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Hercynian high temperature granulites and migmatites from the Catena Costiera, northern Calabria, southern Italy.

EUGENIO PILUSO[1]* and LAURO MORTEN[2]

[1] Dipartimento di Scienze della Terra, Università della Calabria, Ponte P. Bucci, cubo 15b, 87036, Arcavacata di Rende, Cosenza, Italy
[2] Dipartimento di Scienze della Terra e Geologico-Ambientali, Università di Bologna, Piazza di Porta S.Donato, 1 40126 Bologna, Italy

ABSTRACT. — The deepest portion of a Hercynian lithospheric section is exposed in the northern sector of the Catena Costiera, Calabrian-Peloritan Arc. The section consists of migmatites and granulites derived from pelitic-arenaceous sequences, of small volumes of granitoid rocks, of Spl-harzburgites and pyroxenites intruded by metagabbros. The Hercynian P-T evolution of the migmatites and granulites follows a clockwise trajectory. The prograde path, in the stability field of sillimanite, reaches the metamorphic peak condition at 750-800°C and 0.9-1.0 GPa. The retrograde path is characterized by a decompression up to 0.5 GPa and 600°C through two intermediate steps at 0.8 Gpa and about 800°C, and 0.6-0.7 Gpa at 650-700°C, respectively accompanied by a general retrogression under lower amphibolite facies and successively under lower greenschist facies conditions. The exhumation of deepest portion of the Hercynian lithospheric section to middle crustal levels took place along HT extensional shear zones. The following stages of exhumation under amphibolitic and greenschist facies conditions were accommodated by LT shear zones, at the ductile-brittle transition. The crustal sequence of the Catena Costiera is crosscut by unmetamorphosed basaltic dyke dated at 120 ± 1.3 Ma. Therefore, the Alpine orogenesis did not overprint the Hercynian lithospheric section of the Catena Costiera, except for the brittle deformation event.

* Corresponding author, E-mail: e.piluso@unical.it

RIASSUNTO. — In Catena Costiera, settore settentrionale dell'Arco Calabro-Peloritano, affiora la porzione più profonda di una sezione di litosfera continentale ercinica. Questa è costituita da migmatiti e granuliti paraderivate, piccoli volumi di rocce granitoidi, Spl-harzburgiti e pirosseniti intruse da metagabbri granulitici. Tali rocce hanno subito un metamorfismo in facies granulitica di età tardo-ercinica. L'evoluzione P-T delle migmatiti e granuliti segue un percorso in senso orario. Il tratto progrado segue una geoterma caratterizzata da elevati dT/dP. Le condizioni di picco metamorfico si hanno a 750-800°C e 0-9-1,0 Gpa. Il tratto retrogrado è caratterizzato da un riequilibrio fino a 600°C e 0,5 GPa, accompagnato da una generale retrocessione in facies anfibolitica e successivamente in facies scisti verdi. L'esumazione della parte più profonda della sezione di litosfera continentale ercinica fino a livelli crostali intermedi avviene lungo zone di taglio estensionali di alta temperatura. Le successive fasi dell'esumazione avvengono nelle facies anfibolitica e degli scisti verdi, lungo zone di taglio di bassa temperatura, alla transizione fragile-duttile. La sezione crostale della Catena Costiera è attraversata da dicchi basaltici non metamorfici datati a 120 ± 1,3 Ma. Pertanto, in età alpina la sezione di litosfera continentale ercinica è stata interessata esclusivamente da eventi deformativi di tipo fragile.

KEY WORDS: *HT metamorphism, granulites, migmatites, Catena Costiera, Calabria, southern Italy.*

INTRODUCTION

Granulitic rocks and migmatites are the result of petrogenetic processes which occur in the deepest portions of an orogen. The physical conditions that affected the crustal sequence during an orogenic cycle may be depicted with the aid of phase petrology data and thermobarometric calculations. In the last decades the petrological researches on crystalline basement rocks have allowed to define the tectonic environments where the granulites may be formed (Harley, 1989; Rudnick and Fountain, 1995; Muntener *et al.*, 2000). The granulitic rocks and migmatites from the Catena Costiera, northern Calabria, southern Italy were studied from petrographic (Dietrich, 1976; Lanzafame and Zuffa, 1976) and structural (Carrara and Zuffa, 1976; Dietrich, 1988) points of view.

The main aim of the present paper is to briefly summarize recent field geology and petrological data on the granulitic rocks and migmatites involved in the Hercynian and Alpine orogenic processes from the Catena Costiera in order to clarify their petrogenetic evolution and the geodynamic environment of their formation.

OUTLINE OF REGIONAL GEOLOGY

The Alpine nappe stack system of the Calabrian-Peloritan Arc is an element of the Perimediterranean orogenic belt located between the Apenninic and the Maghrebian - Sicilian thrust-and-fold belts (Fig. 1). A supposed tectonic lineament runs along the Catanzaro trough dividing the Calabrian-Peloritan Arc into the northern and southern sector (Tortorici, 1982; Bonardi *et al.*, 2001 and therein references). The northern sector is made of two mountain chains, i.e., the Catena Costiera and the Sila massif, which are separated by the Crati valley, an elongated basin bounded by N-S trending normal faults developed from the late Pleistocene onwards (Cello *et al.*, 1982; Tortorici, 1982). The Catena Costiera has N-S direction and a length of about 70 km and was uplifted from the middle Pleistocene onwards along N-S faults at a rate of about 0.8 – 1 mm/y during the last 700,000 years (Tortorici *et al.*, 1995). It is a stack of thrust sheets formed of three tectonic complexes, from bottom to top: Apenninic units, Liguride and Calabride complexes (Ogniben, 1973). The Apenninic units are formed of Mesozoic carbonatic sequences and Palaeozoic phyllites; the Liguride complex includes ophiolitic slices made of metabasites and associated cover rocks derived from the Mesozoic Tethyan realm; the Calabride complex is made of Palaeozoic crystalline basement rocks (Ogniben, 1973). Each complex is subdivided into several tectonic units (Amodio Morelli *et al.*, 1976, Tortorici, 1982).

