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The Ordovician gneisses of north-eastern Sardinia (Italy): hypotheses for the petrological evolution of their protoliths

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ABSTRACT. — In this paper new whole rock data on Ordovician ortho- and augen-gneisses cropping out in North-Eastern Sardinia are presented. It is evidenced that the core of the outcrop (ortho-gneisses) has a less evolved geochemical composition than the peripheral portions (augen-gneisses). Inter-digitate contacts between the different portions are observed. Within ortho-gneisses are recognised Mafic Microgranular Enclaves, indicating the possible role played by magmatic interaction processes in their genesis, whereas magmatic enclaves are lacking in augen-gneisses.

Discriminant diagrams are used in order to understand the type and extent of metasomatic/alteration processes suffered by these rocks. Analysis reveals that the effect of these processes can be considered negligible and that the geochemical characteristics of studied samples are the result of magmatic evolution.

On the basis of field and geochemical data, a two-stage petrogenetic evolution is suggested to explain the compositional spectrum of studied rocks. Ortho-gneisses are considered as produced by Mixing plus Fractional Crystallization processes whose evolution in time produced, in the core region of the magma chamber, magma batches with different degrees of hybridisation bearing Mafic Microgranular Enclaves. Augen-gneisses are interpreted as the result of Fractional Crystallization processes acting in the peripheral portions of the magma chamber.

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KEY WORDS: *North-Eastern Sardinia, Ordovician gneisses, geochemical evolution, magma mixing, fractional crystallization.*

RIASSUNTO. — In questo lavoro vengono presentati nuovi dati geochimici di roccia totale di ortogneiss e gneiss occhiadini Ordoviciani affioranti nel settore Nord-Est della Sardegna. Evidenze di campagna indicano che i contatti fra ortogneiss e gneiss occhiadini sono interdigitati e l'analisi geochimica mostra che la porzione centrale dell'affioramento (ortogneiss) ha una composizione geochimica meno evoluta rispetto alle porzioni periferiche (gneiss occhiadini). All'interno degli ortogneiss sono presenti Inclusi Microgranulari Mafici che evidenziano la presenza di processi di interazione fra magmi nella genesi di queste rocce. Gli Inclusi Microgranulari Mafici non sono presenti negli gneiss occhiadini.

Al fine di comprendere il tipo e l'entità degli eventuali processi di alterazione che possono aver influenzato la composizione dei protoliti originali vengono utilizzati diagrammi geochimici discriminanti. I risultati evidenziano che tali processi possono essere considerati trascurabili e che, quindi, la variabilità geochimica delle rocce è il risultato di processi di evoluzione magmatica.

Sulla base dei dati di campagna e geochimici, viene

proposto un modello evolutivo dei protoliti magmatici in cui vengono considerati due tipi di evoluzione diversa per gli ortogneiss e per gli gneiss occhiadini. Gli ortogneiss vengono interpretati come il prodotto di processi di Mescolamento + Cristallizzazione Frazionata la cui evoluzione nel tempo ha prodotto, nella porzione centrale della camera magmatica, volumi di magma con diversi gradi di ibridizzazione contenenti Inclusi Microgranulari Mafici. Gli gneiss occhiadini vengono interpretati come il risultato di processi di Cristallizzazione Frazionata che si sono verificati essenzialmente nelle regioni periferiche della camera magmatica.

PAROLE CHIAVE: *Sardegna Nord-orientale, gneiss Ordoviciani, evoluzione geochimica, mescolamento fra magmi, cristallizzazione frazionata.*

1. GEOLOGICAL SETTING AND AIMS

The basement of North-Eastern Sardinia is characterized by a well defined Hercynian metamorphic zoneography prograding toward North-East (e.g. Di Simplicio *et al.*, 1974; Ferrara *et al.*, 1978; Franceschelli *et al.*, 1982; Cappelli *et al.*, 1992) and is constituted by outcrops of variable sizes sharply isolated from Hercynian granitoids (Fig. 1). Three main metamorphic complexes disposed along the NW-SE direction can be identified: *i)* greenschist facies metamorphic complex, of intermediate pressure (chlorite and biotite zone), outcropping in the southern Nurra, in the Goceano and Nuorese (e.g. Carmignani *et al.*, 1982); *ii)* amphibolitic facies metamorphic complex, of intermediate pressure (garnet + albite + oligoclase, staurolite + biotite, kyanite + biotite), outcropping in northern Nurra, Asinara, northern Anglona and in the Siniscola-Mamone area, constituted by micaschists and para-gneisses (containing amphibolitic lenses) associated with Ordovician ortho-gneisses and augen-gneisses (e.g. Di Simplicio *et al.*, 1974; Ferrara *et al.*, 1978); *iii)* amphibolite facies migmatitic complex where coexist ortho-gneisses and para-gneisses characterized by the stable association of sillimanite + muscovite and sillimanite + K-feldspar that represents the maximum conditions of pressure and temperature of the Hercynian regional metamorphism.

In this paper we provide new geochemical data (major and trace elements) on Ordovician ortho- and augen-gneisses outcropping in the area of Siniscola-Mamone and in the migmatitic complex with the aim to understand the type and extent of metasomatic/alteration processes that these rocks suffered and their possible geochemical evolution and petrogenesis.

Geochronological data (Di Simplicio *et al.*, 1974; Ferrara *et al.* 1978) indicate the same age for the ortho-gneiss from Siniscola-Mamone area and those from the migmatitic complex (458 ± 31 Ma). Also petrographic and geochemical characteristicts are very similar (see below), and these features favour, hence, the hypothesis that all ortho-gneisses can be considered as a single group of rocks.

The augen-gneisses surrounding ortho-gneisses in the Siniscola-Mamone area (Fig. 1) have an age that, considering analytical errors, is identical to that of ortho-gneisses (441 ± 33 Ma vs. 458 ± 31 Ma; Di Simplicio *et al.*, 1974; Ferrara *et al.* 1978). Contacts between ortho- and augen-gneiss are interdigitate suggesting that the two masses were still in a rheologically liquid state during emplacement. These characteristics are typical of inversely zoned plutons (e.g. Paterson and Vernon, 1995) whose core is constituted by less evolved rocks and the rim is costituted by more evolved rocks.

2. PETROGRAPHY

Samples have been collected from the lens of ortho- and augen-gneisses outcropping in the area of Siniscola-Mamone and ortho-gneisses from the migmatitic complex (Fig. 1).

From a general point of view all ortho-gneiss samples show a granoblastic oriented texture (Fig. 2A-B) whereas augen-gneisses are characterized by a porphyroblastic texture due to large crystals (up to 5.0 cm across) of K-feldspar and subordinate plagioclase (Fig. 2C-D). All the collected samples are constituted by a similar mineralogical assemblage consisting of: quartz, K-feldspar, plagioclase (albite-oligoclase), biotite, muscovite, ± chlorite, ± garnet, zircon, apatite, ± titanite, and ± opaque

