HERCYNIAN LOW-PRESSURE METAMORPHISM: TECTONO-METAMORPHIC EVOLUTION OF THE MANDATORICCIO COMPLEX (SILA MASSIF - CALABRIA)

ANTONIO LANGONE
Dipartimento di Scienze della Terra e Geologico-Ambientali, Università di Bologna,
P.zza di Porta s. Donato 1, I-40126 Bologna

INTRODUCTION AND GEOLOGICAL SETTING

Low-pressure/high-temperature (LP/HT) metamorphic belts are characterised by rocks that experienced abnormal heat flow in shallow crustal levels (T > 600°C; P < 4 kbar: *e.g.* Thompson & England, 1984) resulting in anomalous geothermal gradients (60-150°C/km). The considerable amount of heat required to reach this thermal state has been related to crustal underplating of mantle-derived basic magmas (Thompson & England, 1984) or to intrusion of huge volume of granitoids in the intermediate crust (Lux *et al.*, 1986; De Yoero *et al.*, 1991). In particular, in this latter context, magmatic or aqueous fluids are able to transport relevant amounts of heat by advection, thus favouring regional LP/HT metamorphism. However, the thermal perturbation consequent to heat released by cooling magmas is responsible also for contact metamorphic effects. A first issue is that time and space relationships between regional LP/HT metamorphism and contact metamorphism are usually unclear. A second issue is related to the high temperature conditions reached at different crustal levels. These, in some cases, can completely erase the previous metamorphic history. Notwithstanding this problem is very critical in lower crustal levels, petrologic and geochronologic studies are typically focused in these attractive portions of the crust. However, only in the intermediate/upper-crustal levels of a LP/HT metamorphic belt the tectono-metamorphic events preceding the temperature peak, usually not preserved in the lower crustal portions, can be readily unravelled.

The Hercynian Orogen of Western Europe is a well-documented example of a continental collision zone with widespread LP/HT metamorphism, intense crustal anatexis and granite magmatism. In particular, the Hercynian massifs exposed in Calabria (Southern Italy) provide a classical example of LP/HT regional metamorphism and granite magmatism documenting an important thermal event whose origin and geodynamic significance are still a matter of debate. Owing to the exposure of a nearly continuous cross-section of the Hercynian continental crust, the Sila massif (northern Calabria; Fig. 1) represents a favourable area to understand large-scale relationships between granitoids and LP/HT metamorphic rocks, and to discriminate regional LP/HT metamorphic events from contact metamorphic effects. The crustal levels trend on average northwest-southeast (Fig. 1), with granulite-facies rocks, of the lower crust (Monte Gariglione and Polia-Copanello complexes), in the southwest and greenschist- to amphibolite-facies rocks, of the intermediate-upper crust (Mandatoriccio and Bocchigliero complex), in the northeast. Metamorphic rocks of these two crustal levels are separated by granitoids emplaced into the intermediate crust during the late stages of the Hercynian orogeny. Up to now, advanced petrologic studies have been focused mostly in understanding P-T evolution of deeper crustal levels and magmatic bodies, whereas the metamorphic history of the shallower crustal levels is poorly constrained. The Hercynian upper crust exposed in Sila has been subdivided in two different metamorphic complexes by previous authors: the low- to very low-grade Bocchigliero complex and the greenschist- to amphibolite-facies

