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High-pressure metamorphism in southern Calabria, Italy: the Cardeto chlorite-garnet metapelites

Selma Russo[1*], Daniela Cutrupia[2], Marcella Di Bella[1], Caterina Minutoli[1]

[1] Dipartimento di Scienze della Terra, Università di Messina, Salita Sperone, 31 - S. Agata, I-98166 Messina (Italy)
[2] Dipartimento di Scienze Geologiche, Università di Catania, Corso Italia, 55, I-95129 Catania (Italy)

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Abstract. — The Aspromonte Massif (southern Calabria, Italy) consists of an Alpine crystalline nappe pile, belonging to the southern Sector of the Calabrian Arc. The Aspromonte Unit, forming the bulk of the Massif, is overlain by the Stilo Unit and overlies, near Cardeto and Africo, phyllites and micaschists. Structural analysis on the Cardeto metapelites emphasized three deformation phases. Abundant "pin-prick" garnets characterize the fine-grained phyllites, porphyroblasts and "pin-prick" crystals are present in the micaschists. Garnets are almandine-rich with a low Mg content and variable amount of spessartine and grossular, depending on the rock composition. The porphyroblastic garnets are strongly zoned and exhibit distinctive bell-shaped Mn profiles typical of a prograde growth. The pin-prick garnets show the same composition as the rims of the porphyroblastic crystals of the same sample, suggesting a late stage growth with respect to the porphyroblasts. Phengitic white mica and chlorite composition suggest crystallization under relatively-high pressure conditions.

Physical conditions, inferred using chlorite-garnet geothermometer and modelled P-T pseudosections in the MnNCKFMASH system for chemically similar metapelites, suggest P in the range of 7.5-10 kbar, in the T range of 500-550°C. The widespread biotite-free chlorite+almandine assemblage suggests a crystallization of almandine prior to biotite, as happens in the Sanbagawa metamorphic region of Japan, where the chlorite, garnet, biotite+albite and biotite+oligoclase assemblages at increasing temperature, indicate a P/T ratio intermediate between the blueschist facies and the Barrovian greenschist facies conditions.

High pressure conditions have never been estimated in the Variscan metamorphism of the Southern Sector of the Calabrian Arc, which, instead, is characterized by medium-low P/T ratio. Only the Aspromonte Unit, tectonically overlying the Cardeto metamorphics, shows a pervasive Alpine overprint, which is characterized by a higher P/T ratio than that of the Variscan metamorphism. Consequently, we assume that the Cardeto metapelites were probably affected by an Alpine metamorphic event.

Owing to the similar structural position, the Cardeto rocks could represent the Calabrian part of the Mandanici Unit, which extensively outcrops in the nearby Peloritani Mountains, that in Calabria has been overprinted by Alpine effects, but no structural or mineralogical relicts which support this interpretation have been observed. More probably, they represent a distinct Alpine tectonic unit which have experienced a relatively-high pressure Alpine (?) metamorphism and that in the Peloritani Mountains was removed from within the tectonic pile during a syn-orogenic extension episode.

* Corresponding author, E-mail: selma.russo@unime.it

Riassunto. — Il Massiccio dell'Aspromonte (settore meridionale dell'Arco Calabro-Peloritano) è formato da una pila di falde Alpine a basamento cristallino tra le quali è prevalente l'omonima unità, sottostante all'Unità di Stilo e sovrastante alle filladi di "Cardeto" e di "Africo", affioranti in finestra tettonica.

Nella finestra tettonica di Cardeto affiorano filladi e micascisti filladici caratterizzati da tre fasi deformative e dalla costante presenza di una paragenesi a clorite e granato senza biotite. Abbondantissimi granati a punta di spillo caratterizzano le filladi e due generazioni di granato, a punta di spillo e in porfiroblasti millimetrici, sono presenti nei micascisti.

Tutti i granati analizzati mostrano composizioni almandiniche con basso Mg e variabile contenuto in Mn e Ca a seconda della quantità di questi elementi nella roccia. I porfiroblasti hanno profili a campana per il manganese, tipici di una crescita in condizioni prograde; i granati a punta di spillo hanno composizioni omogenee, simili al bordo dei porfiroblasti dello stesso campione, suggerendo un tempo di crescita successivo rispetto a questi ultimi. La composizione fengitica della mica bianca e la composizione della clorite sono indicativi di pressioni relativamente elevate.

Le condizioni di temperatura e pressione del metamorfismo sono state dedotte utilizzando il geotermometro clorite-granato e un modello di pseudosezione P-T nel sistema MnNCKFMASH per peliti di analoga composizione. La pressione dedotta è superiore a 7,5 kbar e minore di 10 kbar come indica la mancanza di glaucofane nelle rocce basiche associate. La temperatura è compresa tra 500° e 550°C.

L'associazione mineralogica clorite+almandino senza biotite suggerisce una cristallizzazione del granato prima della biotite, come si osserva nella regione di Sanbagawa, in Giappone, dove la sequenza di cristallizzazione clorite, granato, biotite+albite e biotite+oligoclasio all'aumentare della temperatura è stata interpretata come tipica di un metamorfismo con rapporto P/T intermedio tra quelli delle facies scisti blu e scisti verdi.

Tutte le unità del settore meridionale dell'Arco Calabro sono interessate da un metamorfismo Varisico con rapporto P/T basso o medio. Solo nell'Unità dell'Aspromonte, posta al di sopra delle metamorfiti di Cardeto, è presente una sovrimpronta metamorfica Alpina, caratterizzata da un rapporto P/T più elevato.

Tutte le unità Alpine del settore meridionale dell'Arco Calabro, inclusa l'Unità di Mandanici, presentano basamenti cristallini caratterizzati da un metamorfismo Varisico di media- (barroviano) o bassa pressione. Solo l'Unità dell'Aspromonte, tettonicamente sovrapposta alle metapeliti di Cardeto, ha una sovrimpronta metamorfica Alpina caratterizzata da un più elevato rapporto P/T. Per analogia, il metamorfismo di relativamente alta pressione delle metapeliti di Cardeto potrebbe essere Alpino.

A causa dell'analoga posizione strutturale, le metamorfiti di Cardeto potrebbero rappresentare la porzione calabra dell'Unità di Mandanici, affiorante nei vicini Monti Peloritani, mostrante in Calabria una sovrimpronta metamorfica Alpina, ma non sono stati osservati relitti mineralogici o strutturali a supporto di tale interpretazione. Più probabilmente esse rappresentano una distinta unità tettonica, interessata da metamorfismo Alpino (?) di relativamente alta pressione, non affiorante nei Peloritani perché rimossa da elisione tettonica durante un episodio estensionale sin-convergenza.

Key-words: *Aspromonte Massif, Chlorite+garnet metapelites, Mineral chemistry, High-P metamorphism.*

INTRODUCTION AND GEOLOGICAL SETTING

In the Aspromonte Massif (southern Calabria, Italy) an Alpine nappe pile is exposed (Amodio Morelli *et al.*, 1976; Bonardi *et al.*, 1979). The bulk of the Massif is formed by the low-P medium-high-T Variscan metamorphics, locally reworked in Alpine times, of the Aspromonte Unit, overlain by the low-P low- to medium-T Variscan metamorphics of the Stilo Unit (Bonardi *et al.*, 1984a). In two tectonic windows below the Aspromonte Unit, near Cardeto (Bonardi *et al.*, 1980a) and near Africo (Bonardi *et al.*, 1979) phyllites crop out (Fig. 1A). Together with the Peloritani Mountains (north-eastern Sicily), the Aspromonte Massif belongs to the Southern Sector of the Calabrian Arc (Bonardi *et al.*, 1980b). In Sicily (Amodio Morelli *et al.*, 1976; Bonardi *et al.*, 1976) the Aspromonte Unit is the uppermost thrust sheet of the Alpine nappe pile, underlain by the Mandanici Unit. Going towards the bottom, Alì, Fondachelli, and Longi-Taormina Units crop out below the Mandanici Unit. All the

Units of the southern sector of the Calabrian Arc are composed of Variscan crystalline basements and some of them also have a Meso-Cenozoic sedimentary cover. A pervasive Alpine overprint has been found only in the Aspromonte Unit, both in Calabria and in Sicily (Bonardi *et al*., 1984b, 1992; Platt and Compagnoni, 1990; Messina *et al*., 1990, 1992).

The present study aims to reconstruct the tectono-metamorphic history of the phyllites of the Cardeto tectonic window, and to constrain their P-T evolution.

