MULTIDISCIPLINARY INVESTIGATIONS ON THE RELATIONSHIPS BETWEEN DEFORMATION AND METAMORPHISM ACROSS CRUSTAL RHEOLOGICAL BOUNDARIES

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INTRODUCTION

Research topic

The rheology of crustal rocks plays a key role in lithosphere dynamics, influencing the orogenic cycle and how plate tectonics evolve (*e.g.*, Bercovici, 2003; Bürgmann & Dresen, 2008; Gerya, 2010). Lithosphere deformation involves a complex interplay between metamorphic and deformation processes, whose effects tend to be enhanced in domains characterized by variable composition or inherited petrological and structural history (*e.g.*, Brodie & Rutter, 1987; Passchier & Trouw, 2005; Hobbs & Ord, 2017; Gardner *et al*., 2020; Piazolo *et al*., 2020). These variations may produce heterogeneous rheological behaviours, which develop from micro to regional scale and concentrate stress or strain, such as faults and shear zones (*e.g.*, Tommasi & Vauchez, 2001; Pennacchioni & Mancktelow, 2007; Tajčmanová *et al*., 2015). Given the complexity of the relationships between deformation and metamorphism, reconstructing the reasons controlling the birth and the evolution of tectono-metamorphic structures is challenging, but of fundamental importance for understanding the initiation of geodynamic processes as earthquakes, volcanic activity, detachment faults, orogeneses and rifting (*e.g.*, Handy *et al*., 1999; Bürgmann & Dresen, 2008; Whitney *et al*., 2013; Fossen & Cavalcante, 2017). Therefore, for this kind of complex investigations, the use of multidisciplinary approach is necessary to isolate the contribution of each of the several parameters (seen in terms of Pressure-Temperature-time-Deformation-Composition conditions) that control the rock rheology and consequently how metamorphic and deformation processes occur (*e.g.*, Brodie & Rutter, 1987; Passchier & Trouw, 2005; Wheeler, 2014; Hobbs & Ord, 2017. Since rheology is expected to significantly change in correspondence of major variations in rock composition, the boundaries between contrasting lithologies are identify as the preferential location to study the role of inherited compositional and structural heterogeneities in the interlinked evolution of deformation and metamorphism (Gardner *et al*., 2017; Schmalholz *et al*., 2020; Maino *et al*., 2021).

Research aims and methods

In this work, the interplay between metamorphism and deformation is explored throughout the investigation on how different paired rock types may: 1) record contrasting metamorphic conditions despite sharing a structural coherence, and 2) drive strain localization leading to shear zone nucleation.

These purposes are addressed to natural samples from two case studies situated in the Alpine chain, which were chosen because they are representative of highly heterogeneous lithological boundaries and processes occurring in the middle to lower crust during opposite regional tectonic regimes (compressive and extensional): 1) the Alpine high pressure/high temperature (H*P*/H*T*) occurrence of Cima di Gagnone (Central Alps) and 2) the Tethyan rift-related extensional shear zone (Anzola shear zone, Western Alps). To achieve the work aims, the methods adopted consisted in combining field-based work observations with detailed (micro)structural, petrological, geochemical, and geochronological analyses with particular attention to quantify the time and space variations of metamorphic and deformation conditions as function of the rheological rock behaviour at the interface of heterogenous lithological domains. For these reasons, a wide range of analytical techniques were used including optical microscopy, Scanning Electron Microscopy (SEM), and Electron Backscatter Diffraction (EBSD) for detailed petrographical and microstructural characterization, X-ray fluorescence (XRF) for the determination of the bulk rock chemistry, Electron Probe Microanalyzer (EPMA) and Laser Ablation Inductively Coupled Plasma

Mass Spectrometry (LA-ICP-MS) to obtain quantitative mineral chemistry and U-(Th)-Pb using LA-ICP-MS technique for dating geochronometers (*e.g.*, zircon, monazite, titanite). Finally, the pressure and temperature conditions of deformation and of the metamorphic reactions were constrained through Geothermobarometry (*e.g.*, Fe-Mg garnet-biotite, Ti-in-Amphibole, Si in muscovites/phengites, Garnet-Aluminosilicate-Silica-Plagioclase, Zr-in-Rutile, and so on) and thermodynamic modelling (using Perple_X software; Connolly, 1990, 2005). The result of this approach gave back more accurate local reconstructions of the Pressure-Temperature-time-Deformation-Composition (*P-T-t-D-X*) conditions of the studied rocks in the frame of the regional context.

