactions, petrologically equivalent to those occurring inside the shear zone, take place in the two, massive dolerite and granulite protoliths, exclusively on both sides of the shear channel. Such coronitic metamorphic overgrowths, visible at the naked eye and occurring within a few metres thick volumes side of the shear zone, bear much importance: they announce a spatial progression of replacement of the pre-amphibolite-facies minerals, in accord with the progress of the new foliation stages, up to disappearence of the protolith minerals within the fully gneissified tectonite. In our experience, structural strategies of sampling may take advantage of this phenomenally clear type of transformation accompanying textural changes in similar fabric transitions from coronites to tectonites across the newly foliated zones. Relictual mineral grains may however be rare and dispersed over large volumes dominated by a monotonous mineral assemblage corresponding to penetrative marks of attainment of PT equilibrium; relict minerals (or assemblages) frequency may then configure a large scale modal compositional gradient. In accord with the Scourie Bay type of tectono-metamorphic overprint, such heterogeneous pattern may contain part of assemblages that were dominant before re-equilibration. Useful accounts on the Scourian dikes transformations are by Beach (1974), Cartwright and Barnicoat (1989), and Sutton and Watson (1969).

A further refinement of this approach is represented by maps of degree of fabric evolution (i.e. finite strain) and metamorphic transformation that have been performed in Central and Western Alps, showing regional-scale variations of modal quantities of newly grown minerals, that express re-equilibration conditions, evaluated in detail across different

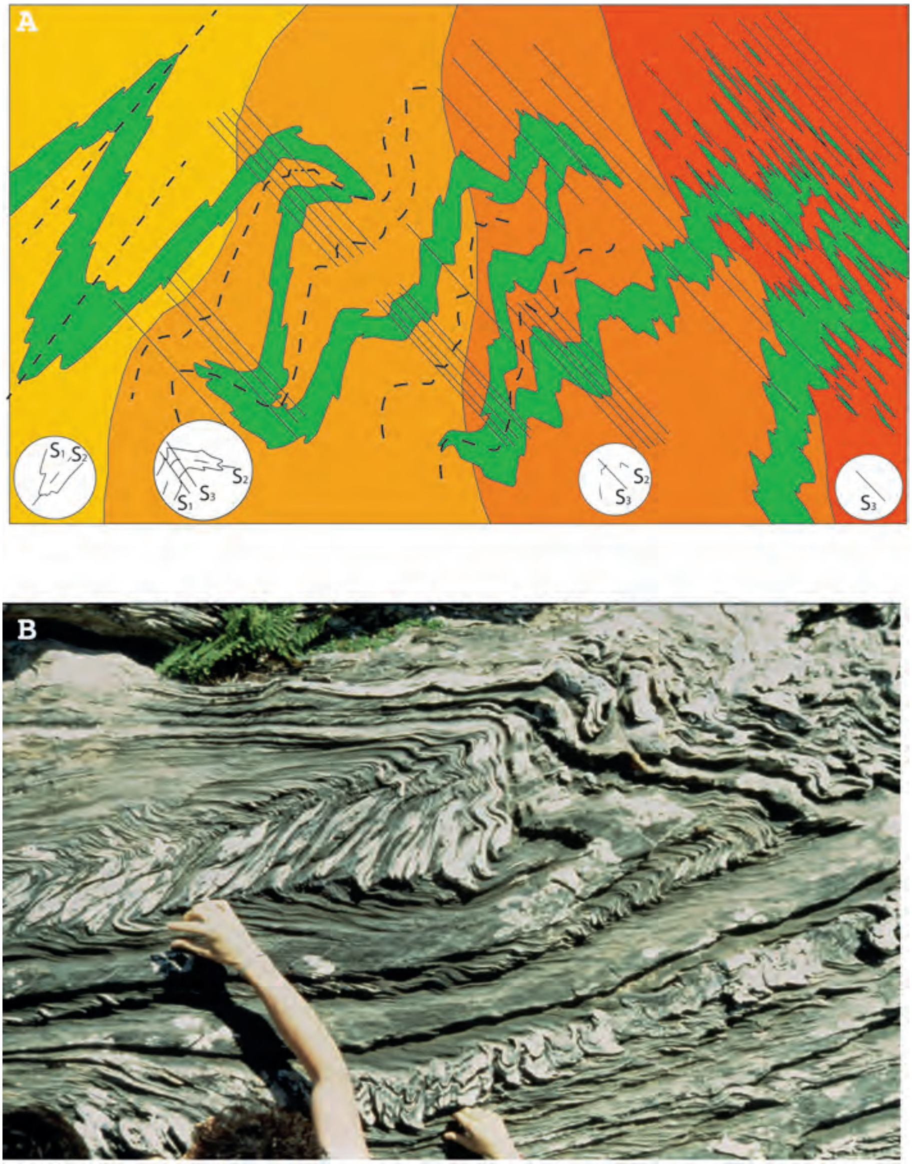


Figure 2. A) Transposed foliations as an idealised case from Turner and Weiss (1963). B) Transposition in the real case of the Calcare Selcifero Fm, at Foce Cardeto, Orto di Donna valley (Alpi Apuane Settentrionali, Northern Apennines, Italy). In A: space-time progressive changes of structural and lithostratigraphic settings are displayed in a tectonic setting generated by two superposed folding episodes; the two diachronous planar fabrics are incrementally added, towards the right side of the map, where their imprint intensifies, displaying a fabric gradient. In B: multi-stratified silex and limestone beds are transposed twice; mineralogical layerings in the two overprinting fold axial surfaces are recorded. Continuity of bedding remnants would have obliterated by further strain addition during second folding.

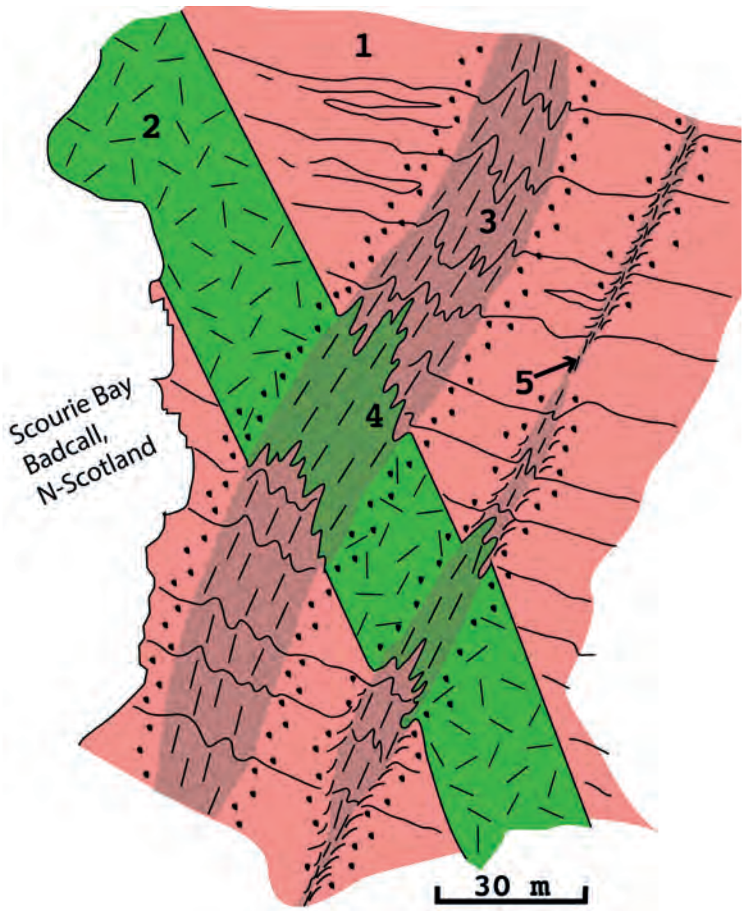


Figure 3. Field sketch (by G. Gosso and J.M. Lardeaux, 1981) in the site of the Laxfordian shear zones of Scourie Bay, Badcall, N-Scotland. Coronite-, tectonite- and mylonite-type of fabrics are coeval with prograde amphibolite-facies metamorphism in a doleritic basalt dyke cross-cutting granulites, and retrograde metamorphic transformations in their country rocks; prograde metamorphic re-equilibrations were first described by Teall (1885) as a transformation ("metamorphosis") of a dolerite into an amphibolite schist. Legend: 1= granulite-facies gneiss with lithologic layering and intrafolial folds; 2 = dolerite (Scourian) dike with ophitic mesoscopic structure; 3 = retrograde amphibolite-facies transformation with S-tectonite fabric in the granulites; 4 = prograde amphibolite-facies transformation with S-tectonite fabric in the ophitic basalts; 5 = retrograde amphibolite-facies transformation with mylonite fabric in the granulite, grading along the shear zone into S-tectonite fabric; dotted areas = corona-type of amphibolite-facies metamorphic fabric forming at margins of the (Laxfordian) shear zones.

degree of fabric evolution over large volumes of gneiss and isotropic (i.e. no preferred orientations) rocks protoliths. Mineral re-equilibrations with respect to fabric changes were studied in the Southalpine basement of Lake Como and in the Austroalpine of the Central and Western Alps, trying to relate mineralogical and textural transformations developing along with new stratigraphies. The first case demonstrates that the construction of a geologically consistent interpretation necessitates the use of the tectono-metamorphic unit (TMU) type of distinction in three adjacent continental units; these units display contrasting and diachronous dominant metamorphic imprints and manifest different memory of tectono-metamorphic histories (Spalla et al., 2000). The second case displays the regional role of strain-partitioning, that results in the coexistence of adjacent zones imprinted by different dominant fabrics, to which contrasting assemblages are connected (Zucali et al., 2002). The third case focuses on 3D percentage estimates of the three classes of mappable planar fabrics (low, medium and high degrees of new planar fabric formation, discriminated using as reference the crenulation/decrenulation stages of Bell and Rubenach, 1983) generated by strain partitioning during superposition of a new deformation episode (Figure 4). One of the main results was that although mechanical and chemical transformations increase proportionally, the synkinematic minerals can achieve total replacement of pre-existing mineral phases only where a critical threshold in the development of new differentiated layerings

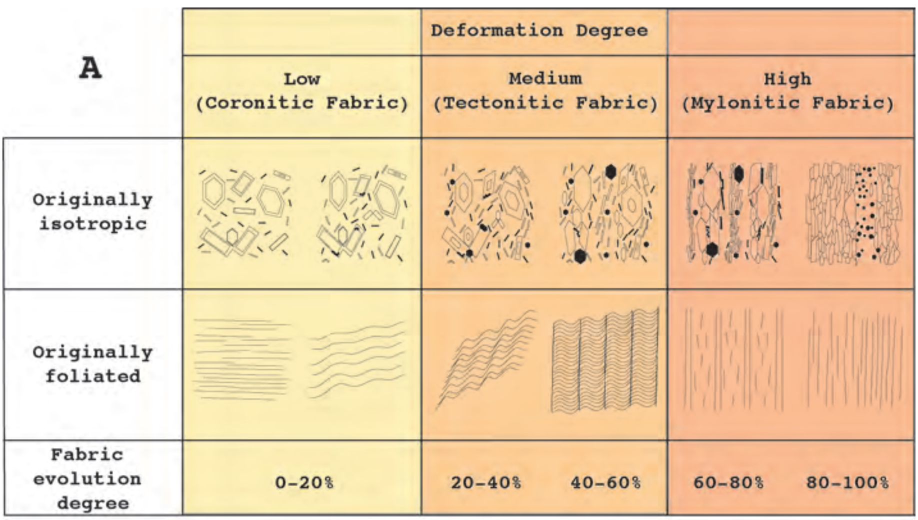


Figure 4. A) Qualitative estimate of fabric evolution degree during progressive foliation development, starting from originally foliated and initially isotropic rocks, as proposed by Bell and Rubenach (1983) and by Salvi et al. (2010). Italic numbers associated to originally foliated rocks refer to successive stages of crenulation cleavage evolution, up to complete decrenulation. The volume occupied by newly-oriented fabric elements, including the newly-differentiated mineral layering, is used to define the degree of fabric evolution, and to establish conventionally a low, medium or high degree of granular scale deformation (LD, MD and HD, respectively). B) Simplified geological map of km-scale strain gradients and related structures within metamorphosed Permian intrusives of the southern part of the Languard-Tonale TMU. Legend: Colour gradients identify fabric gradients, from coronitic to mylonitic fabrics, within metadiorites (1) and metagranitoids (2); 3) Grt-bearing pegmatites; 4) undifferentiated country rocks of Permian intrusives; foliation trajectories are shown for S1 and S2 foliations (5), S3 (6), S4 and S5 (7); axial plane trajectories are also reported (8). Black box localizes the 3D volumetric model of the dominant fabric domains (about 53 km^3); HD = high degree of granular scale deformation domains during D1+2, D3 and D4+5 deformation stages with evaluation of volume rate.

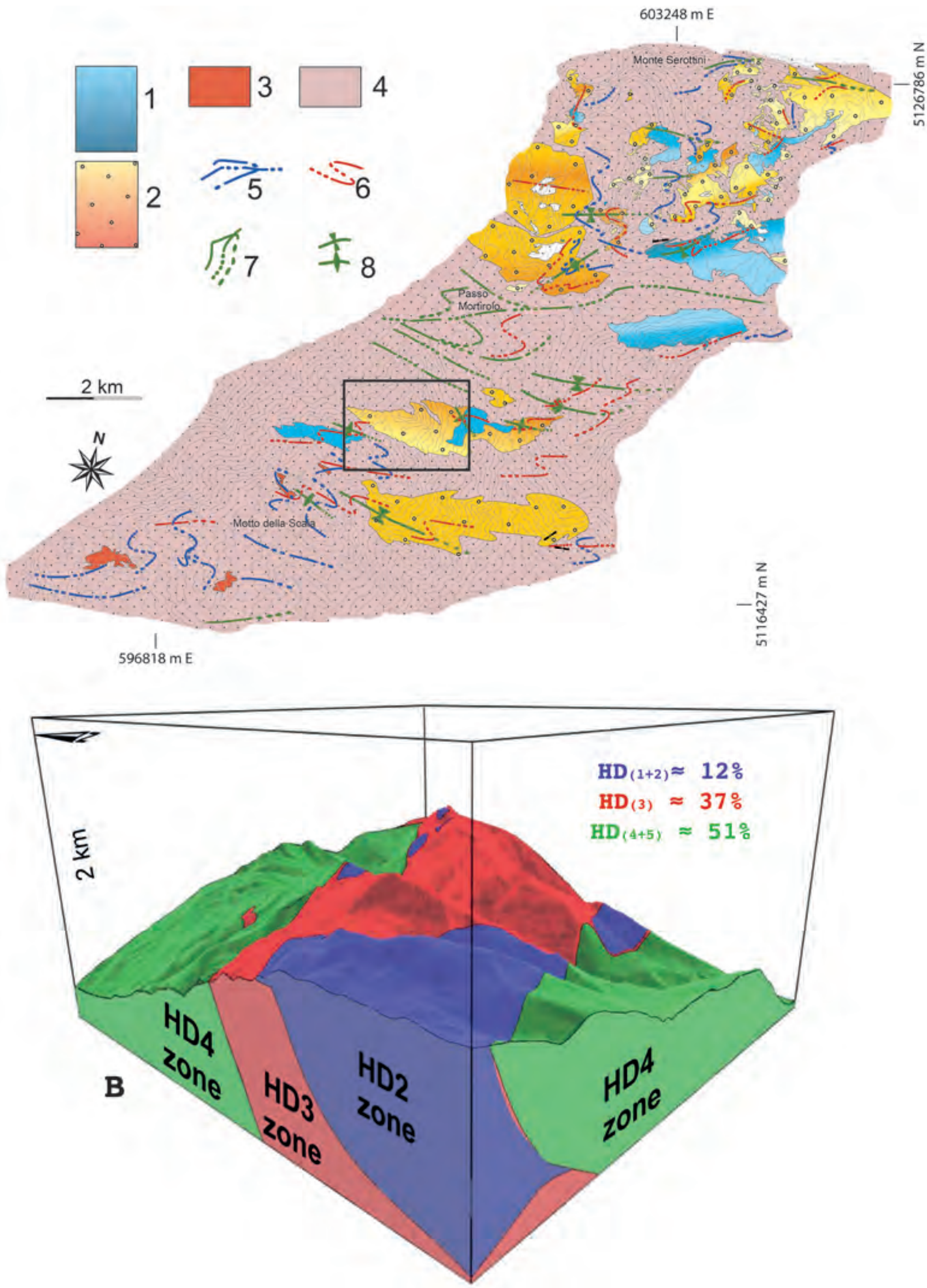


Figure 4. Continued ...

