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RARE-EARTH AND LARGE-ION-LITHOPHILE ELEMENT FRACTIONATION IN LATE-HERCYNIAN GRANITE MASSIF OF THE BIELLESE AREA (SOUTHERN ALPS, ITALY)

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ABSTRACT. — Rare-earth, large-ion-lithophile and Zr-Hf element distributions confirm that the Biellese late-Hercynian granite massif is a zoned complex with W-E differentiated trend, produced by only one intrusive event at meso-epiplutonic setting.

The main gradual variations from mesoplutonic monzo- and syenogranites to epiplutonic syenogranites are: *a*) the decrease of the total REE content (correlated to considerable systematic light REE impoverishment) and also of Ba, Sr, Zr and Hf contents; *b*) the increase of the Rb and Cs amounts; *c*) the U-impoverishment, which denotes the intense weathering process in the massif.

The origin of the relatively *b*- and *a*-type granites is explained by fractional crystallization of a calc-alkaline granitic magma, which results by the partial melting of the late-Ordovician granitoid masses of the « Lakes series » zone.

The depth at which the granitic magma is generated from the melting of cintinental crust is greater than the different levels of intrusion. The high crust thickness (⩾ 30 km), deduced by Rb and Sr correlated contents, agrees with late-orogenic setting of the Biellese granite massif.

RIASSUNTO. — Il massiccio granitico del Biellese manifesta un graduale frazionamento nella distribuzione delle terre rare, degli elementi a largo raggio ionico, di Zr e Hf, che appare essere in diretta relazione con la evoluzione W-E della differenziazione dei litotipi fondamentali e dei diversi livelli di loro messa in posto.

Le principali variazioni notate dai monzo-sienograniti mesoplutonici ai sienograniti epiplutonici sono: *a*) diminuzione del contenuto totale di terre rare (correlata al sistematico impoverimento delle terre rare leggere) e dei tenori di Ba, Sr, Zr, e Hf; *b*) aumento dei tenori di Rb e Cs; *c*) impoverimento di U per mobilizzazione, che denota l'alto grado di alterazione superficiale del corpo granitico esposto.

L'origine dei diversi tipi granitici, formatisi in conseguenza di un unico evento intrusivo, è ricondotta a cristallizzazione frazionata di un magma persiliceo e calc-alcalino, derivato in età tardo-ercinica dalla fusione parziale di granitoidi tardo-Ordoviciani nei terreni della « Serie dei Laghi ».

La profondità a cui il magma si è generato per fusione di crosta continentale è più elevata di quella dei livelli di intrusione granitica. L'alto spessore crostale (⩾ 30 km), dedotto dai correlati contenuti di Rb e Sr, è in accordo con una messa in posto tardo-orogenetica del corpo granitico del Biellese.

Geological setting

The plutonic massif of Biellese (Piemont, Italy), fig. 1, belongs to late-Hercynian «Lakes» granites of the Southalpine domain in the sector of the Western Alps.

This region is located on the inner side of the Insubric Alpine tectonic line and characterized mainly by a pre-Westphalian crystalline basement (known as « Massiccio dei Laghi») of metamorphic grade decreasing from NW to SE (ranging from granulites facies in the « Ivrea-Verbano » zone to staurolite-zone in the « Lakes series ») and by an unmetamorphosed covering, comprising Carboniferous strata at the base, Permian volcanites, Mesozoic sedimentary sequence in slices and late-Alpine molasse (BOCQUET et al., 1978; BIGIOGGERO & COLOMBO, 1981).

Granitic bodies elongated in NE-SW direction, well-known as Montorfano, Mottarone-Baveno, Quarna, Roccapietra-Alzo, Valsessera and Biellese masses, are placed in the western part of the« Lakes series »; specifically Montorfano and Mottarone-Baveno granites are between the two relative subunits «Strona-Ceneri» (mostly composed by metapsammites and augen-gneisses) and « Scisti dei Laghi » (mostly pelitic and semi-

