

## Geochemical fractionation in migmatitic rocks from Serre granulitic terrane (Calabria, southern Italy)

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**ABSTRACT.** — The Hercynian crustal section in the Serre (southern Italy) is about 20 km thick and includes sub-greenschist to granulite facies metamorphic rocks which have been used to study chemical modifications during metamorphism and migmatization. The rocks studied include: (1) Stilo phyllites and Mammola paragneisses from the upper crustal metasediments; (2) migmatitic paragneisses from the lower crustal segment that contain evidence for multi-stage melting and different degrees of partial melting and extraction of melts. The upper crustal rocks and the uppermost migmatites retain the composition of common shales. Descending to the lower levels the migmatitic metapelites show modified bulk compositions relative to common shales. The degree of chemical modification increases towards the base of the investigated section. The bulk-migmatites and the melanosomes show an enrichment in MgO, FeO\*, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, MnO, Sc, Y, V, Cr and REE and a depletion in SiO<sub>2</sub>, K<sub>2</sub>O, Na<sub>2</sub>O, CaO, Rb, P, U. In the lowermost migmatitic metapelites enrichment of Th and Zr is also evident. Bulk migmatites have negative Eu anomaly which is larger in the residua. The migmatites reflect: i) diverse protolith bulk compositions, ii) the effects of hydrous melting and mica dehydration melting producing both melts crystallizing *in situ* and melts which were extracted,

iii) a different degree of melting and of separation melt-restite, iv) different effects of rehydration on cooling. The overall geochemical features suggest that the lower migmatites were derived from a source similar to the Stilo phyllites, and that the upper migmatites from protoliths similar to the uppermost unmodified Stefanacni paragneisses. With these assumptions the major element geochemical fractionation between restites, bulk migmatites and melts formed during the multi-stage partial melting has been modelled.

**RIASSUNTO.** — La sezione di crosta continentale Ercinica affiorante nelle Serre (Italia meridionale) ha uno spessore di circa 20 km ed è costituita da metamorfiti di grado variabile dalla facies scisti verdi fino alla facies granulitica. Allo scopo di valutare le modificazioni chimiche indotte dal metamorfismo e dalla migmatizzazione sono state studiate le filladi di Stilo e i paragneiss di Mammola di crosta superiore e i paragneiss migmatitici di crosta profonda, questi ultimi interessati da più episodi di fusione parziale con diversi gradi di fusione e di estrazione di fusi. Le rocce di crosta superiore e le migmatiti della parte più elevata della sezione di crosta profonda hanno composizione simile a quella di argille comuni, verso le porzioni basali invece il grado di modificazione chimica delle migmatiti aumenta. Le migmatiti e i melanosomi mostrano arricchimenti in MgO, FeO\*, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>,

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MnO, Sc, Y, V, Cr, REE e impoverimenti in K<sub>2</sub>O, Na<sub>2</sub>O, CaO, Rb, Sr, P, U. Nelle migmatiti metapelitiche più profonde si osservano anche arricchimenti di Th e Zr. Le migmatiti hanno anomalia negativa di Eu che diventa più profonda nelle rocce residuali. Le migmatiti studiate mostrano: a) composizione differente dei protoliti, b) effetti di fusione parziale prima in condizioni idrate ed poi anidre per partecipazione delle miche, con produzione di fusi che in parte cristallizzarono in situ e in parte furono estratti, c) gradi differenti di fusione e di separazione fuso-restite, d) effetti diversi di reidratazione durante il raffreddamento. I caratteri geochimici complessivi suggeriscono che le migmatiti della porzione più bassa della sezione di crosta profonda derivano da una sorgente simile a quella delle filladi di Stilo, mentre quelle della porzione superiore sembrano derivare da protoliti simili ai paragneiss di Stefanaceni, della parte più elevata della sezione, che non mostrano modificazioni composizionali. Viene discusso il modello di frazionamento geochimico degli elementi maggiori tra restite-migmatite-fuso durante i diversi processi di fusione parziale.

**KEY WORDS:** Calabria, upper-lower crust, partial melting, geochemical fractionation.

## INTRODUCTION

Many studies have been performed to evaluate geochemical fractionation during metamorphism and anatexis. Studies have been performed on local scale (e.g. Festa *et al.*, 2004 and references therein; Villaseca *et al.*, 1999; Bea and Montero, 1999; Schnetger, 1994) or as a worldwide scale (e.g. Lambert and Heier 1968; Brown and Fyfe, 1970; Taylor and McLennan, 1985; Rudnick and Presper, 1992). In most cases, upper amphibolite to granulite facies rocks have been investigated. Cross-sections through different levels of the continental crust may allow one to study the effects of metamorphic to ultrametamorphic processes on a variety of rocks at different crustal levels. A ~20 km thick crustal section is present in the Serre, southern Calabria (Italy) and extends from greenschist to granulite facies metamorphic rocks. The upper and the lower crustal segments were both affected by Hercynian metamorphism, but are now

separated by huge intrusions of Carboniferous to Permian calc-alkaline and peraluminous granitoids (Fig. 1).

Using samples from the different levels in the Serre section (Fig. 1) we have investigated the chemical modification that occurred in the metasediments ranging from anchimetamorphic to granulite-facies conditions, including the effects of anatexis and the extraction of the melts. In this study we include only the rock-types derived from Al-rich sedimentary precursors (shales) in order to reduce the number of rock-system considered.