(high degree of the new planar fabric evolution) is attained (Salvi et al., 2010). Such conclusion strongly supports the role of strain energy as a catalyst on metamorphic reactions (e.g. Hobbs et al., 2010; Guzzetta and Rebay, 2015) and also calls for considering more broadly the role of granular scale deformation in the preservation *vs.* shortening of the rock memory.

In the light of this reciprocal influence between strain heterogeneity, metamorphic reaction-progress and deformation-induced regeneration of lithostratigraphy, in Alpine-type metamorphic complexes, in accord with techniques exposed in Passchier et al. (1990) for high-grade/strain terrains, the procedure decrypting at best the rock memory and gaining reproducibility of results in different terrains appears to be based on: i) structural mapping reporting, in the form of foliation trajectories, accumulation in space and distinction in time of granular-scale strain imprints; ii) detailed map reporting on lithostratigraphic complexities the mineral changes in various bulk chemistries, and mineral compositional gradients along lithologic layerings; iii) microstructural study of the mineral support of all the new planar fabric development sequences; iv) map location of zones of dominant fabric imprint and associated dominant equilibrium assemblages; v) thermobarometry on time-sequenced assemblages and deduction of Pressure-Temperature-relative deformation time history; vi) identification of shapes and dimensions of TMU and related thermal paleogradients.

The application of this approach takes advantage of grain scale deformation heterogeneity that visibly controls the rock-memory preservation. Revisiting the simple structural case of the Badcall locality of Scourie Bay (NW Scotland) where shear zones of Laxfordian age, developed under amphibolite facies metamorphic conditions, overprint doleritic Scourian dykes and their enclosing granulites, the partitioning of syn-metamorphic strain visibly generates three coeval types of fabrics, which are: Coronites (C), Tectonites (T) (normally foliated), and Mylonites (M). All of the three new fabrics are supported by amphibolite facies re-equilibration minerals (prograde in the dolerite and retrograde in the granulite) and their mappable pattern is unequivocally related to the shear zone kinematics. The significant sampling that can decrypt the full petrostructural memory stored in the Badcall rocks of Figure 3 must deal with the existing number of six tectonometamorphic fabrics: i) granulite facies gneissic protolith layering, ii) coronitic (amphibolite facies) retrograde granulite, iii) normally foliated retrograde (amphibolite facies) granulite, iv) coronitic (amphibolite facies) prograde metadolerite, v) normally foliated prograde (amphibolite facies) metadolerite, vi) mylonitic (amphibolite facies) granulite. All of these structural and compositionally different lithologic types are mappable, thanks to the scale of the structural pattern, that guides the sampling. The relatively low finite strain accumulated at Scourie Bay during post-intrusive shear zoning makes recognition of all types of petrostructural (or tectonometamorphic) fabrics spectacularly easy over the whole rock association; inevitably, a scale broadening of such a pattern or a higher state of bulk strain, may cause reconstruction of the full history more laborious.

Search for these types of coexisting fabrics helped to analyse the mechanism of tectono-metamorphic transformation of rock types during the four-fold metamorphic re-equilibration sequence described by Messiga (1992). In his investigation he made manifest the observer's real ability to individuate the basic three textural types C, T, and M, within the potentially high number of fabrics (or petrostructural rock types) that are to be expected (Figures 5 A,B) from an Alpine subducted gabbro protolith of the western Ligurian ophiolites, subjected to the 4 well known re-equilibration steps widespread

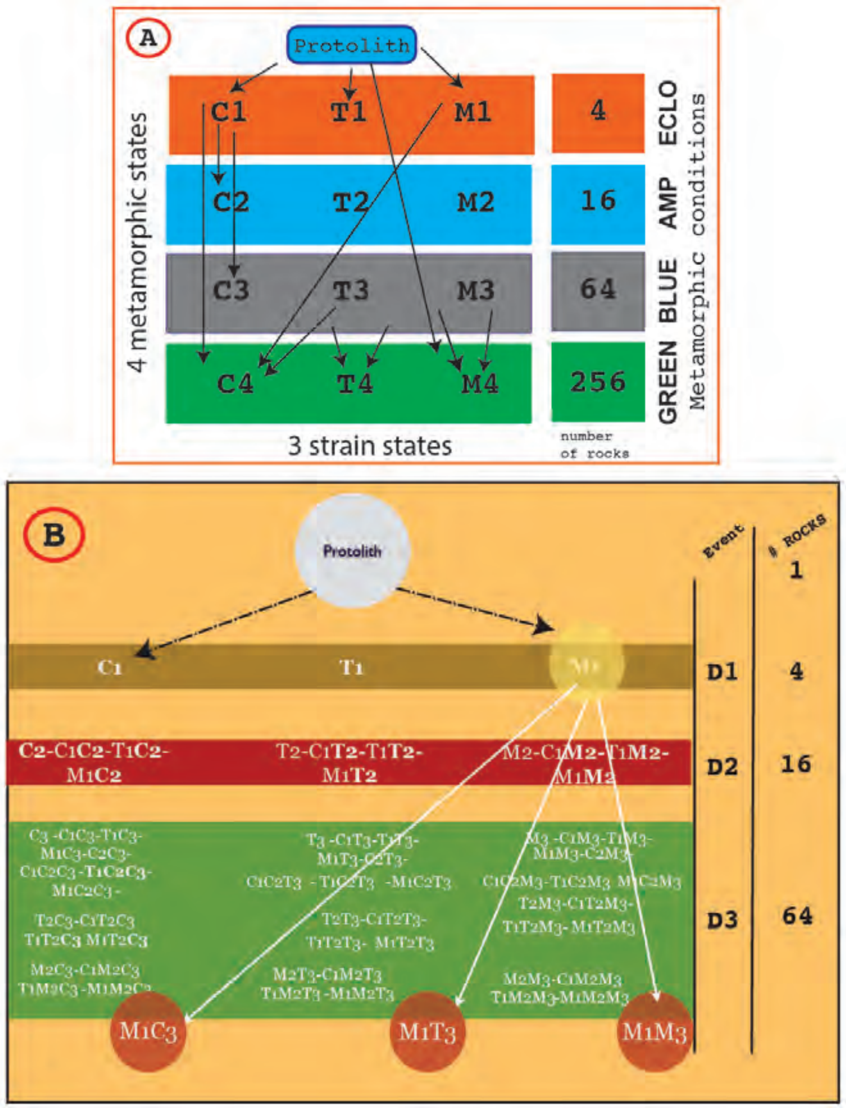


Figure 5. A) Conceptual flow chart of the total number of macroscopic rock types that may be generated from a single protholith during up to 4 metamorphic re-equilibration stages (progressively under eclogite, amphibolite, blueschist, and greenschist facies), provide only 3 textural types (Coronite = C, Tectonite = T, Mylonite = M) can be recognised for each stage. This counting is realistic and accords with the field and petrologic experience gained by Messiga (1992) in gabbroic protoliths of Ligurian meta-ophiolites subjected to 4 metamorphic stages during Alpine subduction-collision history. The 13 arrows connect the two petrostructural fabrics actually recognised in the field and/or in thin section (Messiga, 1992), and the right column reports the maximum expected number of types. See text for the mathematical solution. B) Explicit combination of the 64 rock types potentially generated if 3 possible deformational fabrics form during 3 metamorphic stages. Numerical subscript stays for the relative deformation (and metamorphic) chronology, as D1, D2, D3.

in the region. Only 13 of the possible C, T and M fabric types imprinted during orogeny and combined with the four metamorphic evolutionary episodes, were actually found among the logically much larger expected number. In the view of these rational previous approaches, we examine here the natural feasibility of such unexpected proliferous factory of petrostructural types, referring to an equilibrium mineral assemblage, supporting the C, T, and M fabric, as metamorphic stage):

let us accept that each metamorphic tectonite basically displays a dual property: the "mineral assemblage" of a specific "metamorphic stage" and its expression into "fabrics" (i.e. parageneses marking syn-$D_{1\text{-}n}$ coronite, tectonite or mylonite fabrics); both properties are, in time, subjected to changes. The metamorphic re-equilibration history may form, during geologic time, n mineral assemblages (metamorphic stages), and $k{*}n$ different "basic fabrics" can appear, that is:

$A_{11}\ A_{12}\ \dots\ A_{1k}$

$A_{21}\ A_{22}\ \dots\ A_{2k}$

$A_{31}\ A_{32}\ \dots\ A_{3k}$

...

$A_{n1}\ A_{n2}\ \dots\ A_{nk}$

where:

n = mineral assemblages supporting the fabric (metamorphic stages).

k = types of fabric (contemporaneous states of strain).

We assume that the petrostructural fabric types are given by the superposition of these basic fabrics, metamorphic stage after metamorphic stage.

Namely, they are all the combination of basic fabric types (of length ≤ n) that each basic fabric can produce with the restriction that the row index is strictly increasing.

That is, the fabric type C3 cannot form (i.e. coronite associated with stage 3) before C1 (i.e. coronite associated with stage 1), in implicit accord with time evolution of metamorphic transformations.

Imagine now considering only the combination of length m, where $1 \leq m \leq n$.

There are

$$\binom{n}{m} = \frac{n!}{m!(n-k)!} \qquad \text{Eq. 1}$$

strictly increasing sequences of row indexes.

Clearly, each sequence produces k^m different petrostructural fabrics.

The number of possible petrostructural fabrics after n metamorphic stages is then obtained by summing over m:

$$1 + \sum_{m=1}^{n} \binom{n}{m} k^m = \sum_{m=0}^{n} \binom{n}{m} k^m \qquad \text{Eq. 2}$$

where the unit on the left hand side accounts for the rock which started the process, the protolith.

Substituting 4 for the n metamorphic stages, and 3 for the k types of macroscopically recognizable fabrics in the field, the number of 256 potential petrostructural transformations (i.e. petrostructural rock types) are generated. Of such large number, the 13 cases showed up in the studies quoted by Messiga (1992, and references therein) are from a poorly exposed area of the Mediterranean coast of western Liguria (15-20%), of which gabbros represent less than 3% area. The following examples demonstrate that the theoretical approach is valid and support the expectation of petrostructural types formulated by the presented algorithm.

Examples from orogenic belts

Western Alps

Examples from the axial part of Western Alps come from the Austroalpine domain and namely from the Sesia Lanzo Zone and Dent Blanche Nappe (inset in Figure 6A). The Austroalpine continental crust constitutes the uppermost tectonic domain of the Alps overlying the mix of oceanic and continental slices composing the Penninic Domain, which lies in the axial part of the belt and represents the remnants of the sutured Tethys. Lanzo Ultramafic Massif and Pannonian Basin represent western and eastern terminations of Austroalpine Domain that, in the western portion of the belt, consists of small continental slivers mingled with continental and oceanic units of the Penninic Domain. The Alpine metamorphic evolution of the Austroalpine basement, all along the chain, indicates that large volumes have been deeply involved in a subduction system as accounted by the eclogite- to HP-amphibolite facies widespread imprints (e.g. Bousquet et al., 2004; Oberhänsli, 2004; Thöni, 2006). The lithological affinities between the protoliths of the subducted Austroalpine continental crust and the rocks of the Southern Alps, representing the Adria Alpine hinterland, suggest its provenance from the upper plate of the Alpine subduction system. The Western Austroalpine system comprises two main nappes, the internal Sesia–Lanzo Zone (SLZ) and the external Dent Blanche (DB), and was deformed and metamorphosed from the Cretaceous–Palaeogene to the Eocene-Lower Oligocene, recording different dominant metamorphic imprints (quartz-eclogite- to greenschist-facies conditions: e.g. Dal Piaz et al., 1972; 1983; Hunziker 1974; Compagnoni et al., 1977; Gosso, 1977; Ayrton et al., 1982; Lardeaux et al., 1982, 1983; Spalla et al., 1983; Oberhänsli et al., 1985; Ballèvre et al., 1986; Canepa et al., 1990; Pognante, 1991; Hunziker et al., 1992; Venturini et al., 1994; Roda and Zucali, 2008; Lardeaux, 2014).

Sesia-Lanzo Zone. The eclogitised pre-Alpine continental crust of SLZ (Figure 6B) displays the most preserved subduction tectonic system in the whole Alpine belt; it underwent a tectonic evolution compatible with uplift during active oceanic lithosphere subduction (Meda et al., 2010; Roda et al., 2012 and refs. therein). The SLZ is confined at its footwall by ophiolitic relicts of the Tethys and at its hanging wall by the Periadriatic Lineament, which separates it from the lower crust of the Ivrea Zone (Southalpine domain). SLZ is traditionally subdivided into an upper (the ‘II Zona Diorito-Kinzigitica’ = IIDK) and a lower element (the ‘Gneiss Minuti Complex’= GMC, the ‘Eclogitic Micaschists Complex’ = EMC, and the ‘Rocca Canavese Thrust Sheet’ = RCT) and each complex from both elements is characterised by a different dominant metamorphic imprint (e.g. Dal Piaz et al., 1972; Compagnoni et al., 1977; Oberhänsli et al., 1985; Pognante, 1989 a,b; Bussy et al., 1998; Rebay and Spalla, 2001). Cover sequences of possible Mesozoic age (Venturini et al., 1991; 1994) and Piemonte Zone serpentinised peridotites (Ferraris and Compagnoni, 2003) have been described in the central SLZ.

The structural and metamorphic evolution of the SLZ is polycyclic and was accomplished during pre-Alpine times under granulite- to amphibolite- and then to greenschist-facies conditions (e.g. Lardeaux, 1981; Lardeaux and Spalla, 1991), and during Alpine times under eclogite-facies peak conditions, with a final retrogression under greenschist-facies, throughout a blueschist-facies conditions re-equilibration (e.g. Andreoli et al., 1976; Compagnoni et al., 1977; Gosso, 1977; Pognante et al., 1980; Dal Piaz et al., 1983; Kienast, 1983; Williams and Compagnoni, 1983; Stuenitz, 1989; Pognante, 1991; Spalla et al., 1991; Tropper and Essene, 2002; Babist et al., 2006; Konrad-Schmolke et al., 2006; Rebay and Messiga, 2007; Gosso et al., 2010; Zucali

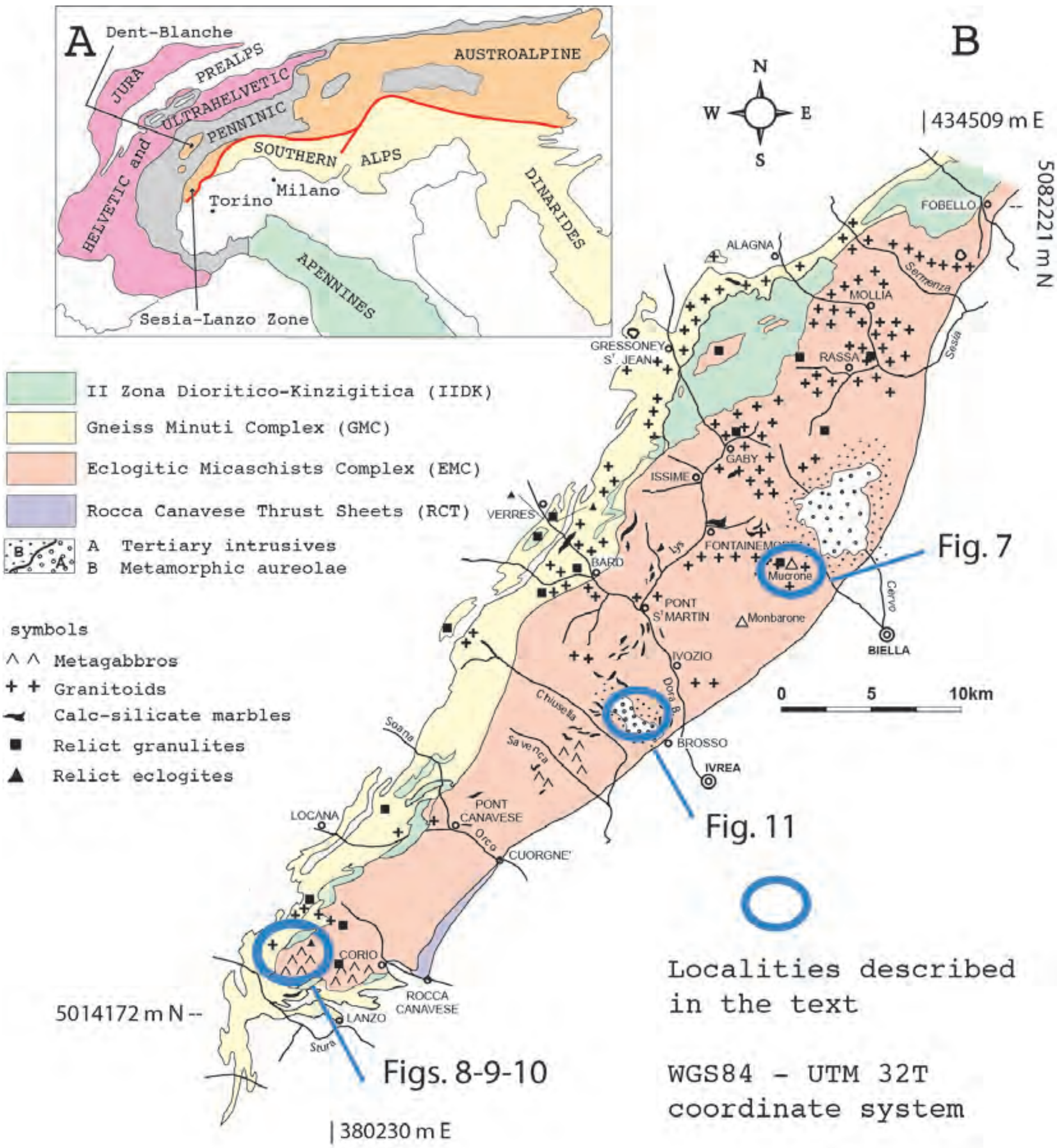


Figure 6. A) Sketch of the Alpine chain with location of the Sesia-Lanzo Zone. B) Localities where main relicts (eclogites and granulites) are found, and the location of the three areas (ellipses) discussed in the text.

and Spalla, 2011; Roda et al., 2012; Lardeaux, 2014). Pre-eclogitic fabrics are locally preserved and marked by P-T prograde blueschist-facies minerals (e.g. Reinsch, 1979; Pognante et al., 1980; Rebay and Messiga, 2007; Gosso et al., 2010). Absolute ages and field relationships suggest an age of 270 Ma for the granulite-facies stage, 240 Ma for the amphibolite-facies, and 170 Ma for the greenschist-facies events; mineral ages ranging between 60 and 85 Ma have been related to the Alpine high-pressure metamorphism (e.g. Lardeaux and Spalla, 1991; Inger et al., 1996; Rubatto, 1998; Rubatto et al., 1999; Rebay and Spalla, 2001; Cenki-Tok et al., 2011).

