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Deformation vs. metamorphic re-equilibration heterogeneities in polymetamorphic rocks: a key to infer quality P-T-d-t path

MARIA IOLE SPALLA[1,2]* and MICHELE ZUCALI[1]*

[1] Dipartimento di Scienze della Terra "A. Desio" Università di Milano, Via Mangiagalli, 34, 20133 Milano, Italy
[2] C.N.R. - IDPA, Via Mangiagalli, 34, 20133 Milano, Italy

ABSTRACT. — The interaction between fabric gradients and reaction rate as a tool for individuating volumes carrying the longest *«rock memory»* is discussed through some examples from continental units of the Alpine chain. Here quality P-T-d-t paths have been inferred using a sampling strategy based on reconstruction of the metamorphic evolution, supported by a regionally valid deformation history and on the choice of sites for investigations on compositional variations, where mineral growth and sequences of overprinting fabrics are known. The examples show that correlation between degree of fabric evolution and progress of metamorphic transformation is positive and influence of strain partitioning on tectono-thermal rock memory must be taken into account during P-T-d-t reconstruction to avoid errors in determining the sequence of P-T re-equilibration steps and to obtain clustered P-T estimates relative to each step.

RIASSUNTO. — L'interazione tra i gradienti di fabric e la velocità di reazione, utilizzata come strumento di individuazione di volumi di roccia caratterizzati dalla *«memoria»* più lunga, è discussa con alcuni esempi dalle unità continentali della catena Alpina. La qualità dei percorsi P-T-d-t è stata attribuita utilizzando una strategia di campionamento basata sulla ricostruzione della evoluzione metamorfica, supportata da una storia deformativa valida a scala regionale e sulla scelta di siti di analisi composizionali solo dove è nota la sequenza dei fabric sovrapposti e della crescita di minerali. Gli esempi mostrano che la correlazione tra grado di evoluzione del fabric e progresso della trasformazione metamorfica è positiva e che l'influenza della ripartizione della deformazione sulla memoria tettonotermica delle rocce deve essere tenuta in considerazione durante la ricostruzione dei percorsi P-T-d-t, per evitare errori nel determinare la sequenza degli stadi di riequilibrazione P-T e ottenere stime P-T coerenti, relativamente ad ogni stadio.

KEY WORDS: *deformation-metamorphism interaction; P-T-d-t; rock memory; Alpine continental crust.*

* Corresponding authors, e-mail: Iole.Spalla@unimi.it; Michele.Zucali@unimi.it

INTRODUCTION

Understanding of structural and metamorphic re-equilibration steps sequence has been successfully applied to infer tectonic evolutions of metamorphic rocks in mountain belts. Since metamorphic mineral associations of a single rock depend on the interplay between physical conditions of metamorphism, deformation history, diffusion, fluid infiltration and kinetics, the rock history cannot be immediately reconstructed (e.g. Fyfe *et al.*, 1978; Vernon, 1978; Etheridge *et al.*, 1983; Brodie and Rutter, 1985; Williams, 1985; Wheeler, 1987; Vernon, 1989; Lardeaux and Spalla, 1990; Passchier *et al.*, 1990; Passchier and Trouw, 1996; Spalla *et al.*, 2000; Brown, 2001). In the construction of Pressure – Temperature – relative time of deformation (P-T-d-t) paths (Spalla, 1993; Johnson and Vernon, 1995) the interaction between reaction progress and deformation history plays a prominent role and reference to a previously defined structural history is therefore essential. In addition in naturally deformed rocks heterogeneity distribution depends on pre-existing structures, on alternating compositional variations, on the onset of localised processes of reaction softening or hardening during reaction development and on the existence of earlier mylonitic bands (e.g. Ramsay and Graham, 1970; Ramsay, 1980; Brodie and Rutter, 1985; Bell *et al.*, 1986). As a consequence adjacent rock volumes experience contrasted deformation mechanisms and/or strain rates, at the same time of the metamorphic history, as it is demonstrated by the common occurrence of undeformed rocks embodied within ductile shear zones. Such structural pattern offers coexistence of coronitic, tectonitic and mylonitic syn-metamorphic textures, generated during the same phase of deformation, reflecting the progressive development of strain gradients in the field. Individuation of zones characterised by different and contemporaneous deformation mechanisms has been the key to unravel the tectono-thermal evolution in poly-deformed and poly-metamorphic tectonites, since the microstructural site of mineral grains influences the evolution of their chemical composition (Cimmino and Messiga, 1979; Brodie, 1980; Lardeaux *et al.*, 1983; Lardeaux *et al.*, 1986; Mørk, 1985; Diella *et al.*, 1992). A useful support of this kind of analytical work is the model of deformation partitioning at the granular scale, which facilitates individuation of microstructural sites where nucleation and growth of new mineral phases are enhanced, and sites in which relics can be preserved, or sites where dissolution and intracrystalline plasticity prevail (Bell and Rubenach, 1983; Bell *et al.*, 1986; Bell and Hayward, 1991). It has also been substantiated at different scales that fabric gradients generally closely match metamorphic re-equilibration gradients (e.g. Myers, 1978; Austrheim, 1990; Altenberger, 1995), and generally the dominant metamorphic imprint at the regional scale is associated to the most pervasive fabric, provide the degree of granular scale reorganisation overstepped a critical stage (Spalla *et al.*, 2000; Zucali *et al.*, 2002).

