A 300 MILLION YEAR-LONG HISTORY. THE METAMORPHIC EVOLUTION OF THE NORTHERN APENNINE VARISCAN BASEMENT

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INTRODUCTION

Collision zones are the loci on the Earth where large portions of continental crust of different ages and origin are processed at different depths and temperatures. The exhumed slices of continental crust from collisional orogens record the overprinting relations between different stages of metamorphic (re)crystallization and deformation. Metamorphic petrologists investigate chemical and structural variations from the outcrop to the micron scale in an effort to better understand the petrogenetic processes occurring in the collision zones.

The Variscan basement of Northern Apennines (Northern Italy) is an example of a continental crust portion affected by a complex polymetamorphic evolution.

This work investigated the metamorphic evolution of this basement occurring in the Cerreto Pass, in the bedrock reached by the Pontremoli well, and in the Pisani Mountains.

The study comprised fieldwork in the Cerreto Pass, sampling, petrography and microstructural analysis, determination of the bulk rock and mineral composition, thermodynamic modelling, conventional mineral-mineral geothermobarometry, monazite chemical dating, and Ar/Ar dating of muscovite.

Geological framework

The Northern Apennines are an Alpine orogenic belt formed during the collision between the Corsica-Sardinia and the Adria microplates in Oligocene-Miocene (Vai & Martini, 2001).

They consist of three tectonic units (from top to bottom): *i*) Liguride Units - ophiolites from the Ligurian-Piedmontese ocean; *ii*) Tuscan Units - Mesozoic-Tertiary sedimentary sequences belonging to the continental Adria crust; *iii*) Tuscan Metamorphic Units - Alpine-age metamorphic rocks of the Adria microplate comprising a Variscan basement and its upper Carboniferous-Tertiary cover.

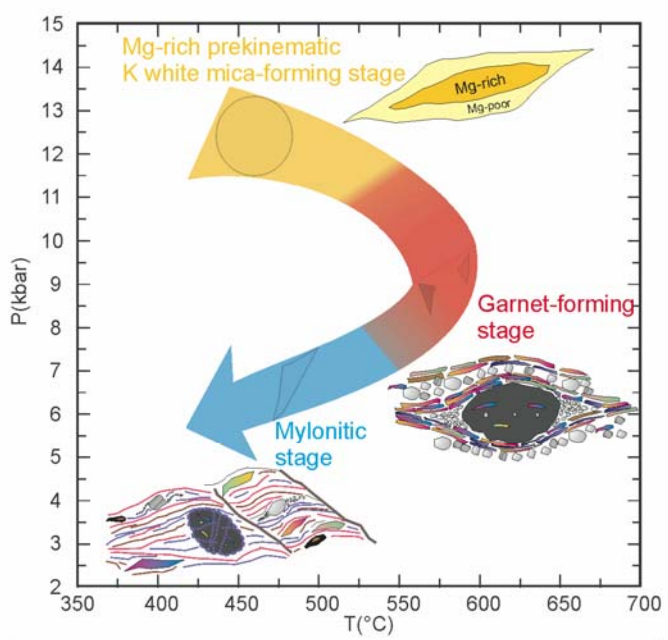
The Variscan basement of Northern Apennines shows a polymetamorphism from the Variscan orogenesis to the Alpine one. While the Alpine tectono-metamorphic history of the Triassic Verrucano Group, a metasedimentary sequence tectonically stacked onto the Variscan basement, is well-known (Theye *et al.*, 1997; Giorgetti *et al.*, 1998; Jolivet *et al.*, 1998; Franceschelli & Memmi, 1999; Franceschelli *et al.*, 2004), the state of knowledge on the Variscan basement is poor and modern studies applying advanced petrologic methodologies are lacking.

The difficulties to study the Variscan basement of Northern Apennines arise from: *i*) a poor exposure of scattered outcrops; *ii*) a strong Alpine overprint on Variscan features (Franceschelli *et al.*, 2004). For these reasons, the Variscan *P-T-t* path is less constrained than the Alpine evolution or, when *P-T* data are available (Bertini *et al.*, 1994; Molli *et al.*, 2002), the reconstructed history refers to the late exhumation-related stages.

One of the outcome of this research was to provide better constraints on the pre-Alpine *P-T-t* path and compare the obtained new paths with others retrieved from several Mediterranean Variscan basements.