CASE STUDY 1: CIMA DI GAGNONE

The Alpine HP/HT metamorphism and deformation during subduction

The Cima di Gagnone area belongs to the Cima Lunga unit, which is part of the southern sector of the Lepontine dome of the Central Alps (Fig. 1; *e.g.*, Maxelon & Mancktelow, 2005; Steck *et al.*, 2013, 2019). It represents an example of ultrahigh-pressure and high-temperature ultramafic lenses enveloped within amphibolite-facies metasedimentary rocks as the result of the Alpine subduction/collision deformation phases (*e.g.*, Gebauer, 1994, 1996, 1999; Scambelluri *et al.*, 2014, 2015). This topic is still a matter of a lively scientificdebate for countless studies for what concern the evolution of this tectonic nappe system (*e.g.*, Schmalholz *et al.*, 2014; Scambelluri *et al.*, 2014, 2015; Schenker *et al.*, 2015; Casini & Maino, 2018; Maino *et al.*, 2021). Recent structural investigations demonstrate that the rheologically strong ultramafics and weak metapelites experienced a common Alpine deformation history in a single tectonic unit (Maino *et al.*, 2021).

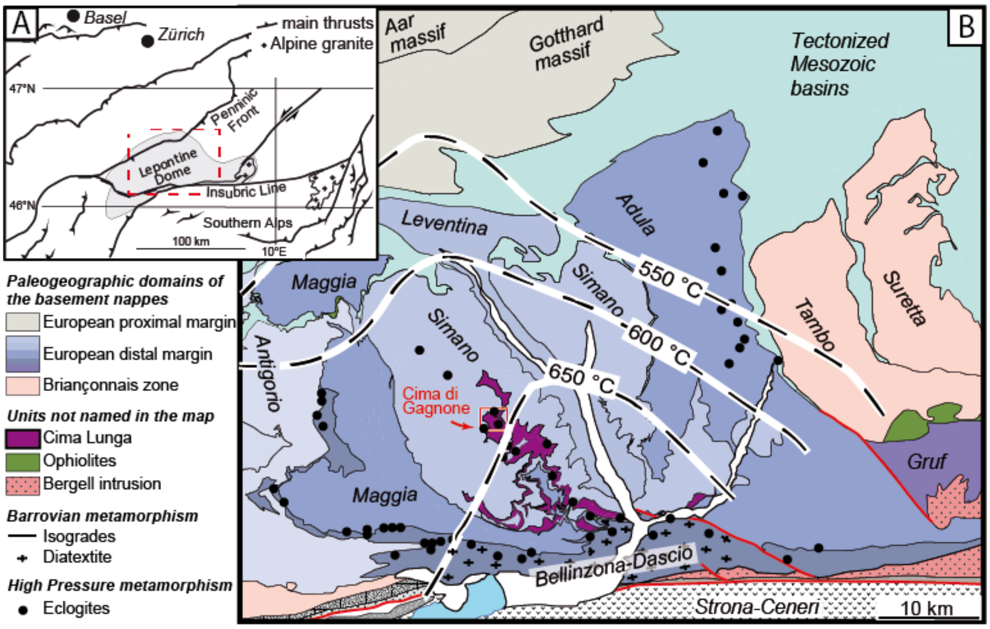

Fig. 1 - Overview(A) and tectonic map (B) of the Cima Lunga unit within the Lepontine Dome (modified after Todd & Engi, 1997; Brouwer *et al.*, 2005; Burg & Gerya, 2005; Steck *et al.*, 2013; Cavargna-Sani *et al.*, 2014; Maino *et al.*, 2021). Isotherms refer to the Barrovian metamorphism.