## GEOLOGICAL SETTING AND PETROGRAPHY

The studied section of the Hercynian continental crust (Fig. 1) consists of middle-lower (7-8 km) and upper crustal metamorphic rocks (~3 km) sutured by late Hercynian calc-alkaline and peraluminous granitoids (~10 km). The upper crustal metamorphic rocks include greenschist facies metapelites, metalimestones, quartzites and metavolcanics (Stilo-Pazzano unit) and amphibolite-facies paragneisses (Mammola paragneiss unit). The two units became in tectonic contact before the intrusion of granitoids (Colonna *et al.*, 1973 in Festa *et al.*, 2004). The lower part of the crustal section is a complex granulite/migmatite terrane which consists of felsic and mafic granulites, large bodies of layered metagabbros and slices of meta-ultramafites overlain by migmatitic paragneisses with minor mafic granulites and augen gneisses. According to Fornelli *et al.* (2002) the migmatites provide evidence for sequential melting events implying: 1) first H<sub>2</sub>O-fluxed melting of Ms + Qtz + Pl (abbreviations according to Kretz, 1983) with a higher Ms/Pl ratio for the melting process occurring at higher temperature and lower pressure (Patiño Douce and Harris, 1998) producing sodic and potassic melts which crystallized *in situ* since they were removed rapidly and in small batches from their sources and, consequently, did not coalesce into large melt pockets permitting mobility over large

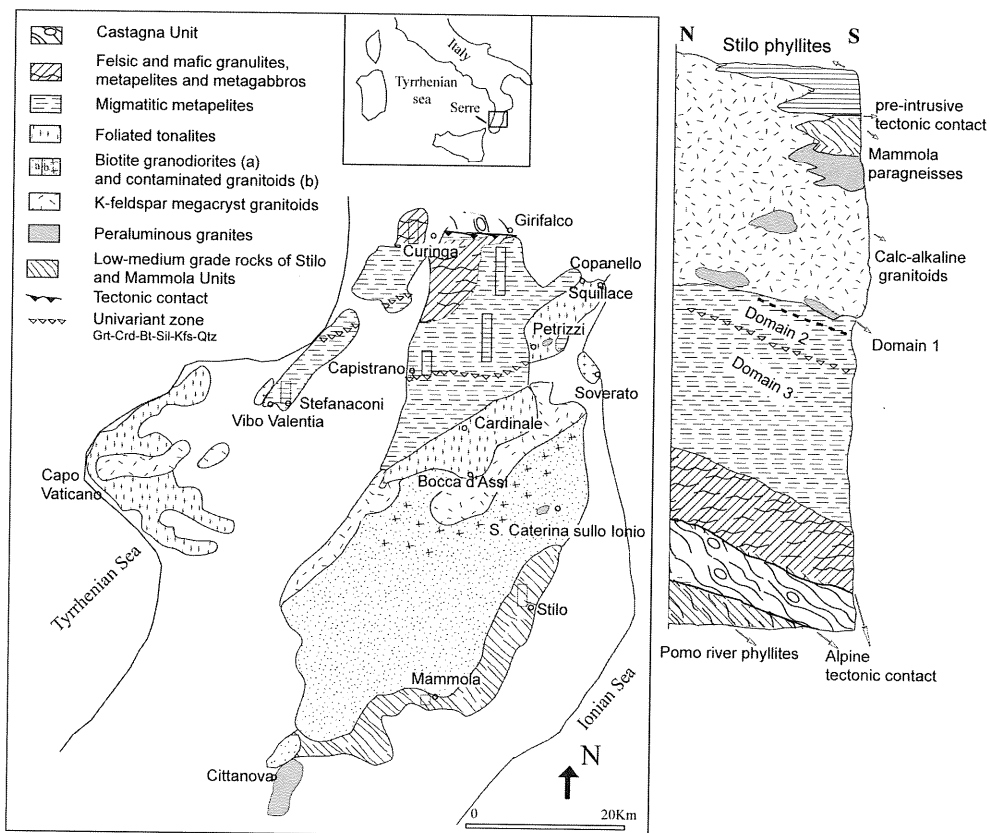


Fig. 1 – Location (inset), geological sketch map and schematic stratigraphic section of the studied area; rectangles indicate the sampled areas.

distances (e.g. Sawyer, 1994); and 2) dehydration melting of micas due to further increase of  $T$ , producing granitic melts, which migrated far from the source.

U/Pb (zircon and monazite) ages of about 300Ma are recorded in the lower crustal metasediments, granitoids and upper crustal rocks (e.g. Gräßner and Schenk, 1999 in Festa *et al.*, 2004). Metamorphic rocks derived from Al-rich sedimentary protoliths were sampled from the upper crustal units far from the contact with the granitoids. Migmatitic metapelites within the lower crustal segment, have been sampled at different structural levels here indicated from the top to the bottom as domains 1, 2 and 3 (Fig. 1). The upper crustal

samples include: fine grained phyllites and medium grained paragneisses. The samples of the lower crust from the top to the bottom include (Fig. 1): 1) strongly foliated migmatites of domain 1; 2) stromatic types containing millimeter – to decimeter – thick leucosomes amounting up to about 30-40 vol% in domain 2; 3) massive to foliated dark-coloured rocks alternating with millimeter or centimeter – thick leucosomes amounting to 10-20 vol% (Caggianelli *et al.*, 1991 in Festa *et al.*, 2004) of domain 3. The modal fraction of garnet tends to increase with the metamorphic grade downwards at the expense of Bt. The leucosomes in the migmatites are granitic to leucotonalitic in composition, the latter are

more abundant (Fornelli *et al.*, 2002). According to Fornelli *et al.* (2002) about 30 vol% and 45 vol% of granitic melts have been extracted from the bulk migmatites of domains 2 and 3, respectively, whereas the most residual melanosomes record 60 vol% loss from domain 2, and 70 vol% from domain 3. Dykes and small masses of peraluminous granites occur in the upper part of the lower crustal section along their contacts with tonalites and more voluminous peraluminous granites intrude (e.g. near Cittanova and S. Caterina sullo Ionio Fig. 1) or mix with the calc-alkaline granitoids far from the border zone.