INSIGHTS INTO THE VARISCAN OROGENY: THE TECTONO-METAMORPHIC EVOLUTION OF THE CERRETO MICASCHIST

The samples from the Cerreto Pass are mylonitic micaschist with a white mica + chlorite ± biotite mylonitic foliation wrapping around plagioclase, quartz and garnet porphyroblasts. Mg-rich prekinematic white mica and fish-shaped white mica are also present. Through an integration between classical microstructural analyses and thermodynamic modelling it was possible to reconstruct a *P-T-D* path for the Variscan collision and exhumation (Fig. 1). Some similarities occur between the Variscan evolution in Northern Apennines and those described for other fragments of the Southern Variscan belt, especially for the metamorphic rocks outcropping in the Posada Valley Area (Sardinia; Elter *et al.*, 1999; Elter & Pandeli, 2005).



	MICROSTRUCTURES	CONSTRAINING PHASES	P-T ESTIMATES
PRE-PEAK STAGE	Mica-fish cores	Mg-rich prekinematic K white mica (Si=3.30; XNa=0.04)	T= 430-480°C P = 11.0-13.5 kbar
PEAK STAGE	Garnet porphyroclasts	Garnet rim ($Alm_{68}Grs_{18}Prp_{12}$)	T= 580-600°C P = 9.0-10.0 kbar
RETROGRADE STAGE	Mylonitic fabric	- Mylonitic K white mica (Si=3.06-3.19) - Chlorite (XFe=0.50-0.60) - Titanite-bearing assemblages	T= 450-500°C P = 6.0-7.5 kbar

Fig. 1 - *P-T-D* path for the Cerreto micaschist. The table on the bottom contains a summary of the tectono-metamorphic evolution, the microstructures, the constraining phases and the corresponding *P-T* estimates.

A NEW *P-T-T* PATH FOR THE POST-VARISCAN HISTORY: LINKING MONAZITE AND GARNET IN THE PONTREMOLI METAPELITES

The metapelites from the Pontremoli well are medium-grained micaschist with a white mica and chlorite schistose fabric surrounding garnet porphyroblasts. Coronitic microstructures around inherited monazite grains in this rock consist of concentric shells of apatite + Th-silicate, allanite and epidote (Fig. 2).

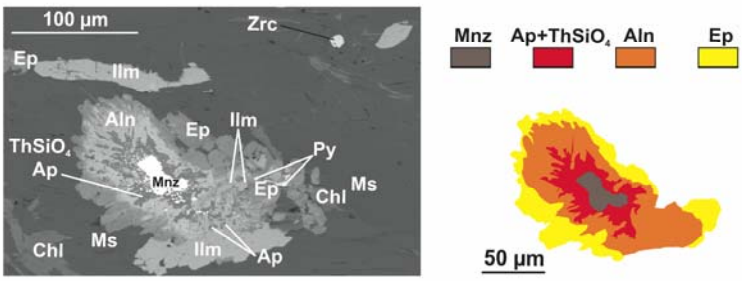


Fig. 2 - BSE images and schematic representations of the coronitic microstructure involving monazite in the Pontremoli metapelites. Abbreviations: Grt = garnet, Chl = chlorite, Ms = K white mica, Ilm = ilmenite, Zrc = zircon, Ep = epidote, Aln = allanite, Py = pyrite, Ap = apatite, Mnz = monazite, Pl = plagioclase.

The chemistry and microstructure of the 294 ± 8 Ma old Th-rich monazite grains suggest that the monazite broke down in an early stage of the metamorphic evolution. An anticlockwise *P-T* path was reconstructed taking into account the effect of garnet fractionation on bulk-rock composition. The obtained *P-T* path postdates 296 ± 6 Ma and results different from the available metamorphic histories of the pre-Mesozoic basement of the Northern Apennines.

DATING THE MYLONITIC STAGE IN THE CERRETO VARISCAN BASEMENT: AR/AR LASER ANALYSIS OF POTASSIC WHITE MICA IN ASYMMETRIC FOLIATION BOUDINS

A combined microstructural-geochronological study was carried out on the shearing fabric in the Cerreto mylonites. This was the first attempt of determining the age of the shearing stage after the Variscan peak in the in the Variscan basement of Northern Apennines. The issue of linking petrology and geochronology has been faced by dating a fabric-forming mineral (*i.e.*, potassic white mica), through *in situ* and step-heating laserprobe Ar-Ar method (Fig. 3). The study provided a comparison of the age distribution in mylonitc foliation and in asymmetric foliation boudins and a possible interpretation of the mylonitic ages.