The Calabride crystalline basement includes Grt-Bt gneisses (mineral symbols, after Kretz, 1983), migmatites, Cpx – Opx – bearing granulites, small stocks of calcalkaline – peraluminous granitic rocks (Piluso and Morten, 2001), small oxide- silicate-bearing marble lenses (Piluso, 1997; Piluso *et al.*, 1998), and slices of peridotites and associated metagabbros (Morten *et al.*, 1999).

The crustal sequence of the Catena Costiera is crosscut by an unmetamorphosed basaltic dyke of alkaline-transitional affinity of which K/Ar dating gives an age of 120 ± 1.3 Ma (Piluso and Morten, 1997). HT metamorphic rocks of Late Hercynian age were described from the Serre (Schenk, 1980; 1984; 1990) and Sila massifs (Caggianelli *et al.*, 2000; Graessner and Schenk, 2001). These rocks were interpreted as middle to lower portions of continuous, comparable continental crust of late Hercynian age (Caggianelli *et al.*, 2000;

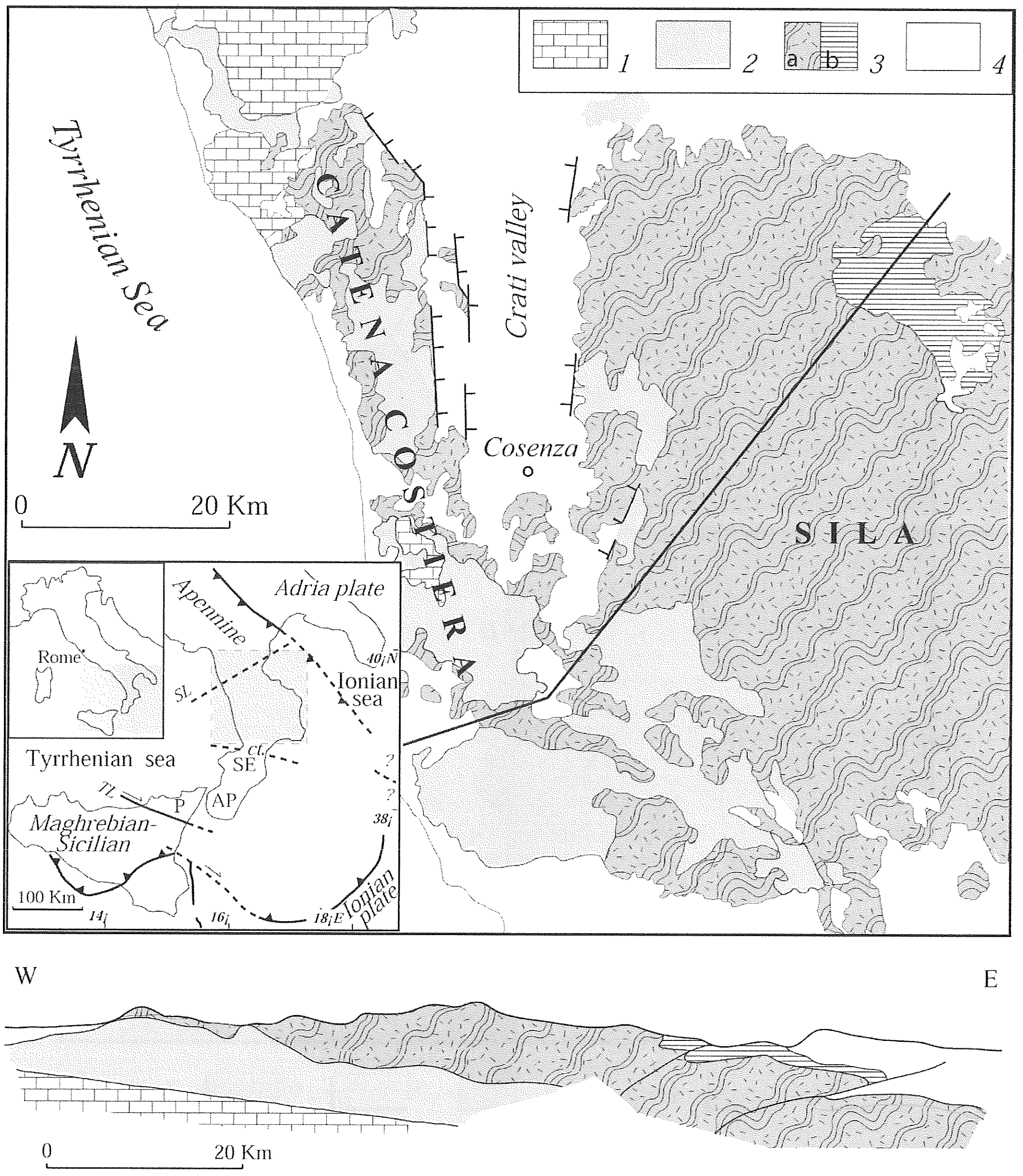

Fig. 1 – Geological sketch map of the northern sector of the Calabrian-Peloritan Arc and geological cross sections. SL, Sangineto line; TL, Taormina line; ct, Catanzaro trough; SE, Serre; AP, Aspromonte; P, Peloritani. 1, Apenninic units; 2, Liguride ophioplitic units; 3a, Calabride complex; Hercynian crystalline basement; 3b, mesozoic sedimentary cover of the Calabride complex; 4, Post-Paleogenic deposits.