Multiscale structural analysis coupled with accurate petrologic investigation of some key areas was crucial in reconstructing a rich geodynamic evolution of SLZ, recognizing a quite complete pre-Alpine history. One of these comprises the famous Monte Mucrone eclogitised metagranitoid (Figure 6B; Koons et al., 1987), in the EMC, characterised by a pervasive metamorphic imprint under eclogite facies conditions, dominant in rocks with tectonitic and mylonitic textures, whereas in the least deformed domains igneous textures and assemblages are preserved (Delleani et al., 2012; 2013 and refs. therein). Coronitic domains are preserved also in the country rocks, where granulite-facies assemblages mark the pre-Alpine fabric (e.g. Lardeaux and Spalla, 1991), and in the Monte Mars metaintrusive (Zucali et al., 2002), outcropping immediately NNW of Monte Mucrone complex. Here the foliation trajectory maps (Figure 7) have been integrated by information on the degree of fabric evolution and progress of metamorphic reactions to perform a map of structural versus metamorphic re-equilibrations (Zucali et al., 2002; Delleani et al., 2012), in which, for each group of structures, areas dominated by a specific fabric are detectable by the distribution of high grain-scale deformation domains. In addition, details on the degree of metamorphic transformation, in terms of modal percentage of new synmetamorphic minerals, complement the petrostructural outline, spotlighting adjacent rock volumes showing different memory of the whole tectono-metamorphic evolution.

Analytical work across Monte Mucrone-Monte Mars areas showed that in tectonitic domains the eclogite facies assemblages are associated with three superimposed deformation phases (D1, D2, D3). Mesoscopic and microscopic observations (Figure 7) support the interpretation that S1 and S2 foliations developed during the prograde burial evolution at conditions of $P \geq 2$ GPa at about 480-580 °C, whereas S3 formed during the earlier stages of decompression (Zucali et al., 2002; Delleani et al., 2012). Successive deformations occurred during the retrograde evolution, under evolving metamorphic conditions, from blueschist- (D4) to greenschist-facies conditions (D5 and D6). This history ends with the intrusion of andesitic dykes of Oligocene age, crosscutting all previous structures, and suggesting shallow-crust conditions. Age determinations seems to locate reliably the prograde evolution between 85 and 60 Ma (Rubatto et al., 1999; Cenki-Tok et al., 2011; Regis et al., 2014), while no data are available for the retrograde stages (D4 and D5) predating the Oligocene magmatic activity. Remnants of pre-Alpine history were detected exclusively in coronitic domains where pre-D1 mineral assemblages indicated LP granulite-facies conditions (Zucali et al., 2002).

The analysis displayed positive correlation between degree of fabric evolution and progress of metamorphic transformation and close correspondence between dominant metamorphic imprint and dominant fabric at the regional scale (S2). As a matter of fact, even if the highest T mineral assemblages marked pre-D1 fabrics, their mineral relics have been rarely observed, since they are confined to rock-volumes poorly deformed during Alpine times. In addition, this

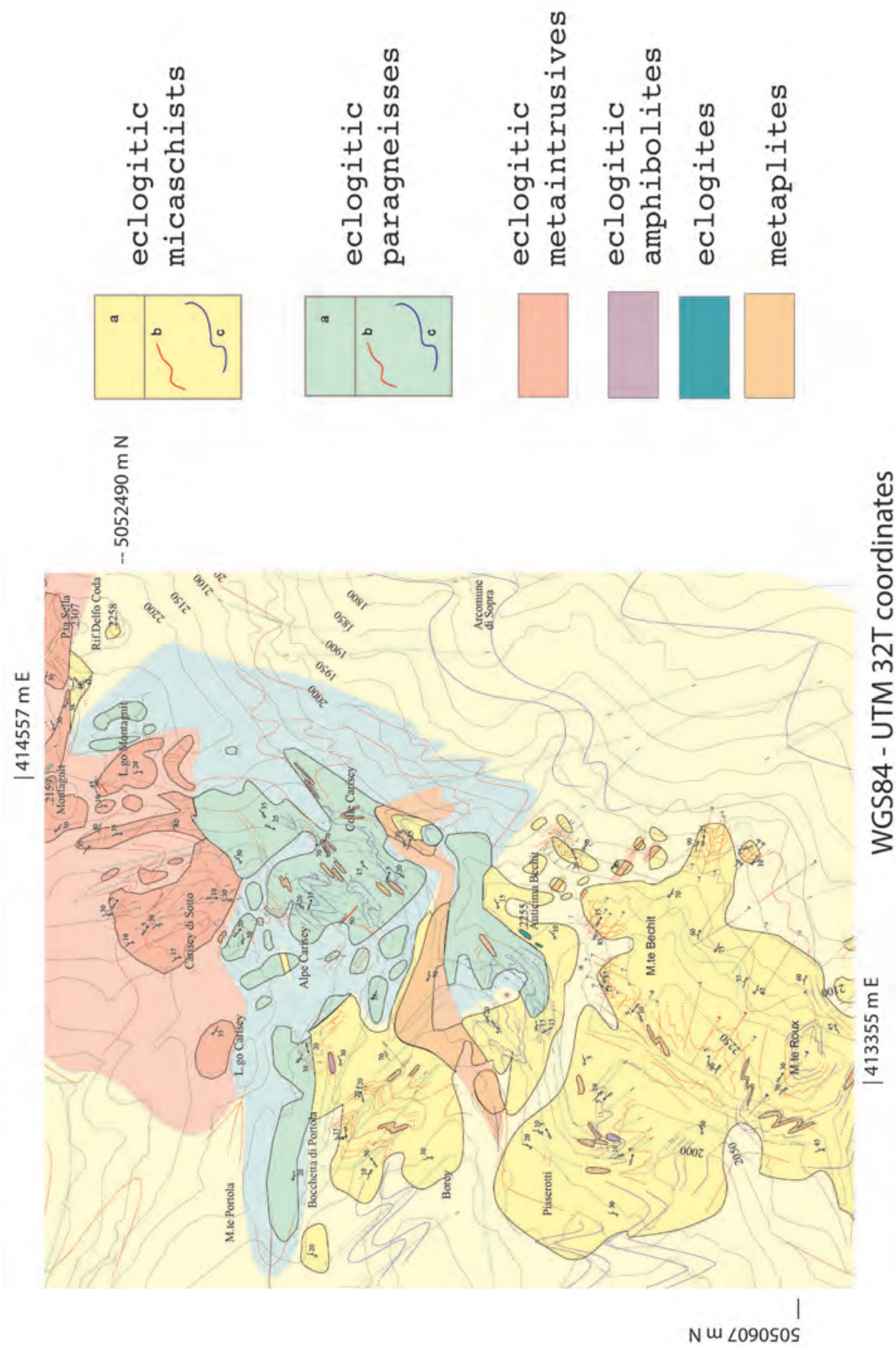


Figure 7A. Portion of the structural map of the Mombarone-Monte Mars area (after Zucali, 2002).

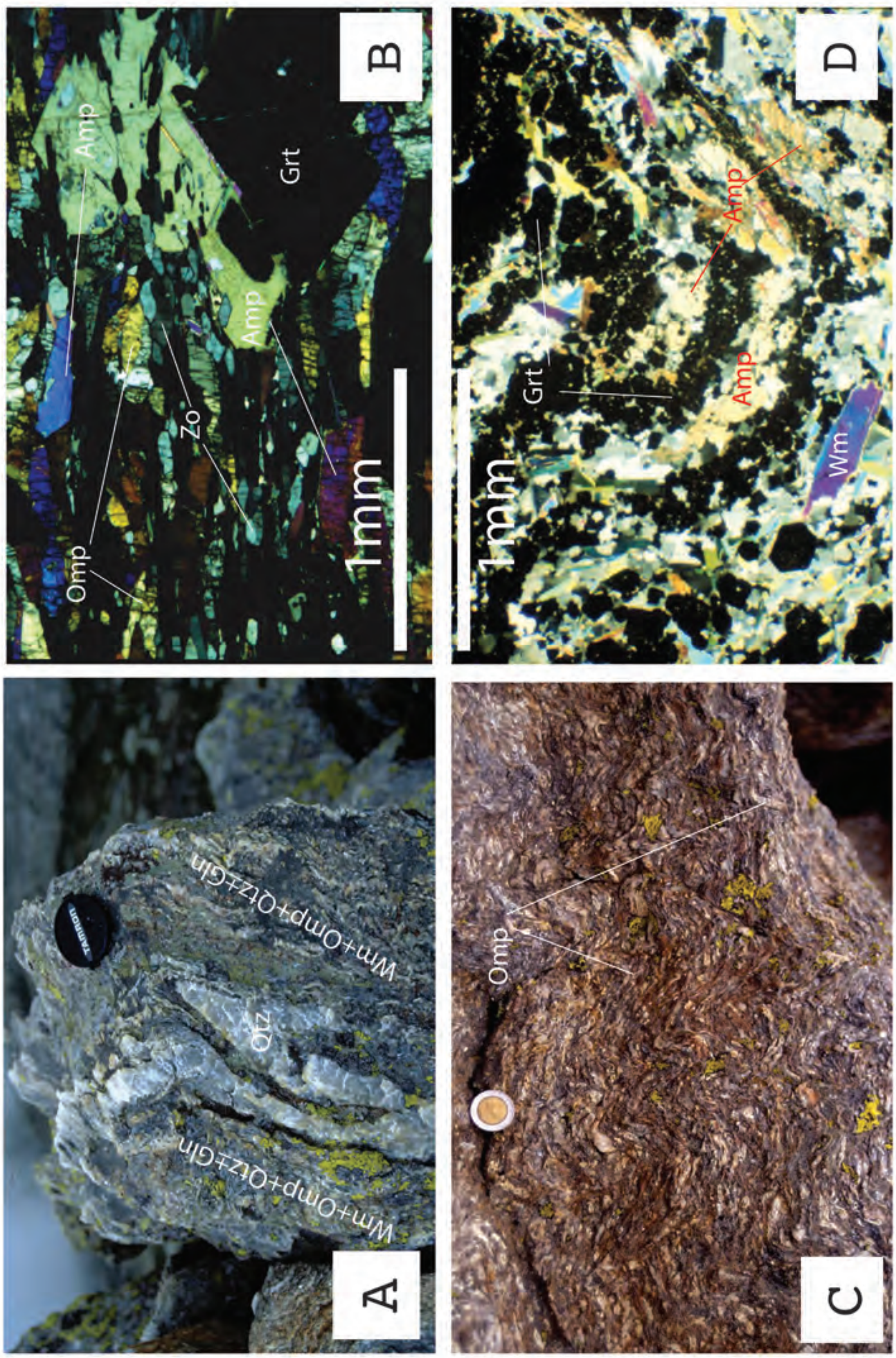


Figure 7B. A) D2 isoclinal folds within paragneisses marked by rootless quartz layers. B) S2 eclogitic foliation within metre-sized eclogite boudins. C) D3 folding within micaschists near the Monte Bechit. D) Photomicrographs of D3 folds showing eclogite facies minerals (garnet + amphibole) marking the folded S2 stable within fold hinges.

map of structural versus metamorphic re-equilibrations made clear that, before attributing a regional significance to structural correlations, it is necessary to widen the analysis to a critical areal extent since structural records in adjacent areas may change, due to broad-scale deformation heterogeneity.

The same integrated structural and petrologic analysis performed in the southern part of SLZ (Figure 6B) individuated a polycyclic tectonic evolution that permitted the exploration of the relationship between degree of fabric evolution and progress of synkinematic metamorphic transformations, for each superposed deformation stage. Here, at the northern margin of the Lanzo Massif numerous metagabbro bodies emplaced during pre-Alpine times in granulitic protoliths of the eclogitised rocks constituting the EMC (Bianchi et al., 1965; Rebay and Spalla, 2001). The main bodies (Corio and Monastero metagabbros)

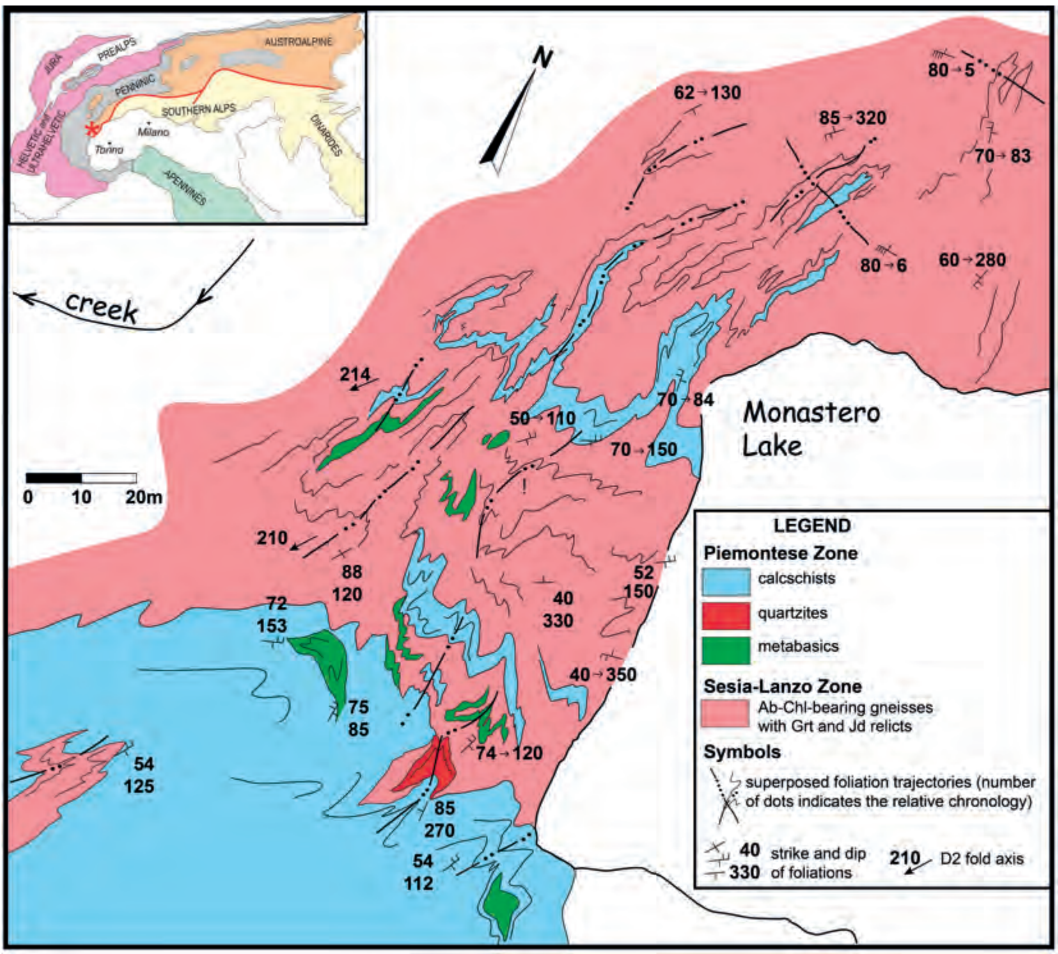


Figure 8. Foliation trajectory map displaying the infoldings between the Austroalpine continental rocks of SLZ (Adria margin) and the Mesozoic metasediments and metaophiolites of PZ (redrawn after Spalla et al., 1983). Original scale mapping 1:200, location on Figure 6.