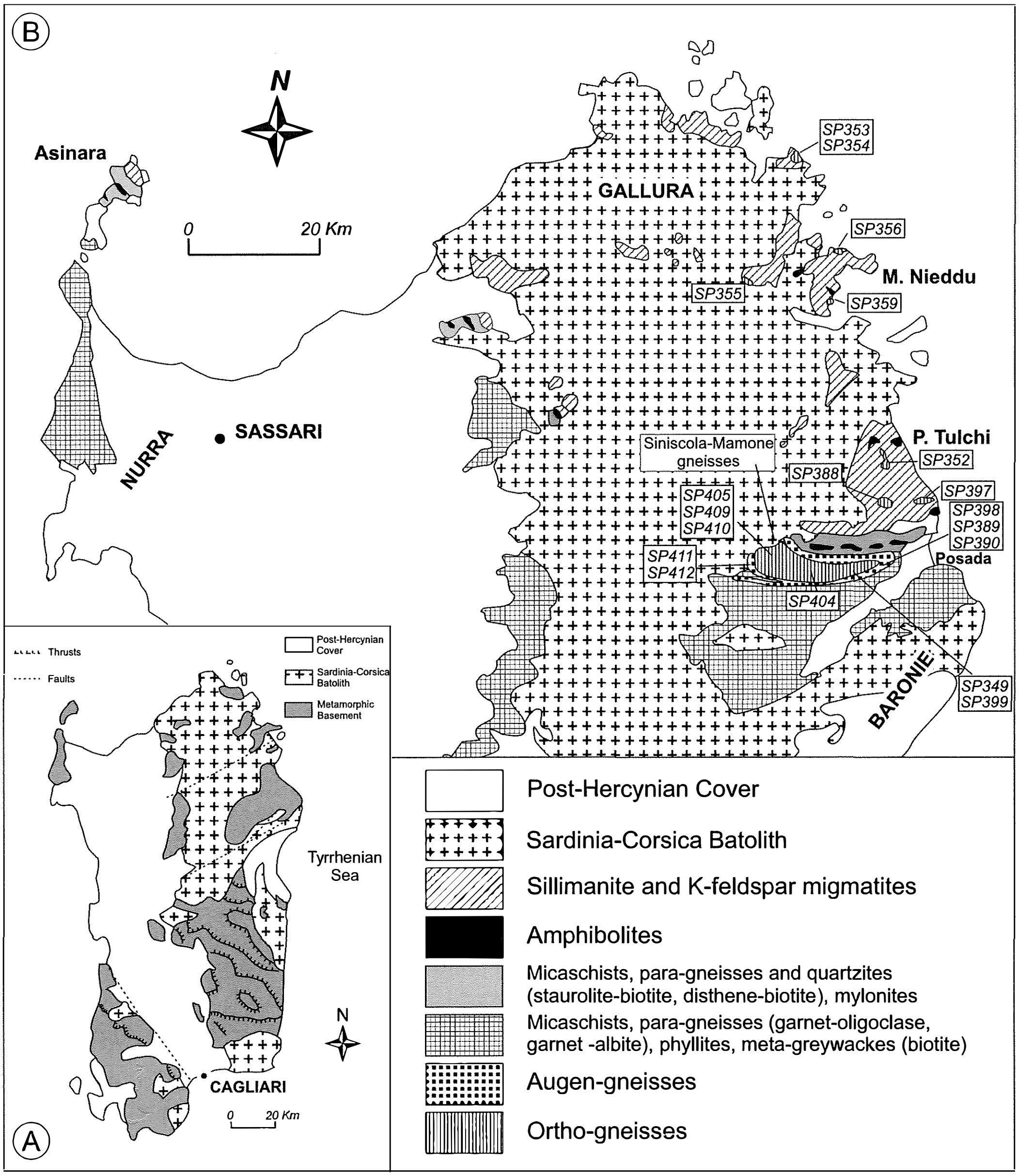

Fig. 1 – A) Sketch map of Sardinia in which are reported the post-Hercynian cover, the Sardo-Corso batolith and the metamorphic basement; B) Schematic geological map of northern Sardinia in which are reported the main geological units and the location of collected samples. After Cappelli *et al.* (1992).

minerals. Since major differences concern the textural features in ortho- and augen-gneisses, the two groups of rocks will be discussed separately. Given the very similar petrography of all ortho-gneiss samples, they will be discussed together.

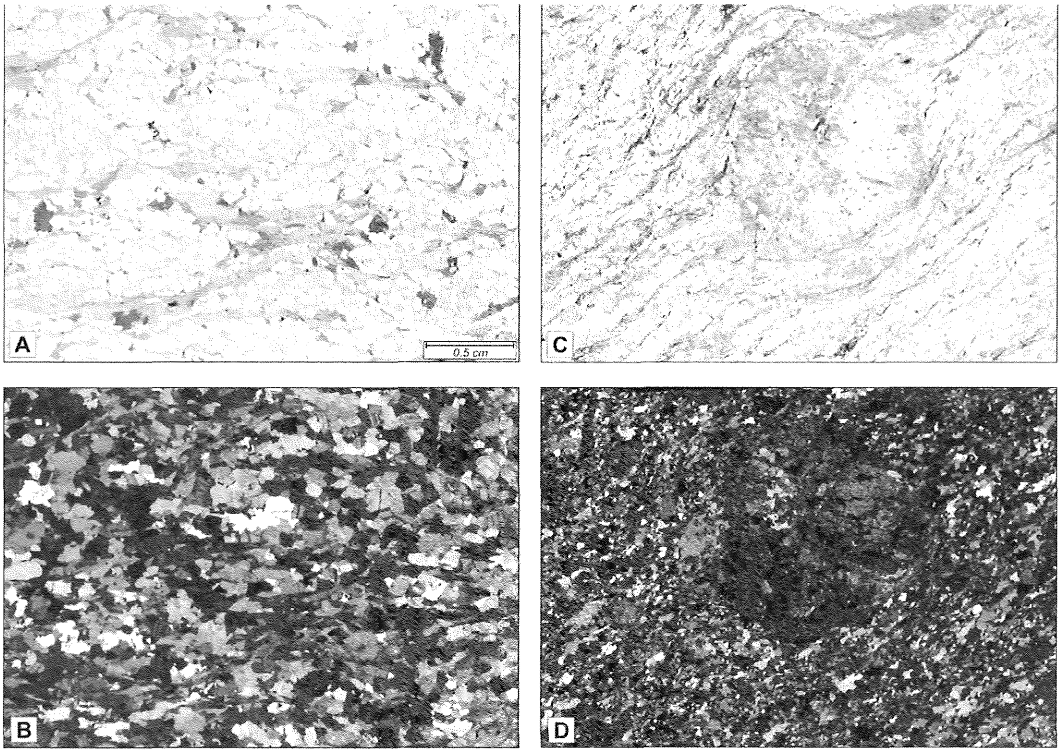

Fig. 2 – A-B) Typical aspect of ortho-gneisses in thin section: lepidoblastic biotite and muscovite separate leucocratic layers constituted by quartz, K-feldspar and plagioclase (A - plane polarized light, B - cross polarized light); C-D) Typical aspect of augen-gneisses in thin section: lepidoblastic biotite and muscovite separate leucocratic layers constituted by quartz, K-feldspar and plagioclase and porphyroblasts of K-feldspar (C - plane polarized light, D - cross polarized light).

Ortho-gneisses are medium- to coarse-grained rocks with layers (3 to 10 cm long) constituted by felsic minerals (quartz, K-feldspar, plagioclase) having slightly oriented granoblastic texture; such layers are separated by lepidoblastic micas (biotite and muscovite; Fig. 2A-B). Quartz occurs mainly as anhedral crystals, shows extensive re-crystallization effects and some crystals display waving extinction indicating intense deformation. K-feldspar occurs as pertitic intergrowths, subhedral microcline and, rarely, as adularia in secondary veins. Its grain size is variable because large poikiloblasts, up to 3.0 cm across, coexist with fine grained crystals (0.1 to 1.0 mm) subjected to syn-kinematic oriented re-crystallization. Some crystals display sericitic alteration that, however, is limited to crystal boundaries. Plagioclase occurs as euhedral to subhedral albite and oligoclase and, less commonly, as large poikiloblasts (up to 1.0 cm). In some cases, plagioclase crystals display very limited alteration in sericite and epidote (saussurrite). Biotite is syn-kinematic and occurs as lepidoblastic aggregates (Fig. 2A-B); few crystals display chloritization phenomena that are generally limited to crystal boundaries (Fig. 3A) and only in rare cases are pervasive on whole crystals. Commonly biotite includes apatite and zircon, the latter well recognizable for the occurrence of the typical pleochroic haloes (Fig. 3B). The occurrence of biotite is mirrored by muscovite with the exception that the latter does not contain accessory phases, but in some cases displays scheletric textures due to partial substitution by iron oxides. Garnet, syn-kinematic, is anhedral and very rare and coexists with chlorite (Fig. 3C). Common accessory minerals are, together with the above mentioned apatite and zircon, euhedral to subhedral ilmenite and titanite (Fig. 3D).