Graessner and Schenk, 2001). The crustal section of the Sila Massif is continuous up to the northern Catena Costiera, where slices of subcontinental mantle-derived rocks outcrop. The subcontinental mantle rocks consist of Spl-harzburgites with included subordinate

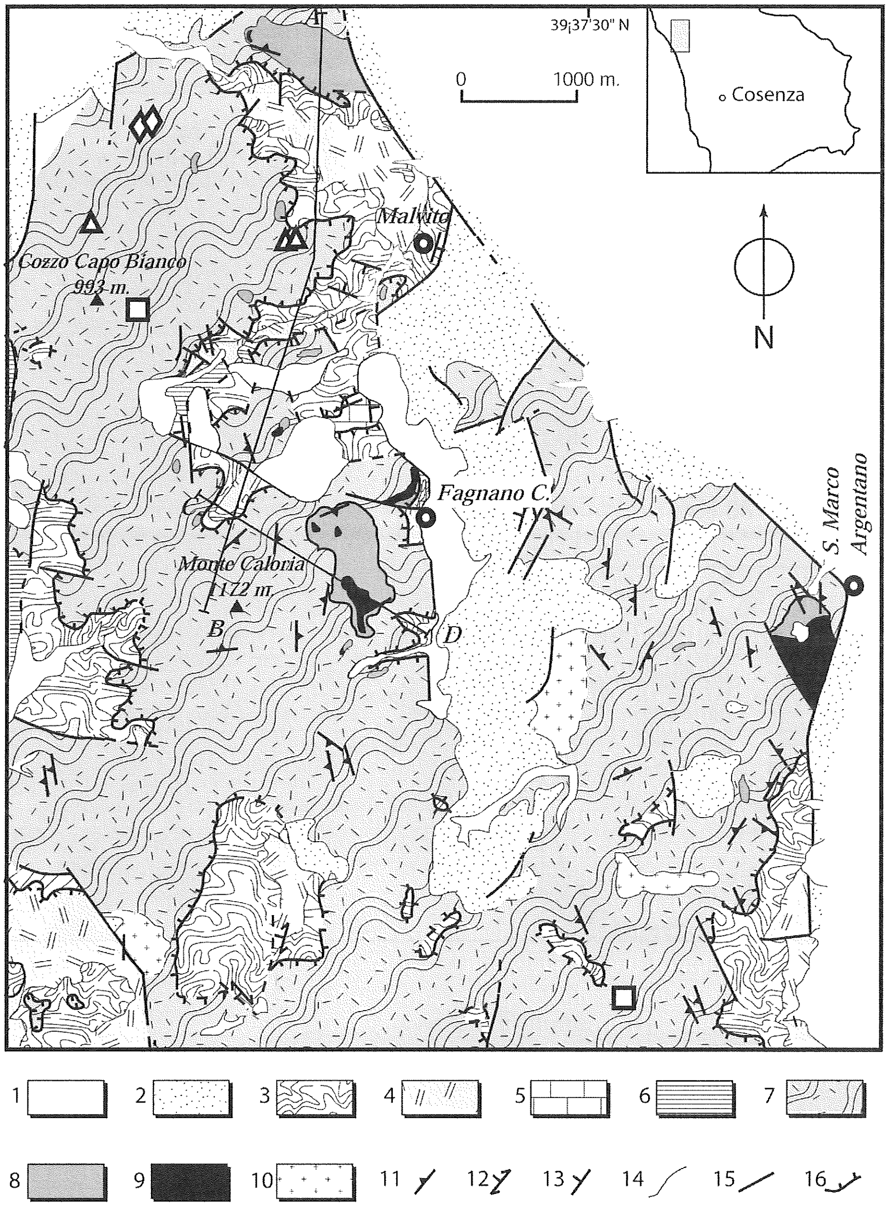

Fig. 2 – Geological map of the northern sector of the Catena Costiera and sample location (squares: restites; diamonds: Grt-Bt gneiss; triangles: Cpx-Opx - bearing-granulites). 1: Quaternary continental and marine deposits. 2: Mio-Plio-Pleistocene sediments. Ophiolitic unit: late Jurassic-early Cretaceous; 3: metalimestones, phyllites and schists, 4: metabasalts (MORB-type). Apenninic units: 5: Mesozoic dolomitic marbles and calcareous-dolomitic sequences, 6: Palaeozoic phyllites. Hercynian Crystalline basement (Calabride complex): 7: Grt-Bt gneiss, Cpx-Opx-bearing granulites, migmatites (cross-cut by unmetamorphosed basaltic dike, Cretaceous in age), 8: metagabbros, 9: ultramafic rocks (serpentinites after harzburgites, harzburgites, pyroxenites), 10: granites. 11: S_2 foliation. 12: main foliation in the ophiolitic units. 13: bedding in the Apenninic units. 14: non-tectonic contact. 15: fault. 16: thrust.

pyroxenites and intruded by gabbroic rocks which were metamorphosed under granulite facies conditions (Piluso *et al.*, 1998; Morten *et al.*, 1999).

On the basis of field geology, geochemical, petrological and gechronological data from the Sila massif (Messina *et al.*, 1994; Graessner *et al.*, 2000; Graessner and Schenk, 2001; Bonardi *et al.*, 2001), the Calabride Complex has been interpreted as a Hercynian continental crust section with the shallowest portions outcropping in the eastern sector of the Sila massif (Fig. 1) (Caggianelli *et al.*, 2000; Graessner and Schenk, 2001). The deepest levels of the continental crust section and the crust-mantle boundary outcrop in the northern sector of the Catena Costiera (Piluso, 1997; Piluso *et al.*, 1998). In this area the Hercynian continental crust section is few hundred meters thick and is made of migmatites and granulites derived from pelitic-arenaceous sequences and of small volumes of granitoid rocks (Figs 2 and 3). (Piluso, 1997; Morten *et al.*, 1999, Piluso *et al.*, 2000).