are exposed close to the boundary with GMC and the metaophiolites of the Piemonte Zone (PZ) and are deformed with the country rocks at least since Alpine times, as shown on detailed foliation trajectory maps (e.g. Figure 8) and regional scale serial cross sections (Figure 9). Rocks of SLZ (GMC and EMC) and PZ underwent together four episodes of deformation, giving rise to a complex regional tectono-stratigraphy resulting from superposed regional scale fold system (see the 3D view of Figure 9). The multi-scale mingling, generating a new cm to km-scale lithostratigraphy between continental rocks and calcschists, is refolded during HP-LT Alpine metamorphism and the successive exhumation-related retrogradation. The earliest deformational structures D1 and D2 are represented by up to ten metre-scale isoclinal rootless folds (Figure 8) and the metamorphic mineral assemblages marking successive foliations indicate that all rock units

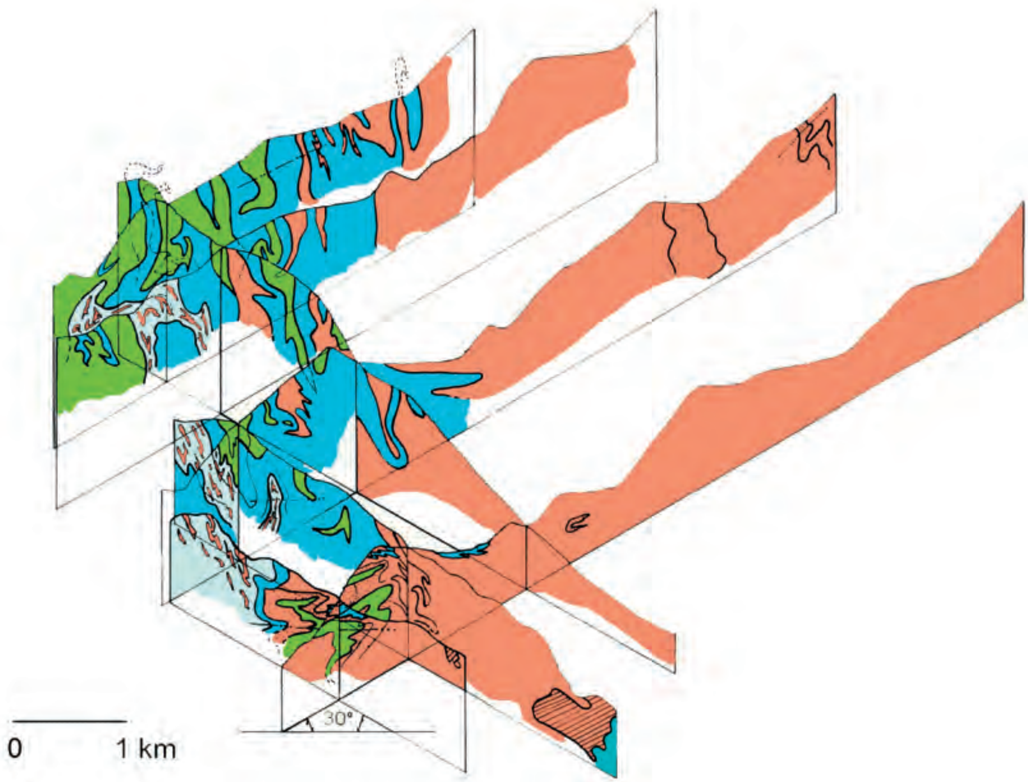
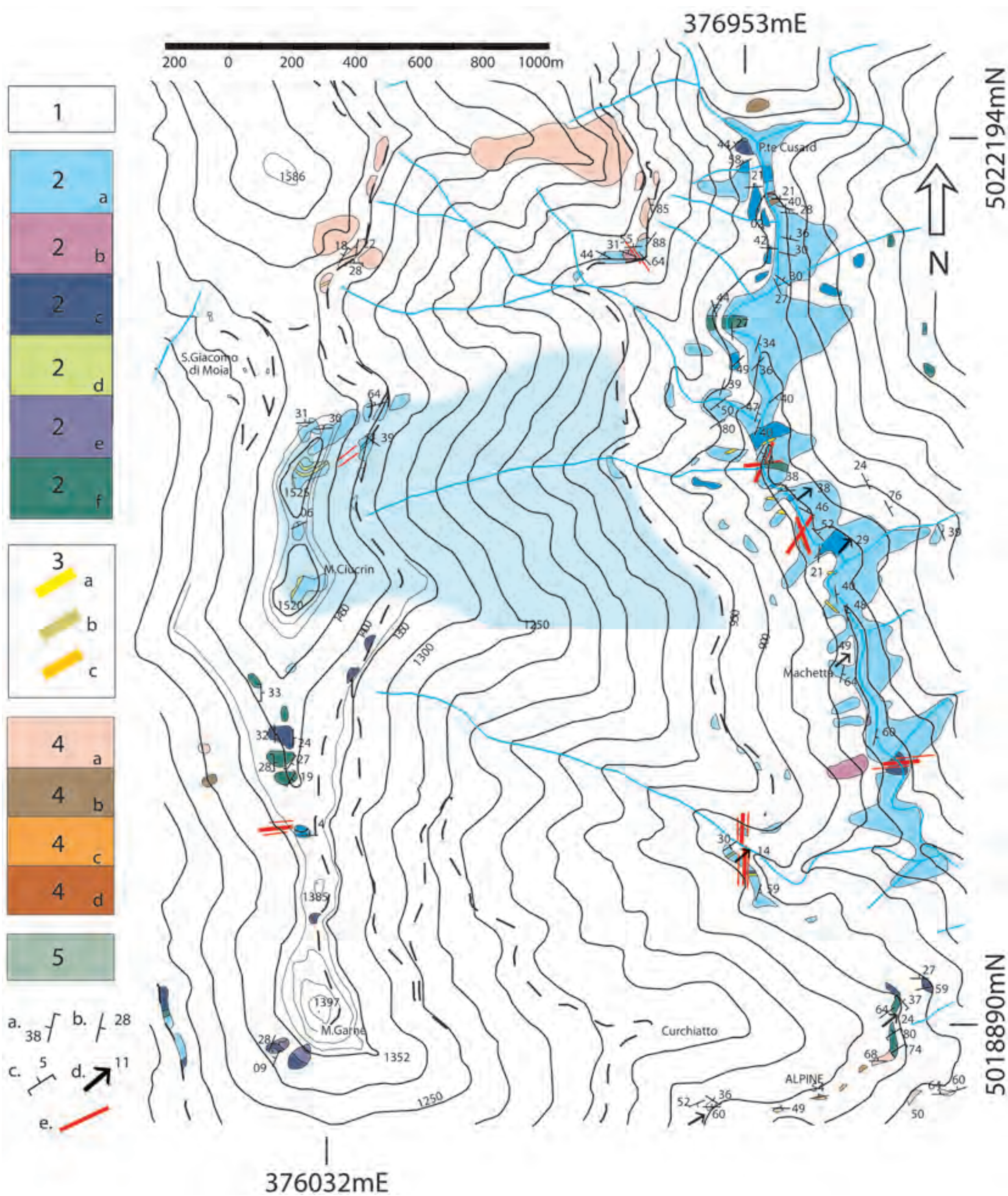


Figure 9. Serial cross sections across the Southern boundary between the Sesia-Lanzo Zone and the Piemonte Ophiolite Zone and related metasediments (Lanzo Valley, Piemonte; location on Figure 6) to facilitate the 3D view of the superposed regional scale fold system (redrawn after Spalla et al., 1983). The multi-scale mingling, generating a new cm to km-scale lithostratigraphy between continental rocks and calcschists, is refolded during HP-LT Alpine metamorphism and the successive exhumation-related re-equilibration. Kilometre-scale superposed folds represented on the cross-sections are coherent with the geometric outline synthesised on the more detailed scale form surface map of Figure 8. Legend corresponds to that of Figure 8, with the addition of dotted orange (= metasediments with HT pre-Alpine relicts), black stripped orange (= retrogressed gluaucophanite), turquoise (= glaucophanite), light blue with orange lenses (= calcschists with thin layers of albitic gneisses).

experienced an early eclogite facies imprint, followed by re-equilibration under blueschist facies conditions. Finally they were widely re-equilibrated under greenschist-facies conditions during the last two deformational episodes, related to development of D3 and D4 structures (Spalla et al., 1983). Structural analysis evidenced that metagabbros (Figure 10A) are deformed by a pervasive foliation occupying around 90% of the total volume (Figure 10B) defined by high-pressure assemblages (glaucophane, chloritoid, garnet, rutile, epidote + omphacite, paragonite; Rebay, 2003). Deformation is heterogeneous at the outcrop scale, and large portions of the metagabbro, wrapped by a network of high-pressure mylonites, display tectonitic to coronitic fabrics (Figure 10B). Within the least deformed domains a series of textural and mineralogical relics still exist, with superposed structures and successive assemblages, resulting from the complex pre-Alpine evolution, from the emplacement of the gabbro body in the deep crust to its re-equilibration under granulite facies conditions (Rebay and Spalla, 2001). Late textural and mineralogical evidences point to the exhumation of the gabbro to near surface conditions, from granulite facies, followed by amphibolite- and then greenschist-facies conditions. Andesitic dykes with chilled margins, intruded in the gabbro (Figure 10B). Mineral and structural records of the prograde evolution to HP conditions are also preserved in less deformed volumes in the metagabbro and its surrounding rocks (the prograde Alpine evolution of the metagabbro and its exhumation are described in Rebay and Messiga, 2007); re-equilibration related to the exhumation of the gabbro body is confined to discrete shear zones, involving

Figure 10A. Corio and Monastero metagabbros from the Southern Sesia Lanzo Zone. Detail of the original 1:10.000 drift and solid map (here reduced from Rebay, 2003). Legend: 1 - quaternary cover and detritus. 2 - Metabasic rocks (Metagabbros). a - Tectonitic metagabbros (pervasive S2), with Gln and Grt ± Ap ± Rt. Plagioclase microdomains are characterised by Ep ± Cld ± Wm ± Grt ± Gln whereas mafic minerals microdomains (clinopyroxene, orthopyroxene or amphibole) by Gln ± Grt. Locally abundant Gln ± Grt or Tr ± Ab veins. b - Little deformed gabbronorites and Fe-gabbronorites lenses with gabbroic, cumulitic, or granoblastic textures, consisting of Opx, Cpx, Pl (labradoritic), brown Amp ± Bt ± Ap ± Opq ± Rt. Pre-alpine, up to millimetric, Cl-Amp and Chl rich veins. c - Metagabbros with a mylonitic Gln foliation up to hundreds of metres wide. Granoblastic Gln and Grt ± Ep ± Rt. Often showing banded textures. d - Dark-green amphibolite bands displaying gabbroic, cumulitic, or granoblastic textures, mainly made of dark green tremolitic-actinolitic Amp, Grt ± Opq ± Ap. Tr may be cut by Cl-Amp veins (M. Ciucrin). e - Coronitic metagabbros. Mafic minerals microdomains are now Gln with Ep and Grt + Qz inclusions. On plagioclase microdomain Ep, Gln and Wm are found. Primary igneous textures are represented by bands and lenses of variable grain size and variable modal mineral composition. f) Mylonitic metagabbros with green tremolitic Amp, Chl, and Ab and Gln + Grt relics. Ab often overgrows the foliation defined by iso-orientated Chl and Amp. 3 - Foliated metadykes of different composition: a) Pegmatites with flaser to mylonitic textures (Ep, Jd, Gln, Wm, Grt). b - Leucocratic dykes, andesitic to dacitic in composition, with mylonitic textures (Qz, Jd with Omph rims, Phe, Grt and Gln). c - Andesitic dykes with porphyric textures. Qz porphyroclasts preserving bay structures and allanite. Ground mass made of Ep, Gln, Jd + Wm and Qz. 4 - Gneiss of the Sesia-Lanzo Zone. a) Paragneiss with intercalations of ortogneiss with Kfs relics and intercalations of Wm, Qz and Pl micaschists characterised by Phe, Grt, Ep ± Ctd ± Jd ± Gln assemblages. b - Gneiss with Qz, Kfs, Pl, Grt, Cd, Sill, Bt, sometimes eclogitised (Ctd, Gln, Grt), in lenses. c - Micaschists with gneiss intercalations. d – Quartzites (Qtz, Wm). 5 - Antigoritic serpentinites and serpentinitic schists of the Ultrabasic Lanzo Massif (Atg, Mag, Chl). Symbols - Pervasive foliation attitudes: a. pre Alpine foliations; b. Alpine-HP foliation (Gln, Grt ± Ctd); c - post HP foliations (Tr, Chl, Ab). d. Fold axes (Alpine-HP) and mineral (Gln) lineations. e. faults and shear planes.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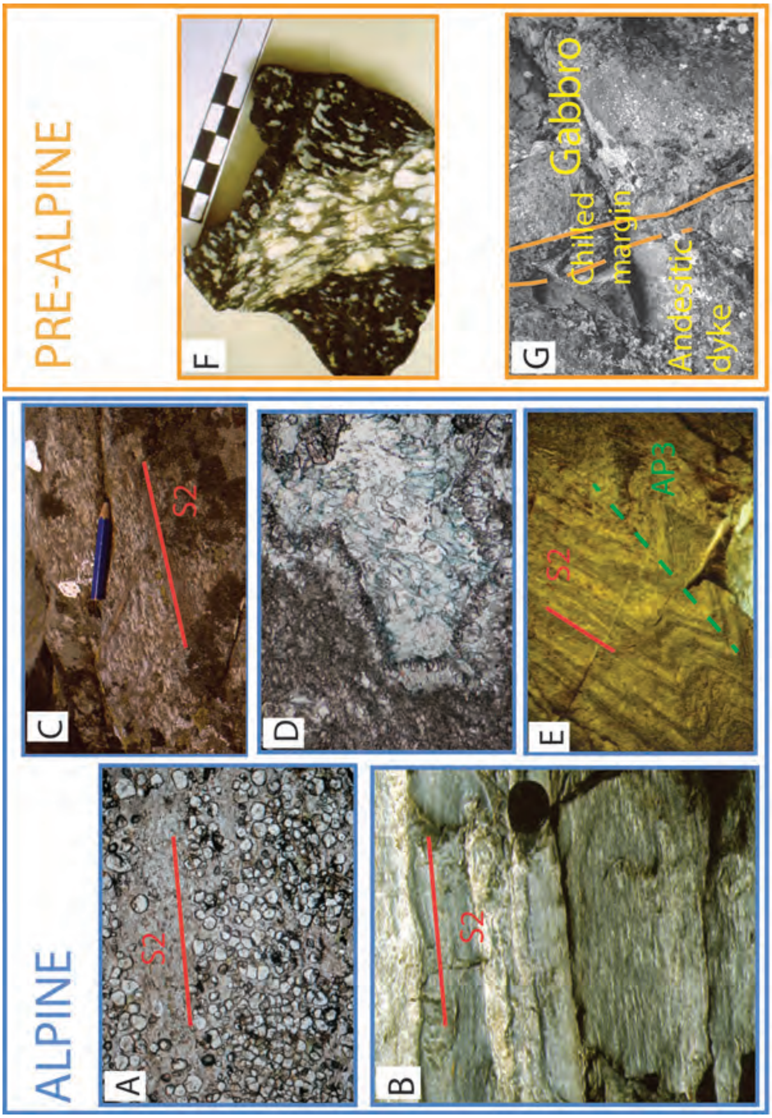


Figure 10B. Micro and meso structures of rocks from the Corio and Monastero region. (A) Garnet-glaucophane mylonite. Glaucophane defines the pervasive S2 foliation. PPL, field of view is 2 cm wide. (B) field photograph of banded gabbro milonite with pervasive S2 foliation. Bands of different colors reflect original igneous banding. Camera lens cap is 5 cm in diameter. (C) Glaucophane-Garnet bearing tectonite. S2 foliation deforms garnet veins. Pencil 4 cm. (D) PPL microphotograph of HP corona texture. Garnet corona delineates original igneous minerals, glaucophane substitutes the mafic mineral domains, garnet, epidote, omphacite substitute original plagioclase. View is 2 cm wide. (E) Greenschist-facies tectonite: S2 foliation is characterised by chlorite, albite, tremolite and kinked by D3 folds. (F) Sheared gabbronorite and "acidic dyke" found in undeformed domains not recording Alpine HP metamorphism. (G) Eclogitised andesitic pre-Alpine dyke intruded in metagabbro with chilled margins, as observed in domains not pervasively affected by D2 deformation.

less that 10% of the gabbro volume, where greenschist-facies mylonites develop (Figure 10C).