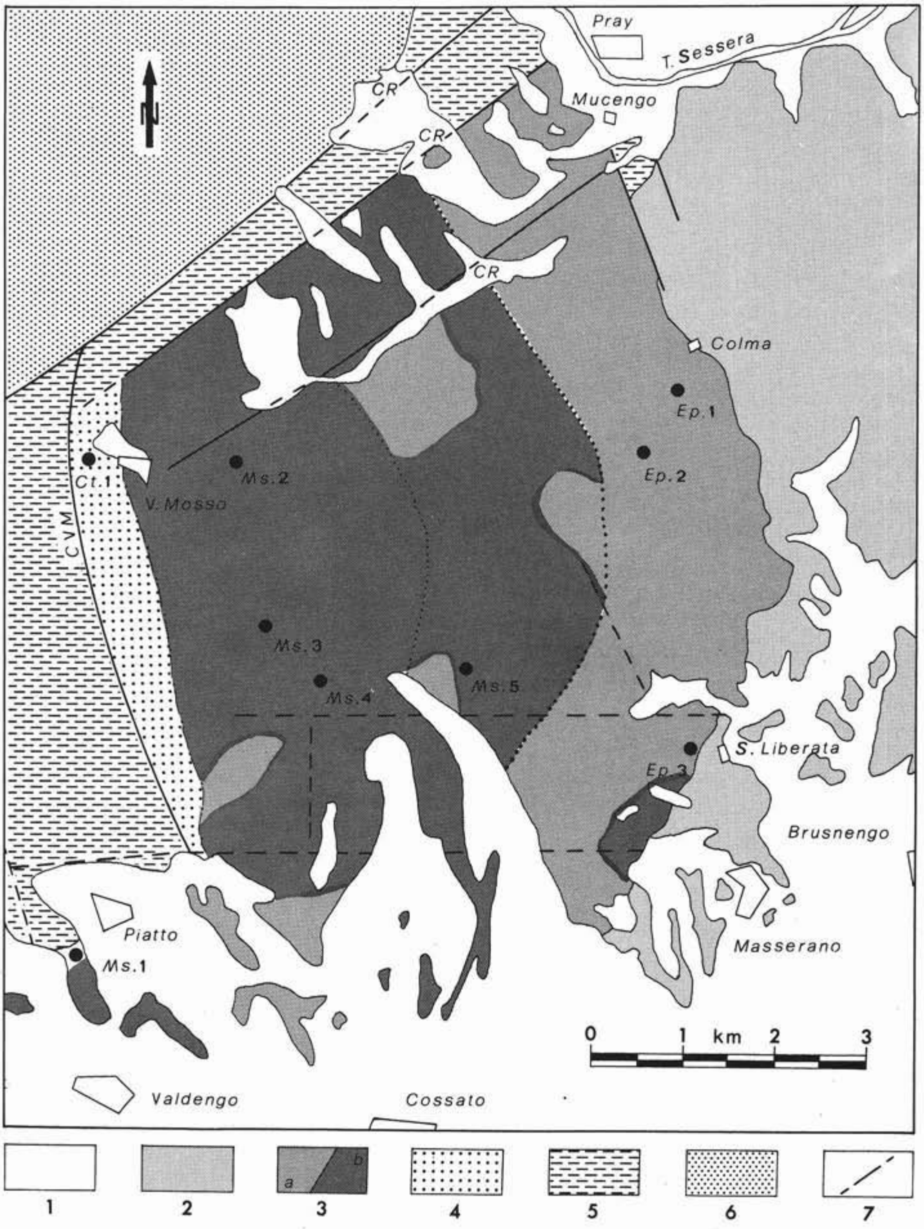

Fig. 1. — Geo-petrographic sketch-map of the Biellese granite massif, with location of the samples for geochemical analyses: 1) Quaternary and Pliocene sediments; 2) late-Hercynian volcanites, mainly rhyolitic ignimbrites; 3) late-Hercynian plutonites, a = syenogranites, b = monzogranites; (······) epiplutonites-mesoplutonites boundary; (·········) differentiated mesoplutinites facies; 4) paragneisses and migmatites of the Strona-Ceneri Zone; 5) and 6), respectively, metapelites and basites of the Ivrea-Verbano Zone; 7) faults: CR = Cremosina (late-Alpine age); CVM = Cossato-Valle Mosso (pre-Hercynian age).

pelitic metasediments and orthogneisses), bounded at W by « Pogallo-lake Orta » late-Hercynian tectonic line (BORIANI, 1970); while Quarna, Roccapietra-Alzo, Valsessera and Biellese granites are more or less near at limit with the « Ivrea-Verbano » zone, represented by « Cossato-Valle Mosso-Brissago » pre-Hercynian tectonic line (BORIANI & SACCHI, 1973).

The relative palaeogeographic setting can be recognized within Neo-Europa Hercynian chain, in the Alpine-Provencal-Sardo-Tuscan-Calabrian Zone, interpreted as a southward branch of the Moldanubian metamorphic Zone (VAI, 1979).

The Biellese massif, exposed over an area of approximately 9 × 7 km, together with Valsessera and Roccapietra-Alzo granitic masses make a single ellipsoidal plutonic body (about 20×7.5 km), elongated in NNE-SSW direction, which has been broken up and crossing dislocated in Alpine age by the tectonic lines of the Cremosina system.

Passive stoping may be the dominant mechanism of emplacement for these intrusions, with a general epiplutonic character (D'AMICO & MOTTANA, 1974); but the different formations at western and eastern contacts, the compositional evolution and the abundance of the myarolitic cavities towards the eastern upper parts of the granites are index of the W-E ranging meso-epiplutonic facies,especially for Roccapietra-Valsessera-Biellese masses (ZEZZA, 1977).

Various isotopic age determinations on the some « Lakes » granites (Rb-Sr: Bi 274 m.y. and Kf 275 m.y.; K-Ar: Bi 268 m.y., JÄGER & FAUL, 1959; U-Pb: Zir 253-273 m.y., PASTEELS, 1964; Rb-Sr: total rock 276 ± 5 m.y., HUNZIKER & ZINGG, 1980) an rhyolites (Rb-Sr: total rock 269 ± 13 m.y., HUNZIKER, 1974) of the « Lakes series » show that the Hercynian comagmatic intrusive and extrusive products are pratically coeval.

The primary direct contact between Hercynian granites and rhyolites in the Southern Alps, which is well-exposed only in the Biellese district, has been interpreted as a probative element both of: *a*) the brief antecedence of the plutonites (BERTOLANI, 1959) or, better, of the volcanites (BALCONI, 1963; BALCONI & ZEZZA, 1965; ZEZZA, 1977) emplacement; and of, *b*) the existence of two granite generations, the former beeng most developped and pre-volcanic of pre-middle Westphalian age, the latter intra-volcanic of Permian age (BORTOLAMI, 1965).

Petrographic data

The Biellese granite complex was affected by intense weathering processes, that have produced diffuse and thick (to 4÷5 m) semi-coherent covering. Limonite, goethite and hematite are responsible for variation from yellow to reddish-brown of the white-grey colour of the granitic mass. Its composition is fairly homogeneous and comparable with that of granites s.s.: b-type granite (or monzogranite) and a-type granite (or syenogranite) which are zoned with W-E evolution. Uncommon differentiated spots from few dm^2 to some m^2 of granodiorite, quartz-syenite and deuterized granite fade into the main body.

This zoneographic sequence, from the western contact with the paragneisses of « Strona-Ceneri » zone to the eastern one with Hercynian volcanites, reflects the following characters.