Petrology of the migmatites and granulitic rocks

The migmatites are the most common rocks of the Catena Costiera, and include stromatites and nebulites. Stromatites have texture characterized by alternating leucocratic and melanocratic bands. The leucocratic bands carry porphyroclastic texture with Grt and Kfs porphyroclasts set up in a granoxenoblastic matrix. Lepidoblastic and nematoblastic structures are present in Bt-Ms and Sil enriched portions, respectively. Large kinked sillimanite grains and flattened garnets with occasionally «pinch and swell» texture are present in the melanocratic bands (Fig. 4a). Small restitic bodies occur within migmatites but are volumetrically small (few hundreds cubic metres).

Migmatites have the following mineral assemblage: Qtz ± Pl ± Kfs ± Grt ± Sil ± Crd ± St ± Bt ± Ms ± Ep ± Chl ± Prh ± Spl ± Ilm ± Rt ± Ttn. The leucocratic and melanocratic portions are mainly made of Qtz + Pl + Kfs and

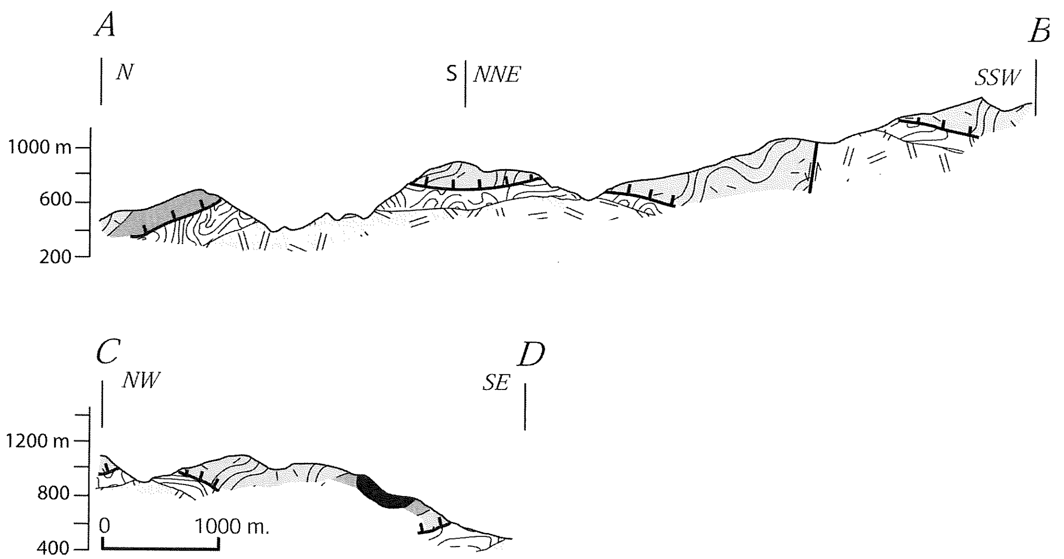

Fig. 3 – Geological cross sections through the northern sector of the Catena Costiera, see traces and symbols in figure 2.

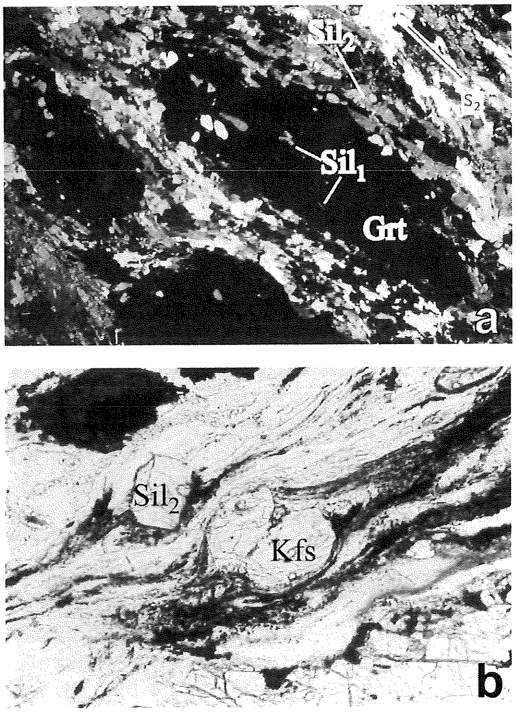

Fig. 4 – a) Porphyroclastic texture with flattened Grt-porphyroclast sourrounded by Sil. The flattening of Grt is produced in a HT shear zone (D_2). (crossed nicols, x12); b) narrow shear bands in migmatites with rotated porphyroblasts (D_3). (plane polarized light, x20).

Grt + Sil + Bt ± Crd, respectively. Garnets have a wide range of sizes from about 3 mm to 2 cm and a large compositional variation (Fig. 5), namely Alm_{66-54} Pyr_{42-28} Grs_{6-3} $Sps_{2-0.7}$. Some are zoned with the Fe/(Fe + Mg) ratio higher in the rims. Sillimanite is present in three different textural locations: 1) passive inclusions in garnet porphyroclasts (Sil_1); 2) large crystals aligned in the main S_1 planar anisotropy (Sil_2); 3) small euhedral grains associated with Qtz and Bt in fine-grained clusters (Sil_3). Biotite occupies three different textural sites: 1) passive inclusions in Grt and Pl (Bt_1); 2) sub-idiomorphic flakes making the main planar anisotropy of the rock together with Sil_2 (Bt_2); 3) retrogression product of Grt (Bt_3). The Bt_1 has an annite component (X_{Fe}= 0.35) that is higher than those of Bt_2 and Bt_3 (0.31) (Fig. 6). Plagioclase crystals have a quite homogeneous composition (An_{32-41}). Cordierite is present in the melanocratic portions in two different textural sites: 1) in the granoblastic matrix (Crd_1); 2) in symplectites at the Grt-Sil contacts (Crd_2). Its composition is quite homogeneous (X_{Fe} = 0.21 – 0.18). The K-feldspar is present as isolated crystals or associated with Pl and Qtz to form granoblastic polygonal aggregates mainly in the nebulitic migmatites. The white mica is commonly associated, sometimes in symplectites, with Qtz and Kfs and has low Si (a.p.f.u.) = 3.1 – 3.9.

