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PETROLOGICAL AND MICROSTRUCTURAL CONSTRAINTS FOR OROGENETIC EXHUMATION MODELLING OF HP ROCKS: THE EXAMPLE OF SOUTHERN CALABRIA PELORITANI OROGEN (WESTERN MEDITERRANEAN)

R. Cirrincione, E. Fazio, P. Fiannacca, G. Ortolano, A. Pezzino, R. Punturo

Dipartimento di Scienze Geologiche, Università di Catania, Italy - Corso Italia, 57 – 95129, Catania (Italy) (ortolano@unict.it – G. Ortolano)

Summary

Quantitative petrological and microstructural analyses allowed to derive P-T estimates and rheological features leading to obtain detailed tectono-metamorphic evolution of a HP metamorphic Unit occurring in the southern sector of the Calabria Peloritani Orogen (southern Italy).

Obtained data allowed to apply a model for this Alpine sector chain, consisting of a tectonic process causing the return flow of HP rocks from depth, which have been extruded along ductile to brittle shear zone developing during the compressional stages of the Alpine orogenesis.

Introduction and geological background

The evolution of the Alpine belts in Mediterranean area (Fig.1a) is often related to the Oligocene-Miocene opening of back-arc basins developed within an overall collisional tectonic setting. In this scenario several tectonic models were proposed (e.g. Rosenbaum et al., 2002 and reference therein), which are mostly associated to the syn-orogenic retreat of the subducting plate, justifying the observed drifting phenomena of some thrust belt (e.g. Calabria).

Nevertheless, the occurrence of high pressure (HP) and ultra high pressure (UHP) metamorphic rocks within some of these belts (Jolivet et al., 2008 and reference therein), raised several questions about the exhumation mechanisms (e.g. syn-convergent extension or extrusion) operating during the uplifting process of these rocks.

For the above reasons, the reconstruction of the tectono-metamorphic evolution of basement units which have experienced HP-UHP metamorphism becomes a tool to understand the Alpine geodynamics which have controlled the evolution of the western Mediterranean realm since late Cretaceous.

In this view, we provide new petrological and microstructural constraints which allow to reconstruct the tectono-metamorphic evolution of a HP unit located in the southern Calabria, useful to define the orogenic modelling consistent with the inferred P-T trajectories and observed deformation mechanisms of rock constituents.

This unit, known as Madonna di Polsi Unit (MPU), represents the deepest metamorphic one of the Aspromonte Massif nappe-like structure, located in southern Calabria-Peloritani Orogen (Fig.1b).

MPU is mostly composed by a greenschist to lower amphibolite facies metapelite sequence characterised by an Alpine multistage metamorphism, presently surfacing in several tectonic windows (Pezzino et al., 2008).

Structural and petrological constraints highlighted as MPU experienced a HP-LT metamorphism, linked with a crustal thickening phase evolving towards a late Oligocene mylonitic stage, testified by the presence of a retrograde *quasi*-adiabatic decompression path and evolving to a (very late) *quasi*-isobaric cooling trajectory (Cirrincione et al., 2008; Fazio et al., 2008).

During this last stage, a crustal scale mylonitic shear zone developed, well exposed along the contact between MPU with the overlying Hercynian amphibolite facies Aspromonte Peloritani Unit (APU). This shearing event produced pervasive mylonitic foliation and stretching lineation with kinematic indicators showing a top-to-NE sense of shear in the present-day geographic coordinates.
The following geodynamic evolution proceeded towards compressive thin-skinned thrust belt system, producing SE verging metric to hectometre asymmetrical folds. This shallower seated deformational stage was responsible for the folding of the original mylonitic foliation causing pronounced thickening of the original mylonitic band, which currently ranges from 0.5 to 0.8 km (Ortolano et al., 2005).
A subsequent upper Miocene NE-SW brittle extensional fault system, finally, marks the change from the collisional processes to an extensional tectonics (Monaco et al., 1996).
Within this complex interplay between compressional and extensional tectonics, new and reviewed pressure temperature deformational (PTd) path are here reported in order to give a contribution to the application of a specified exhumation model, useful to better constrain the geodynamics of this sector of Alpine Mediterranean chain.