1. Structural and textural modifications, comprising compact, pseudoporphyritic and fine-medium as well as medium-coarse-grained facies in the western-central sectors of the massif, and prevalently massive and/or myarolitic medium-grained facies, hypidiomorphic or granophiric in the eastern part. Here is possible to observe structural effects of the peripheric cooling granitic body against volcanites, and homogeneous recrystallization of the groundmass rhyolitic ignimbrites, that are also injected by late-Hercynian porphyritic microgranite, pegmatite and quartzite dykes.

Moreover, cataclastically deformed structural types are present in northern side, striked by the tectonic lines of the Cremosina system.

2. Gradual variations of the mode, which denote three bands of monzogranite, monzo-syenogranite and syenogranite types, 3 - 2 - 2 km thick respectively (table 1).

TABLE 1
Mode of the Biellese granite

granites		b-type	b, a-types	a-type
samples		$\bar{x}_{28}$	$\bar{x}_{22}$	$\bar{x}_{30}$
qz		30.2%	32.2%	34.7%
kf		32.0	34.7	37.3
pl	An < 5	2.7	2.9	3.3
	An > 5	25.9	23.2	20.1
bi		7.0	6.2	3.9
ms		1.6	0.3	0.3
acc		0.6	0.5	0.4
M		9.2	7.0	4.3
Q		33.3	34.6	36.4
A		38.2	40.4	42.6
P		28.5	25.0	21.0

These granite types show aspects of pneumatolitic and hydrothermal alterations. Quartz is often fractured and filled with sericite and limonite. K-feldspars are prevalently microcline in the western band, microcline-orthoclase (mildly sericitized) in one intermediate and only cripto- or microperthitic orthoclase (sericitized, hematized and sometimes tourmalinized) in the eastern band. Albite $An_{2\text{-}5}$ of deuteric stage forms chess-boards and thin rims around plagioclases. The plagioclases $An_{6\text{-}35}$ are mildly sericitized. A poor amount of plagioclase has resister characters, as the biotite, frequently deformed and chloritized. Muscovite is primary.

A part from common zircon, apatite and magnetite, other minor constituents show a discriminated distribution: relic crystals of allanite and garnet appear occasionally into western and eastern sectors respectively; whereas tourmaline, fluorite and hematite are present in syenogranites, specially near the contact with volcanites.

Color index and ratio between normal and leucocratic facies (2.1 for monzogranites, 0.7 for syenogranites) are decreasing with the differentiation.

3. The chemical features of representative analyses (table 2) are compatible with typical granitic calc-alkaline differentiation trend (ZEZZA, 1977).

The modified Larsen index (*MIL* = 1/3 Si + K-Ca-Mg; NOCKOLDS & ALLEN, 1953) and the differentiation index (*DI* = Qz + Or + Ab; THORNTON & TUTTLE, 1960) gradually range respectively from 12.2 to 15.2 and from 84.3 to 94.2 into monzo-syenogranites series.

Variation diagrams of element contents as a function of *DI* and *MIL* show for Si and K positive correlations and for the other major element oxides or cations negative correlations. The linear correlation coefficients between cation v. *MIL* are about 0.90 for Si, Al, Fe and Ca; 0.70÷0.60 for Ti, P, Na and Mg; only 0.06 for K. Weathering is responsible of the last unsatisfactory coefficient. The surplus of H_2O^+-content walued by MIELKE & WINKLER'S mesonorms (0.83 average residue H_2O^+, 0.11÷1.32 range) and C-normative value equal to 1.82 ranging from 0.19 to 3.45) are indexes of the weathering intensity.

In fact, considering the dosed amount of K and K-content derived from the transformation of C-norm in K-feldspar (sum expressed as K*), the linear correlation coefficient raises to 0.63 for K* v. *MIL* and to 0.85 for K* v. *MIL** (*MIL* = 1/3 Si + K*-Ca-Mg).

The phase relations deduced from the isobaric system Qz-Ab-Or-An-H_2O at P_{H_2O} = 5 kb (WINKLER et al., 1975; WINKLER & BREITBART, 1978) and at P_{H_2O} = 1 kb (JAMES & HAMILTON, 1969) indicate an almost homogeneous sequence of crystallization at different low temperatures, from 670°÷675° C for mesogranites to 725°÷750° C for epigranites (see, fig. 2).

The limit meso-epiplutonites is mineralogically marked by the presence of microcline-free granite and disappearance of the anatectic relics of plagioclase into less deep level.

The granites are thought (ZEZZA, 1977) to come from a palingenetic magma, produced by melting of late-Ordovician granitoid masses of the « Lakes series » zone. Ortho-

TABLE 2

Chemical analyses, MIELKE & WINKLER'S *mesonorms and C.I.P.W. norms (weight percent) of the Biellese Hercynian granites*