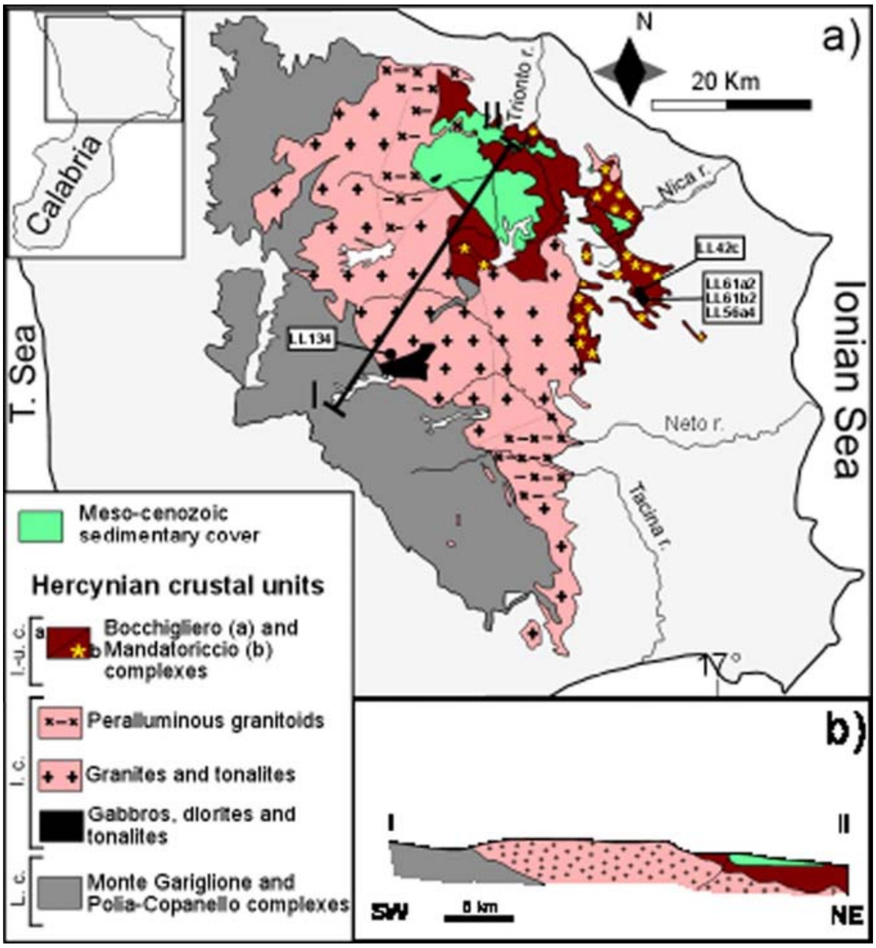

Fig. 1 – (a) Geological sketch map, and (b) section of the Sila massif with location of some interesting samples. L. c. = lower crust; I. c. = intermediate crust; I.-u. c. = intermediate upper crust.

Mandatoriccio complex (Fig. 1). The latter consists mainly of metapelites, meta-arenites, acid metavolcanites and metabasites with rare intercalations of marbles and orthogneisses. Siliciclastic metasediments show a static porphyroblastic growth mainly of biotite, garnet, andalusite, staurolite and muscovite, whereas cordierite and fibrolite are less common. In some localities, metamorphic rocks are injected by numerous aplite/pegmatite veins. Small granite bodies are also present and are always associated to spotted schists with large porphyroblasts. They occur along a NW-SE trending transcurrent cataclastic fault zone, which represents the tectonic contact between the Bocchigliero and the Mandatoriccio complexes. This cataclastic fault zone shows evidence of activity at least from middle-Miocene to Recent, indicating that brittle deformation post-dated the Hercynian orogeny. The Mandatoriccio complex contains favourable mineral assemblages in order to unravel the tectono-metamorphic evolution of the Hercynian intermediate-upper crust. New petrologic and geochronologic data relative to the intermediate-upper crustal rocks of the Mandatoriccio Complex allow the reconstruction of a crustal scale tectono-metamorphic history.

PETROLOGY

On the basis of microstructures, petrography and mineral chemistry of the porphyroblastic rocks a reconstruction of the deformation-crystallisation history has been proposed (Fig. 2). In the Mandatoriccio complex, a major deformational event (D_2) has been recognised. D_2 deformation event led to the crystallisation of new minerals and the development of main regional schistosity (S_2), affecting a pre-existing S_1 fabric. Porphyroblasts largely developed during a period of deformational quiescence after the D_2 deformation (D_2 < P; Fig. 2). Deformation history ended with later folding (D_3) and retrogression that have caused crenulation of S_2 and replacement of minerals by retrograde products, respectively. Temporal sequence of porphyroblast growth in micaschists and paragneisses (Fig. 2) begins with a low-temperature Mn-rich garnet (Grt II core), developed syntectonically with respect to D_2. This syntectonic phase is documented by: crenulated inclusion trails, deflection of foliation planes and pressure shadows around garnet. The first appearance of garnet could be related to two continuous KFMASH reactions, as indicated by pre-tectonic muscovite (Ms I), chlorite (Chl I) and quartz inclusions:

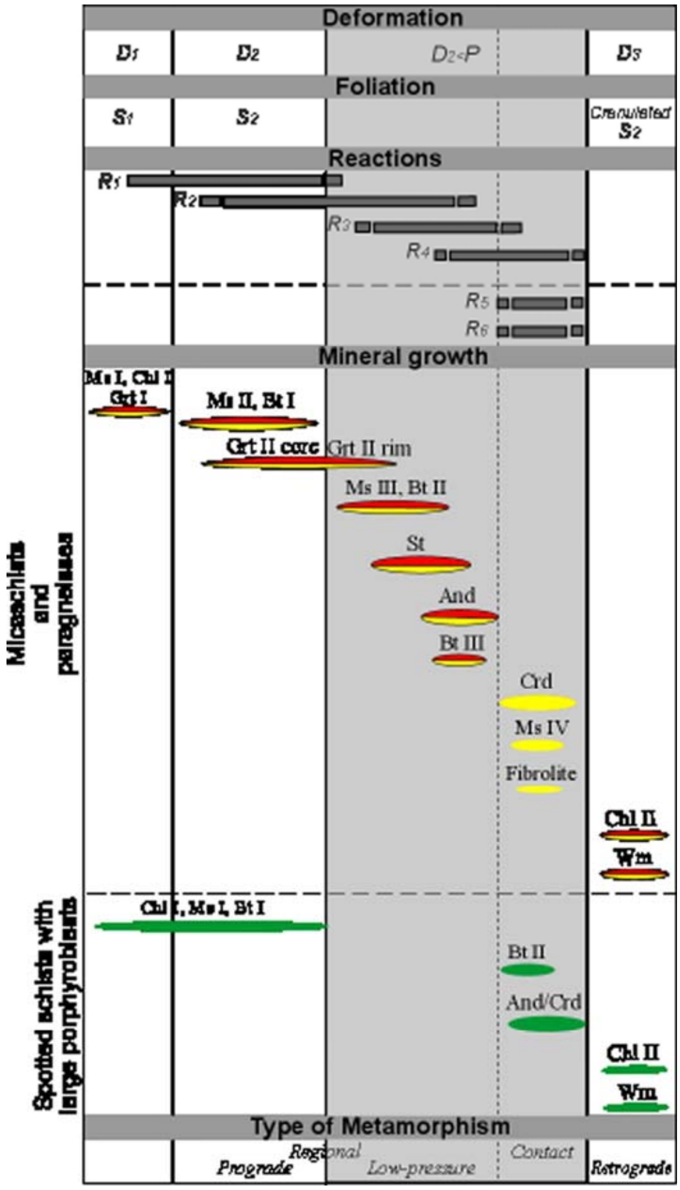

Fig. 2 – Schematic diagram showing relative chronology of mineral growth with respect to deformation (D) and foliation (S) in micaschists (red symbols), paragneisses (yellow symbols), and spotted schists with large porphyroblasts (green symbols). Diagram contains also some of the reactions described in the text.

$$\text{(R1a) } Chl + Qtz = Grt + H_2O$$

$$\text{(R1b) } Chl + Ms + Qtz = Grt + Bt + H_2O.$$

Biotite (Bt II) and staurolite porphyroblasts overgrew on the S_2 schistosity during a period of deformational quiescence ($D_2 < P$); simultaneously, garnet develops static overgrowths (Grt II rim). The formation of staurolite at major expense of muscovite and chlorite could be attributed to the reaction:

(R2) Chl + Ms + Qtz = St + Bt + H_2O.