The medium - grained Grt-Bt gneisses show continuous, in places spaced foliation and granoxenoblastic to porphyroclastic textures. The mineral assemblage is: Qtz + Pl + Kfs + Grt + Bt ± Sil ± St ±Crd ± Ms ± Ep ± Chl ± Prh ± Rt. Garnets have a wide range of sizes. The largest of them carry passive inclusions of Qtz and Bt concentrated in the cores, but the rims are inclusions-free and have sub-idiomorphic outlines. The garnets are commonly zoned with Alm_{61-74} Pyr_{26-28} Grs_{3-14} Sps_{1-2} core composition and rim composition depending on the neighbouring crystals, i.e., increase of Alm and Grs components when in contact with Bt and Pl, respectively. The whole Grt compositions are Alm_{61-74} Pyr_{19-28} Grs_{3-14} Sps_{1-2} (Fig. 5). Plagioclases do not show zoning, except for a slight decrease of An content when in contact with Grt. Their composition ranges from An_{35} to An_{56}. K-feldspar is present as subidiomorphic perthitic crystals and associated with Qtz in symplectites. Sillimanite occurs as relict in very fine-grained sericite aggregates and as small idiomorphic grains associated with Qtz. Biotite occurs in three different textural sites: 1) as passive inclusions in Grt cores (Bt_1); 2) as flakes, sometimes kinked, on the main planar anisotropy of the rock (Bt_2); 3) in symplectites with Qtz around Grt porphyroblasts (Bt_3). The X_{Fe} ratio ranges from 0.35 to 0.43 (Fig. 6) and slightly increases towards the rims. White mica forms very fine-grained aggregates (sericite) of alteration products of Pl and Sil. Retrograde staurolite

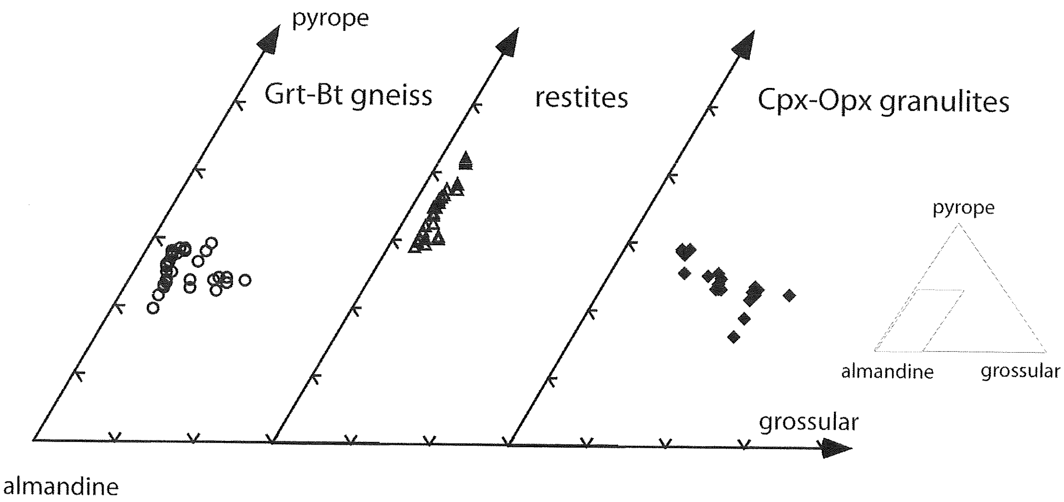

Fig. 5 – Compositions of garnet in the Pyrope- Almandine- Grossular diagram.

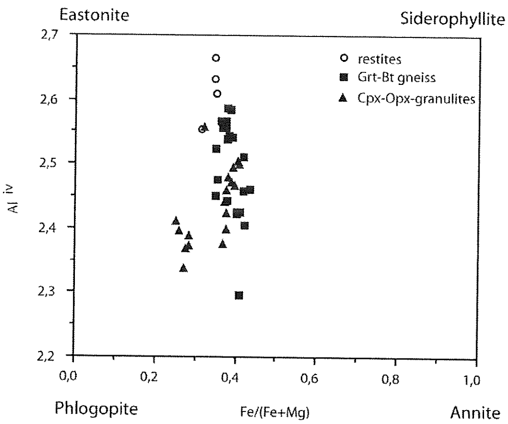

Fig. 6 – Fe/(Fe+Mg) vs Al^{IV} classification diagram of biotite.

occurs as small, colourless idiomorphic crystals in very few samples. Rutile occurs as passive inclusion in Grt and as relict in Ilm.