	Ms.1	Ms.2	Ms.3	Ms.4	Ms.5	Ep.1	Ep.2	Ep.3
SiO_2	66.20	68.39	69.37	70.45	70.31	75.00	76.41	74.38
Al_2O_3	16.39	16.27	15.27	16.03	15.58	14.09	12.77	14.45
Fe_2O_3	1.31	2.08	2.95	0.67	0.69	1.60	0.45	1.17
FeO	1.50	0.61	0.20	1.63	1.26	0.14	0.73	0.30
MnO	0.03	0.09	0.11	0.09	0.09	0.03	0.08	tr
MgO	0.50	0.19	0.32	0.51	0.54	0.11	0.16	0.18
CaO	1.72	2.33	1.41	1.60	0.98	0.98	0.22	0.32
Na_2O	5.43	3.87	4.02	3.91	4.06	2.92	3.76	3.93
K_2O	4.14	5.17	4.12	4.10	4.99	3.96	4.30	4.39
TiO_2	0.61	0.20	0.22	0.12	0.06	0.05	0.05	0.15
P_2O_5	0.15	0.11	0.11	0.08	0.13	0.10	0.04	–
H_2O^+	1.79	0.21	1.41	0.47	0.94	1.12	0.74	0.88
H_2O^-	0.31	0.26	0.28	0.29	0.30	0.25	0.25	0.05
	100.08	99.78	100.09	99.95	99.93	100.35	99.96	100.20
MIL	12.22	13.16	13.07	12.94	14.06	14.20	15.21	14.89
MIL*	12.38	13.42	14.52	14.82	15.61	16.66	16.46	16.93
M.W. mesonorm								
Qz	15.48	21.39	27.79	28.79	25.84	41.02	37.70	34.01
Or	21.75	29.10	23.09	21.16	26.87	22.90	24.23	25.06
Ab	45.99	32.78	34.05	33.12	34.39	24.73	31.85	33.29
An	7.55	10.84	6.27	7.41	4.01	4.21	0.83	1.59
C	0.19	0.32	1.89	2.43	2.02	3.45	1.62	2.64
Bi	4.36	2.45	1.99	5.20	4.37	0.82	2.03	1.43
Mt	1.90	–	–	0.97	1.00	–	0.65	–
Ilm	0.58	0.19	0.21	0.11	0.06	0.05	0.05	0.14
He	–	2.08	2.95	–	–	1.60	–	1.17
Ap	0.35	0.26	0.26	0.19	0.31	0.27	0.09	–
$Rest_{H_2O^+}$	1.61	0.11	1.32	0.27	0.77	1.08	0.66	0.82
Qz	17.0	22.8	31.5	31.8	28.4	44.2	39.8	36.2
Or	24.0	30.9	25.3	23.4	29.5	24.7	25.6	26.7
Ab	50.7	34.8	37.3	36.6	37.7	26.6	33.7	35.4
An	8.3	11.5	6.9	8.2	4.4	4.5	0.9	1.7
C.I.P.W. norm								
Qz	14.47	21.16	27.36	26.98	24.26	40.90	37.04	33.79
Or	24.46	30.54	24.34	24.22	29.48	23.39	25.40	25.93
Ab	45.92	32.73	33.99	33.06	34.33	24.69	31.80	33.23
An	7.55	10.84	6.27	7.41	4.01	4.21	0.83	1.59
C	0.21	0.34	1.90	2.45	2.03	3.46	1.63	2.66
Hy	1.96	0.47	0.80	3.68	3.16	0.27	1.43	0.45
Mt	1.90	1.68	0.37	0.97	1.00	0.40	0.65	0.53
Ilm	1.16	0.38	0.42	0.23	0.11	0.09	0.09	0.28
He	–	0.92	2.70	–	–	1.32	–	0.80
Ap	0.35	0.25	0.25	0.19	0.30	0.23	0.09	–
DI	84.85	84.43	85.69	84.26	88.07	88.98	94.24	92.95

gneisses, connected with metamorphic phase of 325m.y. radiometric age (Rb-Sr, muscovite age) and derived from tonalite to granite intrusions of 466 ± 5 m.y. (Rb-Sr total rock age) of crustal origin ($^{87}Sr/^{86}Sr$ initial ratio equal to 0.7087), are one of the characteristic type rocks of both « Lakes series » subunits: « Strona-Ceneri » and « Serie dei Laghi » (BORIANI et al., 1982-83).

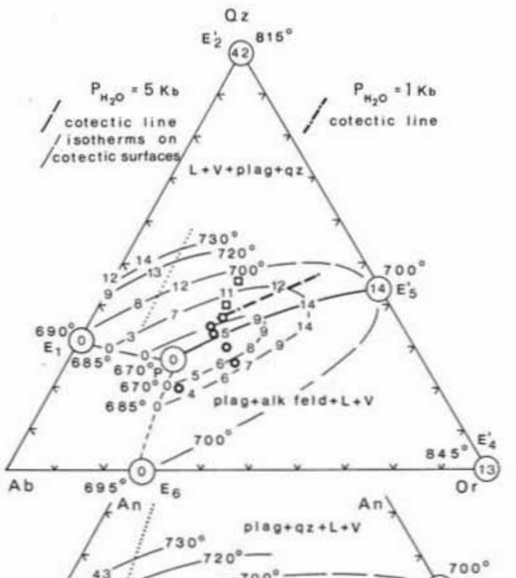

Fig. 2. — Representative points (mesonorms according to MIELKE & WINKLER, 1979) of the epiplutonic (□) and mesoplutonic (○) Biellese Hercynian granites into two planes of the isobaric system Qz-Ab-Or-An-H_2O at $P_{H_2O} = 5$ kb (WINKLER et al., 1975, 1978) and at $P_{H_2O} = 1$ kb (JAMES & HAMILTON, 1969).

Geochemical data

Analyses for REE and Cs, Rb, Ba, Sr, Th, U, Zr, Hf were made on related eight selected samples, representative of the main facies and lithotypes of the Biellese granite (Ms.1÷Ms.5 mesogranites, Ep.1÷Ep.3 epigranites), already utilized for the determination of the major elements, as well as on a specimen (Pr.1) of paragneiss from the « Strona-Ceneri » zone (see fig. 1).

Analytical procedure

Rare-earth elements (REE), large-ion-lithophile elements (LILE) and Zr-Hf contents have been analyzed by instrumental neutron activation tecnique following procedure described by MELONI et al. (1982).

Nuclear data on above-mentioned elements and concentrations (ppm) obtained for the following standard rocks: USGS-AVG-1 (andesite), USGS-G-1 (calc-alkaline granite), ANRT-GS-N (calc-alkaline granite), are presented in Table 4 *a* and 4 *b*).