The Cardeto tectonic window extends for about 5 km along the Fiumara S. Agata, east of the Cardeto village (Fig. 1B). Dark grey garnet phyllites and silver grey garnet micaschists with minor quartzites and marbles crop out. These rocks have been ascribed by Bonardi *et al*. (1980a) to the Mandanici Unit, outcropping below the Aspromonte Unit in the Peloritani Mountains. Messina *et al*. (1993) excludes their comparison with the Mandanici Unit, suggesting that they represent a different tectonic unit, affected by a weak Alpine overprint. In the geological map of the western Aspromonte, Atzori *et al*. (1983) include the Cardeto phyllites in the "lower unit" of Pezzino and Puglisi (1980). Recently, Russo *et al*. (2002a; 2002b) hypothesize that the Cardeto metapelites could represent the Calabrian part of the Mandanici Unit that has been affected, here, by Alpine overprint.

To verify the above hypotheses and to characterize the type of metamorphism, the Cardeto metamorphics have been compared with the Mandanici Unit phyllites (NE Sicily) and with the Alpine overprinted rocks of the overlain Aspromonte Unit.

The *Mandanici Unit* (Ghezzo, 1967; Ogniben, 1969; Bonardi *et al*., 1976) (Fig. 1A) is composed of a Variscan metamorphic basement and of slices of Meso-Cenozoic sedimentary cover. Prevailing phyllites grading to metarenites, with minor quartzites, metabasites, porphyroids, calcschists and marbles have been recognized in

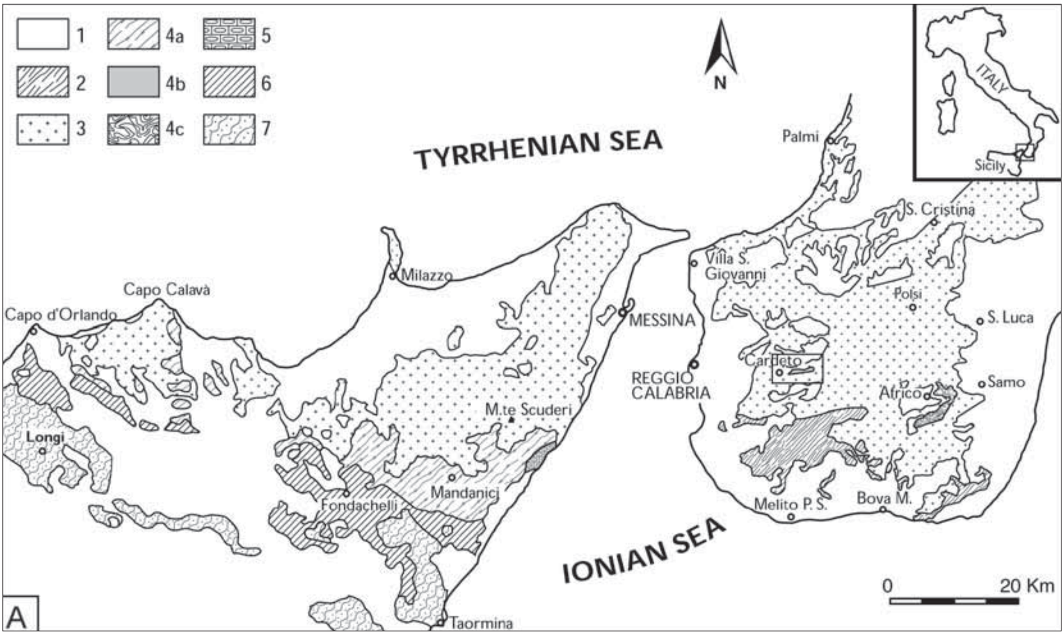


Fig. 1A – *Southern Sector of the Calabrian Arc* (After Bonardi *et al*., 1993, modified). Legend: 1 = Mesozoic to recent deposits; 2 = Stilo Unit; 3 = Aspromonte Unit; 4a = Mandanici Unit; 4b = Cardeto metapelites; 4c = Africo metapelites; 5 = Alì Unit; 6 = Fondachelli Unit; 7 = Longi-Taormina Unit.

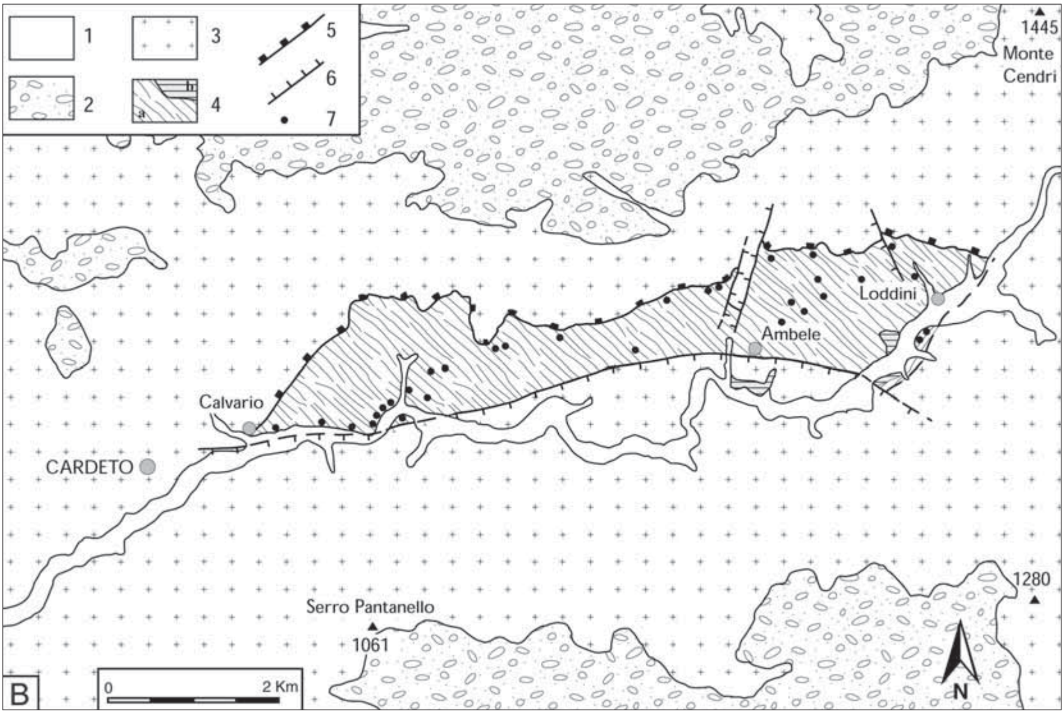


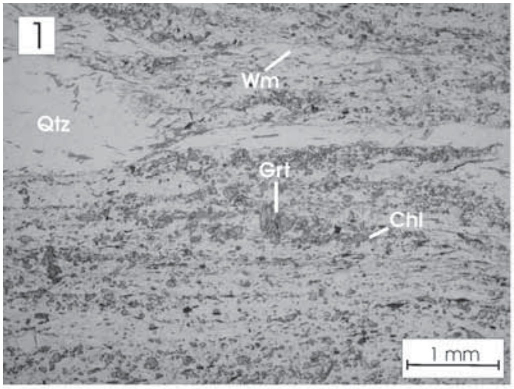
Fig. 1B – *Geological sketch map of the Cardeto tectonic window* (After Bonardi *et al.*, 1980a). Legend: 1 = Alluvional deposits. 2 = Plio-quaternary deposits. 3 = Aspromonte Unit. 4 = Cardeto garnet phyllites and micaschists (a) and marbles (b). 5 = Thrust. 6 = Normal fault. 7 = Sample location.

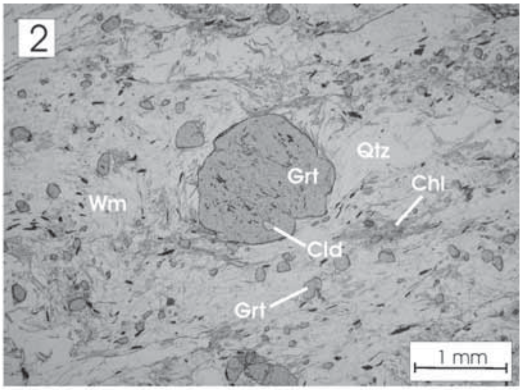
the basement. According to Cutrupia *et al.* (2004) a Variscan metamorphic zoning from chlorite-zone of the greenschist facies up to lower-amphibolite facies are present. The following parageneses, all bearing white mica + quartz + ilmenite ± albite, have been recognised in metapelites: 1) chlorite; 2) chlorite + biotite; 3) chlorite + garnet ± biotite 4) chlorite + garnet + biotite ± chloritoid ± staurolite ± oligoclase rim.