#### SAMPLING AND METHODS

Major and trace element compositions were determined for: (1) phyllites and paragneisses from the upper crustal metasediments; (2) migmatitic paragneisses as well as their constituent leucosomes and melanosomes from high-grade terrane. The samples of domain 1 come from near Stefanacconi south of Crd-Grt isograd (Fig. 1) and their compositions have been taken from Caggianelli *et al.* (1991 in Festa *et al.* 2004); the samples of domain 2 come from areas around the Crd-Grt isograd and those of domain 3 from areas north of the above isograd (Fig. 1).

The rock samples were analysed at Actlabs Laboratory (Canada) and at Bari University. At Actlabs Laboratory the major and trace elements were determined by lithium metaborate/tetraborate fusion using Inductively Coupled Plasma (ICP) and ICP-MS; at Bari University the major and some trace elements were determined by XRF spectroscopy.

#### CHEMISTRY

*Major element compositions.* All the analyzed metasediments are mostly Al-rich having A/CNK ratio  $[Al_2O_3/(CaO+Na_2O+K_2O)$  molar] higher than 1.36; the lowest crustal level (domain 3) includes rocks with very high

A/CNK (up to 15.47) due to the abundance of Grt and Sil. The bulk migmatites and the melanosomes of domains 2 and 3 are rich in FeO\* and MgO but maintain Mg-number  $[MgO/(MgO+FeO^*)*100$  molar] close to that of common shales ranging from 26 to 53. The metasediments of domain 2, however, have higher Mg-number with respect to those of domain 3. The average of each rock-type and some individual analyses of residual rocks (Tables 1\*-2\*) have been considered in order to obtain more general information. For a more comprehensive overview the composition of a migmatitic mega-sample (Schenk, 1990 in Festa *et al.*, 2004), rock analyses given by Fornelli *et al.* (2002) and the averaged composition of the peraluminous Petrizzi granite (Caggianelli, 1988) were considered as the melt extracted during the dehydration melting of micas. The data relative to the metasediments together with those relative to Post Archean Australian shales (PAAS in Taylor and McLennan, 1985), have been projected in Figure 2 that indicates: i) the Stilo phyllites and Mammola paragneisses plot near the PAAS; ii) the bulk migmatites of the domain 3 look like modified compositions of protoliths similar to the Stilo phyllites; iii) the migmatites of domains 1 and 2 depict a pattern at higher MgO with the Stefanacconi migmatites as the least modified composition.

The *Stilo phyllites* and *Mammola paragneisses* of the upper crustal segment have major element compositions (Table 1\*) in the range of the shales. The *Stefanacconi migmatitic paragneisses* from domain 1, also have major element compositions that are within the range of the common shales. Table 1\* shows that they have higher contents of CaO, MgO and FeO than the upper crustal rocks. The overall chemical similarity with the common shales suggests they have undergone little or no melt extraction. Despite the likely differences of the precursors, the normalization to a common sedimentary model (PAAS) has been used as a first approach, in order to facilitate the

\* This item is available as electronic supplementary material on the Periodico di Mineralogia web site at <http://tetide.geo.uniroma.it/riviste/permin/perim.html>

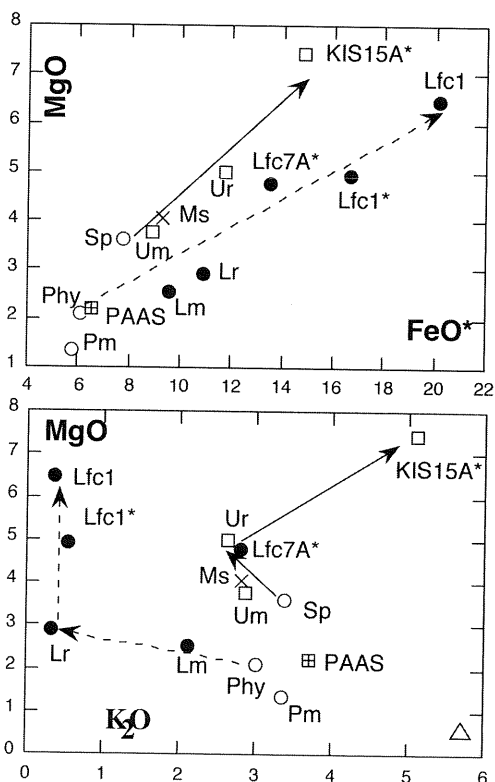


Fig. 2 – MgO-FeO\* and MgO-K<sub>2</sub>O plots for the studied rocks, PAAS and Petrizzi granite (triangle); Phy=Stilo phyllites; Pm=Mammola paragneisses; Sp=Stefanaconi migmatitic paragneisses of domain 1; Um= bulk-migmatites of domain 2; KIS15A\* and Ur = residual rocks of domain 2; Lm = bulk-migmatites of domain 3; Lfc1, Lfc1\*, Lfc7A\*, Lr = residual rocks of domain 3; Ms=migmatitic megasample. The arrows indicate the chemical variations relative to the composition of the possible protoliths of domain 2 and 3 rock-types.

comparison among the chemical compositions of the considered rock-groups.