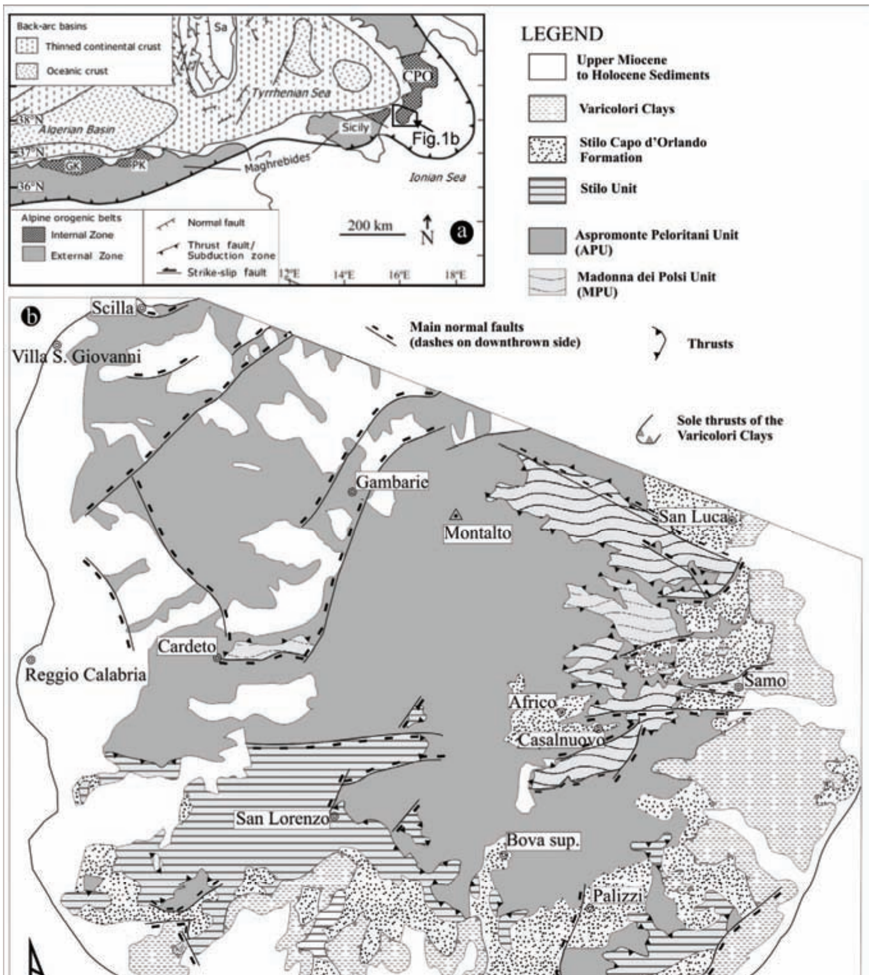

Figure 1. **a)** Schematic map of the Alpine belt in the southern Mediterranean area (GK – Grande Kabylie; PK – Petit Kabylie; Sa – Sardinia; CPO – Calabrian Peloritani Orogen) modified after Carminati et al. (1998); **b)** Geological-structural map of the Aspromonte Massif after Pezzino et al., (2008)

Tectono-metamorphic evolution

Integrated application of inferred petrological and microstructural PT estimates represent one of the basic tool to investigate the thermo-mechanical features of rocks involved in complex tectono-metamorphic evolutions. In this view, the PT trajectory, constrained by means of pseudosection tool (Cirrincione et al., 2008), were here integrated with new microstructural analyses of rocks of both units involved in the joint mylonitic stage related to the retrograde uplifting process.

Petrological constraints

By means of pseudosection tool, was possible to bracket the PT evolution of the Aspromonte Peloritani and Madonna di Polsi Units, which are resulted to be characterised by a multi-stage metamorphic history (Cirrincione et al., 2008).

APU metapelites were involved in an early Hercynian evolution characterised by low $\Delta P/\Delta T$ prograde evolution, defined by a first stage with pressure of 0.56±0.05GPa at temperature of 570°±10°C, evolving towards peak conditions of 0.63-0.93GPa at 650-710°C (Fig.2a). A later metamorphic Hercynian evolution is documented by a retrograde trajectory constrained by 0.25 GPa at ~540 °C PT values.