This continuous KFASH or KMASH R2 reaction largely contributed to the growth of biotite porphyroblasts (Bt II). This stage of the reaction history was probably limited by chlorite availability and it contributed reducing muscovite content in domains and rocks.

Crystallisation under static conditions continued with andalusite formation at major expense of staurolite through the KFMASH divariant reaction:

(R3b) St + Ms + Qtz = And + Bt + H_2O.

Reaction history described until now is plausible for micaschists and paragneisses. Before retrograde evolution, paragneisses experienced other crystallisation events producing fibrolite and cordierite. Probably, fibrolite crystallised as consequence of a heating metamorphic phase occurred just before the retrograde evolution. Fibrolite formed essentially through biotite replacement and rarely there is evidence of a direct And > Sill phase transition.

Generally, cordierite developed during the retrograde evolution at major expense of andalusite. Formation of cordierite is predicted by the KFMASH divariant reaction:

(R4) Bt + And + Qtz = Ms + Crd + H_2O

Spotted schists with large porphyroblasts show a simpler reaction history compared to micaschists and paragneisses. The large porphyroblasts of andalusite and cordierite developed by the KFMASH divariant reactions:

(R5) Ms + Chl + Qtz = And + Bt + H_2O

and

(R6) Ms + Chl + Qtz = Crd + Bt + H_2O

P-T estimates

P-T phase diagrams have been constructed using the THERMOCALC software of Powell & Holland (1988). The modelling has been performed on a micaschist (LL56a4) and on two representative centrimetic thick layers of paragneisses, a Qtz+Pl-rich layer (LL61a2) and a Bt-rich layer (LL61b2; see Fig. 1 for sample location). A tentative to reveal P-T conditions during prograde garnet growth has been performed only in LL56a4 sample, a micaschist characterized by the higher modal content of garnet (*ca.* 1.5%). Two P-T pseudosections in the KMnFMASH and KFMASH systems have been constructed for this sample (Fig. 3a,b) in order to reproduce conditions during prograde garnet growth and after garnet growth, respectively. Paragneisses have been considered garnet-free and the P-T pseudosections have been calculated in the KFMASH system (Fig. 3c,d). Petrographic and microstructural analyses, P-T segments followed by the reaction domains and, rarely, isopleths allowed to trace the P-T paths followed by the samples along a clockwise trajectory (Fig. 3a-d).

