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

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ABSTRACT. — The interaction between fabric gradients and reaction rate as a tool for individualizing 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.

della evoluzione metamorfica, supportata da una storia deformativa valida a scala regionale e sulla scelta di siti di analisi composizionali solo dove è notata 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 tetttonotermica 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 riequilibrare 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.

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

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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 – 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, tectonic 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 EXPLORING 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

* This item is available as electronic supplementary material on the Periodico di Mineralogia web site at <http://tetide.geo.uniroma1.it/riviste/permin/permin.html>.
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 sym-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-D₁ HT-HP conditions, to syn-D₃ 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 recrystallised 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.
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 Goso, 1999 and refs. therein). Four groups of superposed structures exist; the earlier two (D₁ and D₂) 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 D₁a, D₁b and D₂ show a transition from T = 480-540°C (during 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 Si⁺⁺ 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 Orobie Alps (Southalpine Domain, Central Alps)

Structural and microstructural outline: eastern Orobie Alps metapelites belong to the

Fig. 3 – P-T-d-t path of the Texel metapelites redrawn after Spalla (1993); D₁, D₂ and D₃ 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 Hoenkes, 1987) mark S₂ foliation in the Texel Gruppe (see discussion in Spalla, 1993). Grey areas delimitate P-T conditions during D₁, D₂ and D₃ deformations.

Fig. 4 – Central Southern Alps (b in Fig. 1*): different microstructural and mineralogical patterns due to deformation partitioning during D₂, D₁a and D₁b 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).
Deformation vs. metamorphic re-equilibration heterogeneities in polymetamorphic rocks...

$D_{1a}$) to $T = 570-660^\circ C$ (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 ($T<400-550^\circ C$ 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, pre-$S_2$ fabrics (Fig. 4a) is contemporaneous with development of Bt, Wm, Fe-Cld, Qtz, Grt, Ri, 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 greater 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 Orobie 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-

![Diagram](image-url)

Fig. 5 – (a) $P$-$T$-$d$-$t$ path in metametamorphic rocks (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 D₃, 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 Insurbic 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 (D₁ and D₂) affect exclusively the pre-Permian basement, D₃ 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-D₂, D₃ and D₄ 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-D₂ assemblages (Spalla et al., 1995; Zucali, 2001). HP assemblages developed during D₃ in metapelites and in metaintrusives indicate T= 500-600 °C P= 1.1±0.2 GPa (Spalla et al., 1995; Gazzola et al., 2000). D₂ 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 D₃; amphibole compositions cover the full compositional range from Permian igneous
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 tectonic-myolitic 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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Deformation vs. metamorphic re-equilibration heterogeneities in poly metamorphic rocks...