**Bulk migmatites and melanosomes** of domains 2 and 3 show important chemical differences relative to the common shales (Fig. 3). *The bulk migmatite (Um) and the restite averages (Ur)* from domain 2 show parallel patterns even if at slightly different values (Fig. 3a). The most residual melanosome from this domain (the B-rich sample KIS15A\*) is more depleted in Na<sub>2</sub>O and CaO relative to Um and Ur. *The bulk-*

*migmatite average (Lm) of domain 3* (Fig. 3c) results more intensely depleted in Na<sub>2</sub>O, CaO and K<sub>2</sub>O than the bulk migmatites in domain 2. As a whole, the *melanosomes* of domain 3 are more depleted in alkalis than those of domain 2. The melanosome Lfc7A deviates from the other melanosomes of domain 3 being richer in CaO, Na<sub>2</sub>O and K<sub>2</sub>O. The leucotonalitic *leucosomes* are enriched in Na<sub>2</sub>O and CaO and depleted in K<sub>2</sub>O relative to the leucogranitic leucosomes (Figs. 3b-3d).

**Trace element abundances.** The *Stefanaconi migmatitic paragneisses* have a more mafic composition than *Stilo phyllites* and *Mammola paragneisses* being richer in Ni, Cr and Sr (Table 1\*). However, on the whole the three rock-groups show features which are common among the shales (Taylor & McLennan, 1985). The multielemental plots for trace elements are given in Fig. 4. *The averaged bulk-migmatite (Um) and the melanosomes Ur and KIS15A\** from domain 2 (Fig. 4a) have parallel patterns but with some minor differences. The bulk-migmatite Um and the averaged melanosome Ur are very similar but the most residual sample KIS15A\* has higher Rb, Ba, V, Cr, Ni but lower P and Sr. *The averaged bulk-migmatite (Lm) and the melanosomes (Lfc1, Lfc1\*, Lr, Lfc7A\*)* of domain 3 (Fig. 4c), show mostly parallel patterns but at different levels of abundance. The bulk migmatites have lower contents in Th and from Y to Cr relative to the melanosomes, but higher Sr except for the sample Lfc7A\*. On the whole the rock-types of domain 3 have decidedly lower Rb, Ba and Sr than those of domain 2. The *leucosomes* (Fig. 4b-4d) of domains 2 and 3 have trace-element patterns which show antithetic behaviour relatively to bulk-migmatites and melanosomes. Leucotonalitic leucosomes are depleted in most trace elements relative to the leucogranitic ones.

When the REE (rare earth elements) are normalized to chondrite, it appears that the Stilo phyllites, Mammola and Stefanaconi paragneisses (not reported) have similar shape REE patterns ( $La_N/Sm_N$  from 3.16 to 3.73,  $Gd_N/Yb_N$  from 1.56 to 1.66,  $Eu/Eu^*$  from 0.61 to 0.77), which resemble that of PAAS (Table

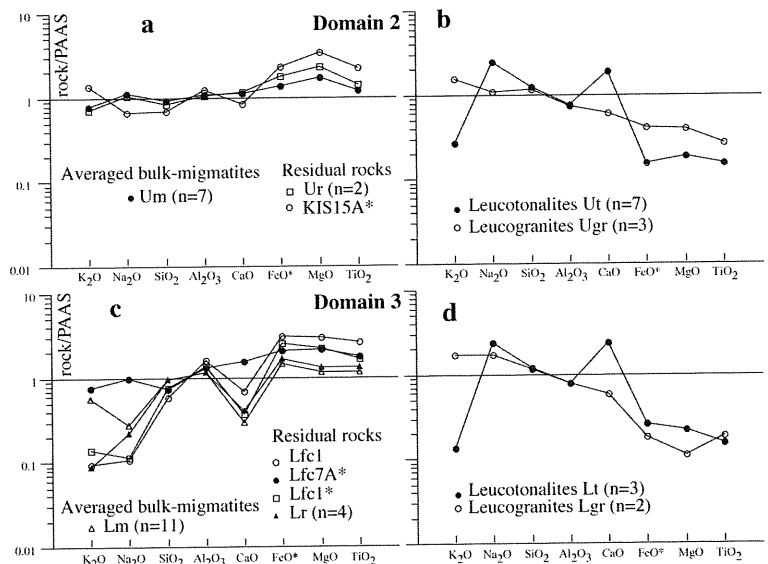


Fig. 3 – Major elements of bulk-migmatites, residual rocks, leucotonalites and leucogranites of domain 2 (a-b) and of domain 3 (c-d) normalized to PAAS.

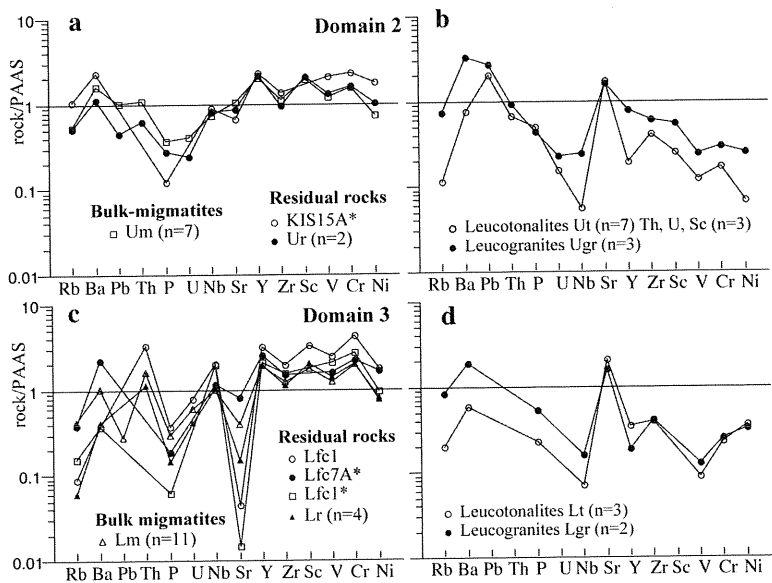


Fig. 4 – Multielemental plots relative to trace element distribution normalized to PAAS for rock-types of the domains 2 and 3.