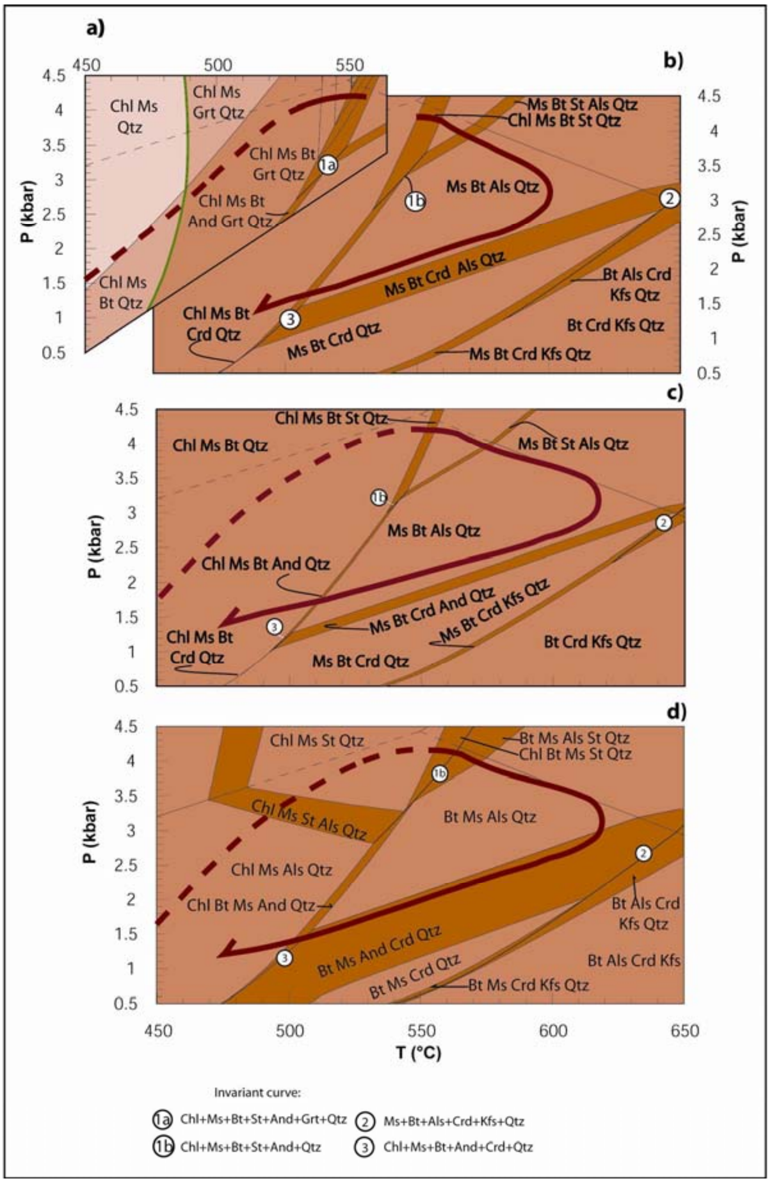

Fig. 3 – P-T pseudosection showing the P-T paths. a, b) KMnFMASH and KFMASH pseudosections calculated for the LL56a4 micaschist; c, d) KFMASH pseudosections calculated for the LL61a2 and the LL61b2 paragneisses. Stable assemblage fields are coloured by assemblage variance. Al_2SiO_5 are absent where dashed.

GEOCHRONOLOGY

Concerning the Hercynian upper crust exposed in Sila (Bocchigliero and Mandatoriccio complexes), geochronologic data are still inadequate to define:

a) ages of protoliths and of metamorphism;

b) time relationships between metamorphic and magmatic rocks;

c) time relationships with lower crustal levels;

d) end of the magmatic activity.

New geochronologic data have been collected both for magmatic and metamorphic rocks of the Sila Massif (Fig. 1). Laser-ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS) U-Th-Pb zircon ages have been obtained from a Ms+Bt+Grt+St+And+Crd±Sil paragneiss (LL61b2), a basic meta-sill (LL42c) of the Mandatoriccio Complex and from a post-tectonic felsic porphyritic dyke (LL134). The latter is in crosscutting relationship with post-tectonic granitoids, representing the product of late magmatic activity. Therefore, the age of this dyke corresponds to the end of the late-Hercynian magmatic activity.

Zircon may not record metamorphic events if they occurred in a subsolidus P-T range (*e.g.* Rubatto *et al.,* 2000), therefore the metamorphic history has been constrained by LA-ICP-MS U-Th-Pb dating on monazite from a Ms+Bt+Grt+St+And+Crd±Sil paragneiss (LL61b2) and from a micaschist (LL56a4) of the Mandatoriccio complex. U-Th-Pb ages of zircons and monazites have been interpreted on the basis of cathodoluminescence and back-scatter images, respectively. Geochronologic data and their interpretations are summarised in Table 1.

Table 1 – Summary of the U-Th-Pb concordia ages from zircons and monazite. * average age.

Sample	**Lithology**	**Min.**	**Age (Ma)**	**Internal structures**	**Age interpretations**
LL61b2	Bt-rich paragneiss	Zr	428-540	Undisturbed oscillatory zoning	Magmatic crystallisation
LL42c	Basic meta-sill	Zr	340±10*	Undisturbed oscillatory zoning	Magmatic crystallisation
LL134	Felsic porphyritic dyke	Zr	287±6*	Undisturbed oscillatory zoning	Magmatic crystallisation
LL61b2	Bt-rich paragneiss	Mnz	299±1*	Omogeneous/weakly zoned	Metamorphic event
LL56a4	Micaschist	Mnz	291±7*	Omogeneous/weakly zoned	Metamorphic event

DISCUSSIONS AND CONCLUSIONS

Petrologic and geochronologic data have been used to unravel the origin and the metamorphic evolution of the Mandatoriccio complex (intermediate-upper crust).