THE MICROSTRUCTURAL SUPPORT TO THE ROCK MEMORY EXPLOITING FOR P-T-D-T PATHS RECONSTRUCTION

A major interest in field analysis is to locate time sequences of fabric superposition and fabric gradients related to single structural steps of the tectonic history (e.g. Williams, 1985). This may ensure sampling of the widest range of thermo-mechanical evolutionary stages and provide microstructural sites where mineral growth and deformation processes interact positively from sites in which relics preservation is favoured. In the following we will review three examples from Eastern and Central Austroalpine and from Central Southalpine domains (Fig. 1*) in which:

i) the metamorphic evolution has been reconstructed after independent determination of a regionally valid deformation history (by means of a foliation trajectory map);

ii) the site for investigation on mineral compositional variations have been chosen taking into account the timing of mineral growth with respect to superposed fabric

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elements and deformation mechanisms acting during the same deformation stage and

iii) the sampling strategy based on the fabric gradients and reaction rate interaction has been fundamental to individuate volumes carrying the longest «rock memory» and consequently to infer with confidence P-T-d-t paths.

Mineral abbreviations are as in (Kretz, 1994), except for amphibole (Amp) and white mica (Wm).

a) The Texel Gruppe metapelites and metagranitoids (Upper Austroalpine, Eastern Alps)

Structural and microstructural outline: the Texel-Gruppe metamorphic rocks belong to the Upper Austroalpine continental crust, comprised between the Tauern and Engadine windows, and are situated immediately north of the Insubric Line (a in Fig. 1*). Texel-Gruppe is located at the border between Oetztal and Campo nappe and contains paragneisses, micaschists, quartzites, marbles, amphibolites and metagranitoids. They underwent a polyphase Alpine tectono-metamorphic evolution, reworking the poly-deformed pre-Alpine continental crust (e.g. Frank *et al.*, 1987; Spalla, 1993; Hoinkes *et al.*, 1999 and refs. therein). The structural evolution, comprising three superposed groups of syn-metamorphic structures (Spalla, 1990) and the sequence of mineral assemblages (Spalla, 1993) are summarised in Table 1* and Fig. 2.

P-T-d-t path: The inferred sequence of mineral associations (Table 1* and Fig. 3) indicates that the metamorphic evolution is retrograde in T and P, from syn-D_1 HT-HP conditions, to syn-D_3 greenschist facies conditions. Mineral compositions were detected in microstructural sites of known mineral growth and fabric superposition sequence, both in metapelites and metagranitoids (Fig. 2). Plotting on the P-T diagram of Fig. 3 the P-T estimates obtained by minerals syn-kinematic to each group of structures, and poorly re-crystallised or dissolved during successive deformation stages, a P-T-d-t path has been