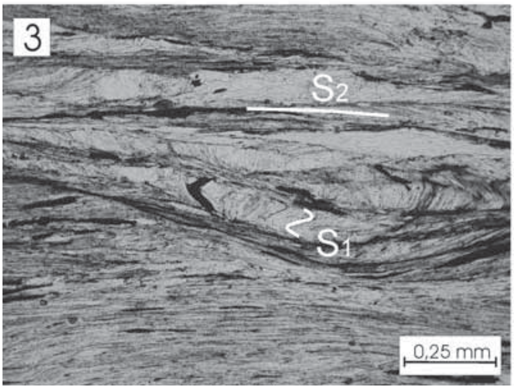
The *Aspromonte Unit* (Ogniben, 1960, 1973; Bonardi *et al*., 1976, 1979) (Fig. 1A) consists of a Variscan amphibolite-facies metamorphic basement, intruded by late-Variscan plutonites. In a large area in Calabria (Bonardi *et al*., 1984b, 1992; Platt and Compagnoni, 1990; Messina *et al*., 1992) and in a smaller one in Sicily (Messina *et al*., 1990), the basement has been overprinted by a greenschist to low-amphibolite facies metamorphic re-equilibration along centimeter-to meter-thick shear zones and increasing towards the bottom. Cataclastic to mylonitic effects up to complete re-crystallization of the Variscan parageneses and development of new pervasive foliations have been observed. Two stages of Alpine metamorphism have been identified (Platt & Compagnoni, 1990; Messina et al., 1990, 1992): 1) the first characterized by relatively high P (T = 500±20°C and P = 5-8 kbar), and by crystallization of garnet, kyanite, green-blue amphibole, chlorite, chloritoid and phengitic white mica; 2) the second stage characterized by lower-pressure, with development of biotite and oligoclase, and accompanied by intense ductile deformation. The overprint has been dated 22-28 Ma in Calabria (Rb-Sr method, on mica separates; Bonardi *et al*., 1991) and 48-61 Ma in Sicily (Ar-Ar method, on mica separates; De Gregorio *et al*., 2003).

PETROGRAPHIC AND STRUCTURAL FEATURES

Two greenschist-facies metapelitic types, showing a widespread mylonitic fabric, have been recognised, in the Cardeto rocks: 1) - *fine-grained garnet phyllites* (Photo 1) characterized by prevalent white mica + chlorite domains interlayered with thin layers of quartz + albite with minor sericite and chlorite. Abundant subhedral or roundish-shaped "pin-prick" garnets are widespread. Tourmaline + ilmenite + apatite are the common accessory phases, epidote is present only in a few samples. 2) - *garnet micaschists* (Photo 2) characterized by white mica + chlorite + "pin-prick" garnet domains interlayered with bands of ribbon-like quartz + albite + minor white mica and chlorite elongate flakes, containing abundant "porphyroblastic" and "pin-prick" garnets. The common accessory minerals are tourmaline, ilmenite, apatite with minor epidote also in this rock type. Chloritoid has been found only in the sample SR 123 as rare inclusion in the porphyroblastic garnet. Amphibole and small







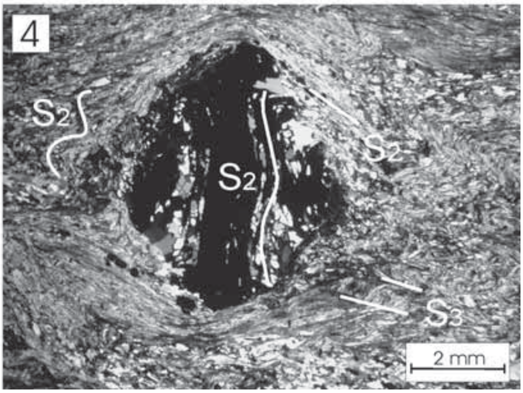


Photo 1 - *Fine-grained garnet phyllite* – Sericite + chlorite layers alternated with quartz + albite domains. Abundant pin-prick garnets are widespread (sample SR 132; plane polarized light).

Photo 2 - *Garnet micaschist* – Roundish compact porphyroblastic garnet showing an internal foliation defined by quartz, white mica, ilmenite and chloritoid in a white mica + chlorite + quartz matrix. Small pin-prick garnets are widespread (sample SR 123; plane polarized light).

Photo 3 - *Garnet micaschist* – White mica islands and microfold hinges, the latter outlined by folded ilmenite, are preserved as relicts of a previous foliation (S1). (Sample SR 126, plane polarized light).

Photo 4 - *Garnet micaschist* – Porphyroblastic skeletal garnet with quartz inclusion trails of the main foliation (S2), pre-tectonic with respect to the crenulation cleavage (S3) (sample SR 170, crossed polars).

biotite flakes are present only in the, more basic, sample SR131.

Porphyroblasts and small crystals of garnet belong to two generations. The *porphyroblasts* form roundish and compact grains with or without an internal foliation (Photo 2) or skeletal and/or spiral-shaped crystals. The pin-prick crystals formed later in isolated grains (Photo 2) or as aggregates of hundreds of individual crystals.

Three deformation phases are recorded. The first phase (D_1) develops a chlorite + white mica + ilmenite foliation (S_1), preserved in the microlithons as fold hinges (Photo 3). The second phase (D_2) generates isoclinal folds responsible for the main pervasive schistosity (S_2), along which white mica, chlorite, quartz, albite, ilmenite crystallized. The third phase (D_3) is responsible for tight folds affecting the main schistosity and develops an approximately axial planar, microscopic crenulation cleavage (S3) (Photo 4). Garnet porphyroblasts show a sigmoidal internal quartz + ilmenite ± chloritoid foliation related to the main schistosity (Photo 4), suggesting a garnet growth from syn- to post-tectonic conditions. The strain shadows and the crenulation cleavage deflect around porphyroblasts indicating that their growth predates the third deformation phase, the pin-prick garnet, on the contrary, shows evidence of post-crenulation cleavage growth. No relict mineral phases which can be univocally related to a previous metamorphic event have been observed.

Phyllites and micaschists show the widespread biotite-free white mica + chlorite + garnet assemblage, suggesting an earlier growth of garnet with respect to biotite.

ANALYTICAL METHODS

To constrain the P-T conditions of the Cardeto metamorphism, the main mineral phases of six representative metapelitic samples, five micaschists (samples SR123, SR125, SR126, SR128, SR131) and one phyllite (SR132) have been analyzed. The whole-rock chemistry of the same samples has also been determined. The analyses were performed at the Dipartimento di Scienze della Terra, University of Modena and Reggio Emilia.

Bulk rock major elements were determined with an X-ray spectrometer Philips PW1480, equipped with a Cr-Au X-ray tube.

Mineral phases were determined using an ARL-SEMQ electron microprobe in the wavelength-dispersive mode with 15 kV acceleration potential and 20 nA beam current. Natural silicates were used as standards. The quantitative microprobe software PROBE by Donovan and Rivers (1990) has been used.

The mineral abbreviations of Kretz (1983) are used.

WHOLE-ROCK CHEMISTRY

The chemical composition of the analyzed rocks is reported in Table 1. All the analyses were recalculated on molecular proportions (SiO_2-free). For comparison the bulk rock compositions used by Tinkham *et al*. (2001) to model P-T "pseudosections" in the MnNCKFMASH system are also reported.

The analyzed samples show, as a whole, a pelitic composition, with scattered oxide values. In the AFM diagram (Fig. 2), they plot in a relatively wide range with an average value intermediate between the Waterville AWBZ and the Waterville High-Al compositions of Tinkham *et al.* (2001).

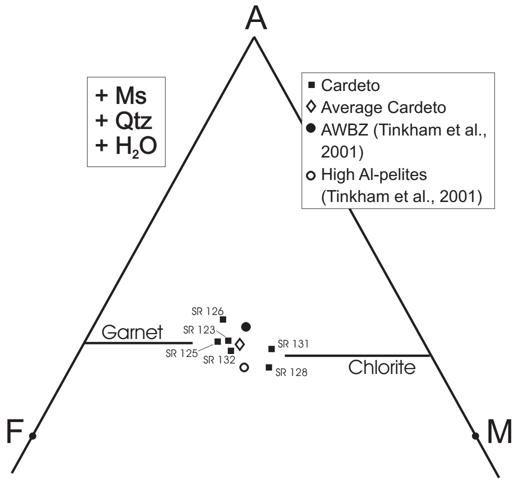


Fig. 2 – AFM projection (Thompson, 1957) showing the bulk rock composition of the analyzed Cardeto metapelites. For comparison the bulk rock composition of Waterville AWBZ and Waterville High-Al pelites from Tinkham *et al.* (2001) are also reported.