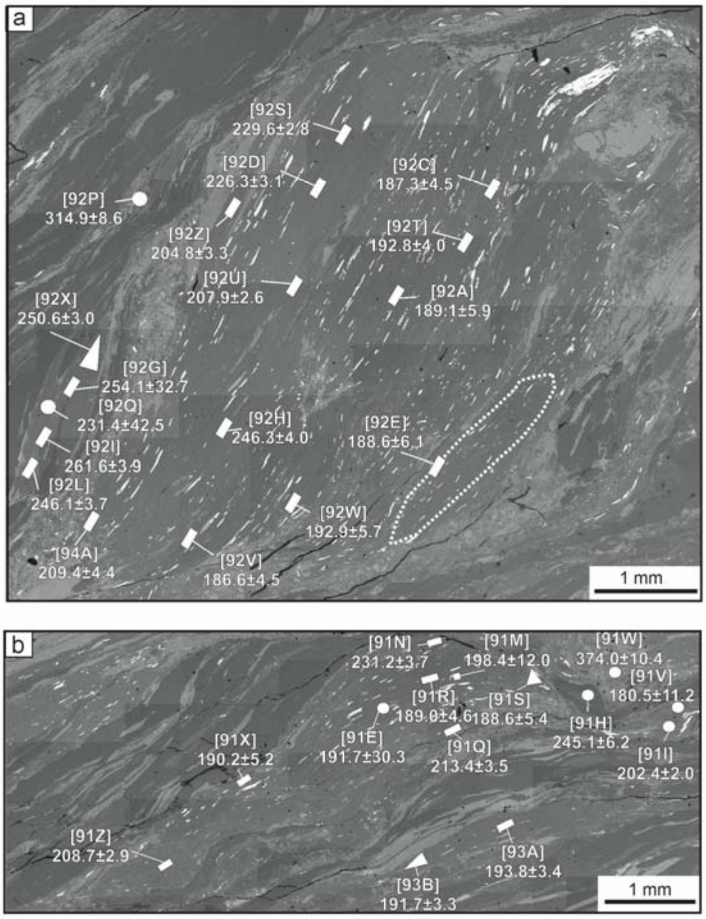


Fig. 3 - BSE images of chip A (a) and chip B (b) with the location of the step-heating area (dotted line), the IR laver spots (circles) and UV laser pits (squares, rectangles and triangles) in the mylonites from the Cerreto Pass. The corresponding ages are reported with the 2σ analytical uncertainty.

THE ALPINE METAMORPHISM AND THE INFLUENCE OF FERRIC IRON IN THE HEMATITE-RICH METASEDIMENTARY ROCKS FROM THE PISANI MOUNTAINS

The samples from the Pisani Mountains are chloritoid-bearing phyllites with abundant hematite bands and disseminated grains. This study investigated the Alpine peak conditions and the effects of different Fe_2O_3 bulk contents on the calculated phase equilibria of low-temperature/intermediate-pressure metasedimentary rocks (Lo Pò & Braga, 2014). Thermodynamic modelling within the MnO-Na_2O-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-O (MnNKFMASHTO) chemical system failed to reproduce the observed mineral compositions when the bulk Fe_2O_3 is determined through titration. The mismatch between observed and computed mineral compositions and assemblage was resolved by tuning the effective ferric iron content by P-$X$$Fe_2O_3$ diagrams. The use of P-T-$X$$Fe_2O_3$ phase diagrams provided chemical and thermobaric constrains about the Alpine peak conditions.

CONCLUSIONS

Petrological findings

The study of the Variscan basement of Northern Apennines allowed to contribute to a better understanding of some general petrological issues generally found in low- to medium-grade metapelites from orogenic settings.

i) Middle-grade mylonitic micaschist usually contains zoned minerals (*e.g.*, garnet and white mica) in different microstructural sites. With suitable samples it is possible to reconstruct a P-T-D path as much complete as possible by combining microstructural analysis and thermodynamic modelling. Prekinematic white mica may preserve Mg-rich cores related to the pre-peak stage. Mn-poor garnet rim records the peak metamorphism. Na-rich mylonitic white mica, the XFe of chlorite and the late mineral assemblage may constrain the retrograde stage.

ii) Metapelites and particularly orthogneiss may contain coronitic microstructures of apatite + Th-silicate, allanite and epidote around unstable monazite grains. In general, it is still not clear which P-T variations are responsible for the development of this kind of corona. In the Pontremoli micaschist, the Th-rich composition and the reaction microstructure of monazite relics surrounded by an apatite-allanite-epidote corona suggest that monazite mineral was inherited and underwent partial dissolution and replacement by REE-accessory minerals at fluid-present peak metamorphic conditions. Element partitioning between garnet and accessory minerals and a detailed microstructural study on garnet inclusion mineralogy (which comprises xenotime in the garnet core, allanite in the outer core and epidote in the rim) allowed to link the crystallization of REE-minerals to the garnet growth in order to reconstruct the reaction history. The replacement of inherited monazite by apatite, allanite and epidote occurred during a prograde evolution at 500-600 °C and 5-7 kbar.