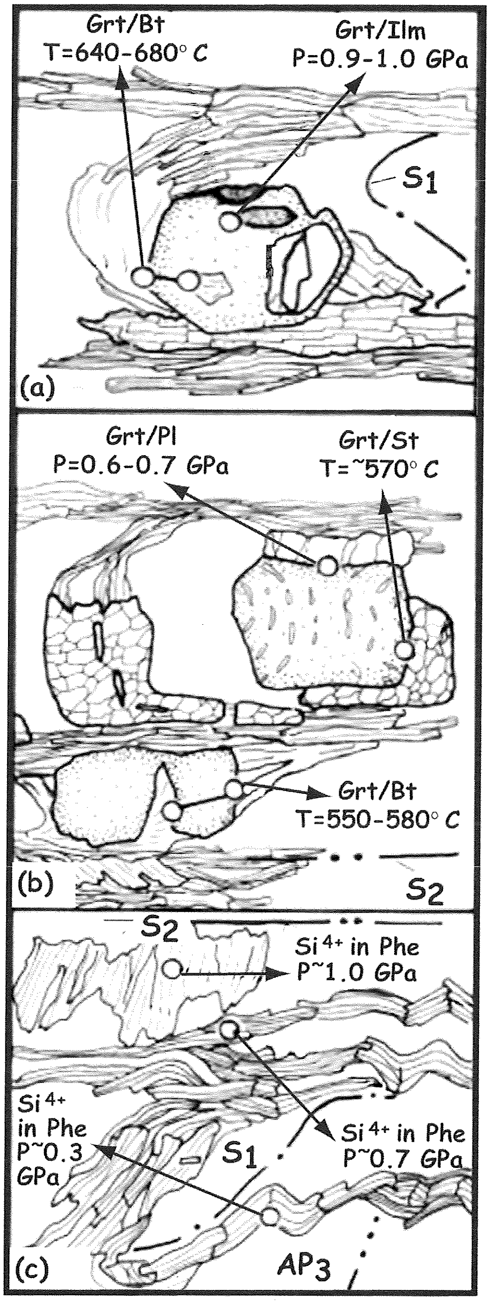


Fig. 2 – Synoptic scheme of P-T estimates obtained in different micro-sites of Texel Gruppe (star a in Fig. 1) metapelites (a and b) and metagranitoids (c), see discussion in the text.

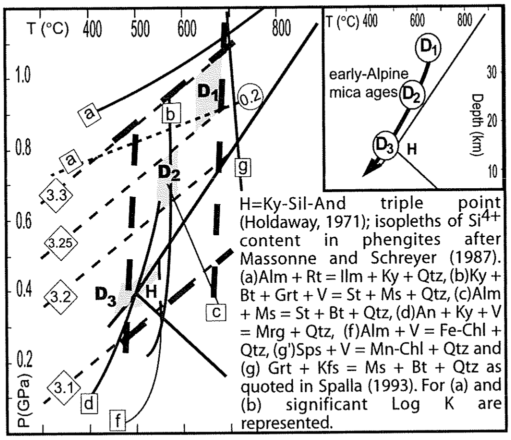


Fig. 3 – P-T-d-t path of the Texel metapelites redrawn after SPALLA (1993); D_1, D_2 and D_3 represent P-T conditions of assemblages during successive generation of structures. Thick dashed lines delimit the area in which inferred T and P values would be scattered without the microstructural support to selection of micro-sites suitable for thermobarometric estimates. Inset: Alpine biotite and white mica (THOENI and HOINKES, 1987) mark S_2 foliation in the Texel Gruppe (see discussion in SPALLA, 1993). Grey areas delimitate P-T conditions during D_1, D_2 and D_3 deformations.

inferred (Spalla, 1993). The P-T intervals, referred to each deformation stage, cluster in a small range (Figs. 2 and 3); without the assistance of microstructural analysis the T and P values would be considerably scattered, as shown by thick dashed lines in Fig. 3. Without microstructural discrimination the garnet biotite pairs, for example, would yield scattered T values (550°-680°C, or more) and the P values, obtained by the Si4+ content of white mica in metagranitoids, would be distributed in a P-range between 0.3-1.0 GPa, instead of the clustering characterising the different microstructural sites (Fig. 2c). The obtained sequence of P-T values is coherent with the inferred succession of assemblages (Table 1* and Fig. 3).

b) The metapelites of eastern Orobic Alps (Southalpine Domain, Central Alps)

Structural and microstructural outline: eastern Orobic Alps metapelites belong to the Southalpine continental crust comprised between the Insubric Line and the Permian-Cainozoic sedimentary cover sequences of the Southern Alps, outcropping west of the Adamello intrusive stock (b in Fig. 1*). Here the Southalpine domain consists of pre-Alpine paragneisses, micaschists, quartzites, marbles, amphibolites and metagranitoids, locally displaying a very low grade Alpine metamorphic imprint (Albini *et al.*, 1994; Colombo and Tunesi, 1999; Spalla and Gosso, 1999 and refs. therein). Four groups of superposed structures exist; the earlier two (D_1 and D_2) are syn-metamorphic and affect exclusively the pre-Permian basement. The pre-Permian structures and the sequence of related mineral assemblages (Spalla *et al.*, 1999) are synthesised in Table 1* and in Fig. 4.