TABLE 1
Bulk rock composition

	Cardeto metapelites							Thinkham *et al.* (2001)	
Sample	SR 123	SR 125	SR 126	SR 128	SR 131	SR 132	Average	Waterville AWBZ (1)	Waterville High-Al
				Wt %					
SiO_2	58.88	73.23	57.74	57.08	60.92	59.50	61.23	60.78	60.14
Al_2O_3	20.91	12.61	22.68	17.71	16.34	19.34	18.27	16.88	23.04
FeO_{tot}	6.95	5.28	5.87	7.85	6.40	7.33	6.61	6.87	6.79
MnO	0.15	0.10	0.10	0.14	0.13	0.25	0.15	0.13	0.13
MgO	2.84	1.91	2.20	5.18	4.36	3.14	3.27	3.44	3.41
CaO	0.33	0.71	0.35	1.09	2.12	0.55	0.86	1.21	1.20
Na_2O	0.96	1.03	1.82	1.91	2.53	0.64	1.48	1.65	1.63
K_2O	4.01	2.16	3.92	3.46	2.59	3.83	3.33	3.70	3.66
L.O.I.	3.25	1.58	3.49	3.4	2.78	3.57	3.01		
Σ	98.28	98.61	98.17	97.82	98.17	98.15	98.20	94.66	100.00
				Molecular proportions					
SiO_2	69.67	80.82	69.21	66.10	69.04	70.14	70.83	69.89	66.98
Al_2O_3	14.58	8.20	16.02	12.08	10.91	13.43	12.54	11.44	15.12
FeO_{tot}	6.04	4.28	5.17	6.68	5.33	6.35	5.64	6.60	6.33
MnO	0.15	0.09	0.10	0.14	0.12	0.25	0.14	0.13	0.12
MgO	5.01	3.14	3.93	8.95	7.37	5.52	5.65	5.90	5.65
CaO	0.42	0.84	0.45	1.35	2.57	0.69	1.05	1.49	1.43
Na_2O	1.10	1.10	2.11	2.14	2.78	0.73	1.66	1.84	1.76
K_2O	3.03	1.52	3.00	2.56	1.87	2.88	2.48	2.71	2.61
Σ	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
				Molecular proportions (SiO_2 free)					
Al_2O_3	48.07	42.76	52.03	35.65	35.24	44.99	43.12	37.99	45.80
FeO_{tot}	19.92	22.31	16.80	19.70	17.21	21.27	19.54	21.93	19.15
MnO	0.50	0.49	0.33	0.41	0.40	0.84	0.49	0.42	0.38
MgO	16.52	16.39	12.77	26.39	23.80	18.49	19.06	19.59	17.13
CaO	1.38	4.38	1.46	3.99	8.31	2.33	3.64	4.95	4.33
Na_2O	3.63	5.75	6.87	6.32	8.98	2.45	5.67	6.11	5.34
K_2O	9.98	7.93	9.74	7.54	6.05	9.65	8.48	9.01	7.87
Σ	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

(1) Average of eigth analyses.

MINERAL COMPOSITION

Garnet

All the analyzed grains show an almandine-rich composition (Alm 50-87%), with low Mg and variable Mn and Ca contents (Prp 3-9, Sps 0.1-36 and Grs 2-27 - Table 2). In the Fe-Mn-Ca diagram (Fig. 3) they show a homogeneous composition within each sample. The pin-prick garnets plot near the rims of the porphyroblastic ones of the same sample reflecting Fe enrichment and Mn and/or Ca depletion, depending on the porphyroblastic garnet composition. This composition suggests that pin-prick garnet grew later than the porphyroblasts.

The porphyroblastic garnets of the micaschist SR 123 are strongly zoned with distinctive bell-shaped Mn profiles (Fig. 4a) typical of a prograde growth under greenschist- to amphibolite-facies conditions. They show core-rim spessartine content varying from 30% to 1.5%; the almandine content ranges from 58% (core) to 87% (rim). The pyrope (6-9%) and grossular (6-2%) components are both low, with almost flat profiles. In the micaschist SR125 the porphyroblastic garnet is moderately zoned and exhibits irregular profiles for all the end members (Fig. 4c). It shows a flatter Fe profile (almandine from 66 to 81%), lower spessartine (0.2-9%) and pyrope (3-8%) contents and higher grossular content (22% core, 12% rim) than SR 123.

The analyzed "pin-prick" garnets (Table 2) are Mn-poor in the micaschists (Sps of 4-8% in the sample SR123 and < 1 in the sample SR125) and Mn-rich in the fine-grained phyllite SR 132 (Sps ranging from 17 to 36%). The Alm content is of 75-83% in the micaschists and 50-62% in the phyllites with a pyrope value of 3-9% both in the micaschists and phyllites; the grossular component is variable from 3-6% in the micaschist SR123 to 10-12% in the phyllite SR132 with a maximum of 13-19% in the micaschist SR125. The analyzed pin-prick grains show flat zoning profiles (Figs. 4b and d).

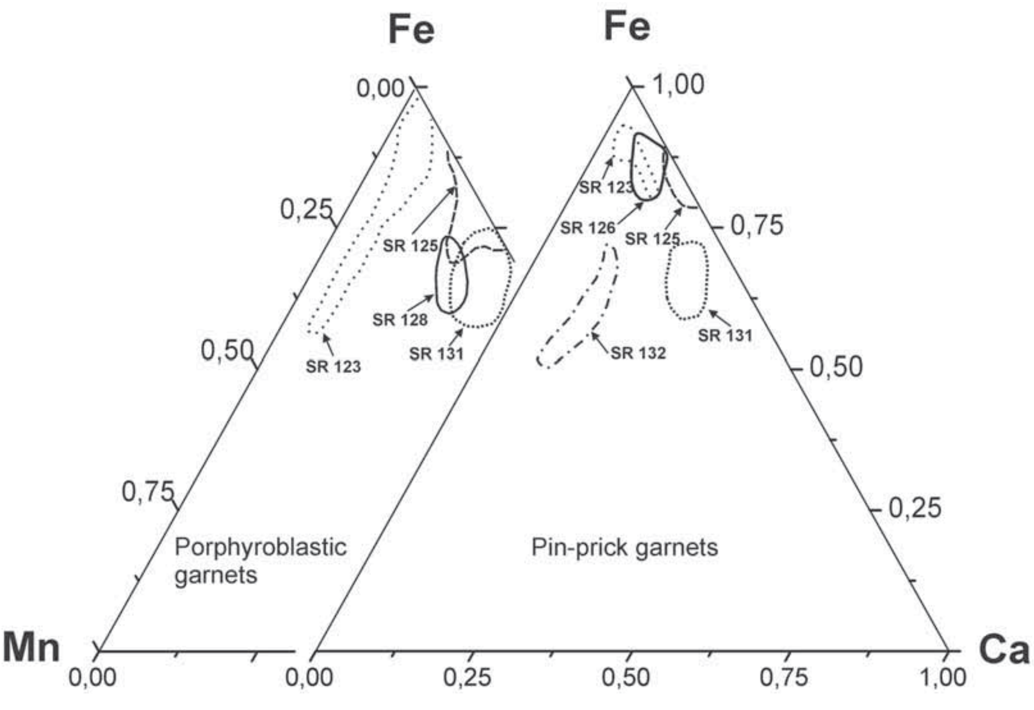


Fig. 3 – Fe-Mn-Ca diagram showing the compositional variations of porphyroblastic and pin-prick garnets in the analyzed Cardeto metapelites.

