TECTONO-METAMORPHIC EVOLUTION OF THE CRYSTALLINE BASEMENT IN THE SOUTHERN-EASTERN SERRE MASSIF (SOUTHERN CALABRIA)

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INTRODUCTION

The aim of this work is the reconstruction of the tectono-metamorphic history of the basement rocks outcropping in the Southern-Eastern Serre Massif (Calabria, Italy). According to Schenk (1989), the Serre Massif constitutes a nearly complete tilted Hercynian crustal section, comprising several late-Hercynian plutonic bodies. Actually, the peak metamorphic estimates are only available for the lower crust, ranging from 750 MPa at 800°C to 550 MPa at 690°C, for the bottom and the top sections, respectively (Schenk, 1984). Nevertheless, Acquafredda *et al.* (2006) suggested a prograde metamorphism from temperature of about 500°C and pressure of 400-500 MPa to $T < 700$°C and $P \sim 800$ MPa for the metapelitic migmatites of the upper part of the lower continental crust.

On the other hand, no reliable P-T values are still available for the upper crustal level of the Massif, which is characterised by the presence of two metamorphic complexes made up of amphibolite to greenschist facies metamorphic rocks (Stilo-Pazzano Phyllite Complex and Mammola Paragneiss Complex) (Colonna *et al.*, 1973), intruded by the late-Hercynian granitoids (Rottura *et al.*, 1990).

In this scenario, the reconstruction of tectono-metamorphic evolution of this sector of the Calabrian-Peloritani Orogen (CPO), inferred both through meso/micro-structural and petrological investigations, was useful to provide new geodynamic constraints relatively to the evolution of this sector of Hercynian belt.

GEOLOGICAL BACKGROUND AND STRUCTURAL FEATURES

The Serre Massif constitutes the joint between the southern and the northern sector of the Calabrian-Peloritani Orogen and is composed by a nearly tilted complete continental crustal section, which is made up of lower and upper crustal metamorphic rocks, sutured by late-Hercynian plutonic bodies (Schenk, 1980, 1990).

The present study is located in the upper crustal portion in the south-eastern Serre, which is composed by the juxtaposition of two Metamorphic Complexes called in literature as Stilo-Pazzano Phyllite and Mammola Paragneiss Complexes (SPPC and MPC respectively).

The former, representing a lower metamorphic grade hanging wall, is constituted by low greenschist facies metapelites, metalimestones, quartzites and metavolcanics, whereas the latter, constituting an higher metamorphic grade footwall, is made up of amphibolite facies metapelites, leucocratic gneisses and amphibolites.

At the top of the SPPC, a composite sedimentary cover lies unconformably over the crystalline basement. Both Complexes were overprinted by contact metamorphism due to the intrusion of the late Hercynian granitoids.

Field investigations (1:10000 scale) allowed to distinguish two metamorphic cycles affecting the rocks of both Metamorphic Complexes: a) a polyphase Hercynian regional metamorphic cycle, and b) a subsequent contact metamorphic cycle related to the late Hercynian granitoid intrusions.

Stilo-Pazzano Phyllite Complex

Structural investigations permitted to identify two main regional phases. The eldest one consists of an isoclinal folding of a pre-existing surface with development of an axial plane foliation S_1 (D_1 phase)[1], locally replaced by a crenulation surface (D_2 phase) (Table 1).

A subsequent deformational phase produced the shallow-seated metric asymmetrical folds evolved in brittle thrusts.

Table 1 – Stilo Pazzano Phyllite Complex: relationships between deformational phases and crystallisation event in the different stages of metamorphic evolution.

	REGIONAL METAMORPHIC CYCLE		CONTACT METAMORPHIC CYCLE
Matamorphic evolution	Prograde evolution		Static evolution
Deformational phases	D_1	D_2	
Field evidences	relics of isoclinal folding	S_2 transponding the S_1 surface by crenulation cleavage	randomly oriented biotite plates and cm-size andalusite spots
Fabrics and microstructures	pervasive S_1 slaty cleavage	S_2 crenulation schistosity	randomly oriented tabular plates of biotite; nodular texture; re-crystallised feldspar
Metamorphic events	V_1	V_2	late to post V_3
Crystallisation events	syn post	syn post	
Quartz	----------------------------	----------------------------	-------------------------------------
White mica	----------------------------	----------------------------	--- low phe content ---
Biotite		-------------	--------------------------------
Chlorite	----------------------------	----------------------------	----------------------------
Plagioclase	----------------------------	----------------------------	------------ oligoclase ------------
Epidote	----------------------------	----------------------------	
Al_2SiO_5 group			--- andalusite ---
Tourmaline	----------------------------		
Cordierite			-----------------------------
Opaque	----------------------------		---------------------?