The Cpx-Opx - bearing granulites are discontinuously interlayered with migmatites and Grt-Bt - bearing gneisses. They are fine to coarse grained and have generally a banded texture with granoblastic polygonal to porphyroclastic fabric. Few samples carry fels appearance. The mineral assemblage is: Pl ± Opx ± Cpx ± Grt ± Qtz ± Amph ± Bt ± Chl + Ep ± Prh ± Spl ± Rt ± Ttn ± Cal. Plagioclase is the most abundant mineral, commonly transformed into an aggregate of sericite and epidote. Pl is present in three different textural sites: 1) included in the core of the Grt porphyroblasts (Pl_1); 2) as subidiomorphic crystals (Pl_2); 3) in reaction products associated with Opx (Pl_3). The Pl composition varies from An_{45} to An_{67} with the rims enriched of An component and the core containing up to 1% mol of Kfs. Garnets are observed as subidiomorphic porphyroblasts (1-4 mm) and small idiomorphic grains (<1mm). Porphyroblast cores include: Qtz, Bt, Rt, Ilm and partly transformed plagioclase. At the rim the porphyroblasts are inclusion-free. The whole Grt compositions are: Alm_{55-64} Pyr_{16-28} Grs_{7-20} Sps_{1-3} (Fig. 5). Generally garnets are zoned with the X_{Fe} ratio and Grs content higher in the rims. The orthopyroxene occurs as xenoblasts in the matrix and sometimes in portions with granoblastic polygonal texture. They have En_{48-65} Fs_{34-51} $Wo_{0.6-3}$ composition and an Al_2O_3 content of 1.3 - 2.8 wt%. The clinopyroxenes are subidiomorphic with variable size. They have En_{35-40} Fs_{14-20} Wo_{45-47} composition and an Al_2O_3 content of 1.3-2.8 wt%. Some Cpx are altered to greenish brown Amph and Chl. The biotite occurs as passive inclusion in Grt (Bt_1, X_{Fe}= 0.32), as medium-large flake (Bt_2, X_{Fe} = 0.37 - 0.40) (Fig. 6) and as alteration product of Grt (Bt_3). Rutile occurs as inclusion in Grt and as isolated interstitial blasts commonly rimmed by ilmenite.

METAMORPHIC EVOLUTION

Five stages characterize the metamorphic evolution of the metasedimentary crustal sequence of the Catena Costiera: 1) a prograde stage, 2) a metamorphic peak under granulite facies conditions, 3) a retrograde stage, still under granulite facies conditions, 4) a subsequent retrogression stage characterized by decompression and hydration under amphibolite facies conditions, 5) a retrogression stage under prehnite- pumpellyite greenschist facies conditions.

Migmatites

On the basis of microtectonic characteristics and of the inclusions in garnets, a prograde stage characterized by the Qtz+Grt+Sil_1+Pl+Bt_1+Ms+Ilm *(a)* mineral association may be inferred. Episodes of muscovite and likely biotite dehydration melting generated anatectic melts that were separated from the restitic portions by an isoclinal folding deformation event. A later transposition separated the leucocratic from the melanocratic portions to form the stromatites (Piluso *et al.*, 1998). The metamorphic peak under granulite facies conditions is characterized by the Qtz+Pl+Kfs+Grt+Sil_2+Crd_1+Rt *(b)* paragenesis. The restites allow to depict an HT retrograde evolution still under granulite facies conditions characterized by the Grt+Sil_2+Crd_1+Rt+Qtz (b_1) mineral association where the Crd_1 is the cordierite included in garnets. Furthermore, multiple reaction coronas made of a Crd moat and of Crd+Spl, Crd+Opx, Crd+Spl±Crn±An symplectites developed at the Grt-Sil contacts (Fig. 7). The mineral association of the restites at this stage is formed of: Grt+Sil_2+Crd_2+Spl+Opx+Ilm+Rt±An± Qtz±Crn (c_1). Conversely the leucocratic portions of the stromatites do not show growth of new minerals related to this retrograde stage and to the c_1 mineral association of the restites since they are mainly made of Qtz, Pl and Kfs. The strong hydration and the temperature decrease cause, in the melanocratic bands, the instability of cordierite and garnet

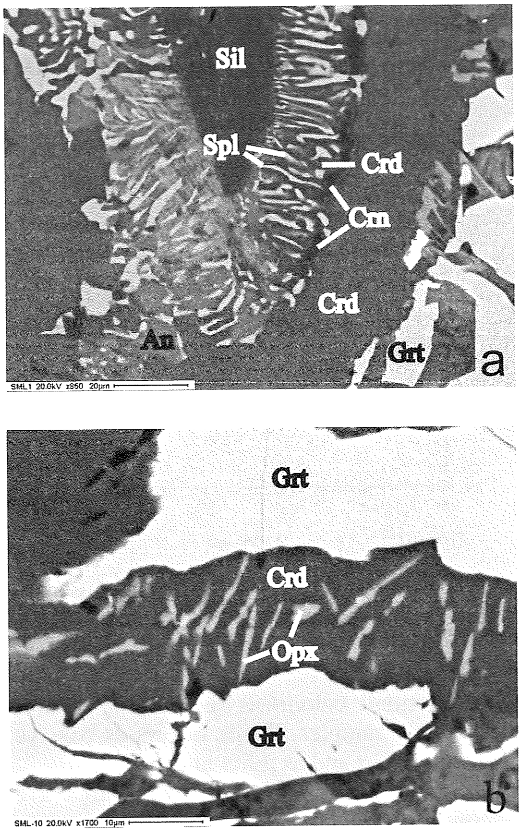

Fig. 7 – a) Reaction corona formed of Crd + Spl + An + Crn at the Grt- Sil contact in restites, BSE image. b) Crd-Opx symplectite replacing Grt- porphyroclasts in restites, BSE image.

which were transformed into an aggregate of Bt_3+Qtz±Pl±Sil_3. K-white mica pseudomorphous after Sil_2 and flakes of K-white mica associated with quartz and K-feldspar occur in the leucocratic bands. These occurrences indicate the retrograde blastesis of the K-white mica. The relative paragenesis is Qtz+Pl+Bt_3+Ms+Ilm+Spl *(d)*. The further P-T decrease causes the growth of chlorite after biotite, cordierite and garnet, and of sericite after plagioclase and sillimanite. Spinel and ilmenite occur as relicts in the magnetite crystal cores. Subordinate prehnite and very rare Mg-pumpellyite crystals also occur. The general mineral association made of: Qtz+Ms+Ab+Ep+Chl+Mt+Prh+Pmp *(e)* indicates low greenschist facies conditions.