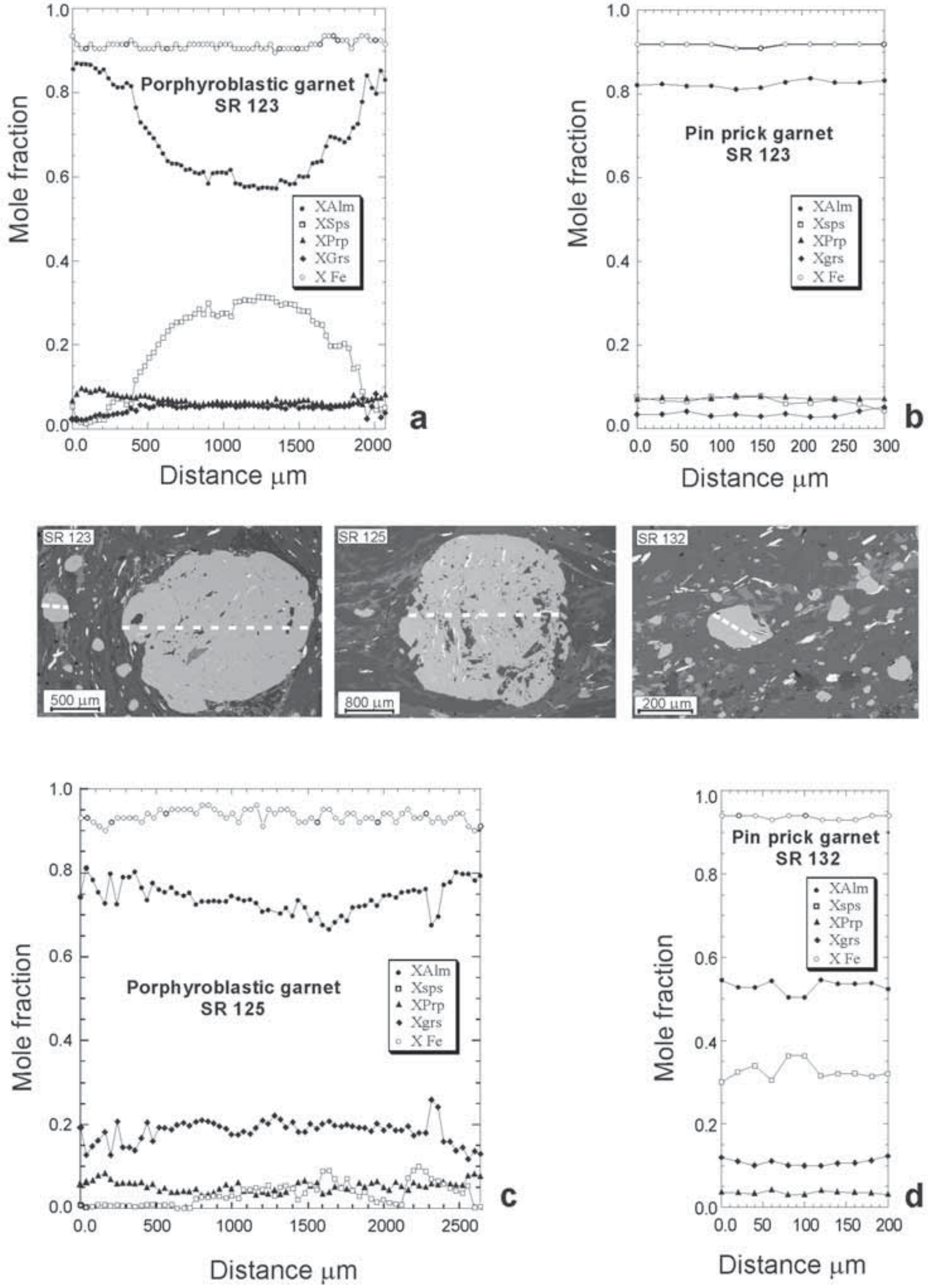


Fig. 4 – Compositional profiles of the Cardeto analyzed garnets. a and b = pin-prick and porphyroblastic crystals, respectively, after micaschist SR 123. The analyzed garnets are shown in the BSE image 1). c = porphyroblastic garnet after micaschist SR 125, shown in the BSE image 2). d = pin-prick garnet after fine-grained phyllite SR 132, shown in the BSE image 3. Each profile extends from rim to rim through the core of the garnet.

TABLE 2
Representative garnet analyses and structural formulae

	Porphyroblastic			Pin prick		Porphyroblastic			Pin prick	
Sample	SR123	SR123	SR123	SR123	SR123	SR125	SR125	SR125	SR125	SR125
Zone	Rim	Int.	Core	Core	Rim	Rim	Int.	Core	Core	Rim
Analysis	104	105	106	296	303	319	322	368	413	419
SiO_2	36.90	37.20	36.79	36.29	36.49	36.88	35.98	36.94	37.04	37.07
Al_2O_3	20.58	20.39	20.75	20.98	20.68	22.15	22.26	21.26	21.00	21.26
FeO	39.06	32.93	26.20	35.90	36.59	34.85	32.01	29.65	35.47	33.92
MnO	0.69	6.60	13.44	3.32	1.87	0.15	0.36	3.95	0.05	0.21
MgO	2.37	1.71	1.55	1.97	1.81	1.65	2.05	0.95	1.66	1.19
CaO	0.79	2.13	1.87	1.16	1.79	5.12	6.23	7.19	4.51	6.63
Σ	100.39	100.96	100.60	99.64	99.28	100.80	99.00	99.94	99.73	100.28
					O = 12					
Si	2.990	3.000	2.981	2.968	2.991	2.975	2.915	2.981	2.999	2.982
Al^{IV}	0.010	0.000	0.019	0.032	0.009	0.025	0.085	0.019	0.001	0.018
Σ	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Fe^{3+}	0.044	0.062	0.038	0.011	0.012	0.043	0.000	0.000	0.000	0.002
Al^{VI}	1.956	1.938	1.962	1.989	1.988	1.953	2.040	2.002	2.003	1.998
Σ	2.000	2.000	2.000	2.000	2.000	1.996	2.040	2.002	2.003	2.000
Fe^{2+}	2.603	2.159	1.738	2.445	2.496	2.291	2.169	2.001	2.402	2.280
Mn	0.047	0.451	0.922	0.230	0.130	0.231	0.025	0.270	0.003	0.014
Mg	0.286	0.206	0.187	0.240	0.221	0.311	0.248	0.114	0.200	0.143
Ca	0.069	0.184	0.162	0.102	0.157	0.177	0.541	0.622	0.391	0.571
Σ	3.005	3.000	3.010	3.016	3.005	3.010	2.982	3.006	2.997	3.009
Alm	86.8	72.5	58.3	81.1	83.2	78.33	72.7	66.6	80.1	75.8
Sps	1.6	14.7	30.3	7.6	4.3	0.34	0.8	9.0	0.1	0.5
Prp	9.4	6.7	6.1	8.0	7.3	6.6	8.3	3.8	6.7	4.8
Grs	2.3	6.0	5.3	3.4	5.2	14.73	18.1	20.7	13.1	19.0
X Fe	0.90	0.92	0.90	0.91	0.92	0.92	0.90	0.95	0.92	0.94

Fe_2O_3 calculated according to the method of Droop (1987).

TABLE 2
(Continue).

	Porphyroblastic				Pin prick			Pin prick	
Sample	SR126	SR126	SR131	SR131	SR132	SR132	SR132	SR132	SR132
Zone	Rim	Core	Rim	Core	Rim	Core	Int	Rim	Core
Analysis	389	396	43	48	520	523	525	540	543
SiO_2	36.61	36.37	37.03	36.93	36.74	36.71	36.57	36.96	37.47
Al_2O_3	20.46	20.24	21.22	20.64	20.75	21.21	20.82	22.19	21.41
FeO	34.81	36.11	30.00	23.22	23.26	21.84	23.79	25.19	27.96
MnO	1.39	1.72	1.98	7.24	14.14	15.53	13.52	11.51	8.62
MgO	1.70	2.04	1.57	1.00	0.90	0.75	1.01	1.10	1.50
CaO	4.06	2.15	8.37	10.06	3.76	3.40	3.35	4.33	4.23
Σ	99.02	98.62	100.17	99.09	99.55	99.44	99.06	101.28	101.19
					O = 12				
Si	2.993	2.994	2.966	2.985	2.999	2.995	2.998	2.952	2.993
Al^{IV}	0.007	0.006	0.034	0.015	0.001	0.005	0.002	0.048	0.007
Σ	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Fe^{3+}	0.035	0.043	0.032	0.049	0.004	0.000	0.000	0.000	0.000
Al^{VI}	1.964	1.957	1.968	1.951	1.996	2.034	2.009	2.041	2.008
Σ	2.000	2.000	2.000	2.000	2.000	2.034	2.009	2.041	2.008
Fe^{2+}	2.344	2.443	1.977	1.521	1.584	1.490	1.631	1.683	1.868
Mn	0.096	0.120	0.135	0.495	0.978	1.073	0.939	0.779	0.583
Mg	0.207	0.250	0.187	0.120	0.110	0.091	0.123	0.131	0.179
Ca	0.356	0.190	0.718	0.871	0.329	0.297	0.294	0.371	0.362
Σ	3.004	3.003	3.017	3.007	3.000	2.951	2.987	2.963	2.991
Alm	78.3	81.6	65.9	51.4	52.9	50.5	54.6	56.8	62.4
Sps	3.2	3.9	4.4	16.2	32.5	36.4	31.4	26.3	19.5
Prp	6.8	8.2	6.1	3.9	3.6	3.1	4.1	4.4	6.0
Grs	11.7	6.2	23.5	28.5	10.9	10.1	9.8	12.5	12.1
X Fe	0.92	0.92	0.91	0.98	0.94	0.94	0.93	0.93	0.92

Fe_2O_3 calculated according to the method of Droop (1987).