Once the less deformed volumes relative to each Alpine main deformation/recrystallisation event are individuated, it is possible to follow in coronites the successive changes of mineral composition related to different equilibration through the complex metamorphic evolution; an example is represented by the compositional changes of amphiboles (Figure 10C) that trace continuously the successive changes in PT conditions. The PT history of gabbro bodies is summarised in Figure 10C, where the successive inferred PT re-equilibration stages (Rebay and Spalla, 2001; Rebay and Messiga, 2007) are also related to the dominant structures/microstructures to which they are associated.

Mechanical and thermal effects of Tertiary pluton emplacement, during Late Alpine times, have been investigated with the same methodology in the central part of SLZ, in correspondence of Biella and Traversella intrusive stocks (Zanoni et al., 2008; Zanoni, 2010; Zanoni et al., 2010; Zanoni, 2015). These two late-collisional Periadriatic Oligocene plutons emplaced in the innermost part of the Sesia Lanzo Zone, post-dating the whole ductile deformation history and record brittle structures. In both cases integrated structural and petrologic analysis allowed to subtract the effects of contact metamorphism going back to explore the Alpine convergence tectonic evolution (Zanoni et al., 2008; Zanoni, 2010; Zanoni, 2015). A good example is that of Traversella pluton and its country rocks, which belong to the EMC, and consist of metapelites and metaintrusives (Figure 11 A,B) that record five ductile deformation stages: the first two (D1 and D2) developed under eclogite facies conditions (Andreoli et al., 1976), as accounted by mineral assemblages marking S1 and S2 foliations (Figure 11C; see details in Zanoni, 2010). Small-scale D3 shear zones found within the aureole postdate these structures and may correspond to those formed under blueschist-facies conditions at M. Mucrone (Zucali et al., 2002). D4 and D5 are fold systems, and D4 is associated with an axial plane foliation marked by greenschist facies minerals (Zanoni, 2010). Contact metamorphism overprinted the subduction-related assemblages. A fine-grained aggregate of contact metamorphic minerals forms in the country rocks (see Figure 11C vs. Figure 11D) generating coronitic fabrics, and ghost pre-intrusive foliations are still visible, even close to the pluton margins. Multiscale structural and petrographic data have been combined on a map showing, in addition to foliation trajectories and mineral assemblages, the different modal amount of contact metamorphic minerals in each lithotypes (Figure 11). A graphic representation of these data reports on map the possible parameters controlling the macroscopic variation of the aureole thickness (amount of white mica in country rocks and relationship between SPO and pluton margin; orientation of dominant foliation in country rocks and pluton margin; amount of mineral phases sensitive to contact metamorphism: see discussion in Zanoni, 2010). In addition, the individuation of four groups of brittle structures, post-dating the ductile deformations and pluton intrusion, and the determination of physical conditions of contact metamorphism indicated the very shallow depth of emplacement (between 7 and 2 km; Zanoni et al., 2010). The same investigation routine applied at the north-eastern margin of the Biella intrusion showed the occurrence of tension gashes sealed by tourmaline-ankerite, and chlorite and epidote slickensides in brittle faults crosscutting both intrusives and country rocks, proving that fluid circulation assisted the late intrusive evolution.

Dent-Blanche Nappe. The DBN is part of the Austroalpine domain (inset Figure 12A) and, as the SLZ, consists of an upper element, formed by lower continental crust rocks, known as the Valpelline Series (VS) and a lower element,

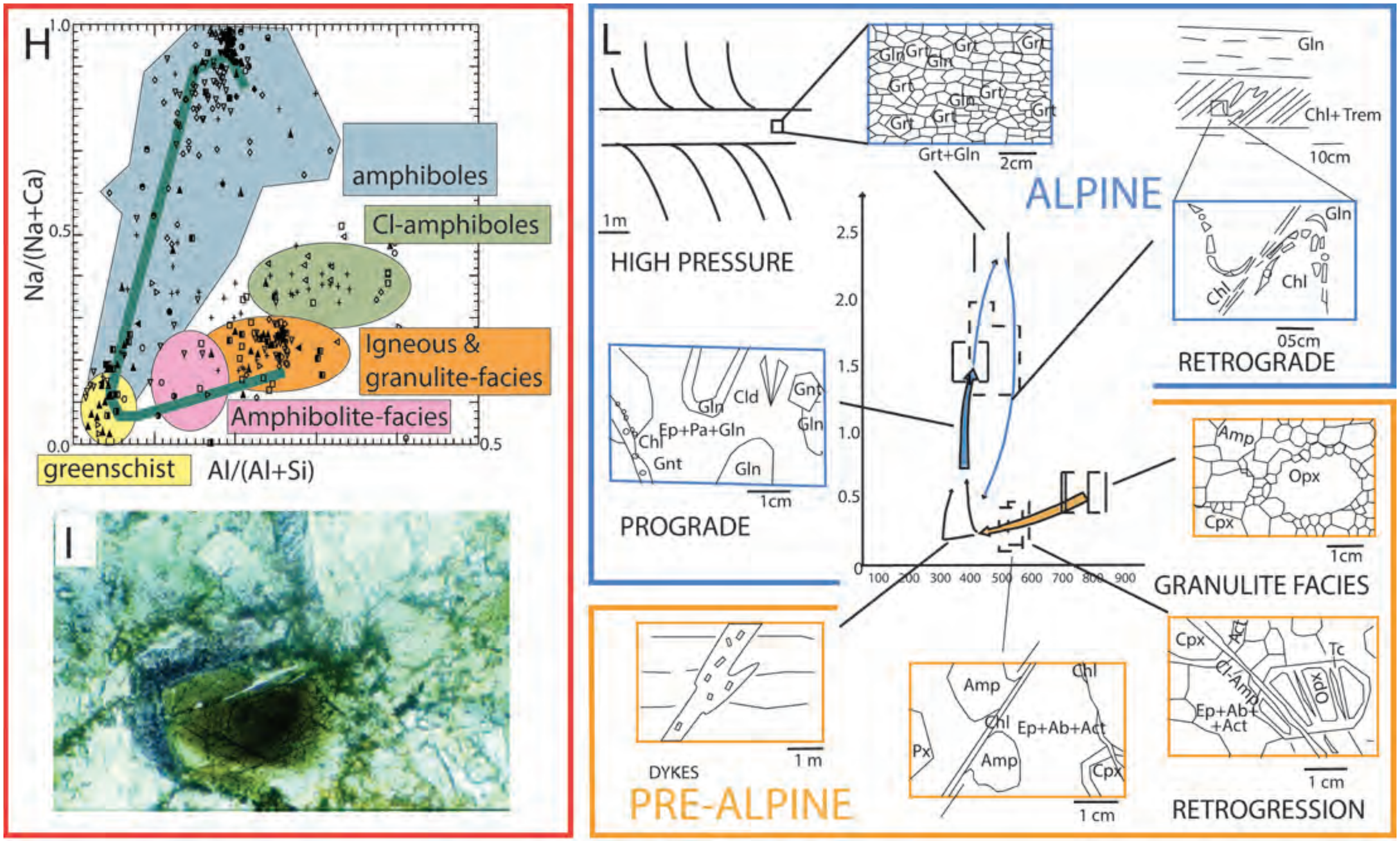
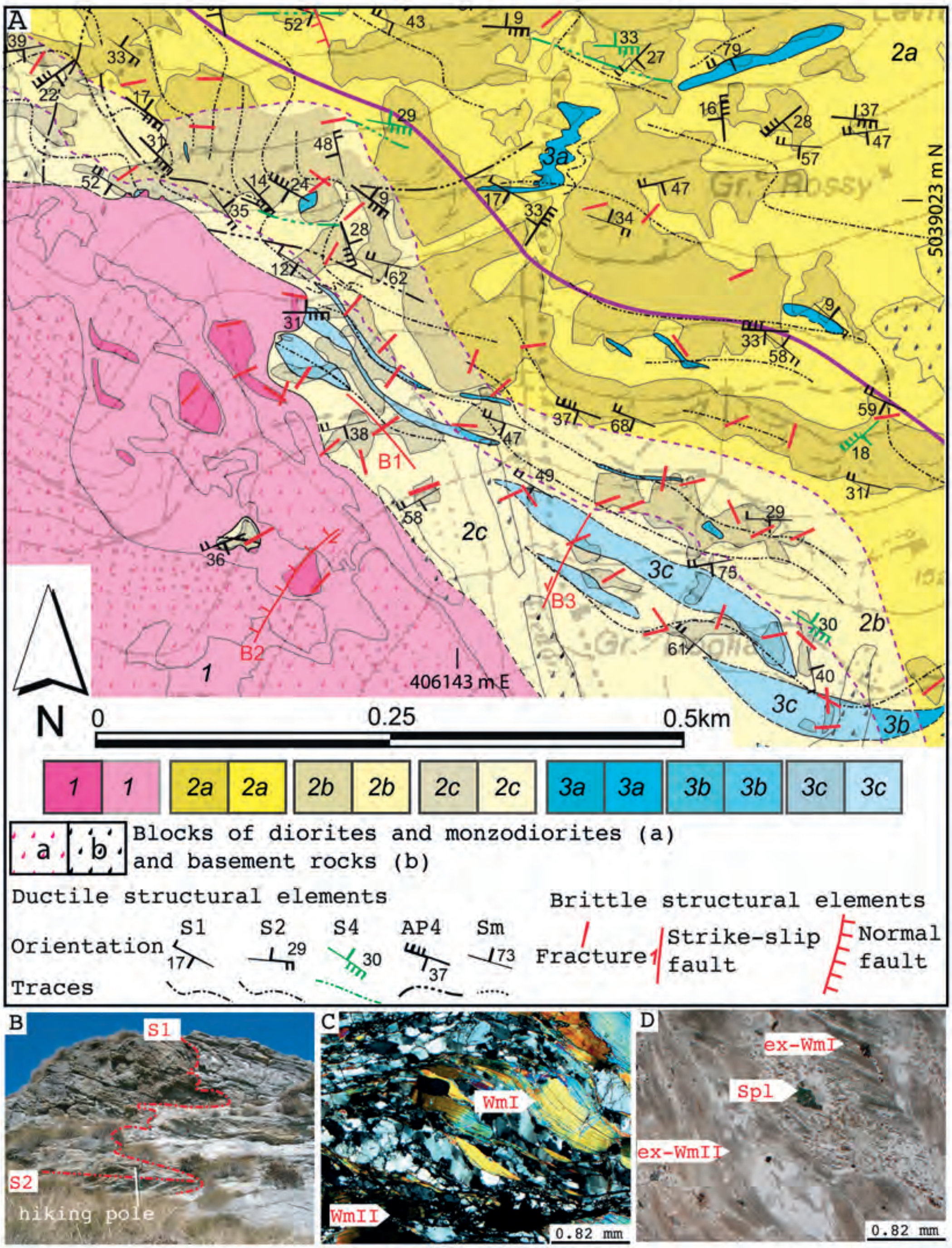


Figure 10C. Relevant mineral chemistry graphs and PT-path from the Corio and Monastero region. (H) Na/(Na+Ca) vs Al/(Al+Si) plot for all amphiboles observed in different microdomains: the compositional variations record changing PT conditions of Corio and Monastero gabbros. (I) photomicrograph in PPL (field of view is approximately 2 cm wide) of a corona texture preserving zoned amphiboles summarising the PT evolution of the metagabbro: pre-Alpine hornblende (core) is mantled by pre-alpine tremolite. A glaucophane rim, then bordered by green amphibole, testifies HP Alpine recrystallisation and subsequent exhumation. (L) PT path of the Corio and Monastero metagabbro, with sketches of different meso- and micro-structures supporting it.

known as the Arolla Series (AS; Argand, 1911). AS is widespread in the North-Western DBN and is mainly formed by Permian acidic and mafic intrusives, associated with minor high-grade gneisses and metabasics. Slivers of Mesozoic metasediments are pinched along a main shear zone, separating DBN into two main tectonic units (DBN s.s. and Mont Mary) and trending NNE-SSW (Canepa et al., 1990); relics of Norian foraminifera and algae have been detected in these metasediments (Ciarapica et al., 2010). Along the same horizon are entrapped marble slivers recording a Palaeozoic HT metamorphic imprint, indicating that pre-Alpine metasediments have been pinched along this major shear zone (Manzotti et al., 2012; 2014). The VS lower continental crust rocks of the upper elements are closely similar to those of the Ivrea Zone (Southern Alps; Stutz and Masson, 1938; Diehl et al., 1952; Manzotti and Zucali, 2013). The pre-Alpine metamorphic evolution was accomplished under a high T/P ratio, associated with gabbro and granitoids emplacement (Diehl et al., 1952; Dal Piaz et al., 1977; Pennacchioni and Guermani, 1993; Monjoie et al., 2005; Roda and Zucali, 2008; Baletti et al., 2012).

The Alpine metamorphic history of the DBN is less constrained with respect to that of the widely eclogitised SLZ. Where Alpine HP mineral assemblages have been described they indicate metamorphic peak conditions compatible with blueschist-facies and interpreted, on the basis of radiometric data, as 48-45 Ma old (Ayrton, et al., 1982; Canepa et al., 1990; Gardien et al., 1994; Kienast and Nicot, 1971; Pennacchioni and Guermani, 1993; Roda and Zucali, 2008).

The lower element is mainly constituted by metaintrusives (granites to gabbros), with protoliths of Permian age (289±2 Ma; Bussy et al., 1998), and remnants of their country rocks (metric lenses of biotite-bearing gneisses and amphibolites), which may have acted as repository of the pre-Permian structural and metamorphic relicts (Diehl et al., 1952; Ayrton et al., 1982; Pennacchioni and Guermani, 1993). Here, undeformed cores preserving primary igneous textures are wrapped by ten-metres- to km-thick mylonitic horizons of Alpine age (Pennacchioni and Guermani, 1993; Roda and Zucali, 2008; 2011) that evolved from blueschist -to greenschist-facies conditions. Similar shear zones also separate the Arolla Series from the Valpelline Series and the Combin Zone (Angiboust et al., 2014; Ayrton et al., 1982; Manzotti et al., 2014; Roda and Zucali, 2008; 2011). The Permian intrusive Mont Morion Complex (MMC) has an undeformed core that allows the investigation on the preserved primary features of the intrusive body and, consequently, the relationships between protolith chemistry, textures, mineral compositions and localization of metamorphic transformations (Figure 12B). With this aim a map, characterised by the synoptic representation of tectonic and metamorphic data integrated with microstructural analysis, (Roda and Zucali, 2008; 2011) synthesises information on rock mineral composition, type of planar and linear fabrics associated with their mineralogical support and relative chronology of superposed structures. All these data are added to a standard lithological map together with the distinction of three classes of fabrics (Coronitic, Tectonitic and Mylonitic), allowing the identification of finite strain states and fabric gradients. It is worth recalling that: coronitic textures are formed during metamorphic reactions associated to limited granular scale deformation; in tectonitic textures newly grown metamorphic minerals mark progressive foliations; mylonitic texture develop in correspondence of localised high strain domains (e.g. Lardeaux and Spalla, 1990). The undeformed core is dominated by coronitic metamorphic textures, developed after igneous assemblages, while in the more external volumes of the MMC Alpine metamorphic assemblages mark tectonitic and widespread mylonitic fabrics (Figure 12). Such structural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0
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0.5km
Blocks of diorites and monzodiorites (a)
and basement rocks (b)
Ductile structural elements
Orientation
S1
S2
S4
AP4
Sm
Traces
Brittle structural elements
Fracture
Strike-slip fault
Normal fault
B
S1
S2
hiking pole
C
WmI
WmII
0.82 mm
D
ex-WmI
Spl
ex-WmII
0.82 mm

information determined sample selection for the microstructural analysis aimed at thermo-barometrical estimates and has been driven by the fabric gradient distribution that in addition allowed correlation between the degree of fabric evolution and metamorphic transformation. The reconstructed structural and metamorphic evolution (Figure 12; Roda and Zucali, 2008) is characterised by two pre-Permian re-equilibration stages, only recorded in the country rocks, and consisting of two superposed foliations, S1 and S2, crosscut by the Permian intrusive and therefore of probable Variscan age. The two foliations are marked by assemblages indicating HT amphibolite-facies conditions, compatible with partial melting, as suggested by the migmatitic layering underlying S2. During D3 Permian intrusives were emplaced at a depth of 10-20 km, under high thermal regime, successively re-equilibrating under greenschist-facies conditions (D4). D5 and D6 groups of structures are associated with the development of coronitic, tectonitic and mylonitic fabrics as shown in Figure 12. Minerals marking D5 tectonitic to mylonitic fabrics indicate that these latter formed under blueschist-facies conditions and are preserved in domains wrapped by the most pervasive fabric S6, associated with greenschist-facies mineral assemblages in all lithotypes.