Irradiations on the standard rocks and Biellese specimens (usually 300 mg samples were inserted into polythene vials for irradiation) were carried out at the Triga Mark II reactor of the University of Pavia. Irradiations of 30 h at a thermal flux of about 1.2×10^{12} n $cm^{-2}sec^{-1}$ were followed by decay times of 6÷40 days before being submitted to radioactivity measurements.

Induced radioactivity was measured (count-time at 500″ to 3000″) by gamma spectrometry by using a 18 % efficiency Ortec Ge(Li) detector (2.1 KeV FWHM at 1332 KeV from peak of ^{60}Co) coupled to analyzer-computer Laben 701. The average precision of two determinations is 8 %.

Rare-earth elements

Analyses of ten REE are given in Table 3, and their normalized values according to HERRMANN'S (1970) average chondrite abundances are shown in fig. 3 and 4.

The amounts of the total REE, partial light-REE include Pr, Ho, Er, Tm amounts obtained by interpolating values on the chondrite normalized patterns (Table 3).

The lanthanides patterns exhibit some constant characteristics and a systematic compositional evolution through the whole granitic complex.

1) Total REE content varies significantly from 359 ppm to 125 ppm; the decreasing is mainly correlated to considerable systematic light REE impoverishment from mesoplutonic monzo- (320÷157 ppm) and syenogranites (197 ppm) to epiplutonic syenogranites (88÷86 ppm).

2) The heavy REE (22÷48 ppm) gradually increase: respectively 21÷41 ppm, 41 ppm and 37÷38 ppm in the above mentioned granite groups.

3) The degree of fractionation, expressed by La_n/Yb_n normalized ratio, decreases from 13.3÷7.0 to 5.3 in mesoplutonic monzo- and syenogranites until 2.3÷1.8 in epiplutonic syenogranites.

4) Eu-anomalies, valued as Eu/Eu* ratio, are defined by the chondrite-normalized

TABLE 3

REE abundance (ppm), by instrumental neutron activation analysis, in paragneiss (Pr.1) of the crystalline basement and Hercynian granite massif of the Biellese area

	Pr.1	Ms.1	Ms.2	Ms.3	Ms.4	Ms.5	Ep.1	Ep.2	Ep.3
La	14.6	31.9	39.8	68.6	48.0	39.0	17.5	17.3	17.6
Ce	58.9	63.1	85.0	168.1	103.9	85.4	33.1	30.9	34.2
Nd	35.5	45.0	28.6	55.3	52.0	51.0	23.6	24.8	24.5
Sm	9.43	5.71	7.87	10.60	9.48	9.43	7.85	7.25	6.07
Eu	1.67	2.51	1.66	2.03	1.35	1.12	1.49	1.25	1.21
Gd	21.03	7.40	8.39	14.60	14.25	13.67	16.23	14.39	11.47
Tb	2.17	0.96	1.08	2.26	2.07	1.66	1.84	1.35	1.23
Dy	15.53	5.38	6.80	11.47	11.93	11.18	12.24	11.72	9.78
Yb	5.84	2.71	2.41	3.05	3.38	4.40	5.87	4.81	4.62
Lu	0.81	0.42	0.44	0.45	0.48	0.41	0.93	0.78	0.74
REE	185.45	178.63	195.35	359.42	266.97	237.10	136.24	128.91	124.81
LREE	127.42	156.74	170.85	319.63	226.37	196.51	87.98	85.94	88.21
HREE	58.03	21.89	24.50	39.79	40.60	40.59	48.26	42.97	36.60
La_n/Yb_n	1.49	6.97	9.80	13.32	8.43	5.25	1.77	2.14	2.26
Eu/Eu*	0.40	1.30	0.71	0.57	0.40	0.34	0.45	0.42	0.50

Eu value and Eu* value interpolated on the straight line from Sm to Gd; these are positive only for deuterized monzogranitic facies, and sharply negative for normal facies: Eu/Eu* is equal to 0.71-0.40, 0.34 and 0.50÷0.42 respectively in meso-and epiplutonic b- and a-type granite rocks. It is worth noting that negative Eu anomaly increases fundamentally with the decrease of the degree of fractionation.

5) Two slightly pronunced anomalies are shown by Ce and Tb elements, which can oxidize to Ce^{4+} and Tb^{4+}: they are slightly positive or negative in monzogranites and become moderately negative in syenogranites.

In general the lanthanides distribution reveals a remarkably systematic variation in the REE fractionations which permits a geochemical subdivision among those three

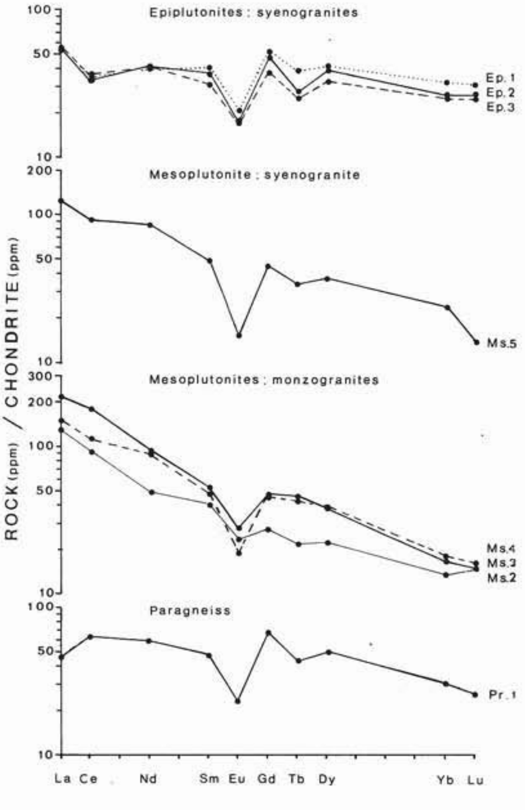

Fig. 3. — Types of lanthanides distribution through the whole complex of the Biellese Hercynian granite and paragneiss of the « Strona-Ceneri » zone.