The variable Ca and Mn contents in garnet of the different samples depend on the whole rock composition (see Table 1).

White mica

The white micas are muscovites with variable phengite content (Table 3). In the Si vs. Mg+Fe diagram (Fig. 5) the data points plot along the line of the phengite substitution with Si values ranging from 3.1 to 3.3, except for a few analyses from the phyllite SR 132 which show a lower Si content (around 3.05). The Fe+Mg content, from ca 0.3 (sample SR132) to 0.40 (sample SR131) suggests a high celadonitic substitution. The scattered phengite content could be related to partial re-equilibration of detrital or previously metamorphic white mica flakes. The RM against Na/(Na+K) diagram (Guidotti and Sassi, 1976; Fig. 6) indicates that white micas compositions are consistent with a medium pressure regime.

Chlorite

All the analyzed chlorites are chamosite according to the Bailey (1980) classification. They exhibit XMg content in the range of 0.45-0.49, with Al^{IV}/Al^{VI} values of 0.85-0.97 (Table 3) and high Mg/Fe ratio (0.77-0.95).

In the Al^{IV}-2 versus Al^{VI}+2Ti-2 (Fig. 7), the analyzed samples plot above the 1:1 tie line of the

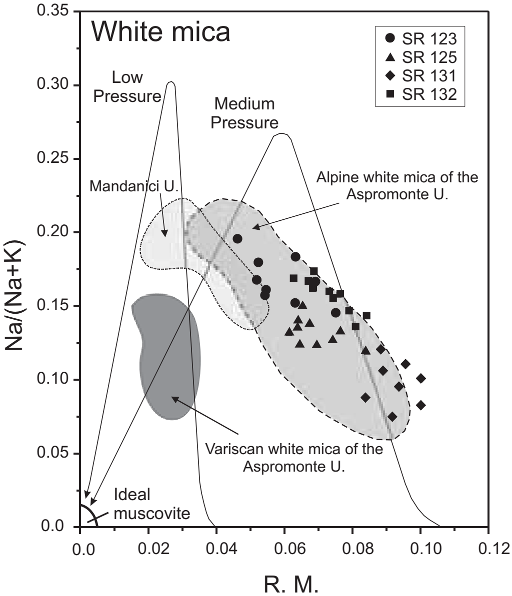


Fig. 6 – R.M. (Mol. Prop. FeO + Mol. Prop. MgO) vs. Na/(Na+K) diagram (Guidotti and Sassi, 1976) showing the compositional variation of Cardeto white mica at increasing temperature (along the arrows) at low and medium pressure conditions. For comparison, the areas of the Mandanici Unit metapelites (Russo *et al.*, 2002c) and of the Variscan and Alpine micaschists of the Aspromonte Unit (Messina *et al.*, 1992) are reported.

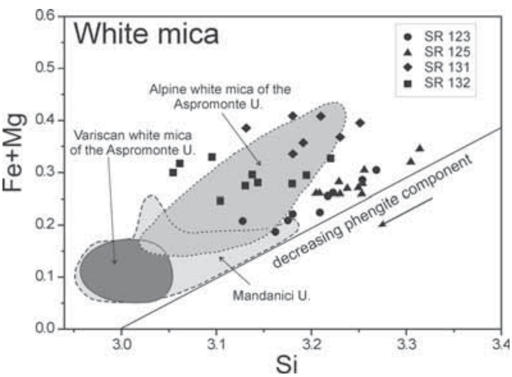


Fig. 5 – Si vs. Fe+Mg diagram for white micas of the Cardeto analyzed samples. The line of phengitic substitution is indicated. For comparison, the areas of the Mandanici Unit metapelites (Russo *et al.*, 2002c) and of the Variscan and Alpine micaschists of the Aspromonte Unit (Messina *et al.*, 1992) are reported.

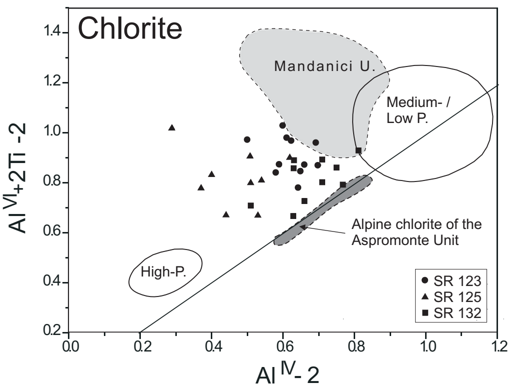


Fig. 7 – Al^{IV}-2 versus Al^{VI}+2Ti-2 diagram for Cardeto analyzed chlorite. The 1:1 line of the Tschermak substitution is indicated. The fields of different pressure regimes after Laird (1988) are reported. For comparison, the areas of the Mandanici Unit metapelites (Russo *et al.*, 2002c) and of the Alpine micaschists of the Aspromonte Unit (Messina *et al.*, 1992) are also drawn.

TABLE 3

Representative White Mica and Chlorite analyses and structural formulae.

Sample	SR123	SR123	SR131	SR131	SR132	SR132	SR132
Analysis	155	158	36	140	122	125	122
SiO_2	47.94	48.35	47.97	45.09	48.25	46.34	48.25
Al_2O_3	32.12	31.05	30.85	30.55	32.60	34.26	32.60
TiO_2	0.31	0.31	0.35	0.55	0.27	0.23	0.27
FeO	2.17	2.35	2.96	4.63	3.63	3.76	3.63
MnO	0.00	0.00	0.01	0.05	0.00	0.02	0.00
MgO	1.33	1.70	2.04	3.02	0.95	0.96	0.95
CaO	0.00	0.00	0.00	0.02	0.00	0.00	0.00
Na_2O	1.13	1.04	0.55	0.46	1.16	1.19	1.16
K_2O	9.62	9.32	9.98	10.36	9.50	9.73	9.50
Σ	94.62	94.12	94.71	94.73	96.36	96.49	96.36
				O = 11			
Si	3.218	3.268	3.230	3.030	3.196	3.054	3.196
Al^{IV}	0.782	0.732	0.770	0.970	0.804	0.946	0.804
Σ	4.000	4.000	4.000	4.000	4.000	4.000	4.000
Al^{VI}	1.759	1.741	1.680	1.460	1.740	1.716	1.740
Ti	0.016	0.016	0.020	0.030	0.013	0.011	0.013
Fe^{2+}	0.122	0.133	0.170	0.260	0.201	0.207	0.201
Mn	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Mg	0.133	0.171	0.200	0.300	0.094	0.094	0.094
Σ	2.029	2.060	2.070	2.050	2.048	2.029	2.048
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.147	0.136	0.070	0.060	0.149	0.153	0.149
K	0.823	0.803	0.860	0.890	0.802	0.818	0.802
Σ	0.971	0.940	0.930	0.950	0.952	0.971	0.952

Sample	SR125	SR125	SR132	SR132	SR123	SR123
Analysis	97	98	135	140	164	166
SiO_2	25.33	24.92	23.52	24.06	25.00	25.22
Al_2O_3	21.29	21.73	22.03	21.58	21.23	21.42
TiO_2	0.08	0.08	0.05	0.05	0.07	0.06
FeO	25.74	25.68	24.93	25.47	27.83	27.20
MnO	0.02	0.06	0.71	0.75	0.12	0.11
MgO	13.62	13.73	13.14	13.01	12.53	12.33
CaO	0.03	0.04	0.02	0.05	0.04	0.05
Σ	86.11	86.24	84.40	84.97	86.82	86.39
			O = 28			
Si	5.490	5.380	5.190	5.290	5.420	5.500
Al^{IV}	2.510	2.620	2.810	2.710	2.580	2.500
Al^{VI}	2.880	2.880	2.910	2.870	2.820	2.950
Ti	0.010	0.010	0.010	0.010	0.010	0.010
Cr	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	4.660	4.640	4.600	4.680	5.050	4.950
Mn	0.000	0.010	0.130	0.140	0.020	0.020
Mg	4.400	4.420	4.330	4.270	4.050	4.010
Ca	0.010	0.010	0.000	0.010	0.010	0.010
Σ	11.960	11.970	11.980	11.980	11.960	11.950
Al^{IV}/Al^{VI}	0.87	0.91	0.97	0.94	0.91	0.85
X Mg	0.49	0.49	0.48	0.48	0.45	0.45

Tschermak substitution, suggesting a significant AM (dioctahedral) substitution and vacancies in the octahedral sites, related, as suggested by Laird (1988), to the pressure. In the same diagram, they plot in an intermediate position between the medium-low and high pressure fields indicated by Laird (1988).