1\*). The Mammola paragneisses have the highest REE but lowest Eu/Eu\* ratio. The bulk-migmatite (*Um*) and melanosomes (*KIS15A\**, *Ur*) of domain 2 (Fig. 5a) show similar REE patterns with  $La_N/Sm_N$  from 3.60 to 4.14 and flat HREE; their Eu anomalies are negative and greater within the melanosomes (Eu/Eu\* up to 0.53). The bulk-migmatite (*Lm*) and the melanosomes (*Lfc1*, *Lfc1\**, *Lfc7A\**, *Lr*) of domain 3 (Fig. 5c) show mostly parallel patterns, but different REE abundances. The averaged bulk-migmatite (*Lm*) is richer in LREE and poorer in HREE than the melanosomes, with the exception of the sample *Lfc1* (Grt + Sil + Rt melanosome), which is strongly enriched in LREE. The melanosome *Lfc7A\** has practically no Eu anomaly and shows similarities with the domain 2 rock types. All the rock-types have negative Eu anomalies (Eu/Eu\* up to 0.13). It is noteworthy that two melanosomes from the same outcrop (*Lfc1*, *Lfc1\**) have quite different LREE abundances, although both are composed essentially of Grt + Sil + Rt (Fig. 5c).

The leucosomes (Fig. 5b-5d) have much lower HREE contents than the bulk migmatites and melanosomes; moreover they have positive Eu anomalies. The leucotonalitic types have lower REE abundance than the leucogranitic ones in domain 2, whereas in domain 3 they have lower LREE but higher HREE than leucogranites. Good positive correlations exist between LREE and Th as well as between HREE and Zr among the studied rock-types (not reported). This is due to the concentration of monazite and zircon hosted in Grt and Bt of the residual rocks.

## DISCUSSION

*Geochemical fractionation during multi-stage melting.* The present study shows that the bulk-migmatites and the melanosomes of the lower part of the crustal section (domains 2 and 3) show variable depletion of the incompatible elements and enrichment of the compatible ones. The chemical variations could reflect: 1)

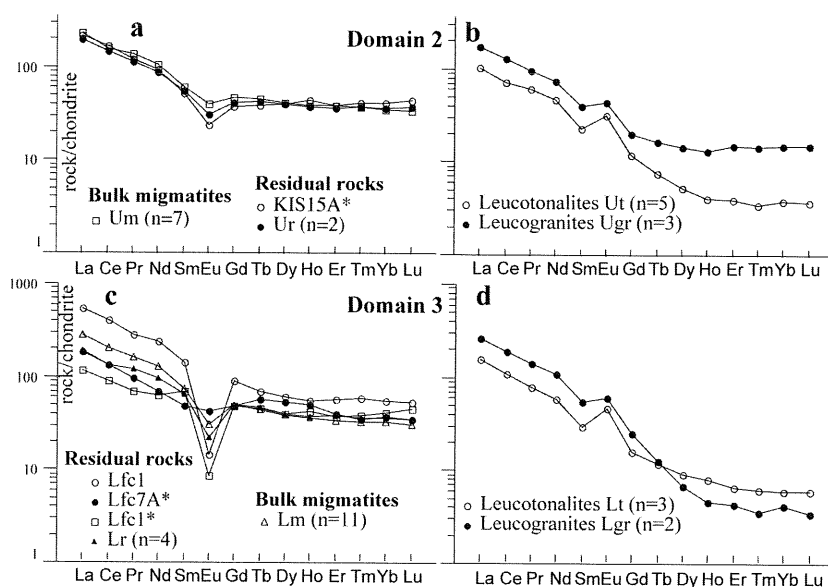


Fig. 5 – REE patterns normalized to chondrite (McDonough and Sun 1995) for the rock-types of domains 2 and 3.

the different phases involved in the melting reactions; 2) variable degree of partial melting, extraction of the melts, accumulation of solid residue of the partial melting, and peritectic phases left behind by segregating melts. Further variation could also result as retrograde phases formed during rehydration and cooling. The migmatites are the result from H<sub>2</sub>O-fluxed melting followed by the dehydration melting first of Ms and then of Bt. Biotite became progressively involved in melting from domain 2 to domain 3 until it was exhausted in the metapelites having low Mg-number (e.g. Lfc1 and Lfc1\* melanosomes) in the lowermost part of the section. The H<sub>2</sub>O-fluxed melts remained within the migmatites whereas the dehydration melts escaped from the source.

In the first stage of melting, the strong involvement of Qtz and Pl partitions Na<sub>2</sub>O, CaO and SiO<sub>2</sub> into the melts, and K<sub>2</sub>O, FeO\*, MgO, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> in the residua, which are absent in the melanosomes. In contrast, during the second stage of melting, accompanied by the migration of the granitic melts, the residua left behind are enriched in Al<sub>2</sub>O<sub>3</sub>, FeO, MgO, TiO<sub>2</sub>, Na<sub>2</sub>O and CaO and depleted in SiO<sub>2</sub> and K<sub>2</sub>O due to the larger proportion of micas consumed relative to plagioclase (e.g. Patiño Douce and Harris, 1998). The interplay of the sequential partial melting effects, however, determines complex geochemical patterns within the studied rocks. In order to evaluate the effects of the sequential partial melting, we have modelled the composition of the residual rocks, LR1 (Lower Residue) and UR1 (Upper Residue) after the segregation of the melts which produced the leucosomes found within the metasediments and the composition of the residua (LR2-UR2) after the extraction of granitic melts formed during the subsequent dehydration melting of micas. We have used the following data: 1) the bulk migmatites and the melanosomes of domains 2 and 3 seem to be derived from protoliths, geochemically similar to the Stefanacani migmatitic paragneisses and to the Stilo phyllites (Fig. 2), respectively; 2) within domain 2 the leucosomes amount to 30-40 vol%, and in

domain 3 they amount to 10-20 vol%; 3) the leucotonalitic types prevail and represent about 70% of the leucosomes sampled; 4) the Petrizzi peraluminous granites have the composition of the melt extracted during the mica-dehydration melting amounting to ~ 45% and 30% in domains 3 and 2, respectively.