The possible protolith of ortho-gneisses can be hypothesised as a rock with a granodioritic composition (e.g. Di Simplicio *et al.*, 1974) that suffered an initial deformation that induced alignment of felsic minerals and micas followed by a second event that folded the previous fabric (Fig. 3E; e.g. Elter *et al.*, 1990).

Within ortho-gneisses fine-grained melanocratic enclaves (1.0-10.0 cm across in size) having globular to elonged morphologies are present. They are constituted by the same minerals occurring in the host rock although mineral proportions of enclaves are different from the host rock since mafic minerals, biotite and opaques, are more abundant. These enclaves do not constitute more than 1.0% of the studied outcrops. These melanocratic enclaves share many structural and textural characteristics with Mafic Microgranular Enclaves (MME) commonly observed in granitoid rocks (for details see Didier and Barbarin, 1991) that are interpreted as relicts of a more mafic magma that interacted with the felsic host magma (Perugini and Poli, 2000; Poli *et al.*, 1996). The lack of textural features that may indicate a restitic or cumulitic origin for the observed melanocratic enclaves, predating the Hercynian metamorphism, indicates that they can be considered as MME and, hence, they suggest the occurrence of magma interaction processes in the protolith of the studied ortho-gneisses. Unfortunately, given the very small size of MME it was not possible to collect enough sample to perform geochemical analysis.

Augen-gneisses are fine- to coarse-grained rocks and are characterized by a banded porphyroblastic texture generated by folded surfaces of micas (biotite and muscovite) mantling felsic minerals constituted by porphyroblasts of pre-kinematic K-feldspar (up to 5.0 cm across in size), peciloblasts of plagioclase and quartz (Fig. 2C-D). Quartz underwent extensive oriented re-crystallization and forms indented textures. K-feldspar, anhedral, occurs mainly as microcline showing oriented re-crystallization; along the boundary of some crystals limited sericitic alteration is observed. Plagioclase occurs as anhedral albite and oligoclase crystals and displays textural features similar to K-feldspar. Syn-kinematic biotite displays tabular habit and commonly contains inclusions of apatite, zircon, with relative pleochroic haloes (e.g. Fig. 3B), and opaque minerals; along the boundary and more rarely inside crystals chloritc alteration is present (e.g. Fig. 3C). Muscovite displays the same textural characteristics of biotite with the exception that it does not include zircon and apatite and, in some cases, scheletric textures due to partial substitution by iron oxides are observed. Rare syn-kinematic garnet, associated with chlorite, is present as dismembered crystals. Zircon, apatite, and rare titanite occur as accessory minerals and are commonly enclosed in biotite laths. Augen-gneisses display higher deformation effects with respect to ortho-gneisses probably related to the low granulometric homogeneity of the protolith, the latter probably represented by an evolved granitoid rock having phenocrysts of K-feldspar and plagioclase. The protolith of augen-gneisses suffered an initial deformation that induced alignment of felsic minerals and biotite followed by a second event that folded the bandings previously generated (Fig. 3E; e.g. Elter *et al.*, 1990). Mafic Microgranular Enclaves are not observed in augen-gneisses.

3. Geochemistry

Given the metamorphic event suffered by studied rocks, particularly evident in the deformation displayed by some samples, it is worth discussing the type and the extent of eventual metasomatic/alteration processes that rocks underwent. In the following the collected samples will be divided into two main groups, ortho- and augen-gneisses; as discussed above this separation is consistent with the geological,

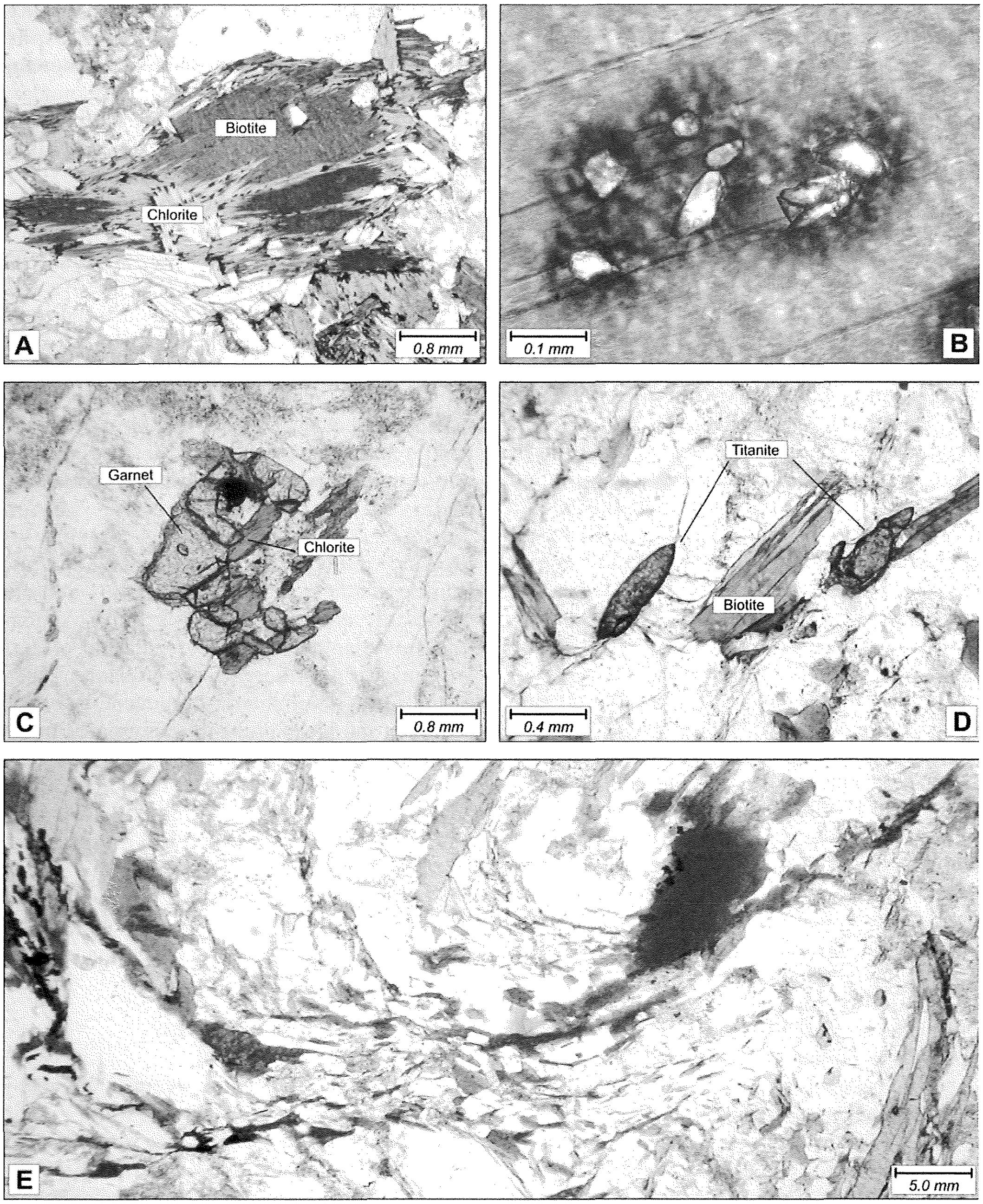

Fig. 3 – Petrographic characteristics typical of the studied rocks. A) Biotite crystals with partly chloritized borders; B) zircon crystals with pleochroic haloes included in a biotite crystal; C) dismembered crystal of garnet (high relief) associated with chlorite (lower relief); D) euhedral and subhedral crystal of titanite coexisting with biotite; E) elongated and folded laths of biotite.

structural, and textural features of studied rocks and the possible protoliths.