Other minerals

Amphibole. It is a calcic amphibole (Leake *et al*., 1997) and shows a prevalent Mg-hornblende-tschermakite composition (Table 4). Its presence in the sample SR 131 can be related to the high Ca content in the rock (see Table 1).

Chloritoid has been found only as rare inclusion in the porphyroblastic garnet of the micaschist SR123. All the analyzed crystals show a Fe-rich composition with a high Al content (Table 5).

All the analyzed *plagioclase* grains show an albitic composition with An content ranging from 1.9 to 4.1 (Table 5).

Epidote, from sample SR 131, has also been analyzed. All the analyzed crystals are clinozoisite (Table 5).

P-T CONDITIONS

The mineral assemblage quartz + white mica + chlorite + garnet ± albite (+ ilmenite + tourmaline ± epidote ± amphibole as accessory phases) has been observed in all the Cardeto metapelitic types. The MnNCKFMASH is the most adequate system to infer the stability field of the studied rocks owing to the significant spessartine and grossular contents in garnet. Metapelite phase equilibria have been modelled in the MnNCKFMASH system by Tinkham *et al*. (2001), using an average of eight biotite-zone metapelites of a Barrovian sequence (Table 1), to calculate the P-T pseudosection in the range of 425-700°C and 1-10 kbar (Fig. 8). Such a system can be applied to the studied metapelites, owing to their chemical similarity with the rocks used by Tinkham *et al*. (2001); the results, however, have to be used with caution because of the scattered bulk chemistry of the Cardeto rocks. As shown by Tinkham *et al*. (2001; their Fig 4b), the addition of Mn and Ca to the KFMASH system enlarges significantly the garnet stability field in

TABLE 4
Representative Amphibole analyses and structural formulae.

Sample	SR 131	SR 131	SR 131	SR 131
Analysis	88	71	82	85
SiO_2	45.70	44.00	43.19	42.51
TiO_2	0.37	0.36	0.38	0.35
Al_2O_3	14.33	13.75	13.81	14.35
Cr_2O_3	0.00	0.00	0.00	0.00
FeO	15.83	15.92	15.62	16.05
MnO	0.09	0.09	0.06	0.11
MgO	8.47	9.29	9.10	8.66
CaO	9.50	9.60	9.92	8.97
Na_2O	2.49	2.23	2.65	2.49
K_2O	0.36	0.41	0.39	0.47
Σ	97.14	95.66	95.11	93.95
		O = 23		
Fe_2O_3	1.41	3.16	1.89	3.54
FeO	14.56	13.08	13.92	12.87
New Σ	97.29	95.98	95.29	94.30
Si	6.713	6.572	6.528	6.475
Al^{IV}	1.287	1.428	1.472	1.525
Σ	8.000	8.000	8.000	8.000
Al^{VI}	1.194	0.993	0.987	1.052
Ti	0.041	0.041	0.043	0.040
Fe^{3+}	0.156	0.355	0.215	0.405
Mg	1.854	2.068	2.050	1.967
Fe^{2+}	1.755	1.544	1.706	1.536
Σ	5.000	5.000	5.000	5.000
Ca	1.495	1.536	1.606	1.464
Na	0.249	0.285	0.443	0.317
K	0.067	0.077	0.074	0.090
Σ	1.811	1.898	2.123	1.871

Fe_2O_3 calculated according to the method of Droop (1987).

TABLE 5
Representative chloritoid. plagioclase and epidote analyses and structural formulae.

Chloritoid		
Sample	SR123	SR123
Analysis	430	431
SiO_2	23.64	23.56
Al_2O_3	38.11	38.00
TiO_2	0.03	0.09
FeO	24.34	24.16
MnO	0.83	0.81
MgO	2.34	2.26
CaO	0.12	0.01
Na_2O	0.12	0.20
Σ	89.53	89.10
	O = 12	
Si	2.370	2.370
Al^{IV}	3.000	3.000
Al^{VI}	1.510	1.510
Ti	0.000	0.010
Fe^{2+}	2.040	2.040
Mn	0.070	0.070
Mg	0.350	0.340
Ca	0.010	0.000
Na	0.020	0.040
Σ	9.370	9.380
XFe	0.83	0.83
XMg	0.14	0.14
XMn	0.03	0.03

Plagioclase			
Sample	SR131	SR131	SR132
Analysis	65	67	550
SiO_2	68.24	67.87	69.38
TiO_2	0.01	0.02	0.00
Al_2O_3	19.31	20.10	19.90
FeO	0.06	0.05	0.06
CaO	0.45	0.66	0.90
Na_2O	12.75	12.56	11.50
K_2O	0.06	0.09	0.05
Σ	100.87	101.34	101.79
		O = 8	
Si	2.974	2.946	2.982
Al	0.992	1.028	1.008
Fe^{2+}	0.002	0.002	0.002
Ti	0.000	0.001	0.000
Ca	0.021	0.031	0.041
Na	1.077	1.057	0.958
K	0.004	0.005	0.003
An %	1.9	2.8	4.1
Ab %	97.8	96.7	95.6
Or %	0.3	0.5	0.3

Epidote		
Sample	SR131	SR131
Analysis	76	81
SiO_2	38.17	37.32
TiO_2	0.19	0.12
Al_2O_3	28.23	28.27
FeO	5.97	5.66
MnO	0.08	0.01
MgO	0.03	0.04
CaO	20.47	21.54
Σ	93.14	92.95
	O = 25	
Si	6.214	6.112
Ti	0.024	0.015
Al	5.416	5.456
Fe^{3+}	0.812	0.775
Mn	0.012	0.001
Mg	0.007	0.009
Ca	3.570	3.780
Σ	16.055	16.146

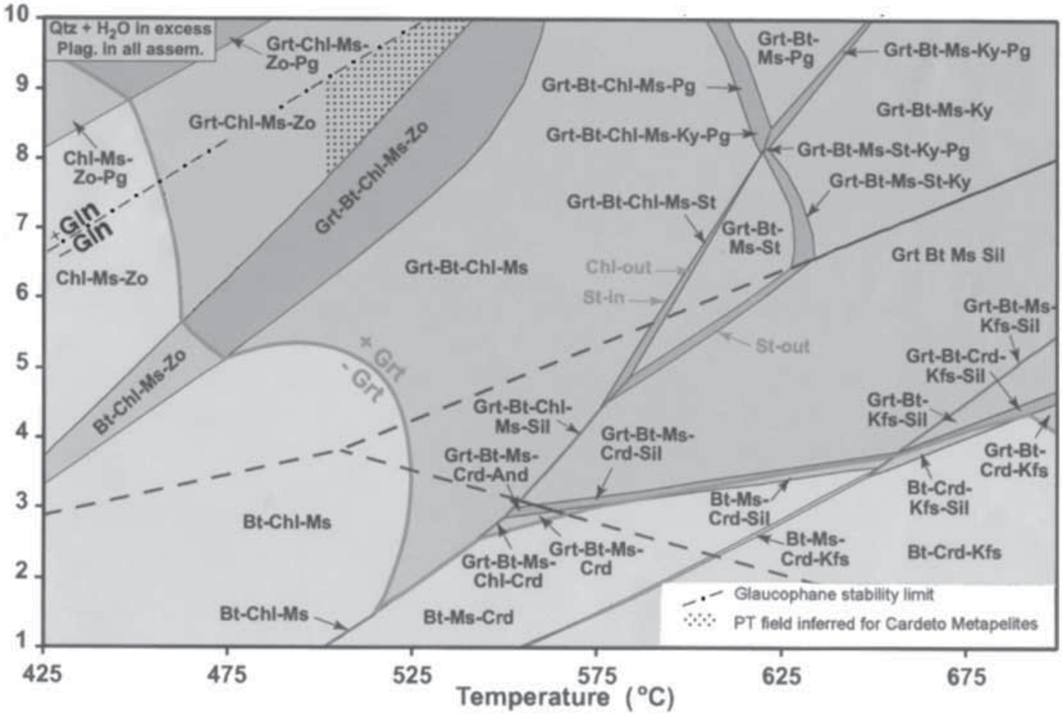


Fig. 8 – P-T pseudosection modelled for the Waterville AWBZ composition in the MnNCKFMASH system (after Tinkham *et al*., 2001). The stability limit of glaucophane after Maresch (1977) is also reported. The dotted area represents the P-T field inferred for the Cardeto metapelites.