For this case study, investigations focused on the metamorphic and deformation evolution of the metasediments, which received minor attention respect with the ultramafic lenses (*e.g.*, Grond *et al.*, 1995; Pfiffner, 1999; Corvò *et al.*, 2021; Piccoli *et al.*, 2021). The aims consisted to i) constrain the *P-T-t-D* path of micaschists in relation with the ultramafics, ii) to investigate the geochemical exchange at the boundary of these compositionally different rock types. Structural, microstructural, and petrological analyses and thermodynamic modelling highlighted that even though the weak metasediments experienced a common Alpine deformation history in a single tectonic unit with the strong ultramafic boudins, large differences in the metamorphic features and *P*-*T* paths are recorded (Corvò *et al*., 2021). Large part of the unit experienced middle pressure and medium temperature conditions (*Country rocks;* P < 1.2; *T* < 700°C), whereas a few occurrences preserve higher metamorphic conditions (*Halos samples;* 1.3-1.7 GPa; 750-850°C). These last estimates approach the *P*-*T* peak conditions experienced by the ultramafic rocks (1.5-3.2 GPa; 740-850°C) and are locally developed close to the rheological boundary depicted by the metapelite-ultramafic contact (Corvò *et al*., 2021; Piccoli *et al*., 2021). This study, indeed, demonstrated that these pressure and temperature deviations (Δ*P* up to 2 GPa; Δ*T* up to 160°C) are not randomly distributed in the unit but changes systematically as a function of the distance from the strong lithology (*i.e*., ultramafic rocks), being maximum at the interface between the two rock pairs (*Halos samples;* Fig. 2). Moreover, bulk rock and mineral chemistry changes during growth of new mineral phases (such as coronitic textures and thick zircon rims) documented fluid-rock interaction (*i.e*., metasomatism) during the H*P*-H*T* deformation phase as being strongly localized at the boundary between ultramafic lenses and the metapelitic host (Fig. 2). The local occurrence of (U)H*P* and H*T* conditions is demonstrated by the absence of significant melting in the unit (*e.g*., migmatites), although around the ultramafic lenses, metapelites show hydrated assemblage at *T* > 800°C stable at variable P stage. Finally, U-Pb zircon and monazite dating indicate that local H*P* and H*T* conditions were accomplished at the early stage of Alpine exhumation (~36 Ma), while the rocks far from the rheological boundaries records only pre-Alpine ages.

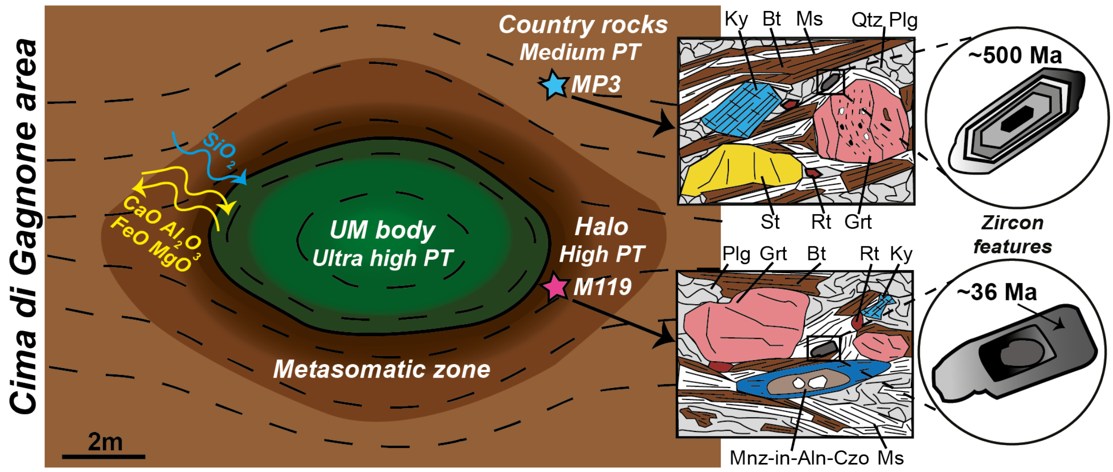

Fig. 2 - Schematic sketch of the reaction zone (brown zoned band) characterized by the interaction between ultramafic (UM) and *Halos* samples (M119). Dashed lines represent the outcrop foliation. Arrows indicate the direction of chemical component mobility (SiO_2, CaO, Al_2O_3, FeO, MgO). Stars indicate the representative sample's location (*i.e*., MP3 - *Country rocks*, M119 - *Halos*); in the sketches on the right the relative mineral assemblages and zircon textures and average ages are reported.