3.1 Metasomatic/alteration processes

In order to assess the eventual metasomatic/ alteration processes on studied gneisses, some tests have been performed utilising geochemical diagrams that have been proven to unravel the type and the extent of metasomatism/alteration that rocks suffered. In particular, the graphs of fig. 4 allow us to discriminate element remobilisation or alteration phenomena. Relationships between

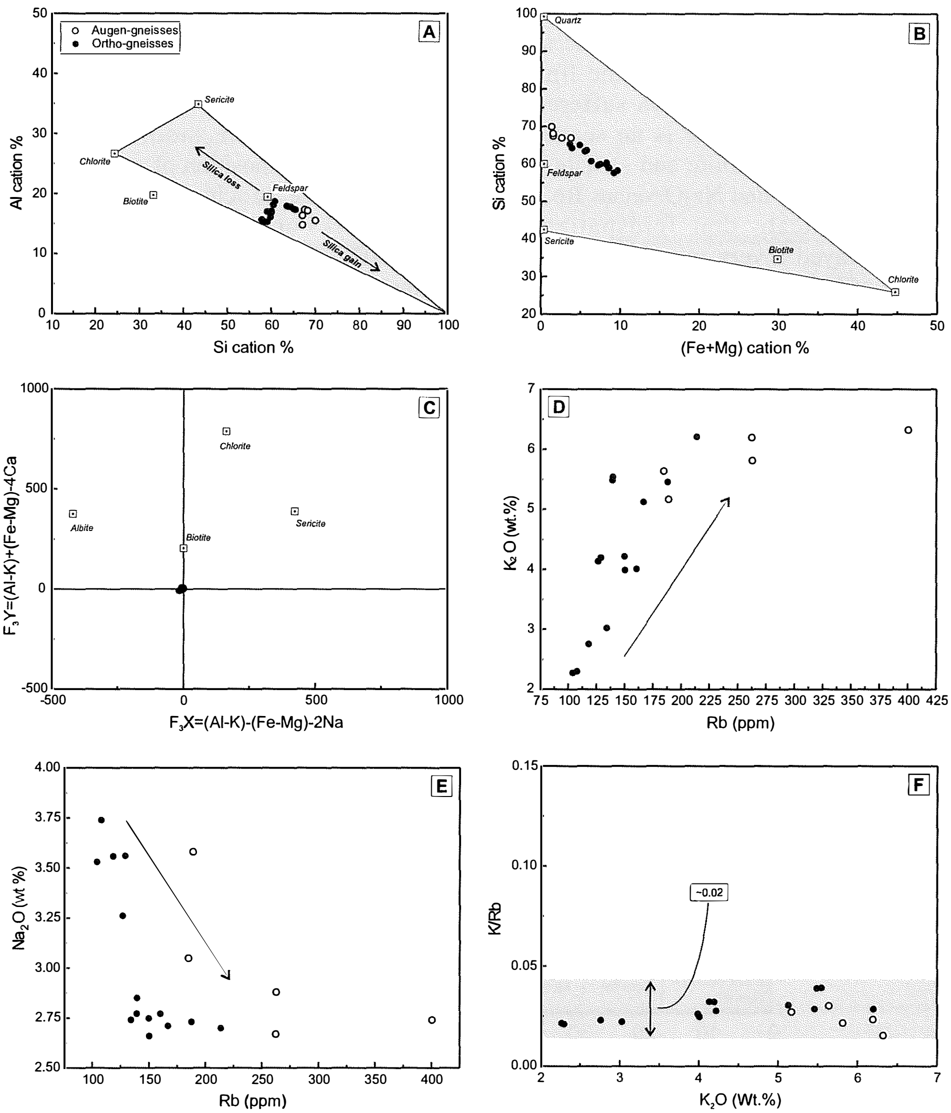

Fig. 4 – Diagrams showing the limited/absent alteration and metasomatism suffered by studied rocks; see text for details.

cation Si and Al or (Fe-Mg) (Fig. 4A and B, respectively; MacLean and Barret, 1993) reveal that gneisses were not strongly influenced by extensive chloritization, sericitization or silicization but, on the contrary, samples are well clustered in restricted areas of the graphs arguing against the occurrence of such processes. In addition, in the diagram of De la Roche (1978; Fig. 4C) the gneisses are strongly clustered at the centre of the graph and do not display scattering toward the biotite and albite fields; the graph also indicates the limited chloritization and sericitization suffered by studied samples since there is no scattering towards the fields of chlorite and sericite (Fig. 4C). The graphs K_2O and Na_2O versus Rb (Fig. 4D and E) indicate that feldspatization phenomena played a very minor role. In fact, Kleeman and Twist (1989) idicate that feldspatization (e.g. albitization or microclinization) should increase Rb content in a granitoid rock since Rb can be readily accomodated into trioctahedral micas that are stabilized during alteration. Further evidence against extensive feldspatization of studied samples is given by the lacking of positive correlation between K/Rb versus K_2O% (Fig. 4F) as the occurrence of feldspatization phenomena would require. On the contrary data plot within restricted ranges of K/Rb (~0.02; i.e. grey shaded area in Fig. 4F) indicating very constant values of this ratio.

In conclusion, there is not geochemical evidence indicating the occurrence of extensive alteration or metasomatic processes in studied samples; this allows us to establish that eventual metasomatic or alteration processes do not appear to have modified the global geochemical composition of analysed gneisses. Therefore, the geochemical features of the studied rocks are considered as indicative of magmatic evolution as discussed in the following sections.

3.2 Magmatic processes

In the Q'-ANOR classification diagram of Fig. 5 (Streckeisen and Le Maitre, 1979) most

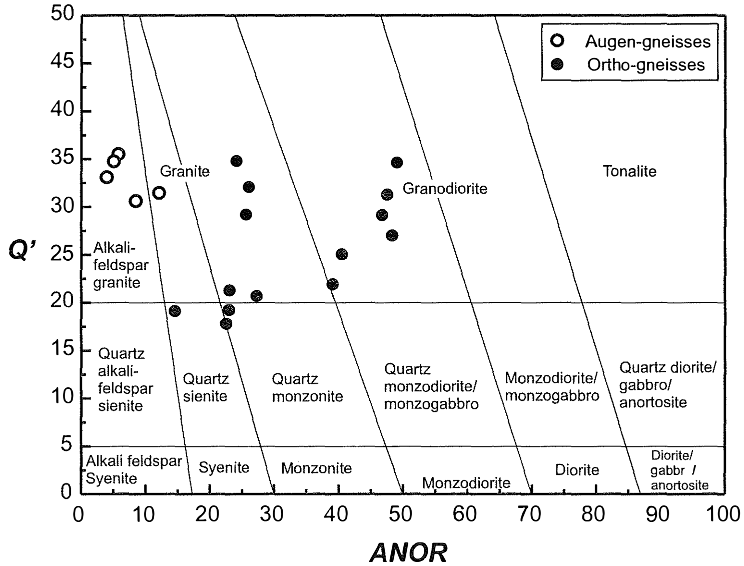

Fig. 5 – Q'-ANOR plot (after Streckeisen and Le Maitre, 1979) used to classify the analysed rocks [Q'=Q/(Q+Or+Ab+An); ANOR=100xAn/(Or+An)]; the norm calculations are made following the procedure reported by Cox *et al.* (1979).