the MnNCKFMASH system. The biotite stability field is very wide in the above P-T pseudosection, where the biotite-in isograd predicts 420°C at 3.5 kbar. Tinkham *et al*. (2001) have calculated the effects of increasing Al_2O_3 in the rock (their Fig. 9), suggesting that the biotite-in line shifts to lower pressures and higher temperatures with increasing alumina, reducing the biotite stability field; the paragonite stability field, on the contrary, increases towards lower pressures; the zoisite stability is not substantially influenced. The Al_2O_3 content of the Cardeto metapelites shows a wide range of compositions from 35.24 to 52.03 on SiO_2-free molecular proportions (Table 1), but the biotite-free chlorite+garnet assemblage is widespread in all the studied samples (except for the more basic SR131 sample), suggesting that such a paragenesis is independent of the Al_2O_3 content in the rock. Also the absence of paragonite in all the analyzed rocks supports this hypothesis. From Fig. 8 it appears that the biotite-free chlorite+garnet+zoisite field is predicted at P higher than 5.5 kbar in the T range of 450-540°C. Relatively high pressures are also suggested for the Cardeto metapelites, by the phengitic content of white mica and by the chlorite chemistry (Figs. 5 to 7).

As is well known, in the Barrovian medium-pressure sequence of greenschist facies, chlorite, biotite and almandine garnet progressively crystallize with increasing temperature. In the Cardeto metapelites, the widespread biotite-free chlorite+almandine assemblage indicates a crystallisation of almandine garnet prior than biotite. Such a condition has been observed in the middle part of the Sanbagawa metamorphic belt (Higashino, 1990; Inui and Toriumi, 2002 with ref.) and is interpreted by Miyashiro (1994) as the relatively low-pressure part of the blueschist facies. Four metamorphic zones have been defined in the Sanbagawa metamorphic belt (Inui and

Toriumi, 2002) on the basis of the distribution of critical mineral assemblage: chlorite, garnet, albite-biotite and oligoclase-biotite zones at increasing metamorphic grade. Estimated peak metamorphic conditions are 520 ± 25°C at 8-9.5 kbar, and 610 ± 25 at around 9-11 kbar for the albite-biotite zone and the oligoclase-biotite zone, respectively (Enami, 1983; Enami *et al*., 1994). According to Miyashiro (1994), the metapelites of this belt are similar in mineral assemblages to those in the chlorite and biotite zones of the Barrovian greenschist facies metamorphism, except for highly Mn-rich garnet formed at temperature lower than that of the biotite isograd. In the Cardeto metapelites, however, garnet with variable Mn contents (see Table 2) crystallized with chlorite, earlier than biotite. The appearance of garnet prior to biotite is consequently related to pressures higher than those of the Barrovian sequence, as deduced by comparison with the P-T pseudosection modelled by Tinkham *et al*. (2001), rather than to the Mn content in the garnet. Also Spear (1993) suggests that the occurrence of garnet at lower metamorphic grade than biotite is a common feature of high-pressure metamorphic sequences.

In the AFM projection (Thompson, 1957) the garnet + chlorite paragenesis forms a two phase field, but the occurrence of chloritoid in the internal foliation of garnet in the sample SR123 suggests that it is a relict of the early-stage prograde divariant AFM assemblage garnet-chloritoid-chlorite which is stable at about 510°C and which suggests the formation of almandine garnet by chlorite-chloritoid decomposition according to the reaction: Chl + Cld + 2Qtz = 2Alm + $5H_2O$ (Bucher and Frey, 1994). The chlorite-garnet geothermometer of Dickenson and Hewitt (1986), Ghent *et al*. (1987) and Grambling (1990), calculated for the Cardeto rocks using the Reche and Martinez (1996) software, gives temperatures ranging from 500°C to 550°C. Such temperatures constrain the pressures inferred for the Cardeto metapelites above 7.5 kbar and below, however, to the ones predicted by the stability limit of glaucophane (Fig. 8), which is lacking.

Pressures of 7.5-10 kbar in the T range of 500-550°C, inferred for the peak metamorphic conditions of the Cardeto garnet zone metapelites, suggest a metamorphism under pressures higher than those of the Barrovian metamorphism and lower than those of the blueschist facies.

COMPARISON WITH THE NEARBY ALPINE UNITS (MANDANICI AND ASPROMONTE UNITS)

The metapelitic rocks of Cardeto have been interpreted as belonging to the Mandanici Unit (Bonardi *et al*., 1980b) or as forming a distinct unit (Messina *et al*., 1993) affected by a weak Alpine overprint which generates new parageneses similar to the Variscan ones. Alternatively (Russo et al., 2002a, 2002b), they could represent the Calabrian part of the Mandanici Unit that has been affected, here, by Alpine overprint.

To verify the above hypotheses and to characterize the type of metamorphism, a comparison with the Mandanici Unit metapelites and with the Alpine overprinted rocks of the overlying Aspromonte Unit has been carried out.

It appears that:

1) In the Mandanici Unit the analyzed garnets are similar to those occurring in the Cardeto metapelites, whereas the muscovites exhibit a lower phengitic substitution (Fig. 5) and a lower RM value (Fig. 6), suggesting a crystallisation under lower pressure conditions (Guidotti and Sassi, 1976); chlorites of the Mandanici Unit and Cardeto phyllites also plot in different pressure fields in the Al^{IV}-2 versus Al^{VI}+2Ti-2 diagram (Fig 7), indicating, again, higher pressure conditions for the Cardeto metapelites; the pin-prick garnet, widespread in the Cardeto phyllites and micaschists, is absent in the Mandanici Unit; the chloritoid, largely present as porphyroblast in the Mandanici Unit, has been found only in one sample of the Cardeto micaschists, as rare inclusion in the porphyroblastic garnet; the biotite, widespread in the Mandanici metapelites, has been observed only in one, more basic, sample of the Cardeto rocks.

2) The growth of medium-pressure minerals such as garnet and phengitic white mica, the presence of abundant porphyroblastic and small garnets, the similar phengitic white micas (Figs. 5 and 6) characterize the Cardeto metapelites and the Aspromonte metapelites reworked by Alpine metamorphism, but biotite and oligoclase are widespread in the overprinted rocks of the

Aspromonte Unit, whereas they lack in the Cardeto rocks; chlorite, very abundant in the Cardeto metapelites, is present only as an accessory phase replacing biotite, in a few samples of the Aspromonte reworked rocks.

DISCUSSION AND CONCLUSIONS

The Cardeto metapelites seem to have experienced a relatively-high pressure greenschist-facies metamorphism as suggested by garnet pre-dating biotite, phengitic muscovite and chlorite chemistry. This is also supported by comparison with the PT pseudosection modelled by Tinkham *et al*. (2001) in the system MnNCKFMASH for metapelites chemically similar to those of the present study (Fig. 8). Taking into account the absence of glaucophane in the associated metabasic rocks and the T range of 500-550°C, deduced by the presence of chloritoid as inclusion in the garnet and by the chlorite-garnet geothermometer, a pressure of 7.5-10 kbar has be inferred.

The crystallization sequence is typical of a P/T ratio intermediate between the blueschist facies and the Barrovian metamorphism of the greenschist facies as happens in the Sanbagawa metamorphic region of Japan.

High pressure values have never been observed in the Variscan metamorphism, which is, on the contrary, characterized by a medium-low P/T ratio. All the Alpine units of the Southern Sector of the Calabrian Arc show Variscan metamorphic basements, characterized by medium- (Barrovian) to low-P metamorphism. Only the Aspromonte Unit shows an Alpine overprint, which is characterized by a higher P/T ratio than the Variscan metamorphism. We strongly support that also the Cardeto metapelites were affected by an Alpine metamorphic event. Only radiometric data can confirm the age of the metamorphism, nevertheless, the Cardeto Alpine (?) metamorphism is characterized by different features relatively to the one affecting the Aspromonte Unit, due to the presence of abundant chlorite and to the absence of kyanite, oligoclase and biotite, in the former.

Owing to the similar structural position, the Cardeto rocks could represent a part of the Mandanici Unit which in Calabria underwent Alpine overprinting, but no structural or mineralogical relicts have been observed which can support this interpretation. Alternatively and more probably, they represent a distinct unit, which have experienced a relatively-high pressure Alpine (?) metamorphism and that in the Peloritani Mountains was removed from within the tectonic pile during a syn-orogenic extension episode of the Alpine tectogenesis, as recognized by Cutrupia and Russo (2005a, 2005b).

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