By contrast the deepest MPU metapelites showed evidence of high $\Delta P/\Delta T$ prograde trajectory (Fig.2a), typical of an Alpine type metamorphic gradient. This fact is constrained by an earlier stage at 0.75-0.90 GPa and 510-530 °C, followed by increasingly peak PT conditions at pressure of 1.24±0.02 GPa with temperature ranging from 540 to 570 °C.

The late mylonitic metamorphism, which affected both APU and MPU is responsible of a quasi-adiabatic retrograde decompression path (0.75±0.05 GPa at 570-600 °C) depicted by a former fast exhumation stage, evolving to a joint cooling trajectory at pressure of 0.38±0.14 GPa at temperature of 490±30 °C (Fig.2a).

Microstructural constraints

Microstructural analysis allowed to highlight the rheological behaviour of those rocks belonging to both units involved in the mylonitic shearing event, mostly by means of the study of quartz c-axis orientation pattern (Heilbronner and Tullis, 2006) by means of AVA generator software (Stöckhert and Duyster, 1999).

Selected mylonitic samples of the APU allowed to recognise feldspars usually forming fragmented porphyroclasts (δ and σ type objects) with bookshelf-sliding structures, locally affected by evidence of intracrystalline deformation, highlighted by bent twin lamellae and undulose extinction. Biotite is interstitial, diffusely parallel to the mylonitic foliation and retrogressed into chlorite. White mica forms very large (up to 500 micron) fish shaped objects and occasionally bouden parallel to the main foliation interbedded by chlorite laths.

Quartz shows both BLG (i.e. bulging recrystallization, T of 300-400 °C ca. – Stipp et al., 2002) and SGR (subgrain rotation recrystallisation, T range of 400-500 °C ca. – Stipp et al., 2002). Undulose extinction is more pronounced within ribbon-like grains, whereas at their edges smaller subgrains depict an oblique foliation (T = 490 °C ca. – Stipp et al., 2002). Computed quartz c-axis pattern highlights for the APU mylonitic rocks a dominant basal <a> dislocation mechanism consistently with shearing temperature ranging from 400 to 450 °C (Fig.2b).

Mylonitic foliation of MPU samples is often isoclinally folded. S-C textures are widespread. Feldspars are scarce and usually constitute small fragments. SGR is the dominant recrystallisation mechanism of quartz. Large quartz grains show chessboard extinction pattern and locally an incipient GBM (grain boundary migration recrystallisation, T > 500 °C - Stipp et al., 2002).

Analysis of quartz c-axis pattern constrains shearing temperature averagely higher than in the APU mylonitic rocks, as evidenced by the dominant rhomb <a> dislocation mechanism (450-500 °C) switching towards an incipient prism <a> dislocation mechanism, highlighting shearing temperature up to 550 °C (Fig.2b).

Above shearing temperatures are also supported by evidence of stretched amygdales of garnet fragments elongated parallel to the mylonitic foliation, often mantled by sericite and chlorite overgrown.