First, starting with the Stefanacani paragneisses and Stilo phyllites we subtracted the proportions of the melt formed by H<sub>2</sub>O-fluxed melting (30 vol% for domain 2 and 10vol% for domain 3); the composition of this melt was obtained combining the composition of sodic (70%) and potassic (30%) leucosomes (i.e. in proportions similar to those present in our suite of leucosomes). This mass balance computation gives the major element composition of the likely residua (LR1-UR1 in Tables 3-3a) in domain 3 and 2 after the segregation of melt. The modelled residue (LR1) representing the first stage after 10% melting in domain 3 (Table 3) has a major element composition in which K<sub>2</sub>O, Al<sub>2</sub>O<sub>3</sub>, MgO, FeO\*, MnO, TiO<sub>2</sub> increase, whereas, Na<sub>2</sub>O, CaO and SiO<sub>2</sub> decrease relative to the Stilo phyllites. The modelled residue (UR1) for domain 2 (Table 3a), shows, instead, a negligible increase of Na<sub>2</sub>O and CaO relative to Stefanacani migmatitic paragneisses despite of the segregation of 30% partial melt which produced the «*in situ*» leucosomes. This might be due to the high initial CaO and Na<sub>2</sub>O contents within the Stefanacani migmatitic paragneisses (Table 1\*). During the subsequent stage of the anatexis the micaceous residua LR1 and UR1, the remaining quartz and plagioclase and the melt trapped in the matrix, were involved in the dehydration melting and produced granitic melts, which migrated from the source leaving behind residua that we have modelled as LR2 – UR2 in Tables 3 and 3a. These residua show very different degrees of K<sub>2</sub>O depletion between domains 3 (from 3.25 in LR1 to 1.38 in LR2) and 2 (from 3.87 in UR1 to 3.15 in UR2) as a result of the different quantities of micas involved in the melting reactions (see also Fig. 2) and depletion of Na<sub>2</sub>O due to the participation or consumption



TABLE 3

Mass balance calculations on anhydrous basis to model the composition of the restites (LR1-LR2) left behind during the multistage partial melting of protoliths similar to the Stilo phyllites for domain 3. The compositions of residual rocks actually present are given. (LR1) modelled restite after extraction of 10vol% melt obtained combining 70% leucotonalitic and 30% leucogranitic melts of the lower part produced during the H<sub>2</sub>O-fluxed melting and crystallized «in situ»; (LR2) restite calculated after extraction from LR1 of 45vol% of peraluminous melt (as Petrizzi granite) produced during the dehydration melting of micas.

	Stilo Phyllites	70%Lt+30%Lgr	LR1	LR2	Lr	mean Lfc1-Lfc1*-Lfc7A*
SiO <sub>2</sub>	66.27	75.40	65.26	60.12	61.20	44.54
Al <sub>2</sub> O <sub>3</sub>	17.63	15.02	17.92	20.34	22.18	27.64
TiO <sub>2</sub>	0.84	0.17	0.92	1.31	1.35	2.06
FeO*	6.36	1.56	6.89	10.63	11.02	17.08
MnO	0.07	0.02	0.08	0.11	0.12	0.24
MgO	2.22	0.42	2.42	3.97	2.96	5.51
CaO	1.00	2.44	0.84	0.19	0.54	1.15
Na <sub>2</sub> O	2.29	2.63	2.25	1.85	0.27	0.50
K <sub>2</sub> O	3.15	2.28	3.25	1.38	0.33	1.24
P <sub>2</sub> O <sub>5</sub>	0.16	0.05	0.17	0.10	0.02	0.03
Al <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub>	20.99	88.35	19.48	15.53	16.43	13.42
CaO/MgO	0.45	5.81	0.35	0.05	0.18	0.21
CaO/Na <sub>2</sub> O	0.44	0.93	0.37	0.10	2.00	2.30
Mg-number	38	32	38	40	32	36
A/CNK	1.96	1.34	2.05	4.17	12.44	6.49

of plagioclase at both the melting stages. There is also a difference in the behaviour of CaO, which is slightly enriched in domain 2 (from 2.39 to 2.71) but depleted in domain 3 (from 0.84 to 0.19), this reflects the different protolith compositions. The comparison between the model LR2-UR2 residua and the compositions of the natural melanosomes actually present (Tables 3-3a) shows a discrepancy for CaO content and CaO/Na<sub>2</sub>O ratio. The CaO in the rock-types of domain 2 decreases slightly from the assumed starting chemical composition to the natural residues (Table 3a), whereas in the model UR2 it increases. The CaO/Na<sub>2</sub>O ratio in the natural residua of domain 3 increases (Table 3), whereas in the calculated residuum LR2 it decreases. Again, these discrepancies might be accounted for the high CaO and Na<sub>2</sub>O contents in the assumed model protoliths for domain 2 and high Na<sub>2</sub>O contents in the assumed protoliths of domain 3 (Tables 3-3a).

There are some important chemical differences between the residua present in the studied section and model residua (LR2-UR2). It should be remembered that the models represent the calculated composition of the solid left after the melting whereas the natural residua include phases which survived melting, phases which formed during melting left behind by segregating melts and phases which formed during rehydration and cooling history. Emblematic are the residual sample KIS15A\* containing more than 40 vol% Bt and the residual samples Lfc1 and Lfc1\* made up essentially of Grt + Sil (Fig. 2).