Grt-Bt gneisses

The metamorphic evolution of the Grt-Bt gneisses is quite comparable to that shown by the migmatites also if the different composition of the protoliths yields different mineral associations at the same physical conditions. The prograde stage is characterized by the Qtz+ Pl +Grt +Bt_1+Sil+Ilm *(f)*. Evidences of very subordinate melting episodes occur also in the Grt-Bt gneisses but to a less extent. The mineral association formed of Qtz+Grt+Pl+Kfs+Bt_2+Crd+Rt *(g)* represents the metamorphic peak conditions. The retrograde stage under granulite facies conditions is not clearly recorded by the Grt-Bt gneisses. A subsequent retrogression and hydration processes lead to a Qtz+Pl+Bt_3+Ms+St+Ilm *(h)* mineral association under amphibolite facies conditions. The staurolite is present as idioblasts associated with Qtz and muscovite after sillimanite and garnet. Biotite-quartz symplectites are common. The followed retrogression stage to greenschist facies conditions is characterized by the Qtz+Ms+Ep+Ab+Chl+Mt+Prh+Pmp *(i)* mineral association.

Cpx-Opx - bearing granulites

The prograde stage of the Cpx-Opx - bearing granulite is documented by the Pl_1+ Bt_1+ Qtz + Rt *(j)* inclusions in the garnet cores. The metamorphic peak is characterized by a well-developed textural equilibrium between the mineral phases and by the Opx+Cpx+Grt+Pl_2+Qtz+Rt *(k)* mineral association. Skeletal garnets and Pl_3+Opx symplectites at the pyroxene-garnet contacts indicate the garnet break-down. These features record the transition from high to middle pressure granulite conditions (Green and Ringwood, 1967; Ito and Kennedy, 1970). Such a transition happened with a slight hydration as indicated by the presence of Bt_2 in textural equilibrium with orthopyroxene. The paragenesis of this stage is made of Pl_3+Opx+Cpx+Bt_2+Qtz+Rt *(l)*. Subsequent hydration developed an hydrous-bearing phases paragenesis, i.e., Pl+Amph (Hbl)+Bt_3+Qtz+Ilm *(m)*, where horneblende and Bt_3 grow on clinopyroxene and garnet, respectively. The following metamorphic stage developed under greenschist facies conditions as indicated by the Qtz+Ep+Amph (Tr-Act)+ Ms+Chl+Mt+Prh+Pmp *(n)* mineral association. The prehnite grows on plagioclase and biotite, and the pumpellyite grows mainly on amphibole.

P-T ESTIMATES

The temperature estimate of a step of the prograde stage calculated with the Fe-Mg exchange reaction in the Grt-Bt_1 pair, according to the widely used thermometers (Ferry and Spear, 1978; Indares and Martignole, 1985; Battacharya *et al.*, 1992), yields average values of 550-600°C.

The physical conditions of the granulite metamorphic peak were calculated on the Cpx-Opx – bearing granulites, where the well preserved Grt - Pl - Cpx - Opx - Qtz assemblage indicates a very slight or absent retrogression. The available thermometers, based on the Mg-Fe exchange reactions between Grt-Opx, Grt-Cpx and Opx-Cpx pairs (Harley, 1984; Bhattacharya *et al.*, 1991; Lal, 1993; Powell, 1985; Sengupta *et al.*, 1989; Wels, 1977; Brey and Kohler, 1990) give a range of temperature of 750-800°C. The pressure estimates, based on Grt-Opx (Harley and Green, 1982; Harley, 1984) and Grt-Opx-Pl-Qtz net-transfer reactions (Bohlen *et al.*, 1983; Harley, 1984; Perkins and Chipera, 1985), are 0.9-1.0 GPa.

The retrogression physical conditions (decompression) in the granulitic facies were calculated on the basis of the T - P estimates on the Grt-Crd pairs of the restitic rocks (Thompson, 1976, Newton and Wood, 1979; Perchuck *et al.*, 1985; Bhattacharya *et al.*, 1988; Perchuck, 1991) and are 650-670°C and 0.6-0.7 Gpa. The Crn+Crd assemblage is consistent with a thermal estimate at about 680°C and 0.6 Gpa as determined on qualitative mineral equilibria calculation in the FMASH system using the THERMOCALC software (Braga *et al.*, 2004).

Pressure estimates on Grt-Bt gneiss during decompression stage were defined using GRIPS (Bohlen and Liotta, 1986) and GRAIL (Bohlen *et al.*, 1983) barometer, giving values ranging between 0.6 and 0.7 GPa.

As for the temperature of the decompression stage in the granulite facies conditions, the highest values, i.e. of about 800°C, were calculated on the Crd-Spl pair in symplectites using the thermometer by Vielzeuf, (1983). A P value of about 0.8 Gpa, calculated with the Crd-Spl-Qtz barometer (Perchuck, 1991), corresponds to the maximum T value.

The P-T estimates of the retrograde stage under amphibolite facies conditions were calculated according to the Grt-Bt thermometers (Ferry and Spear, 1978; Indares and Martignole, 1985; Battacharya *et al.*, 1992). The temperature estimates are 518-598°C for the Grt-Bt gneisses and migmatites, and 603-703°C for the pyroxene granulites. The differences of the calculated temperature are likely due to the different kinetics of the Fe-Mg reaction exchange in the pelitic and arenaceous systems, respectively. Pressure estimates of the Grt-Bt gneisses using the GPBQ (Hoisch, 1990) barometers give comparable values, i.e., 0.4-0.6 GPa at 518-598°C.