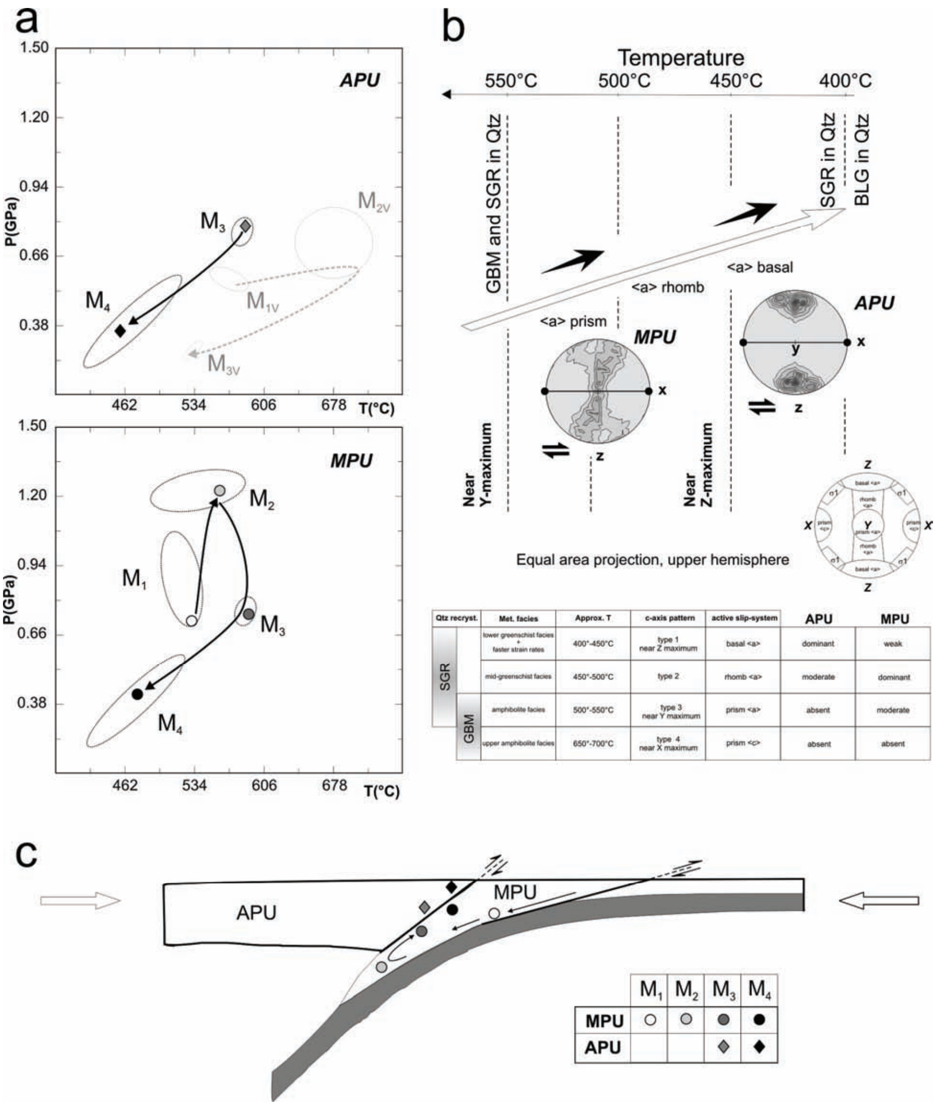

Figure 2. **a)** P-T paths inferred for the Aspromonte Peloritani Unit (APU) and Madonna di Polsi Unit (MPU) (M_{1-4} – Alpine metamorphic episodes; M_{1v-3v} – Variscan metamorphic episodes). Ellipses depict P-T spaces derived from geothermobarometric estimates (after Cirrincione et al, 2008; and Fazio et al., 2008). Symbols represent different stages of the tectonic evolution of rocks involved in the shear zone; **b)** Quartz *c*-axis pattern achieved for mylonitic rocks belonging to the Aspromonte Peloritani Unit (APU) and Madonna di Polsi Unit (MPU). Temperature conditions are after Stipp et al. (2002); Heilbronner and Tullis (2000); **c)** tectonic model proposed for the exhumation of HP rocks of Madonna di Polsi Unit within a convergent environment (M_{1-4} – Alpine metamorphic episodes). Empty and filled symbols depict the evolution of rocks both in the geological section and in the PT-space of Fig. 2a.

Orogenetic modelling: purpose and conclusion

Integrated petrological and microstructural analyses prove to be a key role to investigate the thermo-mechanical features of the tectono-metamorphic evolution of basement rocks.

In this view, the recognition of a relatively HP basement unit in the southern Calabrian Peloritani Orogen, opens new possible purposes for the definition of the exhumation mechanism for this deep-seated metapelite unit.