iii) Fish-shaped white mica is not always a (prekinematic) mica-fish. Observed at high-magnification BSE images it may consist of several white mica grains defining a fish-shaped asymmetric foliation boudin formed during a mylonitic stage. Hence, the asymmetric foliation boudin is a suitable microstructure to obtain geochronological information about the shearing stage (190.7 ± 1.3 Ma in the Cerreto mylonite case study). Differently from the asymmetric foliation boudins, mylonitic foliation may include relics of earlier events as evidenced by the ages of 374 and 315 Ma related to the Variscan orogenic cycle.

iv) Thermodynamic modelling is a useful tool to constrain the P-T conditions experienced by a metamorphic rock. However inadequate assumption (*e.g.*, neglecting important components as C, O_2) may result in calculations that reproduce neither the observed mineral assemblage nor the measured mineral compositions. Quantifying Fe_2O_3 is possible through a P-T-$X$$Fe_2O_3$ approach whereas the titration method may overestimate the bulk Fe_2O_3. The effects of different Fe_2O_3 bulk contents were investigated on the calculated phase equilibria of low-temperature/intermediate-pressure metasedimentary rocks from the Pisani Mountains (Fig. 4). The introduction of ferric iron has the effect of increasing the MgO/(MgO+FeO) ratio in bulk rock chemistry and this in turn affects silicate mineral compositions (*i.e.* chloritoid and chlorite XFe^{2+}) and the Fe-Mg exchange thermobarometry. In Fe_2O_3-rich (and CaO-poor) bulk compositions garnet and carpholite occur at higher temperatures than in Fe_2O_3-poor bulk compositions. Furthermore, carpholite is predicted at lower pressure in the MnNKFMASHTO system than in the MnNKFMASHT system. Our modelling in Fe_2O_3-rich rocks indicates that the formation of biotite, the typical Fe^{3+}-bearing silicate in metasedimentary rocks, can be controlled by the stability of Fe^{3+}-oxides such as hematite.

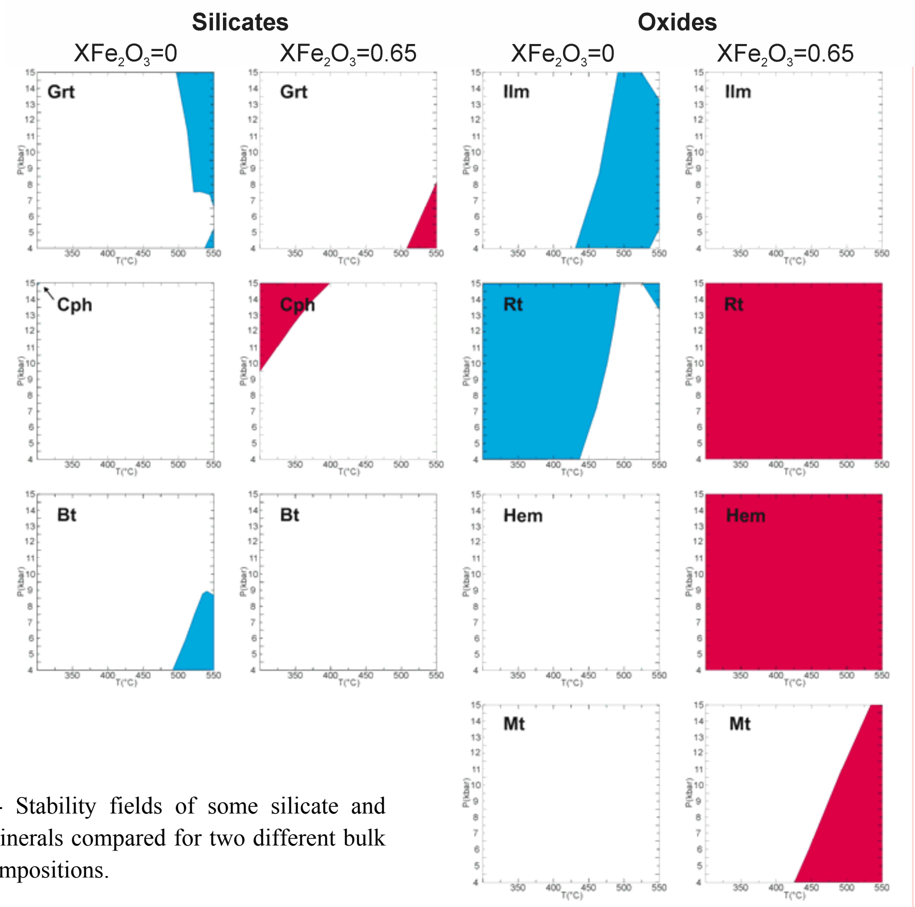


Fig. 4 - Stability fields of some silicate and oxide minerals compared for two different bulk Fe3+ compositions.