of ortho-gneisses occupy the fields of granodiorites and granites with few samples plotting in the fields of quartz-sienites and quartz-monzonites; augen-gneisses can be classified as granites and alkali-feldspar-granites. The ternary AFM diagram of fig. 6A displays that most samples define a calc-alkaline variation trend; the calc-alkaline affinity of studied rocks is also evidenced in the spider diagram of fig. 6B by the striking similarity between studied samples (grey shaded area) and typical calc-alkaline granitoids from Cordillera Blanca and Coastal Batolith (Atherton and Petford, 1996). The negative anomaly of Nb and Ti, and the positive anomaly of Pb, that point to the calc-alkaline affinity of studied rocks, are also noteworthy (Fig. 6B). To show better the calc-alkaline affinity of studied gneisses in the graph are also reported alkaline granitoid rocks

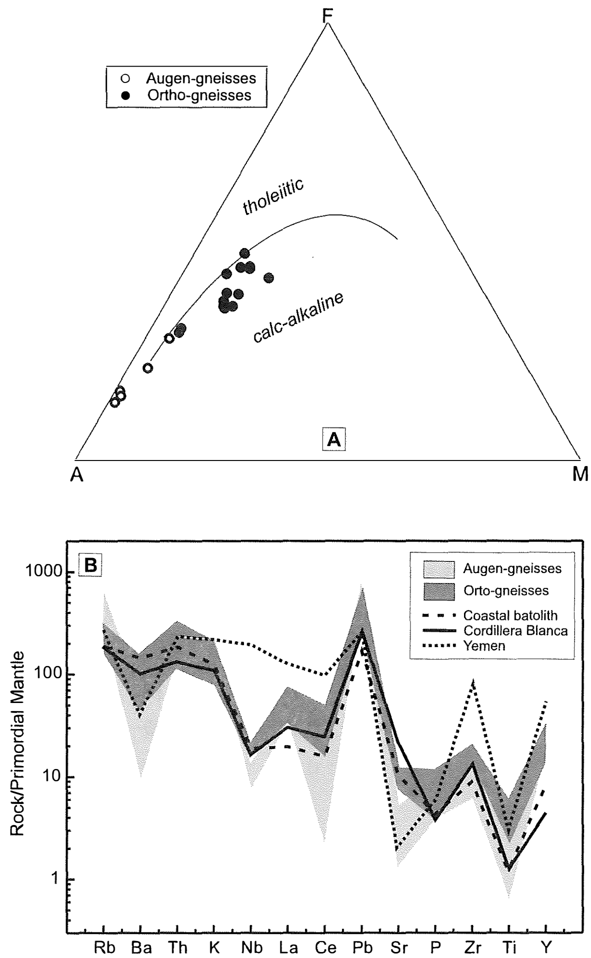

Fig. 6 – A) AFM plot showing the calc-alkaline affinity of the analysed rocks; the curved line separates tholeiitic series from calc-alkaline series according to Irvine and Baragar (1971); B) spider-diagram in which analysed samples are compared with typical calc-alkaline granitoids from Cordillera Blanca and Coastal Batholith (Andes; Atherton and Petford, 1996) and alkaline granitoids from Yemen (Tommasini *et al.*, 1994). Primordial mantle after Wood *et al.* (1979).

from Yemen (Tommasini *et al.*, 1994) showing a different pattern.

Regarding major elements (Table 1), TiO_2, CaO, MgO (Fig. 7A, B and C), Fe_{tot} and MnO (not shown) display good linear negative correlation with SiO_2 although little scatter is observed for CaO and MgO; Al_2O_3 increases initially up to ca. 65-66% of SiO_2 and successively decreases towards more evolved samples (augen-gneisses) defining a bell-shaped trend. K_2O (not shown) display a quite scattered behaviour.

Regarding trace elements, ferromagnesian elements (V, Cr, Co, Ni and Zn) are negatively correlated with SiO_2 (Fig. 8A and B and Table 1). Among HFSE (High Field Strength

TABLE 1

Chemical composition of the analysed samples distinguished in two groups, ortho- and augen-gneiss (see text for details). Major elements [exclusive of FeO, Na_2O, MgO, and LOI (Loss On Ignition) determined by wet chemical analyses] analysed by XRF with full matrix correction after Franzini and

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	V	Cr
Ortho-gneisses														
SP 349	67.08	0.69	15.82	2.14	2.52	0.08	1.56	1.75	2.77	4.01	0.21	1.36	86	54
SP 352	68.95	0.48	15.52	0.36	3.56	0.07	1.28	2.74	3.53	2.27	0.14	1.10	79	28
SP 353	68.47	0.55	15.93	1.67	2.18	0.06	0.71	1.77	3.56	4.20	0.08	0.84	35	47
SP 354	69.44	0.51	15.52	1.05	2.42	0.06	0.69	1.92	3.26	4.14	0.19	0.81	43	18
SP 355	67.35	0.62	16.04	0.08	4.10	0.08	1.59	2.68	3.74	2.30	0.18	1.24	63	37
SP 356	64.58	0.79	16.70	1.94	3.20	0.09	1.73	3.31	3.56	2.76	0.22	1.14	76	62
SP 359	63.81	0.89	16.09	1.64	4.46	0.11	2.48	3.41	2.74	3.03	0.24	1.10	101	83
SP 388	63.02	0.98	14.25	3.12	3.04	0.13	1.79	3.83	2.85	5.55	0.18	1.26	84	67
SP 397	63.16	1.06	14.92	3.53	3.04	0.12	1.75	2.68	2.77	5.49	0.20	1.28	92	74
SP 399	60.61	1.35	13.31	5.60	3.64	0.17	1.84	3.69	2.71	5.13	0.22	1.72	85	75
SP 404	61.68	1.17	13.42	5.36	3.00	0.14	1.59	3.12	2.70	6.21	0.22	1.39	77	69
SP 405	60.52	1.25	13.82	4.64	3.80	0.16	1.96	4.18	2.73	5.46	0.20	1.28	109	77
SP 409	61.66	1.12	14.92	3.38	3.96	0.14	2.01	3.84	2.75	4.22	0.23	1.78	108	87
SP 410	62.44	1.12	14.97	3.29	3.88	0.13	1.90	3.49	2.66	3.99	0.24	1.89	104	88
Augen-gneisses														
SP 389	74.21	0.14	13.84	0.93	0.56	0.04	0.13	0.53	2.67	6.20	0.08	0.66	8	24
SP 390	71.65	0.14	15.46	1.36	0.52	0.05	0.10	0.57	2.74	6.33	0.21	0.86	8	16
SP 398	72.27	0.19	15.29	1.44	0.24	0.03	0.18	0.54	2.88	5.82	0.15	0.97	8	17
SP 411	70.75	0.61	13.09	2.60	1.28	0.08	0.61	0.78	3.58	5.17	0.19	1.24	10	24
SP 412	71.11	0.39	14.56	2.00	0.68	0.05	0.44	1.12	3.05	5.64	0.18	0.78	17	31

Elements), Zr is negatively correlated with SiO_2 (Fig. 8C) whereas Y and Th display reverse bell-shaped trends in which abundances of these elements decrease up to 67-68% of SiO_2 and successively increase in the more evolved samples (Fig. 8D and E). Nb shows a negative correlation with SiO_2 with some scatter in the ortho-gneiss group (Fig. 8F). Regarding LILE (Large Ion Lithophile Elements), La and Ce abundances (Fig. 8G) diminish passing from less evolved to more evolved ortho-gneiss samples, although Ce displays a quite scattered pattern. Ba content decreases passing from ortho- to augen-gneisses despite some scattering. Rb displays a reverse bell-shaped trend passing from less

Leoni (1972); V, Cr, Co, Zn, Ga, Ni, Rb, Sr, Y, Zr, Nb, Ba, La, Pb, Ce and Th by XRF after Kaye (1965). The precision is better than 15% for V, Cr , Ni, better than 10% for Co, Cr, Y, Zr, Ba, and better than 5% for all the other elements. The accuracy has been tested on international standards and is better than 10%.