Summary and discussion.

Sesia-Lanzo Zone.

Summing up, the investigative approach followed in the examples allowed the reconstruction of a complex polycyclic tectono-metamorphic history, as well as conclusions about deformation-metamorphism relationships in crystalline basements and critical consequences in exploiting the rock memory in polydeformed and polymetamorphic terrains.

These results are easily extensible to many other portions of the SLZ where the application of structural and petrographic integrated analysis started in the early 80s (see Gosso et al., 2013 for a recent review) and supported the selection of critical samples useful, as shown in the examples, to infer PT conditions under which superposed fabrics developed, and finally to determine the PTdt evolutions, necessary to discriminate tectono-metamorphic units.

During pre-Alpine times several structural and metamorphic re-equilibration stages have been detected. They occurred under granulite- to amphibolite- and then to greenschist-facies conditions and these variably re-equilibrated granulites are associated with Permian granitoids and gabbros. The latter underwent a similar pre-Alpine P-T evolution. The high-thermal regime characterising the whole pre-Alpine evolution of SLZ has been interpreted, for the first-time, as induced by continental lithospheric

Figure 11. A) Extract from the map of northeastern margin of Traversella Pluton (Zanoni, 2010). Deep and light colours indicate rock outcrops and interpretation of lithostratigrapy below Quaternary deposits, respectively. 1 = Igneous rocks of Traversella pluton, mainly diorites; 2 and 3 = Eclogitic Micascists Complex and its transformed rock-types for contact metamorphism: 2a = Coarse grained metapelites that within the violet line (boundary of thermal aureole) contain up to 30% of contact metamorphic minerals; 2b = Metapelites containing up to 60% of contact metamorphic minerals; 2c = Metapelites containing more than 60% of contact metamorphic minerals; 3a = Coarse grained meta-aplites; 3b = Meta-aplites containing up to 60% of contact metamorphic minerals; 3c = Meta-aplites containing more than 60% of contact metamorphic minerals. For more details see Zanoni (2010). B) Boundary between meta-aplites and metapelites transposed into S1 and folded during the development of S2. C) WmI and WmII in pristine metapelites preserved outside contact aureole. Crossed polars. D) WmI and II in transformed metapelites replaced by a coronitic fine-grained contact metamorphic assemblage mainly consisting of Bt and Pl. Plane polarised light. Mineral abbreviations are after Whitney and Evans (2010).

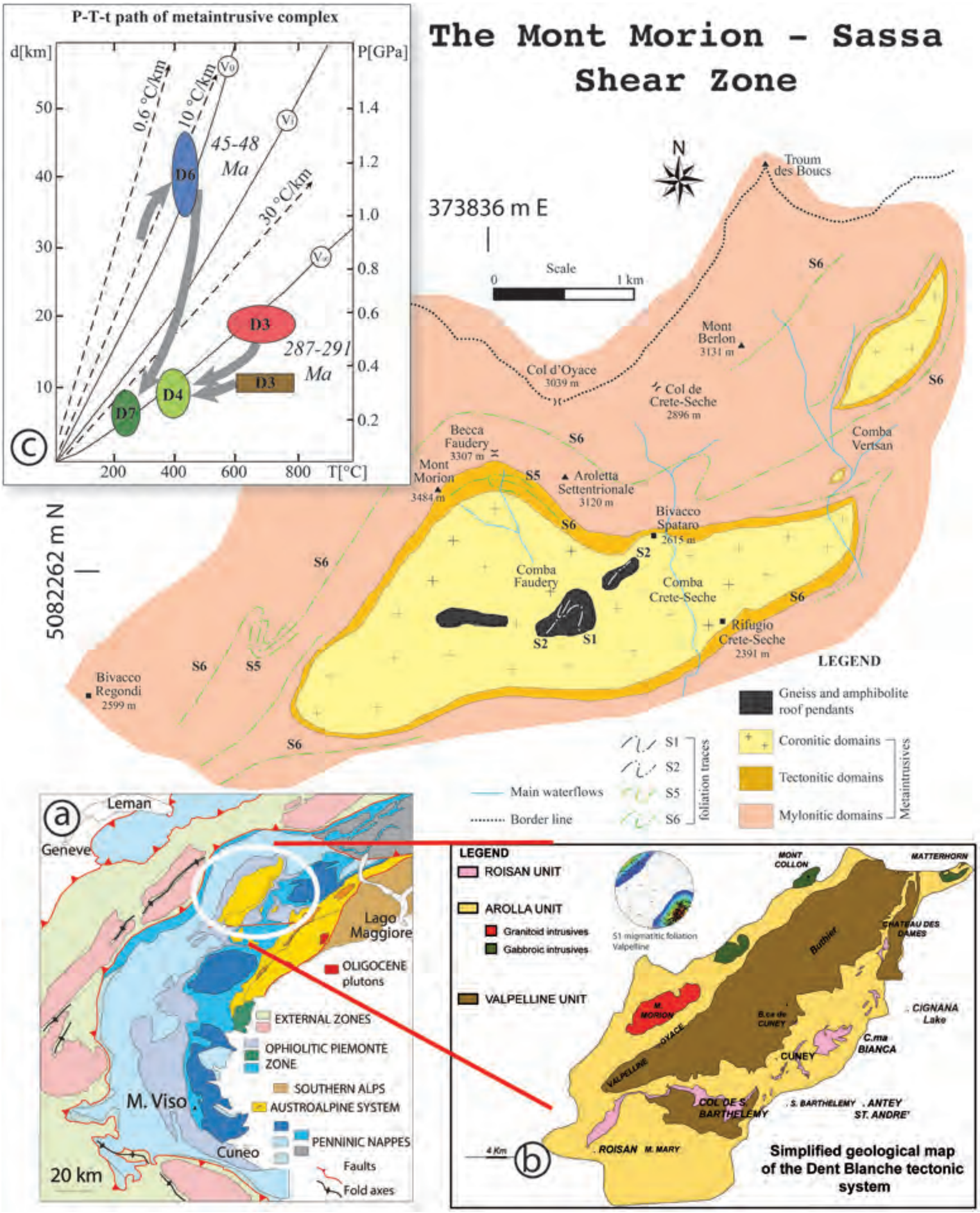


Figure 12A. Map of the Mont Morion - Sassa shear zone (Dent-Blanche Nappe), Austroalpine of Western Alps (Roda and Zucali, 2011). The degree of deformation decreases from mylonitic (pink) to coronitic (yellow) domains where magmatic structures and some roof pendants of country rocks are still visible. After the magmatic stage (D3), three main deformation stages characterise the pre-Alpine (D4) and Alpine (D5-D6) evolution of the complex. Insets: a) localises the Dent Blanche in the Western Alps; b) distinguishes internal units of Dent Blanche; c) shows the P-T-t path of the Mont Morion - Sassa metaintrusives.

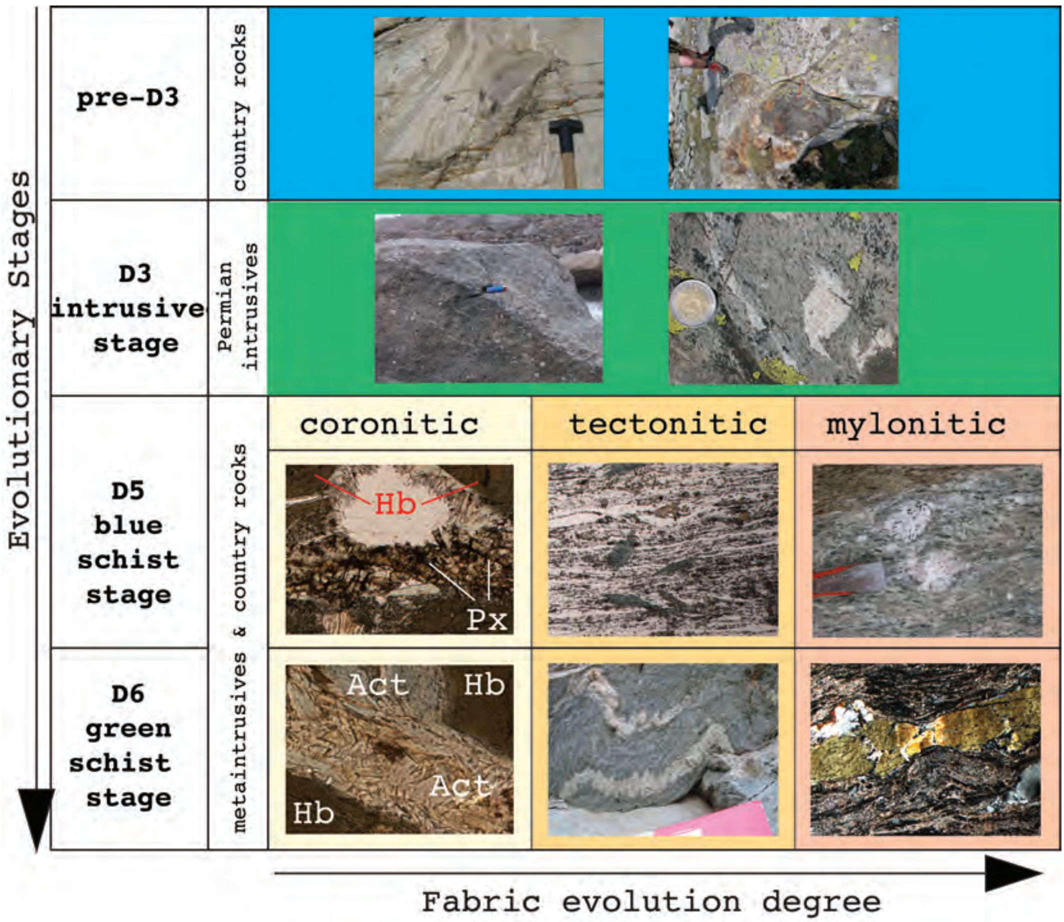


Figure 12B. Fabric evolution characterising the metaintrusives and the country rocks of the Mont Morion complex is reported as a function of the evolutionary stages. The pre-intrusive stage is expressed by a migmatitic foliation of the pre-intrusive country rocks. In the intrusive stage (D3) magmatic structures characterise the intrusives. The Alpine metamorphic re-equilibrations accompaining the deformation stages D5 and D6 evolve from coronitic in low-deformed domains up to mylonitic in high-deformed domains.

thinning during Permian times, as successively suggested for other portions of the Austroalpine and Southalpine domains in Central and Eastern Alps (Lardeaux and Spalla, 1991; Diella et al., 1992; Schuster et al., 2001; Marotta and Spalla, 2007; Schuster and Stüwe, 2008; Marotta et al., 2009).

The Alpine evolution is characterised by polyphasic deformation under blueschist- to eclogite-facies conditions followed by re-equilibration, during decompression, under blueschist to successive greenschist-facies conditions. The different sequences of superposed deformation and metamorphic imprints, inferred in the examples, are detectable also in other parts of Sesia-Lanzo Zone, both Eclogitic Micaschists Complex and Gneiss Minuti Complex (see Roda et al., 2012; Gosso et al., 2013). The contrasted

P-T-t paths accomplished under high P/T ratio, the occurrence of lawsonite as a constituent of assemblages of the P-prograde and the P-retrograde trajectories (Zucali and Spalla, 2011, and references therein), and radiometric ages determined from high-pressure mineral assemblages, span over a wide time-interval in adjacent portions of SLZ (Roda et al., 2012; Lardeaux, 2014 and refs. therein). All these arguments point to consider SLZ as a tectonic assemblage of different Alpine TMU, forged in the still active subduction system, before the emplacement of the Tertiary intrusive stocks. For these reasons, various authors with different models (Meda et al., 2010; Rubatto et al., 2011; Roda et al., 2012), proposed multiple burial-exhumation cycles to justify several stages of re-equilibration under eclogite facies conditions during Alpine subduction. Data related to the metamorphic peak conditions estimated for SLZ rocks indicate the existence of a thermally depressed environment compatible with active oceanic subduction (e.g. Roda et al., 2012), also maintained during the exhumation, as accounted by the blueschist re-equilibrations characterising the majority of exhumation paths (Lardeaux, 2014 and refs. therein). The later brittle- ductile faulting postdating the Oligocene emplacement of Biella and Traversella igneous stocks, together with contact metamorphic assemblages replacing late exhumation-related greenschist facies parageneses, indicated that SLZ was already exhumed at shallow structural levels at ~ 30 Ma (Zanoni et al., 2008; 2010; Zanoni, 2010).

In each example the dominant metamorphic imprint, associated with regional metamorphism, corresponds, in evolved tectonites or mylonites, to that of the most pervasive fabric at the regional scale, with the only exception of the contact metamorphism at the margin of Tertiary intrusive stocks, where ΔT and fluid activity are the main reaction catalysts. The careful detection of the less-deformed domains through detailed structural mapping is critical to reconstruct the sequence of the previous stages of structural and metamorphic re-equilibrations to fully enjoy the rock memory for reconstructing the past geodynamic evolution of crystalline basements. The detailed meso and micro-structural analysis made possible to unravel the complex pre-Alpine and Alpine evolutions of SLZ detecting the mineralogical support of progressively developing fabric elements in different whole rock compositions, as metapelites, metabasites and metaintrusives (from metagranites to metagabbros), before a confident regional scale correlation. As shown in the examples, all along SLZ, both in EMC and GMC, deformation is heterogeneous and strain partitioning is testified, during each deformation and metamorphic re-equilibration phase, by the juxtaposition in adjacent volumes of coronitic, tectonitic and mylonitic textures. Result is synthesised in Figures 13A and 13B showing the distribution of dominant metamorphic imprints, related to degree of fabric evolution (coronitic, tectonitic or mylonitic) in metabasites, metapelites and metaintrusives from EMC and GMC during Alpine and pre-Alpine evolution. As pointed out, pre-Alpine stages are better recorded within rocks that accumulated lower strain during Alpine re-equilibrations, that reveal metamorphic (basic and acid granulites or amphibolites) or igneous protoliths (granitoids and gabbros). Opx + PlI + GrtI + HblI + Ilm + Qtz ± BtI (mineral abbreviations are after Whitney and Evans, 2010) is the oldest metamorphic assemblage in the basic granoblastic granulites, which are frequently crosscut by shear bands in which well oriented AmpII and BtII with Pl and ribbons quartz developed syn-kinematically during re-equilibration under amphibolite-facies conditions. On the contrary acidic granulites show granoblastic and foliated textures, both tectonitic and mylonitic. The early assemblage is Qtz ± Kfs + Pl + GrtI + Sill + BtI + Ilm ± Crd; coronitic BtII, ± CrdII and Spl rim GrtI, and fibrolitic Sill marks the shear planes, forming the successive assemblage that is therefore BtII + Sill + Qtz + Kfs ± CrdII ± Spl. Pre-Alpine amphibolites are coarse grained rocks with both granoblastic and foliated textures and bear the older assemblage AmpI + PlI ± BtI + Ilm + Rt + Qtz, followed by AmpII + BtII + PlII. In all the rocks preserving this pre-Alpine evolution the eclogite facies Alpine overprint is coronitic. The metaintrusives that were not deformed during the Alpine structural development show various degrees of coronitic eclogitic transformations testified by Grt + Phe + Rt + Jd + Zo + Qtz in metagranitoids, or Grt + Omp + Na-CaAmp + Czo + Rt + Phe + Mg-Chl + Qtz in metatonalites and Grt ± Omp + Na-CaAmp/Gl + Czo + Rt + Phe ± Cld + Qtz in metagabbros. The tectonitic foliation of the metagranitoids is defined by Phe + Opq while lithons are occupied by Omp + Grt + Zo/Czo + Qtz, whereas in metagabbros Gl ± Phe and Grt trails mark the HP foliation. Metabasites in which Alpine reworking is pervasive (i.e. Alpine tectonites and mylonites) show widespread eclogitic re-equilibration (Grt + Omp + Na-CaAmp ± Gln + Rt + Zo/Czo ± Mg-Chl + Phe/Pg) and local greenschist syn-tectonic overprint in the EMC (Fe-Chl + Ab + Green-Amp + Czo + Ttn + Ms), whereas in GMC the dominant foliation is marked by greenschist facies mineral assemblages, syn-kinematic with late groups of Alpine structures, and eclogitic parageneses are preserved in less-deformed domains together with Early-Alpine fabrics. In eclogites with coronitic texture rare relicts of brown Hbl are preserved in the Na-CaAmp cores. Metapelites generally show tectonitic textures and the continuous Alpine eclogitic foliations are defined by Phe, Omp, Gln, Grt, Rt, Qtz and Zo/Czo; where the foliation is spaced Omp + Gln + Grt mainly occur in the lithons. Thin quartzites interlayered within metapelites have mylonitic foliation defined by Phe + Opq, while Ky + Grt + Cld + Qtz occur in the lithons. Reconstructed pre-Alpine and Alpine P-T-t-d paths (as those commented in the examples), compared with the respective syn-tectonic transformations, provide a synoptic representation of syn-metamorphic textures vs. protoliths in each P-T stage. When the compatibility of mineral assemblage located in low strain domains, in tectonitic and mylonitic textures is ensured, even the static transformation should be regarded as syn-tectonic at the regional scale. The reconstructed matrix of rocks can now be compared with the expected petrostructural rock types following the formulation of Eq. 2 in the Method of Analysis paragraph. In the Sesia-Lanzo Zone three fabric types have been recognised (i.e. coronite, tectonite, mylonite) developed during 4 metamorphic stages (i.e. pre-Alpine: granulite-amphibolite; Alpine: eclogite, blueschist, greenschist) for metapelites and metabasites, where no protoliths have been recognised. Metaintrusives, Permian in age, are characterised by 2 protoliths but only the 3 Alpine metamorphic stages. Metapelites and metabasites record 12 rock types over the 256 possible petrostructural rock types, solving Eq. 2 for k=3 and n=4, while Permian metaintrusives 10 over the 64 expected, solving Eq. 2 for k = 3 and n = 3.