Pre-Hercynian evolution

In the previous palaeogeographical reconstructions, the Mandatoriccio complex was considered as a Cadomian (Bouillin *et al.*, 1987) or as an Ordovician basement (Acquafredda *et al.*, 1988; Fig.4a), partly overprinted during the Hercynian orogeny. These reconstructions are mainly based on the different metamorphic features of the adjacent Mandatoriccio and Bocchigliero complexes. The palaeogeographical reconstruction proposed by Acquafredda *et al.* (1988, 1994) is based on the consideration that the thermal regional metamorphism, observed in the Mandatoriccio complex, is anorogenic and is related to tensional processes which led to the formation of Palaeozoic basins. In this reconstruction the Mandatoriccio complex formed a part of the basement on which the Bocchigliero basin developed (Fig. 4a). The lack of clasts derived from the Mandatoriccio complex led these authors to suggest that the Mandatoriccio complex did not constitute the direct siliciclastic source of the Bocchigliero Palaeozoic sequence, supposed to lie at greater depths. New geologic and geochronologic data suggest an alternative palaeogeographical scenario. Cambrian to Silurian detrital zircons in the paragneiss of the Mandatoriccio complex show typical magmatic features, thus indicating a direct derivation from intrusive–effusive sequences of this time span (≈ 550÷430 Ma). Moreover, zircon isotope analyses indicate that protoliths of the metasediments of the Mandatoriccio complex originated from a basement containing significant igneous and metamorphic components related to an older orogenic cycle (*e.g.* Cadomian). These data suggest that the volcaniclastic sequence of the Mandatoriccio complex settled in a sedimentary basin, before the Silurian. Therefore, the Mandatoriccio and the Bocchigliero sequences were coeval and, probably, they were deposited in the same sedimentary basin during the Cambro-Ordovician (Fig. 4b), as suggested by similar geologic and geochronologic features (Acquafredda *et al.*, 1988, 1994). This palaeogeographical scenario is coherent with large-scale reconstructions proposed for other Hercynian terranes on the basis of new geologic and geochronologic data (*e.g.*, Trombetta *et al.*, 2004; Giacomini *et al.*, 2006; Micheletti *et al.*, 2007).

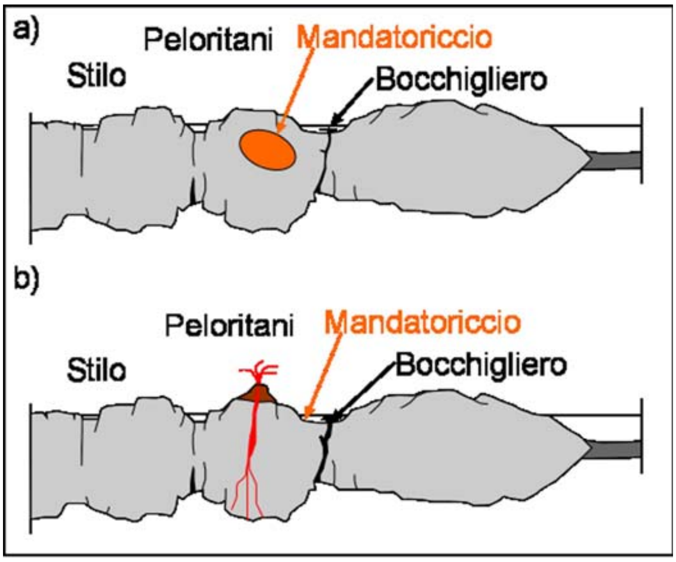

Fig. 4 – Cambro-Ordovician reconstructions of the Calabria-Peloritani terrane inspired to Acquafredda *et al.* (1994). The reconstructions show the palaeopositions of the Mandatoriccio and the Bocchigliero complexes according to (a) Acquafredda *et al.* (1994), and (b) this work.