[1] The subscripts of S (foliation) derive from the relative deformational phase (*i.e.* S_2 from D_2).

The pre-existing regional fabrics were overprinted by static crystallization of random tabular porphyroblasts of biotite and millimetre cordierite spots coupled with andalusite crystals near the contact with the batholith (Table 1).

Mammola Paragneiss Complex

The main foliation consists of a pervasive mylonitic surface, particularly well preserved far away from the intrusive bodies. Anyway, older surfaces of previous metamorphic phases are preserved as relics within the mylonitic foliation. The eldest one is represented by relics of axial plane of isoclinal folds (S_1) (D_1 phase), locally replaced by a crenulation schistosity (S_2) (D_2 phase) (Table 2).

A subsequent phase (D_3), producing the pervasive mylonitic foliation (S_3), locally involved the late-Hercynian granitoid intrusions with formation of a weak sub-solidus foliation, subsequently interested by a later deformational stage in brittle domain (Table 2).

Analysis of kinematic indicators constrained a top-to-the ENE-NE sense of shear in the present-day geographic coordinates. The local occurrence of late- to post-Hercynian undeformed leucocratic dykes, crosscutting the mylonitic foliation, constrained the shearing event in the Hercynian age.

Finally, it was possible to recognize the shallow-seated metric asymmetrical folds evolved toward a brittle thrust-sheet phase.

Table 2 – Mammola Paragneiss Complex: relationships between deformational phases and crystallisation event in the different stages of metamorphic evolution.

	REGIONAL METAMORPHIC CYCLE					CONTACT METAMORPHIC CYCLE
Metamorphic evolution	Prograde evolution			Retrograde evolution		Static event
Deformational phases	Early D_1	Late D_1	D_2	Early D_3	Late D_3	
Field evidences		Relics of isoclinal folding	S_2 crenulation cleavege		Mylonitic foliation S_3 locally involving the intrusive bodies	Randomly oriented biotite plates and cm-size andalusite spots
Fabrics and microstructures	Straight to sigmoid inclusion trails in Grt cores	S_1 defined by poor inclusion outer core Grt in equilibrium with Bt, Pl, Wm	S_2 crenulation schistosity	Mineral intergrowth in Grt rim embayments	σ- and δ-type porphyroclasts; S/C fabrics; shear bands; oblique foliation	Foam texture in Qtz domains; randomly oriented plates of Bt; inclusion free rim Grt; re-crystallised feldspar
Metamorphic events	Early V_1	Late V_1	V_2	Early V_3	late V_3	Late to post V_3
Quartz	-------------------	-------------------	-------------------	-------------------	-------------------	-------------------------------
White mica	-------------------	-------------------	------------	-------------------	--interm. phe--	---low phe---
Biotite	--------------	-------------------	-------------------	-------------------	----high ann----	---------------------
chlorite	-------------------	----------?--------		--interm. daph--	--interm. daph--	--------------
Plagioclase	--------------	-oligocl./andes.-	-------------?	----oligoclase---	----oligoclase---	----oligoclase/andesine----
Garnet	--high grs--	-------------------		----high sps----		----------high alm----------
Sraurolite		--------------				
Epidote	-------------------					
Tourmaline					-------------------	
Al_2SiO_5 group						------------and------
Spinel						?----------?
Cordierite						---------------------
K-feldspar						----------?
opaque						?

The effects of contact metamorphism are testified by randomly oriented biotite plates and cm-size andalusite and cordierite spots in the country rock, gradually most evident in approaching the intrusive bodies (Table 2).

PETROGRAPHY AND MINERAL CHEMISTRY

Petrographic investigations corroborated by mineral chemistry data, carried out on rocks of both Metamorphic Complexes, allowed to characterize completely the poly-metamorphic evolution of this sector of Hercynian belt.