From Tables 3-3a-4 it appears that, due to the interplay between H<sub>2</sub>O fluxed melting, dehydration melting of micas and the migration of melts, the multi-stage partial melting causes increase of MgO, FeO\*, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, MnO and decrease of SiO<sub>2</sub>, K<sub>2</sub>O, Na<sub>2</sub>O and CaO, in the natural residue relative to their chemically

TABLE 3a

Mass balance calculations on anhydrous basis to model the composition of the restites (UR1-UR2) left behind during the multistage partial melting of protoliths similar to the Stefanaconi paragneisses for domain 2. The compositions of residual rocks actually present are given. (UR1) modelled restite after extraction of 30vol% melt obtained combining 70% leucotonalitic and 30% leucogranitic melts of the upper part produced during the H<sub>2</sub>O-fluxed melting and crystallized «in situ»; (UR2) restite calculated after extraction from UR1 of 30vol% of peraluminous melt (as Petrizzi granite) produced during the dehydration melting of micas.

	Stefanaconi paragneiss	70%Ut+30%Ugr	(UR1)	(UR2)	Ur
SiO <sub>2</sub>	62.32	76.39	56.29	49.75	54.80
Al <sub>2</sub> O <sub>3</sub>	16.43	14.33	17.32	18.33	20.80
TiO <sub>2</sub>	0.98	0.19	1.33	1.71	1.47
FeO*	7.91	1.50	10.65	14.22	12.05
MnO	0.12	0.02	0.17	0.22	0.15
MgO	3.73	0.55	5.10	7.05	5.14
CaO	2.27	1.99	2.39	2.71	1.53
Na <sub>2</sub> O	2.59	2.50	2.64	2.59	1.29
K <sub>2</sub> O	3.45	2.46	3.87	3.15	2.71
P <sub>2</sub> O <sub>5</sub>	0.21	0.08	0.26	0.26	0.05
Al <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub>	16.76	75.42	13.02	10.72	14.15
CaO/MgO	0.61	3.62	0.47	0.38	0.30
CaO/Na <sub>2</sub> O	0.88	0.80	0.91	1.05	1.19
Mg-number	46	39	46	47	43
A/CNK	1.36	1.38	1.34	1.45	2.65

similar precursors (Stilo phyllites for domain 3 and Stefanaconi migmatitic paragneisses for domain 2). At the same time the natural residua show that: 1) Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> and CaO/MgO ratios decrease (Tables 3-3a), due to the lower solubility of TiO<sub>2</sub> and MgO in the crustal melts; 2) CaO/Na<sub>2</sub>O ratio increases (Tables 3-3a) due to the higher partition of Na<sub>2</sub>O into the anatectic melts because some CaO is in garnet; 3) Mg-number does not change significantly whereas A/CNK increases (Tables 3-3a). From domain 2 to domain 3, K<sub>2</sub>O and Na<sub>2</sub>O decrease markedly (Figs. 2-3a-3c) within the residua due to the more advanced dehydration melting of Bt and to the consumption of plagioclase during the two stage melting.

Rb and Ba are notably depleted in domain 3 residua, reflecting the consumption of biotite and feldspars (Table 4); sample Lfc7A\* is an exception. Eu and Sr are also depleted within

the residua of domains 2 and 3 (Table 4) due to the dissolution of feldspars into the melt during anatexis. P is depleted within the residues and «in situ» leucosomes (Fig. 4) suggesting that P partitioned into anatectic melts during dehydration melting and was lost when these melts migrated out of the source. This might depend on the solubility of apatite into the peraluminous melt (e.g. Pichavant *et al.*, 1992) and/or the involvement of xenotime in the reactions forming garnet (Bea and Montero, 1999). U, too, decreases within the residual rocks and within the «in situ» leucosomes (Fig. 4), this reflecting its partition either into the fluids generated by dehydration subsolidus reactions, or into the melts producing the «in situ» leucosomes from which U migrated with the late stage fluids (e.g. Bea and Montero, 1999). Alternatively, as happened for P, the U was also partitioned into

TABLE 4

Elemental ratios of domain 2 bulk-migmatite (Um) and melanosomes (KIS15A\*, Ur) with respect to Stefanaconi paragneisses and of domain 3 bulk-migmatite (Lm) and melanosomes (Lfc1, Lfc1\*, Lfc7A\*, Lr) with respect to Stilo phyllites.

	DOMAIN 2			DOMAIN 3				
	Um	KIS15A*	Ur	L m	Lfc1	Lfc1*	Lr	Lfc7A*
	Stefanaconi paragneisses			Stilo phyllites				
SiO <sub>2</sub>	0.96	0.71	0.88	0.96	0.59	0.75	0.96	0.74
Al <sub>2</sub> O <sub>3</sub>	1.29	1.46	1.27	1.30	1.80	1.55	1.31	1.50
TiO <sub>2</sub>	1.24	2.29	1.48	1.43	3.23	2.06	1.66	2.24
FeO*	1.16	1.92	1.52	1.57	3.32	2.76	1.80	2.23
MnO	1.07	1.33	1.23	2.23	3.64	2.80	1.71	3.50
MgO	1.04	2.04	1.38	1.22	3.08	2.35	1.39	2.28
CaO	0.66	0.50	0.67	0.41	0.95	0.52	0.56	2.12
Na <sub>2</sub> O	0.54	0.32	0.50	0.15	0.06	0.06	0.12	0.55
K <sub>2</sub> O	0.85	1.52	0.79	0.71	0.12	0.17	0.11	0.93
P	0.30	0.10	0.22	0.33	0.41	0.07	0.16	0.21
Rb	0.61	1.21	0.59	0.49	0.10	0.18	0.07	0.45
Ba	1.55	2.25	1.09	0.67	0.25	0.25	0.27	1.46
Th	1.02	-	0.58	1.91	3.92	-	1.37	-
U	0.70	-	0.42	0.68	0.86	-	0.46	-
Nb	0.77	0.94	0.86	1.50	3.03	2.95	1.58	1.76
Sr	0.98	0.62	0.80	1.28	0.14	0.05	0.48	2.58
Zr	1.04	1.27	0.88	1.42	2.24	1.78	1.31	1.71
Y	1.50	1.72	1.64	1.65	2.82	1.86	1.74	2.25
Sc	1.31	-	1.38	1.72	3.21	-	1.94	-
V	1.34	2.32	1.51	1.67	3.38	2.82	1.91	2.21
Cr	1.30	1.96	1.34	1.47	3.26	2.08	1.54	1.70
Ni	0.67	1.62	0.93	1.50	3.29	1.80	1.43	3.12
Eu	1.21	0.71	0.96	1.27	0.59	0.35	0.91	1.76
SLREE	1.26	1.22	1.12	1.73	3.32	0.81	1.19	1.10
SHREE	1.72	1.65	1.63	1.72	2.92	1.85	1.83	2.04