Dent-Blanche Nappe. The integrated structural and petrologic investigation of the MMC produced a P-T-t-d path characterised by a low P/T ratio (Figure 12A) during the emplacement of Permian intrusives, interpretatively related to the Permian-Triassic lithospheric thinning (Roda and Zucali, 2008), in agreement with the time span from 250 to 290 Ma of pre-Alpine gabbros and granites absolute ages (Dal Piaz et al., 1977; Bussy et al., 1998; Monjoie et al., 2002) that may be considered as a lithospheric marker for a post-Variscan thinning, possibly corresponding to the Permian-Triassic thinning heralding the neo-Tethys opening. Successive exhumation and cooling of these rocks from the

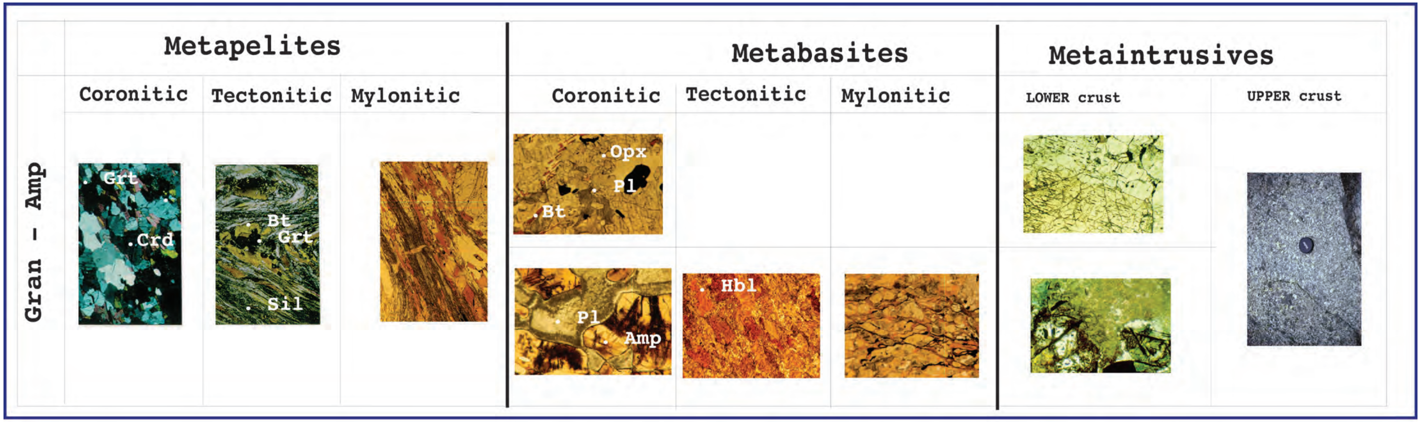


Figure 13A and B. Fabric matrix for the EMC and GMC of the Sesia Lanzo-Zone. This matrix reports field and microscopic examples representative of the rock types expected in accordance with the combination of three fabric types (coronite = C, tectonite = T, mylonite = M) with each of the Alpine metamorphic transformation stages. The relative mathematical formulation of all possible cases is explained in the text and represented theoretically in figure 5. Three main protolith compositions were chosen: pelite, basite, intrusive (basic or acidic). Within the Alpine evolution, dominant (red) vs. exclusive (yellow) fabrics were tentatively and quantitatively described. Dominant fabrics can occur in EMC or GMC but can also be present in the other unit: on the contrary exclusive fabric cannot occur in the other unit. Metamorphic conditions (i.e. facies) are also shown: Gran=granulite, Amp = amphibolite, Eclo = eclogite. See detail explanations in the text.

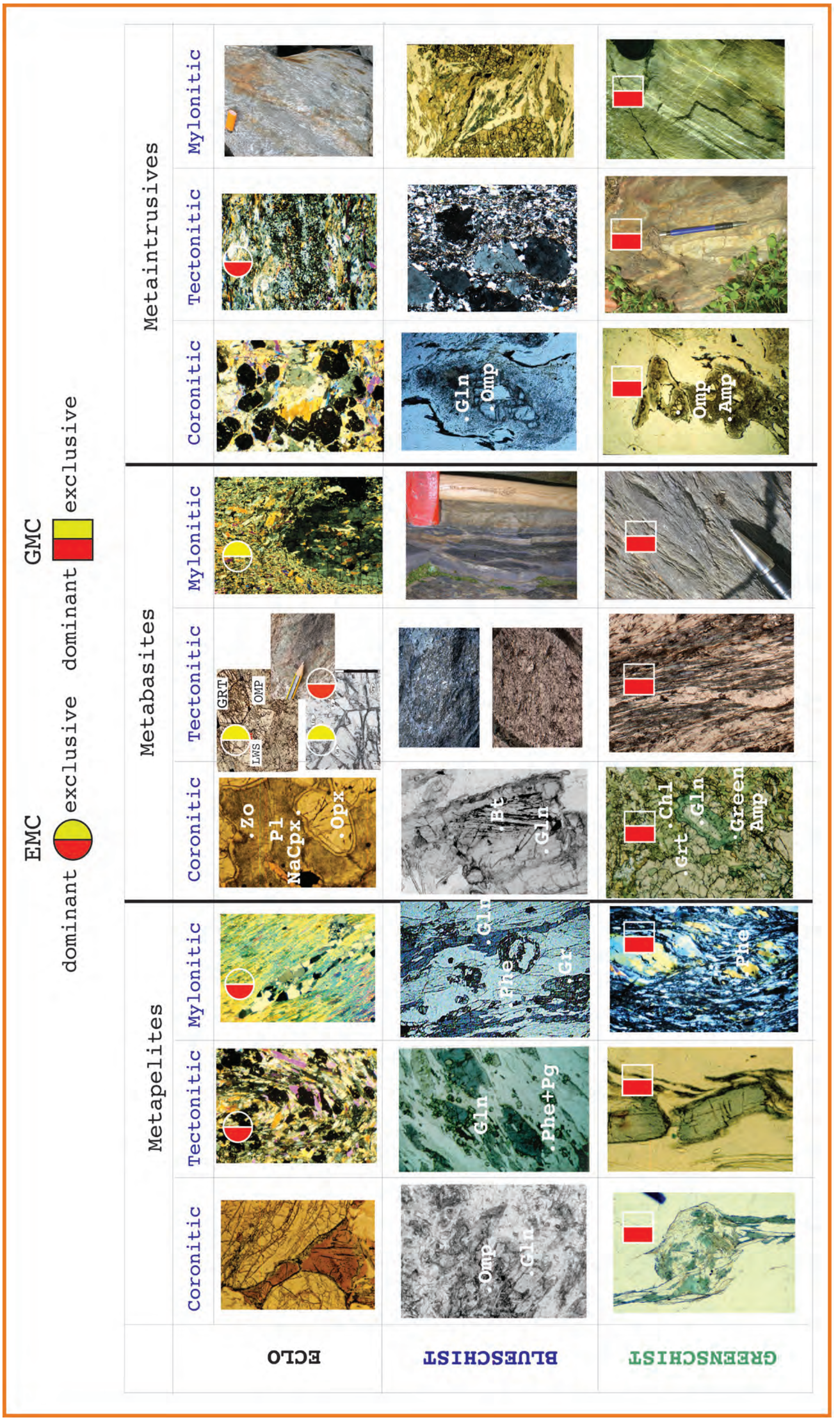


Figure 13A and B. Continued ...

intermediate continental crust (D4) may either be related to this sin-rifting scenario or to the onset of the Alpine cycle, culminating with subduction and collision. Alpine high P/T ratios characterising D5 and D6 point to a prograde-retrograde evolution accomplished under low thermal regime, compatible with a Franciscan-type subduction zone thermal structure (Platt, 1975; Cloos, 1982; 1993) and consistent with subduction and exhumation of crustal fragments within a mature subduction zone under a depressed geothermal regime (e.g. Gerya et al., 2002; Ernst, 2005; Roda et al., 2012).

The structural-metamorphic survey of MMC allowed both individuation of the network of superimposed fabrics with the associated metamorphic mineral parageneses and visualization of the strain distribution at various scales and within different lithotypes. This kind of representation allows an immediate identification of rock volumes preserving different structural memories at the map scale, and therefore of sites potentially preserving the early stages of the structural and metamorphic evolution. The MMC low-strain igneous core contains granites and quartz-diorites with igneous textures. Here intrusive relations with pre-Permian amphibolites and biotite-bearing country gneisses are preserved, together with pre-Alpine HT metamorphic relicts. These cores are surrounded by medium to high-strain domains, from decametre- to hectometre-thick, consisting of tectonitic to mylonitic white mica/chlorite-bearing and glaucophane-bearing gneisses and generating a new Alpine lithostratigraphy, replacing the Permian one, during the Alpine prograde (D5 stage) and retrograde (D6 stage) evolutions, formed after the pre-Alpine granitic and quartz-dioritic intrusions within the thinned Variscan continental crust. This former is still preserved in the coronitic domain.