In conclusion, this study suggests that heterogeneous metamorphism conditions are locally developed, rather than locally preserved. Indeed, the interplay between metapelites and ultramafic exerts a crucial first-order control to allow assemblage equilibrium during H*T* metamorphism (Corvò *et al*., 2021). In the Cima di Gagnone type-locality, different local equilibria during H*T* metamorphism and amphibolite-facies retrogression are related to the proximity to the strong lithology, suggesting that the rheological and chemical contrasts between strong and surrounding weak rocks had a significant role in modifying the local metamorphic gradients. Moreover, the chemical gradient between compositionally different lithologies combined with fluids circulations results in coexisting heterogeneous metamorphic equilibria, which are not representative of the ambient conditions. Therefore, these new findings exclude that the different metamorphic record may be attributed only to differential preservation during the retrograde path. Finally, these new *P-T-t-D* paths highlight the crucial role of the rheological boundaries in modify the *P-T* metamorphic records without necessarily varying lithostatic pressure and thus depth conditions.

CASE STUDY 2: THE ANZOLA SHEAR ZONE

The pre-Alpine HT metamorphism and deformation of extensional shear zone

The Anzola shear zone represents a major extensional structure from one of the best-preserved cross-sections through the middle to lower continental crust of a fossil passive margin, the Ivrea-Verbano Zone (IVZ; Southern Alps, Italy; Fig. 3). The IVZ always attracted many geoscientists since it experienced a long-lived tectono-metamorphic history going from the Variscan to the Alpine orogenesis. Recently, it has been emphasized the role of the IVZ was during extensional processes leading to the Alpine Tethys rifting (*e.g.*, Rutter *et al.*, 1993; Beltrando *et al.*, 2015; Petri *et al.*, 2019). In this frame, the Anzola shear zone is interpreted as one of the main rift-related structure of the Late Triassic-Jurassic deformation in the lower crust of the Adriatic margin. Nevertheless, the timing of its activity is still poorly constrained. Furthermore, it is believed to have developed within a rheologically hard and isotropic mafic body rather than in the surrounding weaker and anisotropic metamorphic sequence (Brodie, 1981; Altenberger, 1997; Stünitz, 1998). However, a wide detailed characterization at the meso-microscale of its compositional and structural features is still lacking.

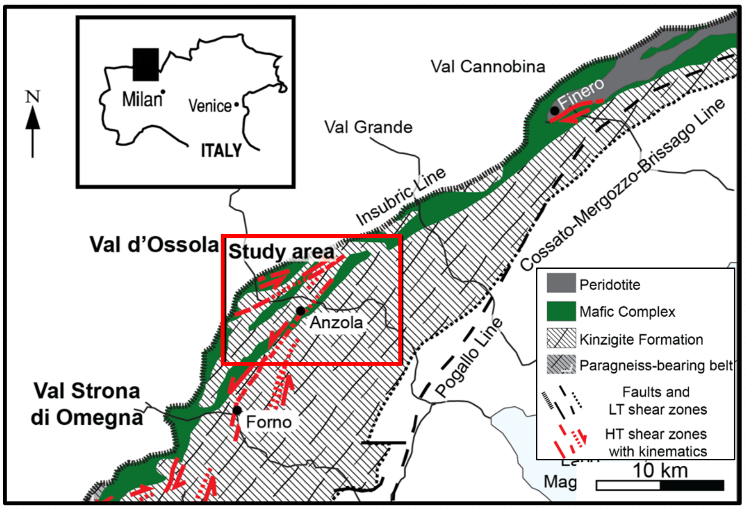

Fig. 3 - Geological sketch map of the Anzola shear zone area within the Ivrea-Verbano Zone, modified after Ewing *et al.* (2015) and Simonetti *et al.* (2021). The locations of high-temperature shear zones are after Rutter *et al.* (1993). The studied area is reported in the red box.