Regional metamorphic cycle

Stilo-Pazzano Phyllite Complex: The SPPC is essentially made up of greenschist facies metapelites (Chl, Wm, Ab, Qtz, Tur, Ep, Ilm)[2]. The petrographic investigations showed several transposition stages from pervasive S_1 foliation, represented by slaty cleavage essentially defined by Chl and Wm (D_1 phase), to widespread S_2 crenulation surface defined by blastesis of Qtz, Chl, Wm, Pl (D_2 phase) (Table 1).

Mammola Paragneiss Complex: The main micro-structural feature is linked to a pervasive mylonitic foliation well preserved in the quartz-feldspatic rocks far from the intrusive bodies. Nevertheless, structures related to the previous regional evolution are well preserved as relics.

In effect, the pre-mylonitic history is testified by relics of straight to sigmoid inclusion trails (early-S_1), mainly defined by tiny epidote grains within relatively high grossular garnet cores (Grt_1: $Alm_{56\text{-}58}Sps_{14\text{-}12}Grs_{27}Py_3$) in assemblage with Wm, Pl, Bt ($ann_{23}phl_{17}east_{26}sdph_{34}$), and Qtz, suggesting the presence of a first prograde garnet growth event (early-V_1) controlled by the following reaction: Chl + Wm + Ep + Qtz = Grt + Bt + Pl + H_2O. This first event, related to the early-D_1 deformational phase, evolves to a further one (late-V_1), producing an epidote inclusion-free garnet outer core (Grt_2: $Alm_{64}Sps_8Grs_{23}Py_5$) (late-$D_1$), probably linked to the reaching of the regional peak metamorphic conditions. Observed smooth decrease in grossular and spessartine content toward the outer core, suggests that this garnet overgrowth originated itself at expenses of chlorite, white mica and quartz due to the total resorption of epidote during the early-V_1 metamorphic event (Table 2).

The subsequent microcrenulation phase (D_2) is rarely identifiable at the microscopic scale and locally produces a S_2 schistosity defined by the syn-kinematic growth (V_2) of Qtz + Pl + Wm ± Bt (Table 2).

The regional metamorphic evolution proceeded towards a multistage retrograde metamorphism consisting both in an earlier and in a later stage of D_3.

The former is testified by garnet embayments characterised by an abrupt increase of spessartine content in garnet rims (Grt_3: $Alm_{64\text{-}61}Sps_{17\text{-}23}Grs_{13\text{-}9}Py_7$), in equilibrium with B ($Ann_{17.69}Phl_{11.31}East_{27.69}Sdph_{43.31}$), Pl ($An_{34.3}$), Chl ($Daph_{30.5}Clin_{30.5}Feames_{19.5}Ames_{19.5}$), Wm ($Phe_{2.85}$) intergrowths (early-$V_3$). These features, related to the breakdown reactions of the previous high-grossular garnet cores, together with the recognized reversal Mn zoning-profile, suggest resorption during the retrogression event (Table 2).

The latter (late-D_3) is better identifiable in the quartz-feldspatic samples, where is possible to observe S/C fabrics, oblique foliations, pinch-and-swell textures and σ- and δ-type porphyroclasts, consistent with a top-to-the ENE/NE sense of shear already recognized at the outcrop scale. Both the

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[2] Mineral abbreviations after Kretz (1983); additional abbreviations are: Wm, white mica; Phe, phengite; Kfs, K-feldspar.

syn-mylonitic crystal growth of Bt ($Ann_{48.98}Phl_{30.02}East_{7.98}Sdph_{13.02}$), Wm ($Phe_{16.4-19.3}$), Pl ($An_{24}$), Chl ($Daph_{33}Clin_{27}Feames_{22}Ames_{18}/Daph_{40.8}Clin_{19.2}Feames_{27.2}Ames_{12.8}$), Ep in pressure shadows of feldspar porphyroclasts and the asymmetric single girdle quartz c-axes fabric on well preserved oblique foliation microstructure indicate a greenschist-facies shearing event (Table 2).

The shearing phase affected partly the intrusive bodies as testified from high to low temperature sub-solidus microstructures (*i.e.* quartz chessboard texture, quartz grain boundary migration recrystallisation deformation mechanism, bending of biotite).

According to Kruhl & Vernon (2005), the local evidence of sub-solidus HT deformation in granitoids, not consistent with the observed greenschist facies shearing temperature, can be related to the heat of the cooling magmatic bodies, operating during the later shearing activity.

By contrast, the widespread undeformed granitoids can represent the post-shear magmatic intrusion stage, characterised by crystallization fabric unaffected by strain under subsolidus conditions.