P-T-d-t path: Thermobarometric estimates of assemblages formed during D_{1a}, D_{1b} and D_2 show a transition from T = 480-540°C (during

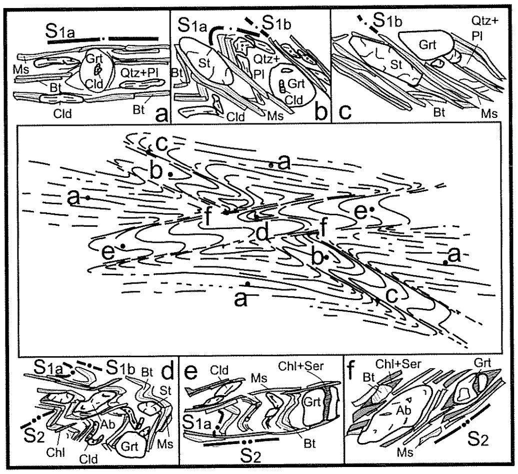
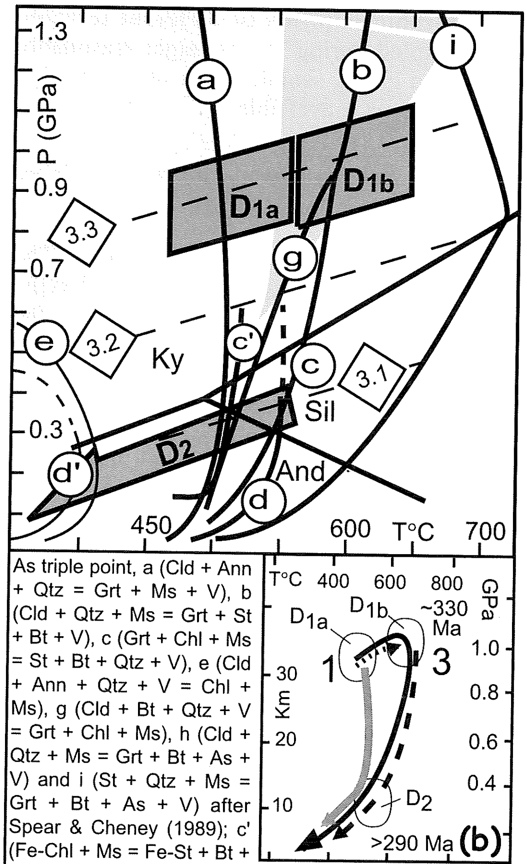


Fig. 4 – Central Southern Alps (b in Fig. 1*): different microstructural and mineralogical patterns due to deformation partitioning during D_2, D_{1a} and D_{1b} fabrics superposition. The corresponding meso-scale structures that result from overprinting during three deformation phases are idealised in the central drawing where area extent of microstructural stages is not realistic: in reality, stages e and f represent 95% volume and stages a, b, c and d are 1 to 10 metre-size relict domains within remnant space (redrawn after SPALLA *et al.*, 1999).

D_{1a}) to T = 570-660°C (during D_{1b}), corresponding to a slight pressure-increase from 0.75-0.95 GPa to 0.85-1.15 GPa; D_2 greenschist retrogression corresponds to a P and T-decrease (T<400-550°C and P<0.3-0.4 GPa; Spalla *et al.*, 1999). This P-T-d-t path (Fig. 5) results from sampling domains recording the majority of thermo-mechanical re-equilibration steps (Fig. 4d). Deformation heterogeneity originates different microstructural patterns and contrasting sequences of mineralogical assemblages due to different overprinting combinations between D_2 and the pre-D_2 composite fabrics (D_{1a} and D_{1b}). In a samples group, a pre-S_2 fabrics (Fig. 4a) is contemporaneous with development of Bt, Wm, Fe-Cld, Qtz, Grt, Rt, opaque minerals, variably replaced by Ab, Ttn, opaque minerals, minor Ep and carbonates where S_2 is a pervasive fabric (Fig. 4e). In a second samples group, St formed during a late stage of a pre-S_2 foliation, which is marked by aligned Wm, Bt and Ilm (Fig. 4c); Chl, Wm and Ab replaced Bt, Grt and St, during S_2 development (Fig. 4f). In the third group, a grater number of stages of structural and metamorphic evolution are recorded: Cld and St occur together and occupy different microstructural positions. Cld, included in Grt or partly dissolved and bent in S_{1a}, is preserved in S_{1b} crenulation cleavage microlithons; St grew during S_{1b} late development stage (Fig. 4b). Greenschist facies retrogradation was synchronous with S_2 (Fig. 4d), marked by Chl, new Wm, Ab, Ttn and Cal. Different P-T-d-t evolutions can be deduced from samples corresponding to stages a - f of figure 4, demonstrating that the Orobic Alps metapelites maintain a highly heterogeneous structural and metamorphic memory: only samples from site d recorded the complete sequence of the inferred tectono-metamorphic re-equilibration stages. Samples from the other sites show only a partial memory; in particular, samples from site a and c recorded a single stage, corresponding to D_{1a} and D_{1b}, respectively. If the third group of relics had not been found, the D_{1a} and D_{1b} stages could have been interpreted as earlier tectono-