According to Pezzino et al. (2008), inferred petrological and structural constraints are indeed consistent with an Alpine evolution for the southern sector of CPO, which is characterised by a prograde crustal thickening phase probably due to the underplating of a Mesozoic sedimentary sequence (i.e. MPU), covered a thinned continental crust, beneath the European plate. This phase was followed by an Africa-verging late-Alpine exhumation along a deep-seated mylonitic shear zone, responsible at the same time for the Alpine metamorphic overprint which partly reworks the Hercynian APU basement rocks.
In this view, the rocks of the Aspromonte Peloritani Unit can clearly be described as the result of a relic metamorphic cycle, in which HT/LP mineralogical assemblages (Hercynian evolution) were overgrown by later Alpine mylonitic shearing parageneses. Conversely, the rocks of the underlying Madonna di Polsi Unit can be considered to be the result of a single Alpine metamorphic cycle, characterised by an early HP/LT stage (peak P-T of 1.2 GPa at 550 °C) evolving to the joint shearing event involving the overlying APU.
In agreement with the model proposed by Burov et al. (2001), it is possible to suggest that MPU, can been affected by positive buoyancy due to its average low density, and consequently extruded along a fast subduction channel activated by both the lower descending plate and the shear flow created by the overriding one (i.e APU) (Fig.2c). This motion is also responsible for the formation of the observed mylonitic shear zone, overprinting the boundary of the backstop (i.e APU) in the late Oligocene (Bonardi et al., 1987).
This model can be also supported by Gueguen et al. (1998) geodynamic reconstruction, which ascribe the change from a compressional to an extensional tectonic regime for the CPO to the late Burdigalian, coevally to the opening of the Vavilov basin and following the separation of the CPO from the Sardinia block, as well as by the geological evidences of a persisting compressional thrust-belt emplacement up to early Miocene. This is also demonstrated by thin-skinned SE-verging thrust-sheet planes involving also the base of the late Oligocene-early Miocene sedimentary sequence deposited on the Aspromonte Massif (Ortolano et al., 2005).
In this scenario, it is possible to suggest that the tectonic evolution of the Aspromonte Massif is dominated until upper Miocene by orogenic thickening and nappe emplacement of metamorphic and non-metamorphic rocks.

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THE ROLE OF THE LITHOSPHERIC STIFFNESS AND PLATE AGEING ON TRENCH KINEMATICS: INSIGHTS FROM NUMERICAL MODELS

E. Di Giuseppe[1,2], J. van Hunen[3], F. Funiciello[2], C. Faccenna[2], D. Giardini[1]

[1] *Institute of Geophysics, ETH-Zurich, Hoenggerberg Campus, Schaffmattstr. 30, CH-8093, Zuerich (Switzerland)*
[2] *Dipartimento di Scienze Geologiche, Universita' degli Studi Roma Tre, Lgo S.L.Murialdo, 1, 00146, Roma (Italy)*
[3] *Department of Earth Sciences, Durham University, Durham DH1 3LE (United Kingdom)*

Summary
By means of two- and three-dimensional numerical modelling of subduction, we investigate the dominant dynamic controls on trench migration. Geometrical and rheological parameters are systematically changed to study the role of the plate stiffness and lithospheric ageing on trench migration. Plate stiffness depends on slab thickness and relative viscosity and density contrasts, and can be interpreted as the key parameter in controlling trench motion. Stiff lithosphere promotes advancing trench migration, whereas weak slabs retreat. As revealed by the global kinematic data from current subduction zones in different hot spot reference frames, young trenches move on Earth's surface in retreating (e.g. rolling back), and old plates advance (forward). By combining model results and natural data, we argue that old/stiff plates migrate in advancing, whereas young/weak slabs roll back.

Introduction
Subduction process operates by bending at trench. This feature suggests that the plate lithosphere might be weakened somehow (Tao and O'Connell, 1993) when bends. Multibeam bathymetry and seismic images show that the bending-related faults cut the lithosphere at trench and may promote hydration and serpetization, favoring the plate weakening (Ranero et al., 2003; Hirano et al., 2006). Despite the many studies to the lithospheric strength (Kohlstedt et al., 1995), and its weakening caused by the yield stress the bending mechanism in the subduction process is still poorly constrained. The slab strength at the trench has important consequences for the kinematics of the subduction process as well. Bellahsen et al. (2005) highlight for the first time that the "free" subduction occurs with two main styles: an advancing and a retreating one. The first compilations of global data on the trench motion revealed that most of the trenches was migrating backward with respect to the upper plate (Jarrard, 1986; Garfunkel et al., 1986). This view has been progressively consolidated despite Carlson and Melia (1984) showed that the Izu Bonin-Mariana subduction zone, which is the oldest subduction zone on Earth, is presently advancing in the hotspot reference frame towards the Philippine overriding plate. In recent works (Heuret and Lallemand, 2005; Funiciello et al., 2008) such a partition of the subduction zones between retreating and advancing styles can be recognized in different geographical reference frames. Heuret and Lallemand (2005) found an inverse relationship between trench migration and age of the lithosphere at trench, where old subducting plates advance, and young ones retreat. This relationship contradicts the common idea that