Hercynian evolution

The Hercynian tectono-metamorphic evolution has been constrained mainly by P-T pseudosections and U-Th-Pb dating. P-T pseudosections show that micaschists and paragneisses of the Mandatoriccio complex followed a clockwise P-T path characterised by four main prograde phases: thickening, peak-pressure condition, decompression and peak-temperature condition (Fig. 5). During the thickening phase, garnet blastesis started up with spessartine-rich syntectonic core developed within micaschists and paragneisses. Coevally (340±9.6 Ma), mafic sills and dykes injected the upper crustal volcaniclastic sedimentary sequence of the Mandatoriccio complex. After reaching the peak-pressure condition (≈ 4 kbar), the upper crust experienced a period of deformation quiescence marked by the static overgrowths of Almandine-rich-garnet rims and of biotite and staurolite porphyroblasts on S_2. Probably, this metamorphic phase is related to isotherms relaxation after the thickening episode recorder by the Rb/Sr isotopic system (326±6 Ma isochron age). The post-collisional period was mainly characterised by decompression with increasing temperature (Fig. 5). This stage is documented by the andalusite+biotite coronas overgrown on staurolite porphyroblasts and represents a critical point of the metamorphic history, since metamorphic rocks begin to record a significant thermal perturbation. Peak-temperature conditions (≈ 620°C) were reached at the end of this stage (Fig. 5). They are well constrained by some reaction textures and mineral assemblages observed almost exclusively within paragneisses. The later appearance of fibrolitic sillimanite documents a small excursion of the P-T path across the And-Sil boundary due to the heating. Stephanian U-Pb ages of monazite crystals from the paragneiss, can be related to this heating phase. Similar monazite U-Pb ages from the micaschist combined with the lack of fibrolitic sillimanite

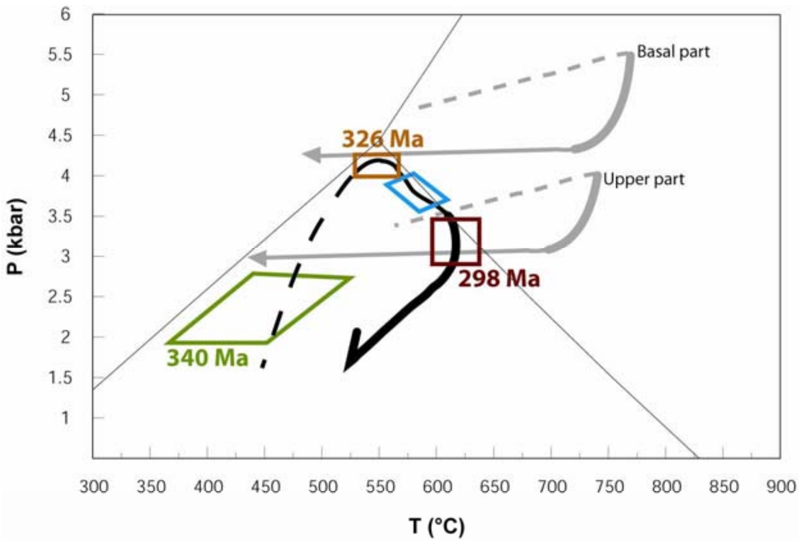

Fig. 5- P-T paths of the Hercynian crustal levels exposed in Sila: intermediate-upper crust (black lines) and lower crusts (grey lines; Graessner & Schenk, 2001). Coloured boxes represent the prograde metamorphic phases of the intermediate-upper crust. Thick segments of the P-T paths refer to the decompression P-T history directly comparable. See text for explanation.

suggest that, during the same thermal perturbation, micaschists recorded temperatures slightly lower than those reached by paragneisses. The metamorphic history ended with the crystallisation of cordierite, mainly at the expense of andalusite. Consequently, the Ms+Bt+St+And+Sill+Crd mineral assemblage observed in the paragneisses is the result of a polyphasic evolution and is characterised by the metastable persistence of the staurolite in the cordierite stability fields. Geologic, geochronologic and petrographic data suggest that the thermal peak recorded by the intermediate/upper crust could be strictly connected with the emplacement of large volumes of granitoid magmas in the middle crust. Probably, the lithospheric extension in the relatively heated crust favoured ascent and emplacement of granitoids and further exhumation of metamorphic rocks.