As triple point, a (Cld + Ann + Qtz = Grt + Ms + V), b (Cld + Qtz + Ms = Grt + St + Bt + V), c (Grt + Chl + Ms = St + Bt + Qtz + V), e (Cld + Ann + Qtz + V = Chl + Ms), g (Cld + Bt + Qtz + V = Grt + Chl + Ms), h (Cld + Qtz + Ms = Grt + Bt + As + V) and i (St + Qtz + Ms = Grt + Bt + As + V) after Spear & Cheney (1989); c' (Fe-Chl + Ms = Fe-St + Bt + Qtz) after Hoschek (1969); d (Alm + V = Fe-Chl + Qtz) and d' (Sps + V = Mn-Chl + Qtz) after Hsü (1968) and Naggar & Atherton (1970); dashed lines (isopleths of Si^{4+} in phengites after Massonne & Schreyer (1987); light grey area (glaucophane stability field) after Maresch (1977); grey (stability field of biotite and chloritoid) after Kepezhinskas & Khlestov (1977)

Fig. 5 – **(a)** P-T-d-t path in metapelites of the Eastern Orobic Alps (SPALLA *et al.*, 1999); D_{1a}, D_{1b} and D_2 correspond to P-T conditions for assemblages formed during D_{1a}, D_{1b} and D_2 successive generation of structures. **(b)** Different P-T-d-t evolutions recorded in samples corresponding to stages 1-6 of figure 4: only samples from site d recorded the complete sequence of the inferred tectono-metamorphic re-equilibration stages. Samples from the other sites show partial memory; in particular samples from site a and c recorded a single stage corresponding to S_{1a} and S_{1b} respectively. Dotted P-T-d-t path would be deduced from samples of site b, whereas the dashed, grey and black paths from sites f, e and d respectively.

metamorphic imprints of different tectonic units coupled during D_2, as might reasonably be inferred if only samples from sites e and f of Fig. 4 were made available.

c) The Languard Campo metaintrusives (Upper Austroalpine, Central Alps)

Structural and microstructural outline: The Upper Austroalpine units in Central Alps comprise the Languard - Campo nappe and the Tonale Series, and crop out right north of the Insubric line (c in Fig. 1*; Schmid *et al.*, 1996). Languard – Campo nappe and Tonale Series consist of gneisses and micaschists with interlayered amphibolites, marbles, quartzites and pegmatites. In both these units post-Variscan intrusives (granitoids, diorites and minor gabbroids) commonly occur. Mineral ages of these rocks yield two groups of values: earlier ages (298-224 Ma) are interpreted as igneous cooling ages, whereas the later (125-78 Ma) as the effect of Alpine reworking (Gazzola *et al.*, 2000 and refs. therein). The occurrence of Permian intrusives allowed the separation of Alpine from pre-Alpine structures. Five groups of superposed syn-metamorphic structures have been detected; the two earlier groups (D_1 and D_2) affect exclusively the pre-Permian basement, D_3 is the earlier Alpine group of structures affecting also Permian intrusives (Fig. 6* and 7*). The structural evolution and the sequence of mineral assemblages (Gazzola *et al.*, 2000) are summarised in Table 1*.