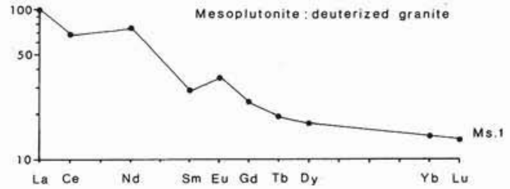

Fig. 4. — Lanthanides distribution in deuterized monzogranitic facies.

TABLE 4 *a)*

Nuclear data of the determined elements

Element	Nuclear reaction	Half-life produced nuclide	Target nuclide %	σ (barn)	Measured γ ray (KeV)	Interferences
La	$^{139}\mathrm{La}(n,\gamma)^{140}\mathrm{La}$	1.68 d	99.9	8.9	1595(100), 485(43)	$^{47}\mathrm{Ca}$, $^{115}\mathrm{Cd}$, $^{143}\mathrm{Ce}$
Ce	$^{140}\mathrm{Ce}(n,\gamma)^{141}\mathrm{Ce}$	33 d	38.48	0.6	145(100)	n.s.
Nd	$^{146}\mathrm{Nd}(n,\gamma)^{147}\mathrm{Nd}$	11.1 d	17.18	2	91(100), 531(45)	$^{161}\mathrm{Tb}$, $^{67}\mathrm{Cu}$, $^{169}\mathrm{Yb}$
Sm	$^{152}\mathrm{Sm}(n,\gamma)^{153}\mathrm{Sm}$	1.96 d	26.63	210	103(100)	$^{107}\mathrm{W}$, $^{239}\mathrm{Np}$
Eu	$^{151}\mathrm{Eu}(n,\gamma)^{152}\mathrm{Eu}$	12.2 y	47.7	5900	344(100),1408(90)	n.s.
Gd	$^{152}\mathrm{Gd}(n,\gamma)^{153}\mathrm{Gd}$	242 d	0.2	125	98(100)	n.s.
Tb	$^{159}\mathrm{Tb}(n,\gamma)^{160}\mathrm{Tb}$	73 d	100	46	879(100)	n.s.
Dy	$^{164}\mathrm{Dy}(n,\gamma)^{165}\mathrm{Dy}$	2.36 h	28.18	800	95(100)	$^{187m}\mathrm{Hf}$
Yb	$^{168}\mathrm{Yb}(n,\gamma)^{169}\mathrm{Yb}$	32.6 d	0.14	11000	64(100), 198(85)	n.s.
Lu	$^{176}\mathrm{Lu}(n,\gamma)^{177}\mathrm{Lu}$	6.75 d	2.6	2100	208(100)	n.s.
Cs	$^{133}\mathrm{Cs}(n,\gamma)^{134}\mathrm{Cs}$	2.1 y	100	30	796(90)	$^{186m}\mathrm{Ru}$
Rb	$^{85}\mathrm{Rb}(n,\gamma)\ ^{86}\mathrm{Rb}$	18.7 d	72.15	0.73	1077(100)	n.s.
Ba	$^{130}\mathrm{Ba}(n,\gamma)^{131}\mathrm{Ba}$	11.5 d	0.101	10	216(100), 496(28)	$^{97}\mathrm{Ru}$, $^{47}\mathrm{Ca}$, $^{103}\mathrm{Cu}$
Sr	$^{84}\mathrm{Sr}(n,\gamma)\ ^{85}\mathrm{Sr}$	64 d	0.56	0.6	511(100)	n.s.
Th	$^{232}\mathrm{Th}(n,\gamma,\beta^-)^{233}\mathrm{Pa}$	27 d	100	7.33	312(100)	$^{192}\mathrm{Ir}$, $^{169}\mathrm{Yb}$
U	$^{238}\mathrm{U}\ (n,\gamma,\beta^-)^{239}\mathrm{Np}$	2.35 d	99.28	2.74	278(65)	$^{167}\mathrm{Nd}$, $^{193}\mathrm{Os}$
Zr	$^{94}\mathrm{Zr}(n,\gamma)\ ^{95}\mathrm{Zr}$	65 d	17.4	0.09	756	n.s.
Hf	$^{180}\mathrm{Hf}(n,\gamma)^{181}\mathrm{Hf}$	44.6 d	35.44	1.0	482	n.s.

zones, subparallel to the major axis of the granitic massif, which were petrographically characterized before (see fig. 1 and fig. 3).

The REE distribution pattern of one paragneiss sample of the crystalline basement is nearly like as the lanthanides patterns of the epiplutonic syenogranites, with the exception of the La/Ce normalized ratio, that is lesser than one.

Large-ion-lithophile elements

Data are represented in Table 5 and partly with K correlated in fig. 5.

The average Cs content ($\bar{x}_{\mathrm{s}} = 5.7$ ppm) increases in the most differentiated granites: from 2.4 ppm of the monzogranites (including the deuterized type) to 8.9 ppm of the meso-epiplutonic syenogranites, prevalently in leucocratic facies.

These values agree with the abundance of Cs estimated by various authors (HEIER & ADAMS, 1964; BUTLER & THOMPSON, 1963) in persilicic plutonic rocks. K/Cs ratio decreases with differentiation: 21,971 and 4,700 are the averages of the two granite groups.

The differentiation process within Biellese granite complex is clearer considering the Rb abundance.