Approaching the contact with the granitoids, the mylonitic rocks were clearly annealed by static re-crystallisation due to the thermal effects. Nevertheless, a record of the relic strong quartz *c*-axes patterns is anyway observable in the rich-quartz domains preserved by annealing effects, allowing to confirm the top-to-the ENE/NE sense of shear.

Contact metamorphic cycle

Static equilibria were detected using metapelite samples, from both the Metamorphic Complexes, collected along transects perpendicular to the main intrusive body.

The first effect of the thermal metamorphism was related to the appearance of Crd spots plus grains of decussate Bt that overgrowth pre-existing regional fabrics, coupled with the decrease in Chl (Table 1-Table 2), suggesting the KFMASH reaction:

$$Wm + Chl + Qtz = Crd + Bt + H_2O$$

Approaching gradually to the granitoids, the recognized mineral assemblage is given by Wm + Bt + Crd + And + Pl + Qtz, suggesting the development of And + Bt (Table 1-Table2) because of the two following KFMASH reactions:

$$Wm + Chl + Qtz = Crd + And + Bt + H_2O$$
$$Wm + Crd + Qtz = And + Bt + H_2O$$

Locally, only in one metapelite sample of MPC, the development of Kfs + And coupled with the decrease of Wm + Qtz (Table 2), suggested the white mica breakdown reaction:

$$Wm + Qtz = Kfs + And + H_2O$$

In all studied rocks, a range of textures indicative of hydrous retrogression at different stages in the cooling of the aureole occurred.

In effect, the presences of relics of And in Crd porphyroblasts and pinitization of Crd (Table 1 and 2) suggest the two following KFMASH reactions, respectively:

$$And + Bt + Qtz + H_2O = Wm + Crd$$
$$Crd + Bt + H_2O = Wm + Chl + Qtz$$

Finally, all the previous fabrics are overgrown by static blastesis of decussate Wm.

At place, the MPC metapelites exhibit locally micro-textural equilibria of tabular porphyroblasts of Bt ($Ann_{28.80}Phl_{16.20}East_{19.80}Sdph_{35.20}$), associated with inclusions-free almandine-rich garnet rims (Grt: $Alm_{81-82}Sps_{3-4}Grs_{3-4}Py_{11-12}$) and plagioclase ($An_{25.8}$) (Table 2).

P-T ESTIMATES

The P-T data were obtained from the lowermost MPC, which resulted to have well recorded the Hercynian metamorphic evolution, using an integrated approach between the conventional geothermobarometry and the P-T pseudosection computations (PERPLEX; Connolly & Petrini, 2002).

The former method applied on selected couples of minerals from parageneses of early and late V_1 event provided wide P-T range (400-570°C and 0.3-0.7 GPa for early V_1 event; 480-600°C and 0.44-0.68 GPa for late V_1 event).

Nevertheless, the P-T pseudosections of selected samples allowed to constrain more reliably the prograde metamorphism (from early to late V_1) in medium-pressure-temperature conditions (from 0.61 GPa and 516°C to 0.68 GPa and 550°C).

The estimated shearing P-T conditions, taking into account the match between observed and computed syn-shear mineral assemblages, are typical for retrograde greenschist-facies shearing phase (P = 0.38±0.07 GPa and T = 485±15 °C).

A micaschist collected near the contact with the granitoids allowed to estimate the P-T peak values for the contact metamorphism. In this case, the intersection between the ratio Fe^{2+}/Fe^{2+}+Mg in the biotite (X_{Fe2+} = 0.70) and the ratio Mg/Mg+Fe^{2+} in the cordierite (X_{Mg} = 0.46), integrated with the petrographic observations allowed to constrain the peak P-T range (613±8 °C and 2.0±0.2 kbar).

Lacking of further mineral chemistry data about retrograde static parageneses made no possible to reconstruct the retrograde P-T path for the contact metamorphism.

DISCUSSION AND GEODYNAMIC IMPLICATIONS

Structural-geological and petrographic investigations, integrated with the minero-chemical data were useful to unravel the tectono-metamorphic evolution of the southern-eastern sector of the Serre Massif, proposing a new geodynamic scenario for this key sector of the CPO.

The crystalline basement in the southern-eastern Serre Massif was characterised by a poly-metamorphic evolution consisting of: a) a prograde low amphibolite-facies Hercynian regional metamorphism, followed by a retrograde greenschist-facies mylonitic overprint for the MPC and a greenschist facies metamorphism for SPPC; and b) a pervasive contact metamorphism affecting both the Metamorphic Complexes.