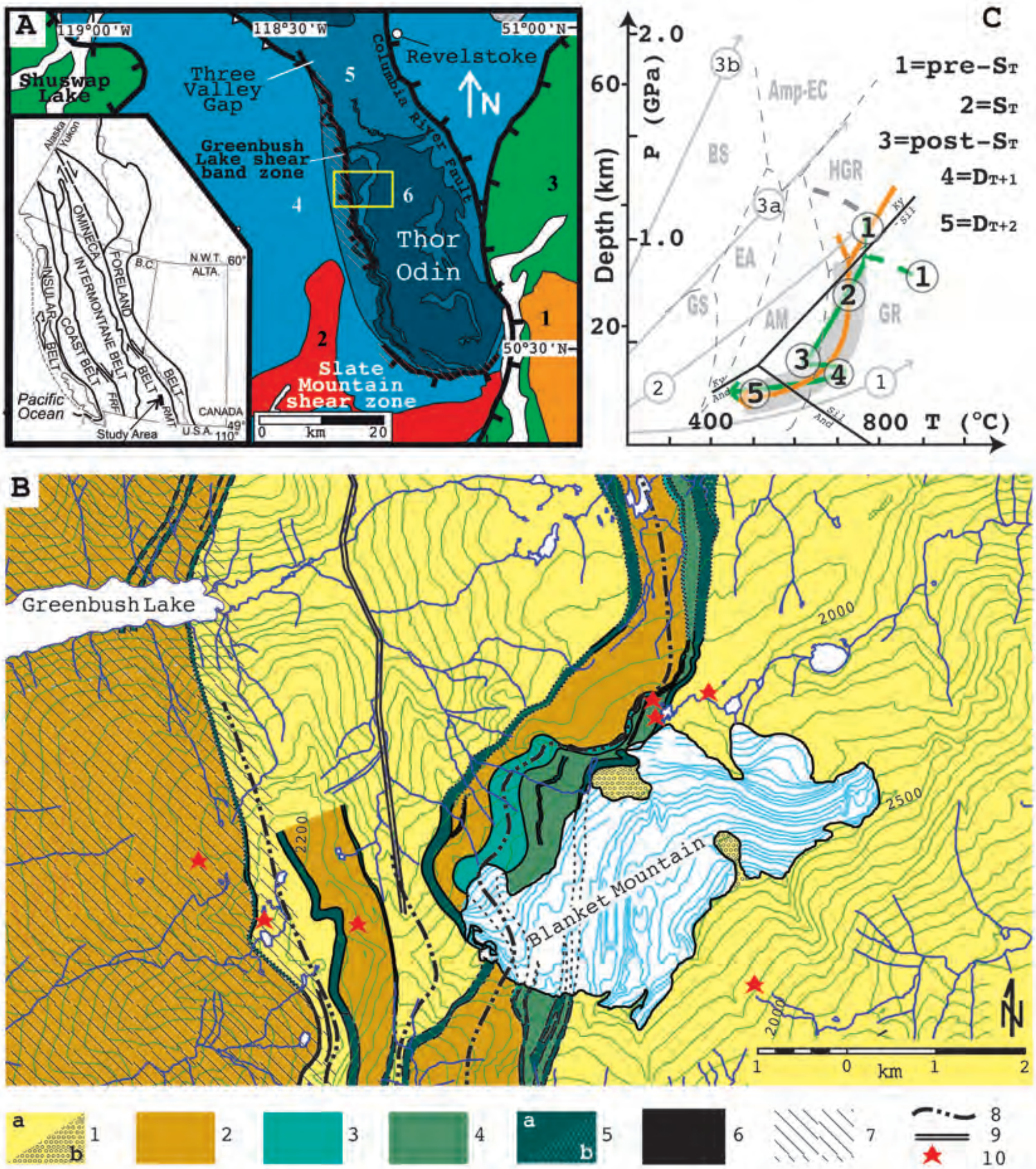
Southeastern Canadian Cordillera

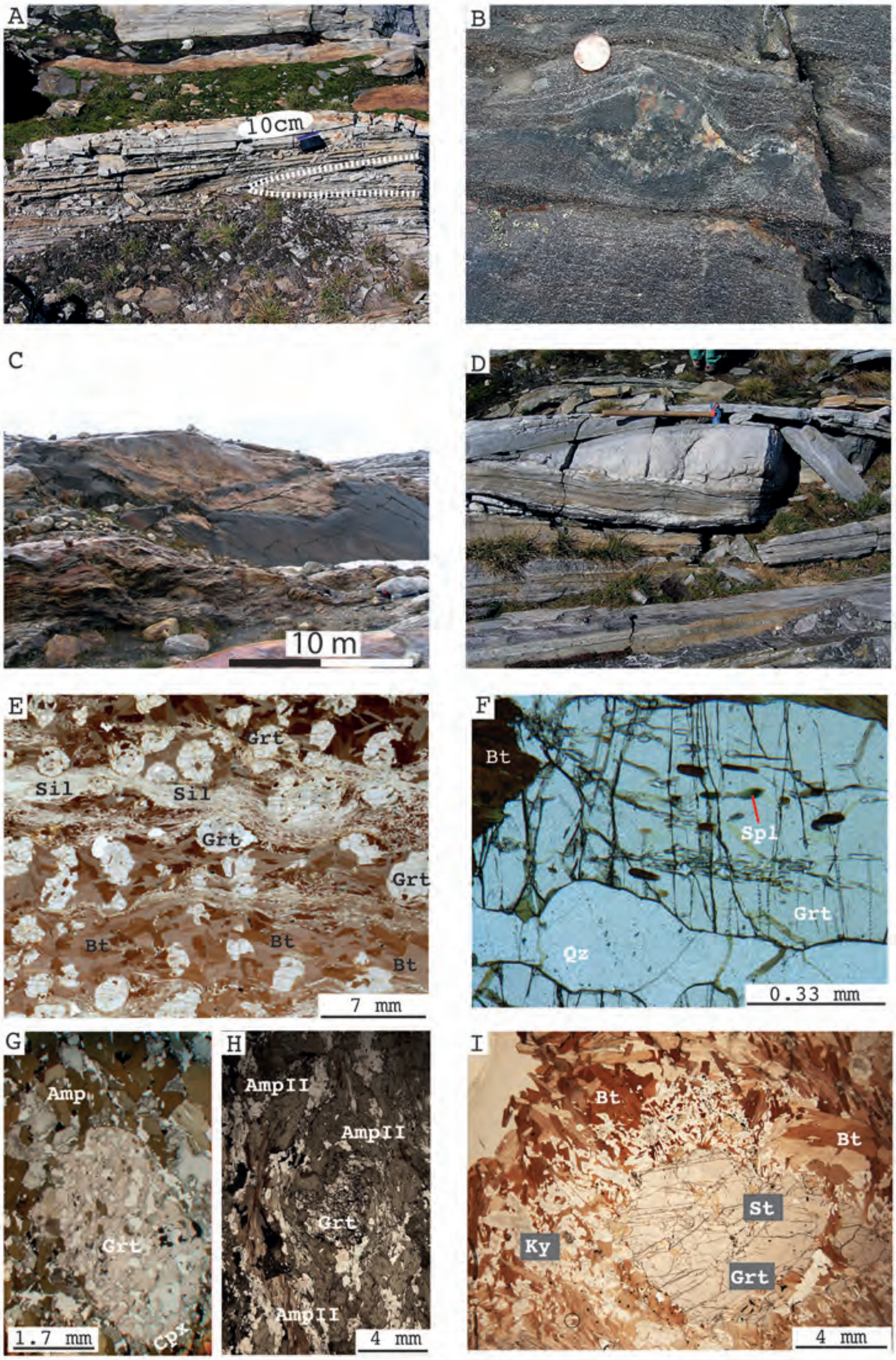
In the SE Canadian Cordillera rocks preserving a long-lasting structural and metamorphic evolution, since Paleoproterozoic to Tertiary, constitute the axial part of the chain and one of the internal belts (Figure 14A). Such a wide time range represents a unique opportunity to reconstruct a geodynamic evolution extended particularly backward in time, in addition to being an excellent test bed corroborating the validity of the analytical approach on a structural and metamorphic history lasting so much. The Thor-Odin dome offers this opportunity, in addition with a large scale well constrained structural framework (Kruse et al., 2004). It is the southern culmination of the Monashee Complex that is the deepest structural level of the Canadian Cordillera (e.g., Brown and Read, 1983), and part of the Shuswap complex of the Omineca belt (inset of Figure 14A). In the southeastern British Columbia the Omineca belt consists of polydeformed igneous and metamorphic rocks of the Precambrian North American shield, overlain by Paleoproterozoic to early Paleozoic metasedimentary sequences exhumed as a consequence of Middle Jurassic to Eocene Cordilleran deformation (e.g. Armstrong et al., 1991; Gabrielse et al., 1991; Crowley, 1997; 1999; Kuiper et al., 2006; Kruse and Williams, 2007; Gibson et al., 2008 and references therein). Thor-Odin (Figure 14A) consists of metasedimentary cover and basement rocks that are part of the Precambrian North American craton and of Paleoproterozoic high-grade polymetamorphic migmatitic paragneisses and orthogneisses (Wanless and Reesor, 1975; Parkinson, 1991). The metasedimentary cover comprises Paleoproterozoic to early Paleozoic quartzite, pelitic schist, semipelitic schist, marble, calc-silicate gneiss, and quartz-feldspathic gneiss (Read, 1980; Journeay and Brown, 1986; Scammell and Brown, 1990; Parrish, 1995; Johnston et al., 2000; Kruse et al., 2004; Kuiper et al., 2014) (Figure 14B). A top-to-the-northeast noncoaxial flow, affecting both basement and metasedimentary rocks, is responsible for the development of a regional transposition foliation (S_T, representing the dominant fabric at the regional scale), two generation of intrafolial folds (F1 and F2), and a F3 folding affecting S_T itself, during Cordilleran convergence (Johnston et al., 2000; Williams and Jiang, 2005; Spalla et al., 2011). An upright F4 folding is associated with localised shearing and the intrusion of pegmatite dykes that are crosscut by lamprophyre dykes (Johnston et al., 2000; Adams et al., 2005; Spalla et al., 2011; Dixon et al., 2014). The western Thor-Odin culmination is separated by the structurally overlying rocks by the Greenbush high strain zone (Figure 14B), formed during Eocene (Johnston et al., 2000; Kruse and Williams, 2007; Spalla et al., 2011; Zanoni et al., 2014). Thermobarometric estimates have been performed on rocks from various localities of Thor-Odin but generally they have not been related to the regional scale deformation history (700 °C < T < 800 °C and 0.6 < P < 1.0 GPa; Lane et al., 1989; Nyman et al., 1995; Norlander et al., 2002; Goergen and Whitney, 2012). P-T-dt evolutions, relating the structural and metamorphic histories have been only recently described in the northern part of the Thor-Odin dome, and namely in Blanket Glacier area (Spalla et al., 2011) and more to the north in the Joss Mountain domain (Zanoni et al., 2014) using the working method experimented in the alpine case studies; in this case some geochronological data have been integrated to the procedure, applied to all types of bulk compositions of this portion of the Monashee Complex (metapelites, calc-silicates, meta-intrusives, metabasites), allowing the reconstruction of a P-T-dt path (Figure 14C) between Blanket Glacier and the plateau south of the Greenbush Lake (Figure 14B; Spalla et al., 2011). As in the rest of the culmination, the dominant fabric is S_T, which preserves F1/F2 isoclinal folds (Figure 15A), and with F3 folding is included in DT deformation (Williams and Jiang, 2005; Spalla et al., 2011). Despite the pervasiveness of S_T at the regional scale, poorly deformed domains are fairly widespread (Figure 14B) and consist of metre- to hectometre-sized boudins or lenticular domains, wrapped by S_T, that at the boudin margins is a continuous foliation. These boudins have been accurately sampled, from cores to margins following incremental strain states, to correlate mineral assemblages marking mylonitic or tectonitic S_T with those developed in the internal coronitic textures. Metabasite boudins consist of granulite (Figure 15B), Grt-bearing amphibolite and amphibolite (Figure 15C), whereas acidic boudins consist of possibly metaintrusive (Figure 15D) and felsic metasedimetary protoliths. In the boudin's country rocks S_T is dominantly marked by BtII and Sil, with SPO parallel to the foliation that wraps around Grt porphyroblasts (Figure 15E). Metabasic granulite boudins are dominated by a Grt-Cpx-bearing pre-S_T assemblage overgrown by Amp and Pl (Figure 15G), whereas Grt-bearing amphibolites are dominated by AmpII and Bt marking the S_T foliation at the boudin margins and wrapping Grt-Cpx-bearing pre-S_T relict domains (Figure 15H). In felsic boudins St relicts are preserved in Grt porphyroblasts associated with Ky (Figure 15I). Locally S_T is also marked by SPO of relict Ky porphyroclasts, that are passively re-oriented; relicts of Spl are preserved in Grt porphyroblasts (Figure 15F). Shear zones associated with F4 folding (D_{T+1} in Spalla et al., 2011) overprint S_T and are coeval with the formation of Crn-bearing assemblages and partial melting. During the reactivation of S_T foliation within the Greenbush high strain zone (D_{T+2} in Spalla et a., 2011), Wm and Chl grew in fractures intersecting S_T. P-T-dt paths reconstructed for metapelites and metabasics, summarised in Figure 14C, show that $S_T$developed during the exhumation of this portion of Cordilleran deep crust, that occurred under an anomalously high thermal regime, between 54 and 48 Ma, as constrained by field relationships with dated igneous rocks (pegmatite and lamprophyre, respectively). Thermobarometric estimates inferred by the distinct pre-S_T relic assemblages are contrasted and suggest that different PT trajectories have been followed before the development of S_T, marking the beginning of the common tectono-metamorphic evolution for rock volumes with different pre-S_T paths. The results of similar investigations performed in the Joss Mountain domain show that they record a similar exhumation path, but at earlier times and lower temperatures, coherently with the occurrence of white mica in the assemblage marking S_T in metapelites (Zanoni et al., 2014).

Summary and discussion. Also in this case the accurate use of multiscale structural analysis integrated with petrology has been the "thread of Ariadne" to restore a complex geodynamic evolution, going back up to Neoproterozoic times.

Different relict pre-S_T imprints indicate re-equilibrations that occurred under different P/T ratios compatible with different geodynamic scenario (Spalla et al., 2011). In our opinion the Spl-bearing assemblages are compatible with the geothermal gradient of a thinned continental crust, like the one most reasonably related to the Rodinia rifting (see Dalziel, 1997; Li et al., 2008), in agreement with migmatisation ages, between 860 and 750 Ma, recorded in southern Thor-Odin (Duncan, 1984) and intraplate magmatism between 724 and 740 Ma in the northern Monashee complex (Okulitch, 1984; Crowley, 1997). Relict St-bearing assemblage in felsic boudin may be compatible with the thermal gradient characterising a continental collision during Cordilleran accretion (e.g. Monger et al., 1982; Gibson et al., 2008), whereas the following Ky- and Grt-Cpx-bearing assemblages, respectively in metapelites and metabasite boudins, can be compatible with a thermal relaxation of a thickened orogenic crust (Spalla et al., 2011). The PT conditions estimated for syn-S_T assemblages, marking tectonitic or coronitic fabric, in the different rock-types are consistent with an exhumation from 30 to 15 km mostly under thermal gradients higher than those characteristic of continental collision and consistent with a lithospheric thinning. After transposition a Crn-bearing assemblage and late partial melting in metapelites testify a further

Figure 14. A) Geological sketch map of the Shuswap metamorphic complex of the Omineca belt at the latitude of the Thor-Odin culmination, Canadian Cordillera (modified after Carr, 1991). 1 = Jurassic plutons; 2 = Cretaceous and Eocene plutons; 3 = Palaeozoic and Lower Jurassic stratified rocks; 4 = Late Proterozoic Mesozoic metamorphic assemblages; 5 = Late Proterozoic or younger North American metasedimentary cover; 6 = Proterozoic North American basement rocks. Tectonic contacts: with teeth = fault and shear zones, with open triangles = Monashee décollement. Yellow rectangle is Figure 14B. B) Geological map of the area between Blanket Mountain and Greenbush high strain zone, modified after Kruse et al. (2004). Basement sequence (Proterozoic): 1a = Undifferentiated para- and ortho-gneisses dominated by Bt-Fsp-Qz-migmatitic gneisses, with metabasic boudins or layers; 1b = Hbl-Bt granodioritic gneisses, with metabasic boudins. Intermingled cover and basement rocks: 2 = Undifferentiated paragneisses with pelitic schists, calc-silicate gneisses, metabasics and minor marbles. Metasedimentary cover sequence (Proterozoic to Palaeozoic?): 3 = pelitic and semi-pelitic schists and gneisses, commonly containing Bt, Grt, and Sil; 4 = calc-silicate gneiss containing Cpx, Pl, Tr and Qz; 5 = quartzite (a) and quartzitic gneisses (b) with Sil, Kfs, Bt, Wm, and Tur; 6 = marbles. 7 = Greenbush Lake shear-band zone. Symbols: 8 = Axial surface trace of F2 folds; 9 = Victor Creek fault; 10 = boudins of acidic granulites, metabasites, and calcsilicates. C) P-T paths inferred for the metapelites (grey) and metabasics (black); the shaded area represents the variation between minimal and maximal estimated T values in metabasics (Spalla et al., 2011). Geotherms: 1 = near spreading ridge or volcanic arc, 2 = normal gradient of old plate interior, 3a = "warm" subduction zones, 3b = cold subduction zones (Cloos, 1993). Metamorphic facies after Ernst and Liou (2008).


A
119°00'W
118°30'W
51°00'N
Shuswap Lake
Three Valley Gap
Revelstoke
Columbia River Fault
Greenbush Lake shear band zone
Thor Odin
Slate Mountain shear zone
50°30'N
km
C
1=pre-ST
2=ST
3=post-ST
4=DT+1
5=DT+2
P (GPa)
Depth (km)
T (°C)
B
Greenbush Lake
Blanket Mountain
km


A
10cm
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D
E
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Sil
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Bt
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Grt
Qz
0.33 mm
G
Amp
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Cpx
1.7 mm
H
AmpII
AmpII
Grt
AmpII
4 mm
I
Bt
Bt
St
Ky
Grt
4 mm

thermal rise during the final decompression stage compatible with on-going lithospheric thinning (DT+1 in Figure 14C). The final cooling is better recorded within the Greenbush high strain zone, where greenschist-facies metamorphism is clearly testified by Chl and Wm filling in necks of Sil microboudins. This re-equilibration is postdated by 48 Ma lamprophyre emplacement, which in turn is overprinted by brittle deformation along the Victor Creek fault (Kruse and Williams, 2005). In summary the positive use of petrostructural heterogeneities detected in the western Thor-Odin dome individuated very old pre-Cordilleran structural and metamorphic imprint relatable with the Rodinia rifting at about 750 Ma, followed by the imprints possibly developed during a terrane accretion at the western margin of Laureantia, during Cordilleran collision earlier than 54 Ma, at the time of post-collisional thermal relaxation between 54 and 50 Ma, and during a late- to post-collisional lithospheric extension between 50 and 48 Ma (Spalla et al., 2011).

Conclusive remarks

The selected Alpine and Cordilleran examples indicate that even in polymetamorphic and polydeformed terrains, once the progressive geometries of the changing lithostratigraphy are recognised, and the sequence of granular fabrics evolution is connected with meso- and mega-structures and with the sequence of metamorphic re-equilibration stages, the apparently chaotic heterogeneities of the finite strain local fields become readable. The mineralogical support of each of the meso- or micro-fabric changes deserves therefore petrologic testing that may reveal attainment of new equilibria, even local.

This kind of structural and metamorphic reconstructive analysis is the key to decipher the geodynamic evolution even in orogenic scars that have been reactivated several times during successive cycles of continent separation and accretion, as shown in the continental rocks of the Alpine belts. Here two Variscan syn-metamorphic foliations, predating a Permian-Triassic rifting-related superposed fabrics, are preserved in least deformed domains that escaped the polyphase structural and metamorphic Alpine re-equilibration. The latter generated superposed structures that developed under different thermal regimes, evolving consistently from active oceanic subduction into late orogenic evolution. Also the Cordilleran rock memory was surprisingly exploited back in time to identification of the stages correlated to Rodinia break-up, which predate the convergent Cordilleran tectonics.

The simultaneous detection of strain and metamorphic patterns demonstrated the high heterogeneity in the rock memory of orogenic rocks that makes fundamental the adoption of structural maps displaying the degree of fabric evolution and metamorphic transformations.

Figure 15. Canadian Cordillera A) Intrafolial isoclinal fold (highlighted by the dotted red line) preserved in S_T (transposition foliation) recorded in marble at the plateau west of Victor Creek fault. B) Cpx-Grt-bearing metabasite boundin in amphibolite boudinaged layers in migmatitic gneiss; northern slope of Blanket Mountain. C) Metre-sized amphibolite boudin in migmatitic gneiss close to the northern toe of Blanket Glacier. D) Felsic boudin in Bt-bearing migmatitic gneiss at the plateau west of Victor Creek fault. E) S_T marked by Sil and BtII wrapping Grt porphyroblats; northern slope of Blanket Mountain. Scan of thin section. F) Relict Spl enclosed within syn-S_T Grt porphyroblast; west of Victor Creek fault; plane polarised light. G) Metabasic granulites with Grt in equilibrium with Cpx and Amp; west of Victor Creek fault; plane polarised light. H) Grt-bearing amphibolite to west of Victor Creek fault. Grt and AmpI are wrapped by S_T foliation marked by AmpII and Bt. Plane polarised light. I) St enclosed in Grt in a matrix foliation marked by Ky and Bt in a felsic boudin from northern slope of Blanket Mountain. Plane polarised light. Mineral abbreviations are as reported in Figure 11.

These maps must however be extended to the critical volumes that may include the scale of strain partitioning (and therefore that of metamorphic re-equilibration heterogeneity), before attributing a regional significance to a succession of structural and metamorphic re-equilibration steps, since the recorded deformation sequence may change within each of the adjacent areas.

In other words in deep subduction-collision zones lithostratigraphic affinities spread within the finite petrostructural pattern are of lesser help in the definition of tectonic units and, secondarily, the structural and metamorphic reworking makes risky the individuation of a tectono-metamorphic unit on the only base of P-T determinations gathered without the structural support here in use, which validates at the regional scale the relative chronology of the fabrics and of the related mineral assemblages. Finally, the proposed examples support the theoretical formulation of the manifold recognizable petrostructural rock types that may develop during successive stages of mechanical and metamorphic re-equilibrations, marked by specific parageneses.

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