P-T-d-t path: Thermobarometric estimates of syn-D_2, D_3 and D_4 assemblages allow to infer for the igneous assemblage of metadiorites T=880 ± 110°C and P= 0.4-0.7 GPa, in agreement with estimates performed in country rocks on syn-D_2 assemblages (Spalla *et al.*, 1995; Zucali, 2001). HP assemblages developed during D_3 in metapelites and in metaintrusives indicate T= 500-600 °C P= 1.1±0.2 GPa (Spalla *et al.*, 1995; Gazzola *et al.*, 2000). D_2 greenschist retrogression corresponds to a pressure and temperature-decrease (T<400-550°C and P<0.3-0.4 GPa). This P-T-d-t path (Fig. 8) has been reconstructed selecting microstructural sites to investigate variations of mineral compositions syn-kinematic to each group of structures and poorly re-crystallised or dissolved during successive deformation stages. P-T boxes referred to successive deformation stages fit into relatively small ranges. As an example, the compositional variations of amphiboles in metadiorites would be scattered in a T range of 980°-550°C (thick dashed lines in Fig. 8) without the microstructural selection of sites more suitable for chemical analyses, because of their textural equilibrium relationships (Fig. 7a-i*). Matching of fabric gradients with metamorphic re-equilibration rate is striking comparing quantitative fabric data (Quantitative Textures Analyses - QTA; Zucali, 2001) together with compositional variations in amphiboles (Gazzola *et al.*, 2000) from metadiorites deformed during D_3; amphibole compositions cover the full compositional range from Permian igneous

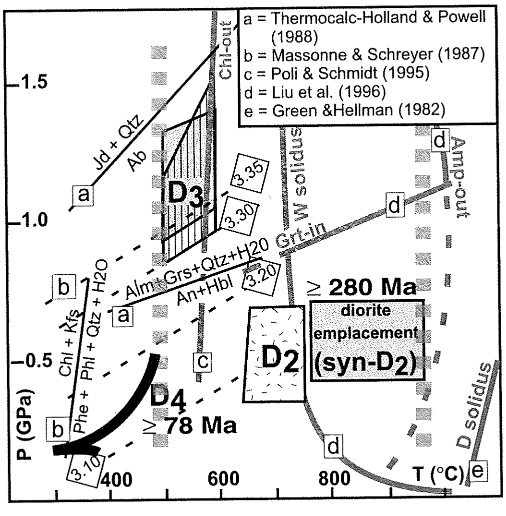


Fig. 8 – P-T-d-t path inferred from metadiorites (grey) and metagranitoids (vertical stripes) of Languard Campo nappe and Tonale Series (GAZZOLA *et al.*, 2000). Syn-D_2, D_3 and D_4 represent P-T conditions estimated with respect to successive deformation stages. D_2 stippled box indicates P-T of country rocks during Permian intrusives emplacement (SPALLA *et al.*, 1995; ZUCALI, 2001).

high-Ti amphibole to Alpine metamorphic tschermakitic amphibole, exclusively in coronitic metadiorites, whereas in mylonitic diorites no Ti-rich amphibole compositions are preserved.

Conclusive remarks

In the poly-metamorphic continental crust from Eastern and Central Alps the correlation between degree of fabric evolution and progress of metamorphic transformation is positive and the influence of strain partitioning (deformation heterogeneity) on tectono-thermal memory of poly-metamorphic rocks must be taken into account during P-T-d-t reconstruction. Actually rocks with a longer tectono-thermal memory are those in which the superposed planar fabrics are poorly evolved, and consequently the associated metamorphic re-equilibrations highly incomplete or, in other words, structural and metamorphic relics of the early evolution abundant.

Recognition of sites where nucleation and new mineral growth prevail, from sites where dissolution and intracrystalline plasticity dominate, is essential to obtain clustered P-T estimates relative to successive tectonic imprints.

Volumes recording the full step sequence in the tectono-metamorphic evolution are generally rare and small-sized; therefore independent determination of a valid and regionally correlated deformation history is the fundamental support for the reconstruction of the metamorphic evolution. If the influence of strain partitioning on the preservation of relics is ignored, the sequence of P-T re-equilibration steps might be misunderstood.

The combined use of coronitic domains (very low-strain and poorly re-equilibrated compositionally) and tectonitic-mylonitic domains (high-strain and widely re-equilibrated compositionally) and the correlation of their time succession at the regional scale, facilitate the reconstruction of more complete P-T-d-t paths in which successive re-equilibration steps are confidently constrained and are representative of a much wider geological span of time.

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