P - T - D PATH

The migmatite and granulite rocks from Catena Costiera underwent a complex and multistage tectonometamorphic evolution (Piluso, 1997; Piluso *et al.*, 1998) that can be summarized as follows (Fig. 8):

1) a prograde event in the amphibolite facies (550-600 °C and about 0.5 GPa) is followed by anatectic processes of the pelitic - arenaceous sequence. A syn- to early post-anatectic

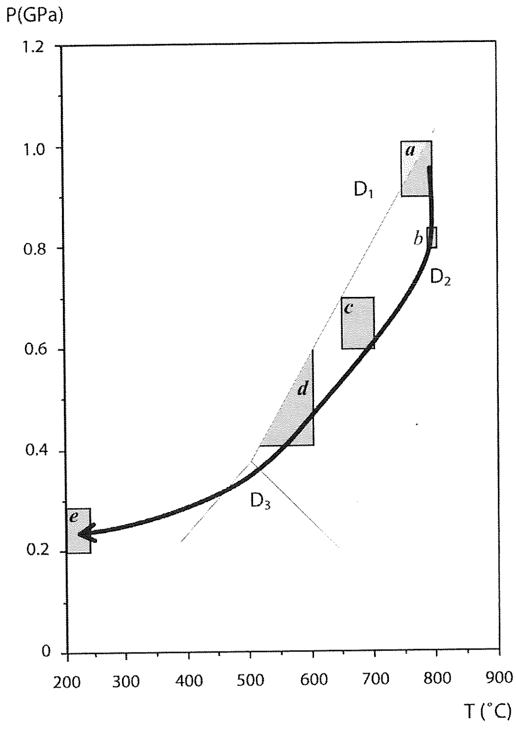

Fig. 8 – P-T-D path of the Grt-Bt gneiss, Cpx-Opx-bearing granulites and migmatites of the Hercynian crystalline basement from the northern sector of Catena Costiera. Al_2SiO_5 phase diagram after Holdaway (1971).

deformation event (D_1) developed isoclinal folds and separated the melts from the melanocratic portions (Piluso, 1997; Piluso *et al.*, 1998). This stage is not shown in figure 8 since proper baric constraints do not exist;

2) the metamorphic climax has been reached under granulite facies conditions at 750 - 800°C and 0.9 - 1.0 GPa and it is characterized by the development of granoblastic polygonal texture (box *a* in Fig. 8);

3) exhumation of the high-grade rocks took place along HT extensional shear zones (Piluso *et al.*, 1998) following a decompression path characterized by a first stage of isothermal decompression in the granulite facies conditions (Fig. 7) at about 800°C and 0.8 Gpa (box *b* in Fig.8) and a second stage of decompression and cooling ended at about 650-700°C and 0.6-0.7 Gpa (box *c* in Fig. 8). During this stages, the deformation event (D_2) generated HT mylonites characterized by a well developed and pervasive S_2 anisotropy (Fig. 4a), which transposed the previous isoclinal folds (Piluso *et al.*, 1998);

4) a general retrogression under lower amphibolite facies conditions, 520°-600°C and 0.4 - 0.5 Gpa (box *d* in Fig. 8) affected the crystalline basement rocks;

5) the last metamorphic event took place under lower greenschists facies conditions, 250°-350°C and less than 0.3 Gpa (box *e* in Fig. 8). The retrogression effects are widespread and pervasive, and, in places, they almost fully obliterated the older mineral associations.

LT extensional shear zones developed during the stages 4 and 5 with formation of S - C mylonites (D_3) (Fig. 4b); a later brittle deformation event (D_4) produced pseudotachylytes and cataclasites, mainly along normal faults.

Discussion

The P-T evolution of the migmatites and granulites from the northern sector of the Catena Costiera had a clockwise trajectory (Fig. 8). The prograde stage is characterized by crustal anatexis in a compressive tectonic environment and reached the metamorphic peak at 1.0 GPa and 750-800°C following an high-T geotherm. No age determinations are available on the HT crystalline rocks of the Catena Costiera, but an age of about 300 Ma is supposed for the metamorphic peak based on age data of similar rocks from the Sila massif (Graessner *et al.*, 2000). The anatectic event produced, other than the migmatites in the middle-lower crust, the calcalkaline granitoid melts, which emplaced at 293-270 Ma in the Sila massif (Ayuso *et al.*, 1994; Graessner *et al.*, 2000) and probably at the same time also in the Catena Costiera (Piluso and Morten, 2001). A composite decompression path showing an early isothermal decompression followed by cooling took place along HT extentional shear zones (D_2) with very fast exhumation rates. Texturally, this is shown by deformation of the metamorphic peak assemblage, blastesis of phases during decompression under static conditions, and development of coronitic and granoblastic polygonal textures (Figs. 4 and 5). The following stages of exhumation took place under lower amphibolite and lower greenschists facies conditions, and the D_3 deformation was accommodated by LT shear zones at the ductile-brittle transition. The structures from D_1 to D_3 of the Catena Costiera sequence are crosscut by unmetamorphosed basaltic dykes of alkaline-transitional affinity of which K/Ar dating gives an age of 120 ± 1.3 Ma (Piluso and Morten, 1997).

Concluding Remarks

The deepest part of an Hercynian continental crust and crust-mantle boundary outcrop in the Catena Costiera. This crustal sequence underwent a pervasive anatectic event, and was dragged down to about 30 km of depth during the Hercynian continental collision. Astenosphere upwelling generated crustal heating during lithospheric extention, and the resulting magmatism produced the underplated gabbroic rocks of the northern sector of the Catena Costiera (Morten *et al.*, 1999; Piluso *et al.*, 2000). The underplated magmatism is well documented in the Permian age in the Ivrea-Verbano zone, western Alps (Sinigoi *et al.*, 1995; Vavra *et al.*, 1999). The subsequent stages of exhumation took place under lower amphibolite and lower greenschists facies conditions along LT shear zones. At Cretaceous age, the lower crust was exhumed to shallow depth and did not experience any metamorphic events later than 120 Ma. The Alpine orogenesis did not overprint the crustal section of the Catena Costiera, except for the brittle deformation event.

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