As a matter of fact the Rb content increases and K/Rb ratio decreases from monzogranites (Rb = 170 ppm, ranging from 106 to 238 ppm; K/Rb = 232, range 324÷143) to syenogranites (Rb=271 ppm, range

TABLE 4 *b*)

Contents (ppm) of ten REE, LILE and Zr-Hf in USGS and ANTR standard rocks

ELEMENT	STANDARD ROCKS								
	USGS-AGV-1			USGS-G-1			ANTR-GS-N		
	this work		FLANAGAN (1973)	this work		FLANAGAN (1973)	this work		MELONI et al.(1982)
La	34	± 2	35	99	± 1	101	71	± 4	68
Ce	61	4	63	169	4	170	129	2	130
Nd	37	3	39	53	2	56	52	3	52
Sm	5.6	0.4	5.9	7.9	0.3	8.3	7.9	0.4	7.7
Eu	1.6	0.1	1.7	1.2	0.1	1.3	1.46	0.04	1.3
Gd	5.7	0.3	5.5	5.1	0.2	5	7.1	0.3	6.9
Tb	0.73	0.06	0.70	0.61	0.03	0.54	0.54	0.06	0.55
Dy	3.7	0.2	3.5	2.2	0.3	2.4	8.1	0.3	7.39*
Yb	1.8	0.1	1.7	1.1	0.1	1.06	1.9	0.1	2.1
Lu	0.27	0.04	0.28	0.17	0.02	0.19	0.23	0.04	0.33
Cs	1.7	0.2	1.4	1.6	0.1	1.5	4.91	0.01	5.64
Rb	69	2	67	230	10	220	179	2	181
Ba	1190	10	1208	1190	10	1200	1310	40	1407
Sr	670	10	657	260	11	250	561	10	570
Th	6.21	0.08	6.41	48	1	50	42.2	0.3	43.9
U	1.61	0.02	1.88	3.01	0.02	3.4	7.41	0.02	7.3
Zr	229	3	225	216	8	210	241	10	231
Hf	5.9	0.6	5.2	5.7	0.1	5.2	4.3	0.3	4.1

* S. MELONI and M. ODDONE, unpublished data by INAA.

273÷322 ppm; K/Rb = 135.5, range 162÷121). These values are already characteristic. The perfect graduality of the two trends appears for Rb* values (113÷255 ppm for monzogranites and 273÷322 ppm for syenogranites) and K*/Rb* ratio (318÷207 and 201÷172, respectively), that consider the effects of weathering during which Rb is closely related to K (Rb_{soil}/Rb_{rock} ratio equal to 1.07; K-content derived from transformation of C-norm in K-feldspar).

Ba amount, ranging from 871 to 214 ppm, shows negative correlation with SiO_2, K and even K* contents of the Biellese granite. Therefore K/Ba ratio increases in the types with a higher K-feldspars abundance: 42÷49 in monzogranites and 55÷167 in syenogranites.

This distribution is interpreted by the tendency of Ba to captured into early K-minerals, rather than into plagioclases, of the monzogranites and by the consequent Ba impoverishment in the following differentiated syenogranites.

Fractionation Ba/Rb is coherent and, more than other parameter, emphasizes the distinction between mesoplutonic monzo-syenogranites (Ba/Rb = 7.0÷3.2 and 3.0) and epiplutonic syenogranites (Ba/Rb = 1.1÷0.8).

Positive correlations with Ca and negative with SiO_2 and K are also shown by Sr; the constancy of the Ba/Sr ratio, equal to 4.4±0.2 has to be noted.

The average value of Sr, $\bar{x}_N = 135$ ppm, agrees with that of all granites, 147 ppm (FAURE, 1978). Its distribution shows again a gap between the two decreasing trends: mesoplutonic monzo-syenogranites ($\bar{x}_5 = 180$ ppm, ranging from 210 to 160 ppm) and epiplutonic syenogranites ($\bar{x}_3 = 60$ ppm; 69÷49 ppm).

The relation between Rb, Ba and Sr, discussed on ternary diagram (see fig. 6) of TUREKIAN & WEDEPOHL (1961) and of EL BOUSEILY & EL SOKKARY (1975), shows a linear trend for the mesoplutonic and epiplutonic granites of the Biellese, which are respectively referred to «anomalous granites» and «strongly differentiated granites» by the

TABLE 5

LILE, Zr and Hf contents (ppm), relative ratios, also with K

	Pr.1	Ms.1	Ms.2	Ms.3	Ms.4	Ms.5	Ep.1	Ep.2	Ep.3
Cs	1.2±0.1	0.94±0.06	5.7±0.2	1.7±0.3	1.4±0.1	9.3±0.4	9.4±0.3	4.5±0.3	12.5±0.4
Rb	152±4	106±10	187±4	148±3	238±11	255±3	267±2	262±1	301±3
Ba	275±16	739±19	871±19	805±73	770±13	760±15	287±15	214±15	278±15
Sr	65±3	160±4	210±4	185±3	170±2	175±6	69±2	49±2	63±4
Ba/Rb	1.8	7.0	4.7	5.4	3.2	3.0	1.1	0.8	0.9
Rb/Sr	2.3	0.66	0.89	0.8	1.4	1.4	3.9	5.3	4.8
K	15192	34369	42919	34203	34037	41425	32874	35697	36444
K*	48329	35979	45523	48721	52755	56937	57486	48157	56772
K/Cs	12660	35563	7530	20480	24312	4454	3497	7933	2916
K/Rb	100	324	230	231	143	162	123	136	121
K/Ba	55	47	49	42	44	55	115	167	131
K/Sr	234	215	204	185	200	237	476	729	578
Th	24.6±2.2	9.7±0.5	11.6±0.3	19.8±0.9	20.8±0.8	19.4±0.3	20.3±0.1	20.5±0.7	16.8±0.5
U	1.6±0.01	0.97±0.01	n.d.	0.76±0.03	1.41±0.03	1.65±0.04	1.72±0.03	2.18±0.04	2.04±0.03
Th/U	15.4	10.0	-	25.4	14.8	11.8	11.8	9.4	8.3
Zr	310±4	382±5	357±5	361±3	271±4	239±4	200±3	210±2	171±4
Hf	7.5±0.5	9.4±0.2	8.7±0.7	8.7±0.6	6.7±0.7	5.8±0.3	4.9±0.8	5.1±0.9	4.1±0.9
Zr/Hf	41.3	40.6	41.0	41.5	40.4	41.2	40.8	41.2	41.7

K* = K-content derived from the transformation of C-norm in K-feldspar, plus K-content analyzed.

distinct impoverishment in Ba and enrichment in Rb.