Co	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr	Nb	Ba	La	Pb	Ce	Th
13	21	12	79	23	160	161	36	190	13	615	37	31	70	13
7	8	9	67	23	104	221	23	169	11	454	24	21	46	10
7	5	12	68	20	129	165	21	209	12	782	33	27	45	12
5	8	9	61	20	127	181	25	229	13	1088	34	24	69	15
13	12	11	74	23	108	191	27	159	12	309	29	29	40	11
12	15	15	75	23	118	220	21	184	15	591	43	22	45	10
15	23	21	93	20	134	270	36	210	13	875	47	19	89	11
18	17	26	81	24	140	240	37	149	10	748	46	51	45	18
11	21	29	102	23	139	259	32	153	13	949	35	49	29	18
18	22	36	102	24	167	253	53	231	16	696	62	45	72	26
10	29	30	94	24	214	182	34	222	9	693	34	41	96	14
15	25	39	110	24	188	265	40	194	13	625	52	51	76	21
17	22	26	97	23	150	225	39	197	15	609	53	28	72	19
17	27	29	92	20	150	241	39	223	15	642	51	46	93	21
2	8	7	62	20	263	39	40	71	6	156	34	57	13	19
1	12	10	52	24	401	29	28	69	10	68	25	52	8	15
4	4	12	37	17	263	40	32	78	7	176	28	42	4	13
6	7	15	47	18	189	114	33	166	9	428	30	33	34	21
8	7	12	31	17	185	115	36	121	9	429	39	32	9	15

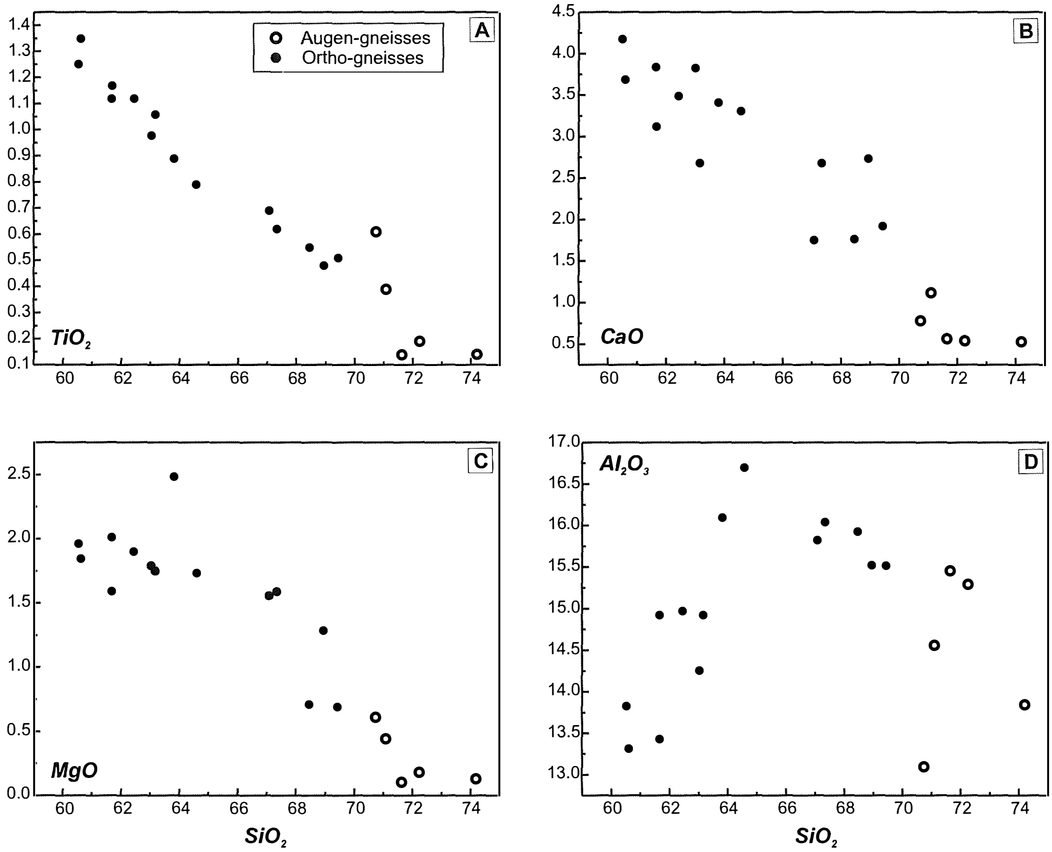

Fig. 7 – Representative inter-elemental diagrams of some major elements.

evolved to more evolved samples (Fig. 8H); augen-gneisses have the higher abundances of this element. Sr contents diminish as SiO_2 increases defining a slightly curved negative trend towards augen-gneisses.

On the whole it is noteworthy that in inter-elemental diagrams all samples (ortho- + augen-gneisses) define continuous patterns arguing in favour of common evolution processes. However, it is also evidenced that some trace elements display quite complex variation patterns as the degree of evolution of studied samples increases. The possible causes of the occurrence of such patterns are discussed in the next section.

4. DISCUSSION

Given the metamorphic events that studied rocks suffered it is not possible to use their textural and mineralogical features to constrain the possible magmatic evolution processes since metamorphism masked the original magmatic textures. On the contrary, as evidence above, geochemical criteria and, when possible, field observations can be utilised.

Several processes can be hypothesised to explain the patterns of variation of chemical elements of studied rocks. However, whatever is the process that one can envisage, it is clear