Regional reconstructions

This work aimed also to unravel the metamorphic history of the Northern Apennine Variscan basement as much comprehensive as possible, including the pre-Alpine stages, the possible correlations with other Variscan basement, the evolution between the Variscan and the Alpine orogeneses, and the Alpine peak conditions (Fig. 5).

In late Carboniferous the Cerreto micaschists underwent a high-pressure event at 430-480 °C and 11-13.5 kbar, probably due to the Variscan thickening stage.

The Pontremoli samples record a different metamorphic history. Detrital monazite yields U-Th-Pb chemical ages of 294 ± 5 Ma, interpreted as a late-Variscan thermal stage unrelated to the reconstructed metamorphic evolution. The Pontremoli micaschist experienced a prograde evolution at 500-600 °C and 5-7 kbar, followed by a pressure peak at 520 °C at 8 kbar and then a nearly isothermal cooling to 500 °C at 2 kbar. The overall anticlockwise shape of the *P-T-D* path is different from the available metamorphic histories of the pre-Mesozoic basement of the Northern Apennines, and may be due to the post-Variscan shear zone tectonics or to the Alpine orogeny.

A shearing stage affected the Cerreto mylonite at 190.7 ± 1.3 Ma (Ar/Ar isotopic age of Na-rich mylonitic muscovite) and was accompanied by a strong ductile deformation at 450-500 °C and 6-7.5 kbar. This age suggests that the exhumation of the Cerreto mylonite took place during the rifting stage of the Adria margin before the opening of the Ligurian-Piedmont ocean.

The high-pressure greenschist-facies conditions (475 °C and 9-10 kbar) preserved in the chloritoid-bearing phyllites from the Pisani Mountains indicate that, from the late Oligocene onwards, the Northern Appenine basement attained similar P-T conditions as the overlying metasediments (Verrucano).

As a whole, the results on the Cerreto, Pontremoli and Pisani Mountains samples allowed to reconstruct a long-lasting metamorphic history straddling the Variscan and Alpine orogeneses.

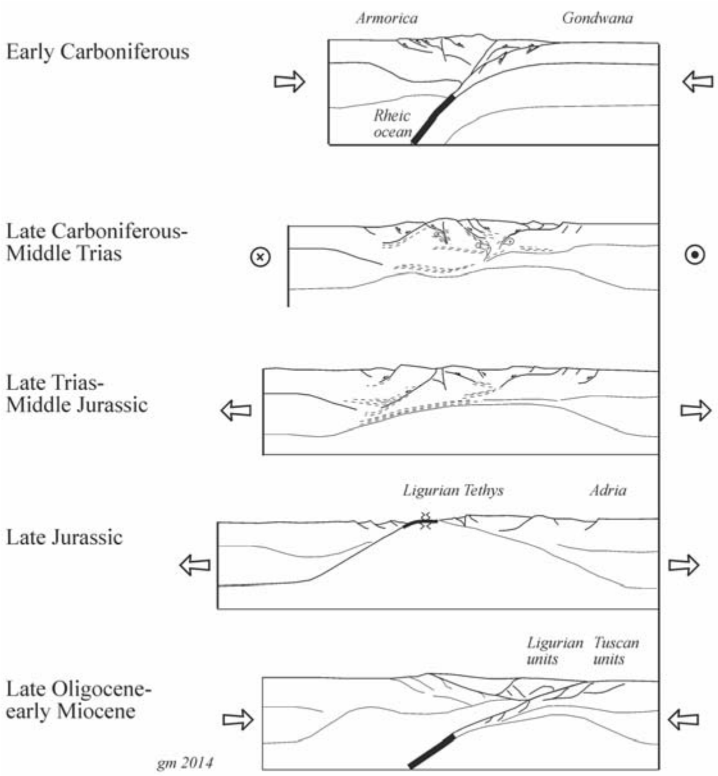


Fig. 5 - Tectonic sketches drawn in collaboration with G. Molli (University of Pisa) reporting the main events recorded in the Variscan basement of Northern Apennines.

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