For this case study, investigations focused on the: i) characterization of lithological, compositional, and structural features and ii) identification of the protolith of the shear zone rocks, with the aim to decipher the role of inherited rock heterogeneities as drivers of weakening and strain localization at middle/lower crustal layers.

Field and meso-structural results revealed that the Anzola shear zone overprinted basement rocks characterized by inherited lithological heterogeneities and structural (folds) features (Corvò *et al.*, 2022). Gabbroic rocks and migmatites define the hanging wall and footwall of the shear zone, respectively. Thanks to the petrographical and geochemical results, we demonstrated that (ultra-)mylonitic rocks developed at the expense of a metamorphic volcanic-sedimentary sequence, consisting of alternating paragneisses, mafic rocks and calcsilicates, showing amphibolite to granulite facies metamorphic conditions and deformation features related to pre-shearing (Variscan) event (Fig. 3). Estimated *P-T* conditions obtained by the combination of several geothermobarometric methods on the different rock types, indicate that mylonitic deformation started at high temperature (~820°C) with presence of melt and continued as solid-state deformation down to amphibolite facies (~650°C).

Overall, it is demonstrated that besides the rheological contrasts due to the compositional and structural anisotropies, strain localisation was further promoted by i) the close intrusion of a nearly strong isotropic mafic body and ii) the occurrence of rocks showing transitional metamorphic conditions between granulites (dominated by anhydrous minerals) to amphibolite facies (rich of hydrous minerals). In particular, the lithological contrast between the isotropic strong gabbro and the weaker multi-lithological assemblages provides the ideal place to drive the strain localization into a narrow rock volume (Fig. 4). In addition, we highlighted that syn-deformational partial melting and small amounts of free fluids enhanced the viscosity contrasts of the multi-lithological complex, acting as further weakening mechanism controlling the strain localization. This last aspect was further investigated through a detailed microstructural and petro-chronological study performed on titanite collected from the mylonitic amphibolites of the Anzola shear zone. We observed that titanite recorded contrasting correlations between microstructural and petrochronological features at the micro-scale in dependence of the composition and rheology of the host rock (amphibolite versus calcsilicates). We suggest that the different titanite behaviour were strongly influenced by the fluid-rock interaction occurring along the grain boundaries of microscale lithological heterogeneity. As regard the timing, preliminary petrochronological results from titanite of the mylonitic amphibolites recorded recrystallization event under amphibolite facies at about 185 Ma, which is coeval to deformation occurred at different crustal levels in the IVZ (*e.g.*, Simonetti *et al.*, 2021).