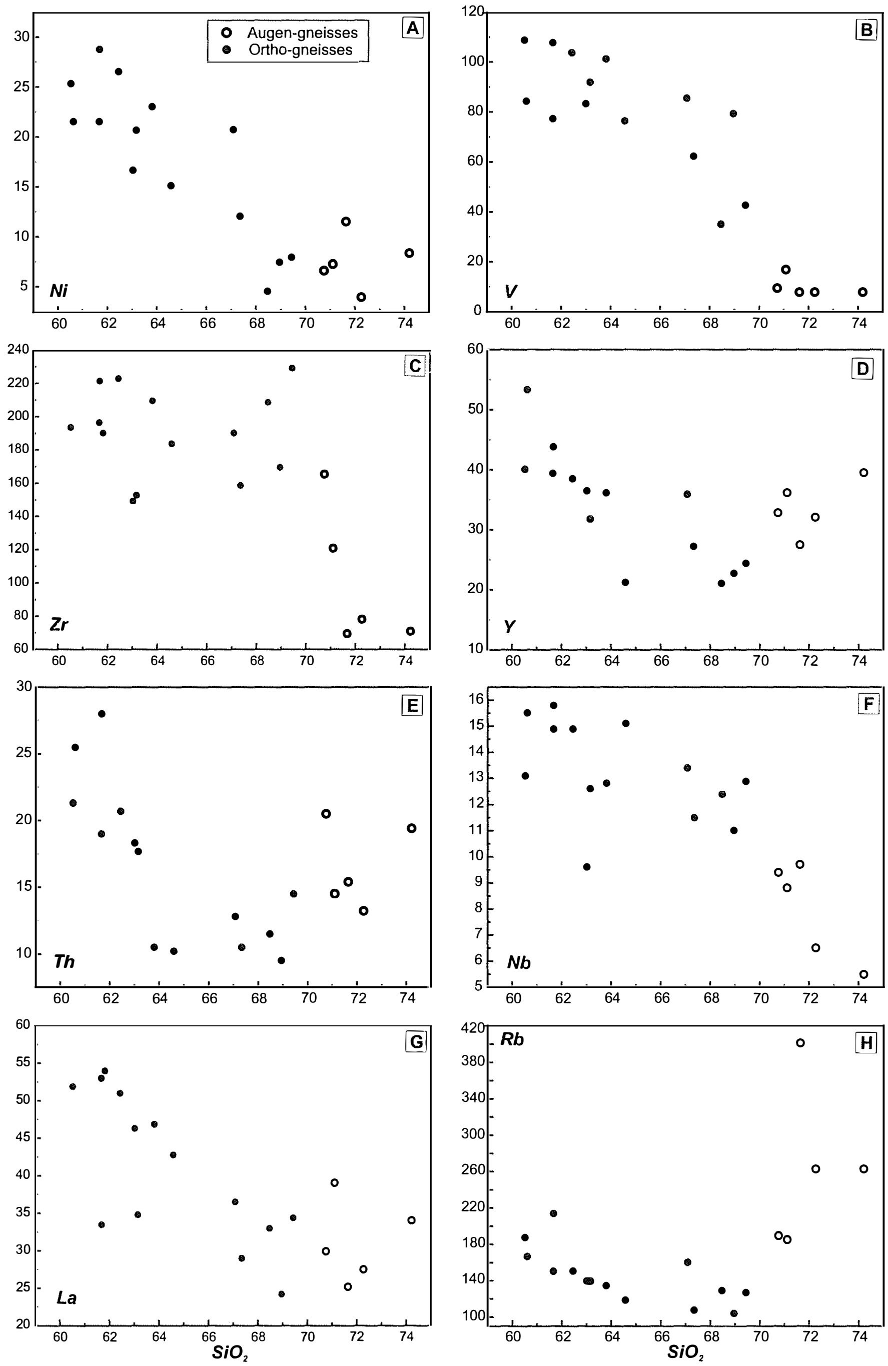

Fig. 8 – Representative inter-elemental diagrams of some trace elements.

that a single evolution process fails in giving an adequate explanation to element variations. In fact, from the variation of major and, more clearly, trace elements, some elements such as Rb, Y and Th do not follow patterns that can be derived from a single evolution process (Fig. 8). For instance, Rb, Th, and Y abundances decrease in ortho-gneisses and increase in augen-gneisses with increasing SiO_2 content (Fig. 8). Therefore, at least two evolution processes must be taken into account for the geochemical modelling of studied rocks. However, the two models should be howsoever linked because field evidence indicates that ortho-gneisses are surrounded by the more evolved augen-gneisses and contacts between the two are interdigitate.

Possible petrogenetic processes may occur as closed or open systems. Regarding closed systems, fractional crystallization is the most important process that can explain element variations of igneous rocks. Therefore, a two-stage FC process could be claimed to explain evolution of ortho- and augen gneisses, respectively. Although this process may appear at first sight reasonable from a geochemical point of view, it is not in agreement with field evidence where the occurrence of MME indicates that ortho-gneisses were generated by magma interaction processes (e.g. Didier and Barbarin, 1991; Perugini and Poli, 2000). However, a pure two end-member mixing process is not very likely to have occurred because of geochemical, rheological and thermodynamic barriers (e.g. Grasset and Albarède, 1994; Poli *et al.*, 1996). Regarding geochemistry, a two end-member mixing process requires that in inter-elemental plots rectilinear pattern should be observed for all elements; the plots of Fig. 7 and 8 indicate that this is not the case because some diagrams displays curved trends (e.g. Mg vs. SiO_2, V vs. SiO_2), and, hence, the two end-member mixing process can be ruled out. Regarding rheological and thermodynamic barriers, many studies have shown that a pure two end-member mixing process is not likely to occur between magmas having different rheologies and thermodynamic properties (e.g. Grasset and Albarède, 1994; Poli *et al.*, 1996). On the contrary, the interaction process between a felsic and a mafic magma induces the felsic magma to be superheated by the mafic magmatic mass while the mafic magma undergoes fast cooling and starts to crystallize (e.g. Sparks and Marshall, 1986; Huppert and Sparks, 1988; Poli *et al.*, 1996).

On the basis of these considerations, we attempt to model evolution of ortho-gneiss protolith by a Mixing plus Fractional Crystallization process (MFC). Note that MFC model is mathematically analogous to the Assimilation plus Fractional Crystallization (AFC) model of De Paolo (1981). However, there is an important conceptual difference between the two models because the MFC process occurs between two liquids/crystal mush, whereas the AFC requires that the assimilant is a solid rock.

Regarding augen-gneisses, the lacking of MME and the absence of crustal xenoliths indicates that open system processes such as magma interaction or assimilation may have played a minor role in the evolution of their protolith. Therefore, we attempt to model their evolution by fractional crystallization.

Fig. 9 shows the quantitative geochemical models discussed above. Cobalt has been chosen as differentiation index because this element discriminates well the geochemical evolution of studied rocks. Regarding the MFC model the felsic end-member is considered as having a geochemical composition similar to the least evolved augen-gneiss sample (SP 412; table 1). Regarding the mafic end-member, its original composition is actually quite hard to recover because of the impossibility to collect and analyse MME and the lacking in the sampled area of mafic bodies that may be interpreted as the less evolved end-member. However, the geochemical composition of the least evolved ortho-gneiss sample can be considered as the most similar to the least evolved magma (SP 399; table 1). Regarding the FC process, the parental magma is considered to be similar to the least evolved

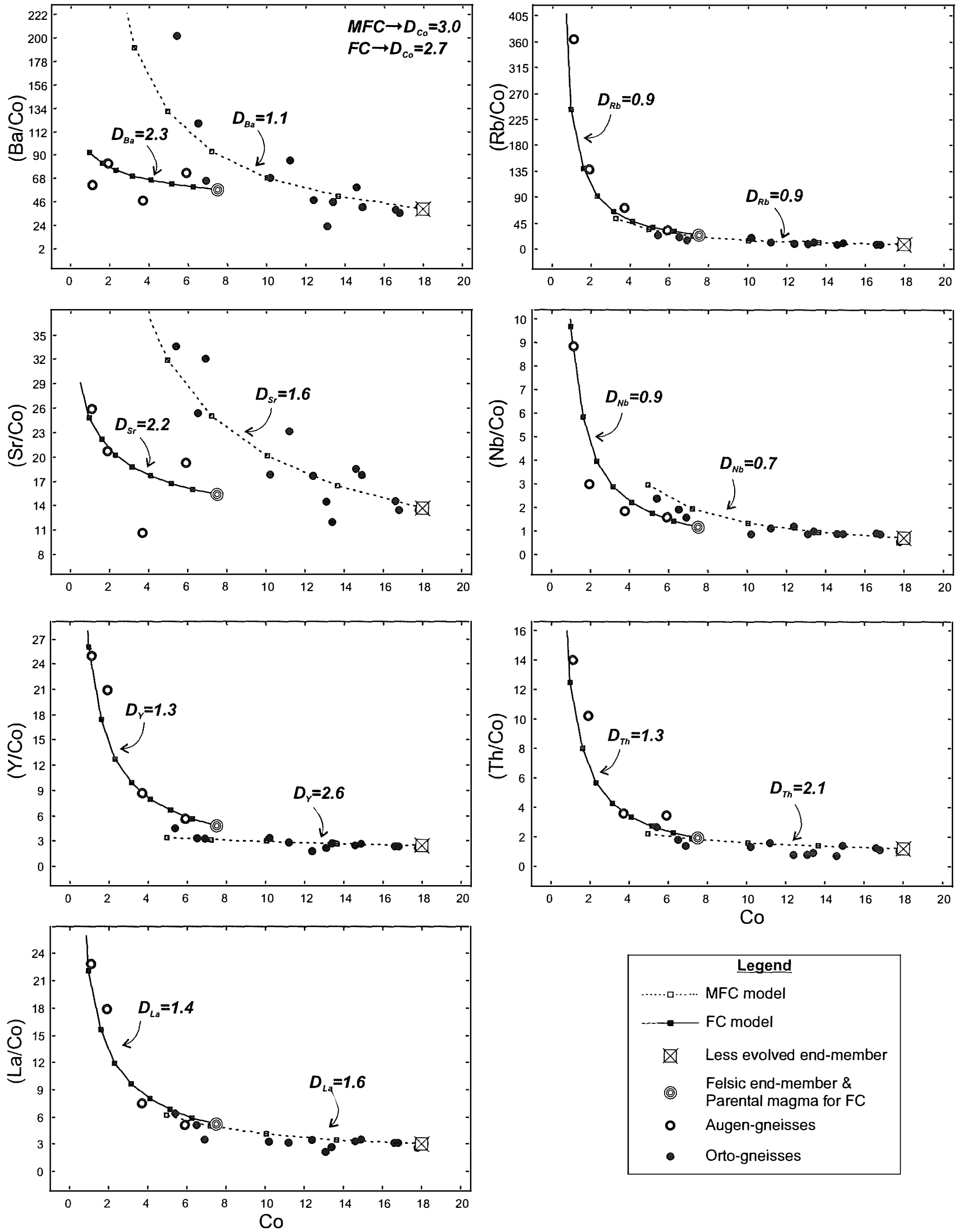

Fig. 9 – Mixing plus Fractional Crystallization (MFC) and Fractional Crystallization (FC) modelling. In the plots are also reported values of bulk partition coefficients for the modelled elements. Increments in the MFC and FC model are equal to 10% (F=0.1).