After a comparison between the tectono-metamorphic evolutions of the lower and the intermediate/upper Hercynian crustal levels exposed in Sila (Fig. 5), it is concluded that:

a) the intermediate/upper crust offers the possibility to reconstruct a more detailed tectono-metamorphic history;

b) the P-T paths proposed for the lower crustal levels probably underestimate the amount of decompression;

c) the P-T paths at various crustal levels in the Sila cross section are well compatible with a unique geologic scenario, characterized by post-collisional extensional tectonics and magmas ascent;

d) the different cooling histories during decompression, after the thermal peak, could be explained in terms of different cooling rates after the thermal perturbation.

REFERENCES

Acquafredda, P., Lorenzoni, S., Zanettin-Lorenzoni, E. (1988): La sequenza Paleozoica dell'Unità di Bocchigliero (Sila, Calabria). *Rend. Soc. Geol. It.*, **11**, 5-22.

Acquafredda, P., Lorenzoni, S., Zanettin-Lorenzoni, E. (1994): Palaeozoic sequences and evolution of the Calabrian-Peloritan Arc (Southern Italy). *Terra Nova*, **6**, 582-594.

Bouillin, J.P., Majestè-Menjoulas, C., Baudelot, S., Cygan, C., Fournier-Vinas, C.H. (1987): Les formations paleozoiques de l'arc calabro-peloritan dans leur cadre structural. *Boll. Soc. Geol. It.*, **106**, 683-698.

De Yoreo, J.J., Lux, D.R., Guidotti, C.V. (1991): Thermal modelling in low-pressure/high temperature metamorphic belts. *Tectonophys.*, **188**, 209-238.

Giacomini, F., Bomparola, R.M., Ghezzo, C., Guldbransen, H. (2006): The geodynamic evolution of the Southern European Variscides: constraints from the U/Pb geochronology and geochemistry of the lower Paleozoic magmatic-sedimentary sequences of Sardinia (Italy). *Contrib. Mineral. Petrol.*, **152**, 19-42.

Graessner, T. & Schenk, V. (2001): An exposed Hercynian deep crustal section in the Sila Massif of northern Calabria: mineral chemistry, petrology and a P-T path of granulite-facies metapelitic migmatites and metabasites. *J. Petrol.*, **42**, 931-961.

Lux, D.R., De Yoreo, J.J., Guidotti, C.V., Decker, E.R. (1986): Role of plutonism in low-pressure metamorphic belt formation. *Nature*, **323**, 794-797.

Micheletti, F., Barbey, P., Fornelli, A., Piccarreta, G., Deloule, E. (2007): Latest Precambrian to Early Cambrian U-Pb zircon ages of augen gneisses from Calabria (Italy), with inference to the Alboran microplate in the evolution of the peri-Gondwana terranes. *Int. J. Earth Sci.*, **96**, 843-860.

Powell, R. & Holland, T.J.B. (1988): An internally consistent thermodynamic dataset with uncertainties and correlations. III. Application methods, worked examples and computer program. *J. Metam. Geol.*, **6**, 173-204.

Rubatto, D., Williams, I.S., Buick, I.S. (2000): Zircon and monazite response to prograde metamorphism in the Reynolds Range, central Australia. *Contrib. Mineral. Petrol.*, **140**, 458-468.

Thompson, A.B. & England, P.C. (1984): Pressure-Temperature-time paths of regional metamorphism II. Their inference and interpretation using mineral assemblages in metamorphic rocks. *J. Petrol.*, **25**, 929-955.

Trombetta, A., Cirrincione, R., Corfu, F., Mazzoleni, P., Pezzino, A. (2004): Mid-Ordovician U-Pb ages of porphyroids in the Peloritan Mountains (NE Sicily): paleogeographical implications for the evolution of the Alboran microplate. *J. Geol. Soc. London*, **161**, 265-276.