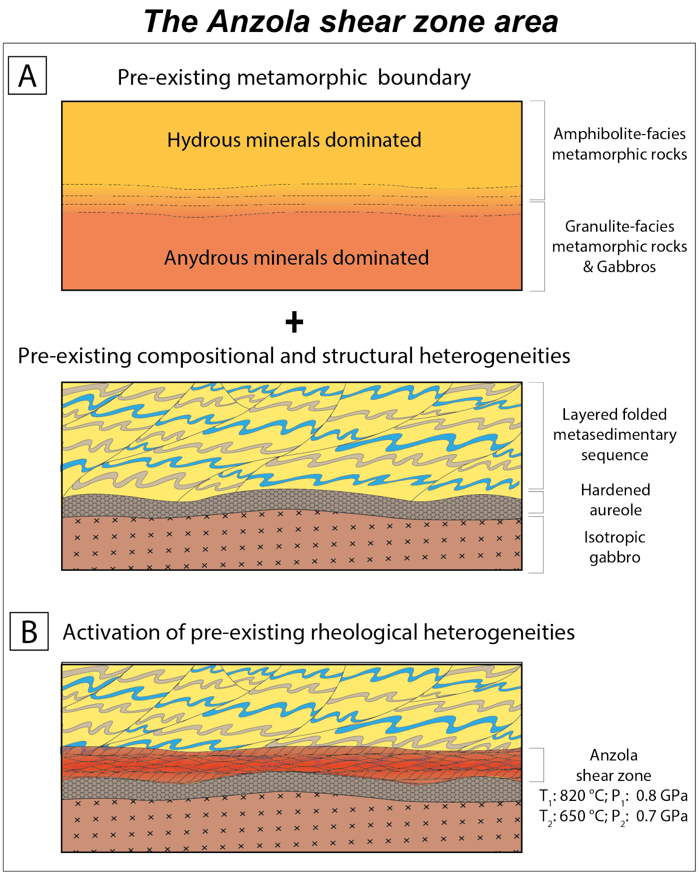

Fig. 4 - Interpretation of the geological conditions that promoted the nucleation of the Anzola shear zone at the transition between middle to lower crust at the meso-scale (A, B) (modified after Gardner *et al.*, 2017). A) Before the Anzola shearing, the transition between middle to lower crust is characterized by the juxtaposition of i) a gradual transition from anhydrous conditions (granulite facies) to hydrated assemblages (amphibolite facies rocks) and, ii) pre-existing compositional and deformational heterogeneities (late Variscan undeformed isotropic gabbro and its contact aureole *vs.* folded Variscan metamorphic volcano-sedimentary sequence made of mafic rocks, paragneisses and calc-silicates). B) The combinations of these factors resulted in the formation of strong rheological contrasts that promoted the initiation of the Anzola shearing during Triassic, when the Tethyan rifting stage triggered renewed extensional tectonics. *P-T* conditions for deformation are reported as T_1, T_2, P_1, P_2 to indicate that deformation started at high temperature (T_1: ~820°C; P_1: 0.8 GPa) and continued down to amphibolite facies (T_2: ~650°C P_2: 0.7 GPa) following a retrograde path.

These results further confirm our interpretation about the role of the Anzola shear zone in the framework of the regional context.

In conclusion, this study suggests that detailed petrological, structural, and geochemical investigations allow a better comprehension at the outcrop scale of the role of structural and compositional heterogeneities leading the initiation of shear zone nucleation. In particular, in-depth trace elements study resulted as the most powerful tool to reconstruct the pre-shearing relationships between wall rocks and mylonites and thus determine the protoliths of the shear zone rocks. Moreover, the boundaries characterized by alternated different lithologies and pre-existing structural features combined with the inherited deformation and metamorphic patterns, become the preferential loci. Our findings finally suggest that the boundaries characterized by pre-existing significant heterogeneities relate to rock composition, deformation and metamorphism represent the preferential *loci* for the nucleation of large-scale deformation structure in the mid to lower crust of passive margins (Corvò *et al*., 2022).

CONCLUSIONS

This work explored the interplay between metamorphism and deformation at rheological boundaries generated by inherited lithological and micro-structural differences. Summing up, despite the differences, the two case studies highlight how context characterized by different compositional rock types produced divergent rheological behaviour in the rock assemblages at local scale. For both case studies, indeed, pre-existing rock compositional and micro-structural heterogeneities promoted highly variable rheological behaviours, producing local concentration of stress or strain, which finally resulted in local complex interaction between deformation and metamorphic processes. In Cima di Gagnone area, rheological and lithological contrasts produced different local compositional and metamorphic records, while in the Anzola area contrasting micro- and meso-scale compositional + structural + metamorphic features promoted the initiation of a major crustal shear zone (Corvò *et al*., 2021, 2022). As a final remark, it is highlighted the crucial role of careful investigations on: i) all the lithologies involved in the study area; ii) the rheological behaviour of the studied rocks; iii) the relationships between deformation and metamorphic processes at the boundary of different paired rock types. In conclusion, this work provides new information from natural occurrences with the aim to improve the comprehension of the mechanisms of deformation and metamorphism. Finally, this study highlights that the use of a calibrated multidisciplinary approach on complex rock assemblages is fundamental for providing key information to interpret the evolution of the tectonic structures more carefully.

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