augen-gneiss sample (SP 412; table 1). From the graph it can be seen that the modeling can be considered satisfactory indicating that the envisaged geochemical evolution explains the trace element variation in studied rocks. Bulk partition coefficient utilised to fit the various elements by MFC and FC process are reported in the graphs. Using literature crystal/liquid partition coefficients (Table 2) and the modelled bulk partition coefficients, a mineralogical assemblage was calculated using a least square method. Such assemblage is consistent with that of granitoid rocks having geochemical composition analogous to studied gneiss samples. The value of *r*, that is the rate of mixing over the rate of fractional crystallization (De Paolo, 1981), required by the MFC model is equal to 0.2 and this indicates the major role played by fractional crystallization with respect to the mixing process. This indication is consistent with the quantities of MME (< 1%) that have been observed in the studied rocks.

It is worth noting that MME in the studied rocks are the only evidence of the occurrence of magma interaction processes and no flow structures, generated by the intimate commingling of the mafic and felsic magma, are observed, as in many calc-alkaline granitoid complexes (e.g. Poli and Tommasini, 1991; Perugini and Poli, 2000). Conversely, in volcanic environment such flow structures are typically associated to magmatic enclaves (Perugini *et al.* (2002). Although the absence of flow structures related to magma interaction in granitoid rocks is still matter of debate, recent studies have shown that this occurrence may be stictly related to the kinematics of the magma interction process. In detail, Perugini *et al.* (2002) and Perugini *et al.* (2003) have shown that magma interaction is a non-linear process characterized by the occurrence, within the same system, of chaotic regions in which magmas interact very efficiently producing large portions of magmas having variable degree of hybridisation (Active Mixing Regions, AMR) and regions in which magmas do not undergo efficient mixing (Isolated Mixing Regions, IMR). Within AMR, the mixing process, induced by powerful stretching and folding dynamics, generates flow structures where the mafic and the felsic magma are in contact along wide contact surfaces. On the contrary, within IMR the magmas maintain a globular shape and do not suffer strong deformation. Following these considerations MME have been interpreted as Isolated Mixing Regions in which the mixing dynamics were much less efficient than in the rest of the system and survived the mixing process (e.g. Flinders and Clemens, 1996; Perugini *et al.*, 2002). Accordingly, in Active Mixing Regions, the wide contact surfaces between magmas allow chemical diffusion processes to operate very efficiently generating in short times volumes of magmas with high and variable degrees of hybridisation (Perugini *et al.*, 2002). These considerations explain the reason of the common absence of flow structures in granitoid rocks and the common presence of MME and justify the presence of only MME in studied rocks.

Concluding, fig. 10 reports a sketch that illustrates the possible geological scenario in

TABLE 2

Crystal/liquid partition coefficients from compilations of Henderson (1982), Sawka (1988), Rollinson (1993), and GERM database (available on-line at http://earthref.org/). Bi: biotite; Kf: K-Feldspar; Ti: titanite; Plg: plagioclase; Ap: apatite; Zr: zircon.

	Bi	Kf	Ti	Plg	Ap	Zr
Ba	5,4	6,12	-	-	-	-
Nb	6	-	7,6	-	-	-
Rb	8	0,9	-	0,06	-	-
Sr	0,12	3	-	5,8	-	-
Y	0,46	-	-	-	40	100
Th	-	-	17	-	17	91
La	-	-	60	-	46	3,3
Co	30	-	-	-	-	-

which the petrogenetic evolution of studied rocks occurred. We consider a magma chamber in which a magma with geochemical composition similar to the least evolved augen-gneiss samples is resident. At some time, a less evolved magma intrudes the chamber and the interaction process (Mixing plus Fractional Crystallization, MFC) with the resident magma occurs (Fig. 10A). The interaction process develops in the core region of the magma chamber (Fig. 10A and B) and generates, with the passing of time, magma batches with the geochemical composition of ortho-gneiss samples containing MME (Fig. 10D). While the core region of the magma chamber undergoes the MFC process, in the peripheral regions the felsic magma undergoes fractional crystallization (Fig. 10C) generating the compositional spectrum of augen-gneisses. At the end of the process a zoned magma chamber is produced (Fig. 10D) with the outer portions represented by magmas evolved by FC and with the core region that recorded MFC processes.

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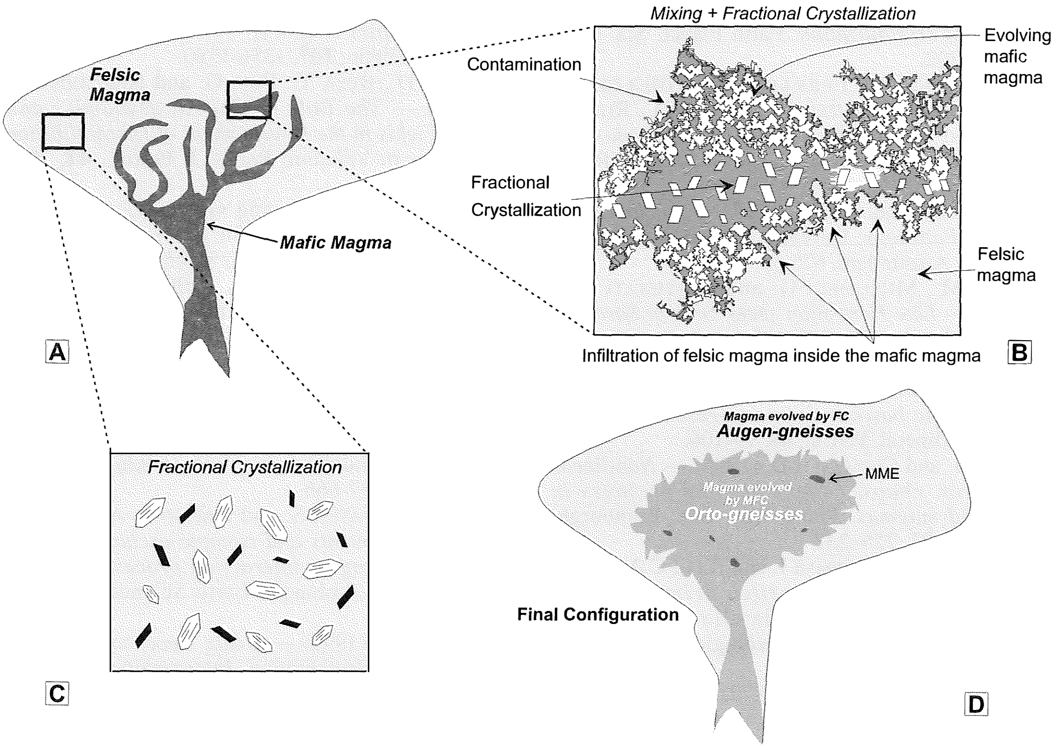

Fig. 10 – Schematic evolution of the magmatic system (see text for details).

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