the mobile granitic melts during dehydration melting. The garnet-forming reactions must release U given its low affinity with the solid phases produced by such reactions (e.g. Hensen and Harley, 1990; Thompson, 1996) and is likely to stay dissolved in either the fluids or partial melts. The decrease of U causes a sudden increase of Th/U ratios in the residua of domains 2 and 3. Y, Sc, V and Cr are concentrated within the residual rocks especially in domain 3 (Table 4) where garnet is decidedly more abundant. Nb and Zr are enriched in the melanosomes of domain 3, and

the REE enrichment in both domains 2 and 3 is due to the concentration of monazite and zircon. The concentration of LREE and the size of the negative Eu anomalies depend on the relative proportions of feldspar and monazite incorporated into the melts or left in the residue (e.g. Watt and Harley, 1993; Bea and Montero, 1999); the «*in situ*» leucosomes have positive Eu anomalies and the residual melanosomes have variable negative Eu anomalies which become larger in samples in which monazite is abundant (determining LREE enrichment) and/or feldspar has been

exhausted during melting (causing Eu-depletion). Interestingly, the samples Lfc1 and Lfc1\* are from the same outcrop and have the same mineralogy (Grt+Sil+Rt), but have quite different LREE abundances (Fig. 5c). It is possible that Lfc1 has the highest LREE content because it contains mostly Grt as a solid residue of the melting, whereas Lfc1\* contains mostly peritectic Grt without inclusions of accessory phases. The destruction of Bt during dehydration melting that produced peritectic Grt may have allowed the included accessories to be available to the granitic melts.

*Geochemical fractionation within the crustal section.* The upper crustal rocks and the migmatites of domain 1 in the crustal section of the Serre have compositions within the range of the common shales. In contrast, the bulk migmatites of domains 2 and 3 experienced significant chemical modification relative to common shales. Subsolvus reactions and H<sub>2</sub>O-fluxed melting did not cause significant chemical modification at the whole-rock scale because the melts crystallized «*in situ*» or near to their source. The geochemical modifications were caused by the subsequent dehydration melting of micas, which produced abundant granitic melts that migrated far from their sources. When the compositions of the bulk migmatites (Table 4) are compared to the compositions approaching those of the precursors (the Stefanconi paragneisses and the Stilo phyllites for domains 2 and 3, respectively), it appears that MgO, FeO\*, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, MnO, Sc, Y, V, Cr, Zr and REE were enriched in the lower part of the crustal section of the Serre whereas Na<sub>2</sub>O, CaO, K<sub>2</sub>O, P, Rb and U were depleted. These trends intensify downward in the section, due to the extraction of significant volumes of granitic melt. Nb, Th, Ba and Ni show contrasting behaviours. Nb, Th and Ni are enriched in domain 3 and depleted in domain 2 bulk migmatites, but the opposite happens for Ba. Despite the enrichment of Eu with respect to the assumed compositions of the protoliths (due to the presence of the «*in situ*» leucosomes), the bulk migmatites

maintain (domain 2) or have greater (domain 3) negative anomalies due to the increase of both LREE and HREE contents. Th/U ratio increases significantly in the bulk migmatites of domains 2 and 3 due to the severe depletion of U.

## CONCLUSIONS

The present study shows that the metapelites of the crustal section of the Serre underwent significant chemical modifications, either on a small scale, or on a large scale mainly during anatexis. H<sub>2</sub>O-fluxed melting caused the differentiation of metapelites in the lower crustal segment into leucosomes (mostly sodic) and melanosomes. Fractionation on a large scale, however, did not occur since most leucosomes crystallized near their sources. Subsequent mica dehydration melting produced peraluminous granitic melts, which migrated towards the upper crustal levels. The extraction of the peraluminous granitic melts caused depletion of Si, Ca, Na, K, P, Rb, U and enrichment of Al, Ti, Fe, Mg, Mn, Zr, Y, Sc, V, Cr, REE in the bulk migmatites of the domains 2 and 3. Depletions and enrichments are larger in the melanosomes and increase towards the base of the lower crust. In the residua of domain 3 elemental depletions are up to 90% (e.g. Na, K, Rb, Sr, P) and some enrichments higher than 300% (e.g. Ti, Fe, Mg, Mn, Th, Nb, Zr, Y) relative to the assumed protolith compositions. The bulk migmatites and the residual rocks of domain 3 have larger negative Eu anomalies than the common shales, and their Eu/Eu\* ratio attains a value of 0.13.

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