The attention was focused on the lowermost MPC, which preserved the Hercynian poly-metamorphic evolution.

Thermodynamic phase equilibria associated with the polyphase regional cycle allowed to reconstruct the prograde metamorphism (from early to late D_1) in medium-pressure-temperature conditions (Fig. 1).

The peak P-T conditions (P = 0.68 GPa; T = 550°C) are consistent with a low amphibolite-facies metamorphism probably related to the crustal thickening during the early stage of Hercynian orogenesis (Fig. 1).

Petrographic evidences of ragged edges in garnet porphyroclasts as well as reversal Mn zoning-profile are related to a subsequent retrograde event (early-D_3).

Indeed, thermodynamic phase equilibrium calculations yielded pressure value of 0.56 GPa and 0.40 GPa at peak or slightly decreasing temperature indicating a near-isothermal decompression path of about 0.28 GPa. This last path was followed by uplift and exhumation of the crystalline basement rocks along the deep-seated extensional shear zones (late D_3) (Fig. 1).

The shearing P-T conditions were constrained by matching between the observed and computed syn-shear paragenesis in a range of P = 0.38±0.07 GPa and T = 485±15 °C, suggesting a nearly isobaric cooling following the near-isothermal decompression event (Fig. 1).

Meso, micro-structural kinematic indicators as well as *c* axes pattern of quartz suggest a top-to-the NE/ENE sense of shear in the present-day geographic coordinates.

The near-isothermal decompression and isobaric cooling are also referred to basement rocks in the northern Serre (Schenk *et al.*, 1990) and are ascribed to a late Carboniferous-early Permian regional extensional regime (Ziegler, 1993), testified in the Hercynian basement of southern-eastern Serre Massif by pinch-and-swell microstructures in mylonitic rocks and by absence of deep-seated compressive structures.

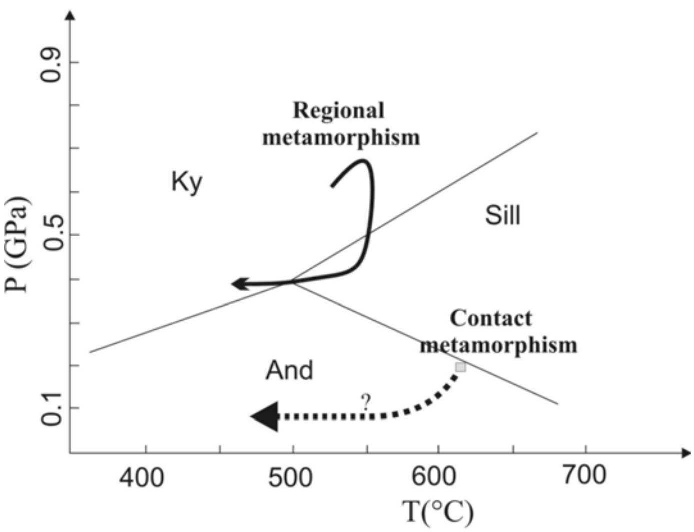

Fig. 1 – Estimated P-T path of MPC.

The isothermal decompression path was followed by the intrusion of the granitoids, which were driven towards the emplacement levels by extensional shear zones.

Locally, crosscutting relationships between mylonitic wall rocks and late Hercynian undeformed leucocratic dykes as ramifications of the main plutonic body as well as both the recognized sub-solidus microstructures in the granitoids and isotopic dating on intrusive bodies, allowed to constrain the late-Hercynian age of the shear zone.

The evidence of both sub-solidus microstructures and crystallization fabrics unaffected by strain in the intrusive bodies, suggests a late to post-tectonic emplacement of the granitoids in the southern Serre Massif.

The magmas emplacement caused a mineralogical and textural re-equilibration of the wall rocks; the calculated P-T peak estimates for this thermal event were T = 613±8 °C and P = 2.0±0.2 kbar (Fig. 1).

In this scenario, all the available data suggest that the upper greenschist facies basement of the SPPC and the lower amphibolite facies rocks of the MPC can constitute a unique tectono-stratigraphic sequence in agreement with Bonardi *et al.* (1984); according to this model, the omission of medium grade metamorphic rocks can be imputable to the extensional late-Hercynian regime.

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