Rb and Sr contents in Hercynian granite massif of the Biellese area suggest also, on the levels of Rb and Sr related crustal thickness (CONDIE, 1973; FERSHTATER et al., 1980), that the crust thickened to ⩾ 30 km during its emplacement.

The large variations of the Th/U ratio (25.4÷8.3) and relative individual values, which appear to be rather high especially for monzogranites (25.4÷10) but also for syenogranites (11.8÷8.3), can be explained by U-mobilization processes, if correlated with those of granites from various localities and of different age (ROGERS & ADAMS, 1969).

In fact the investigated granites have normal Th-concentrations (9.7÷20.8 ppm) and very low U-concentration both in mesogranites (0.76÷1.65 ppm) and in epigranites (1.72÷2.18 ppm). On the basis of the

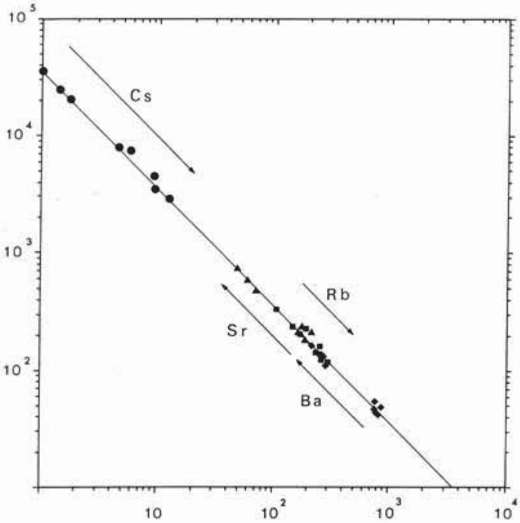

Fig. 5. — Relationship between K/Cs, K/Rb, K/Ba and K/Sr ratios and respectively Cs, Rb, Ba and Sr in Biellese Hercynian granites. The linear correlation coefficients are: 0.86 by K/Cs v. Cs (●); 0.96 by K/Rb v. Rb (■) and K/Ba v. Ba (◆); 0.95 by K/Sr v. Sr (▲).

constant ratio K/U = 10^4 into crustal products (HEIER & ROGERS, 1963), Uranium drawn out the Biellese granites by oxidation and consequent solution of the uranyl ion UO_2^{++} is at least 2÷2.26 ppm for the monzogranites and 1.4÷1.6 ppm for the syenogranites; if estimated considering K* values it is equal to 2.6÷4.1 ppm.

Zirconium and Hafnium

The distribution of Zr and Hf is not uniform but evolves into the differentiated granitic products; the contents decrease respectively from 382÷239 ppm and 9.4÷5.8 ppm in mesoplutonic monzo-syenogranites to 210÷171 ppm and 5.1÷4.1 ppm in epiplutonic syenogranites.

The Zr/Hf ratio remains fairly constant in granites of the different types and emplacement levels. It is 41, range 40.4÷41.7. This value agrees with the average Zr/Hf ratio in Hercynian granitic rocks; for example, Hercynian granites of the Central Urals (LIPOVA et al., 1957).

Conclusions

The lanthanides distribution, that in granitoid rocks is essentially determined by accessory phases (e.g. KOVALENKO et al., 1979; FOURCADE & ALLEGRE, 1981; GROMET & SILVER, 1983), confirms that the Biellese late-Hercynian granite massif is a zoned complex with W-E differentiated trend.

LILE appear the most sensitive indicators of the gradual differentiation process into granite body (Rb, especially), of the zoning levels (Sr and Ba) and of the discrimination of the two main lithotype (Cs). Moreover, U-impoverishment shows the high degree of weathering.

Also Zr and Hf contents mark the graduality of the differentiation process, denotin only one intrusive event at different crustal levels.

The depth at which the granitic magma is generated from the melting of continental crust is greater than the different levels of intrusion. The high crust thickness (≥ 30 km), deduced by Rb and Sr correlated contents (CONDIE, 1973; FERSHTATER et al., 1980), agrees with late-orogenic setting of the granite complex.

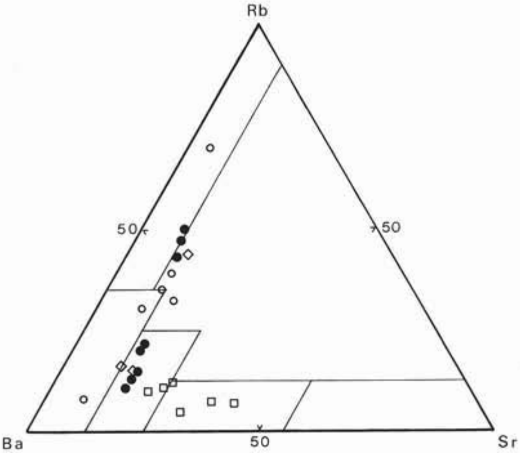

Fig. 6. — Representative points of the Biellese late-Hercynian granites (●) and of orthometamorphites of the crystalline basement (data in BORIANI et al., 1982-83): « Strona-Ceneri » augen-gneisses (○) and « Scisti dei Laghi » orthogneisses, hornblende-free (◇) and hornblende-bearing (□).

Collectively considering emplacement, petrographic features and major, minor, trace element data, the origin of the examined granite body can be explained by fractional crystallization of a persiliceous calc-alkaline magma. This magma results by the partial melting of the late-Ordovician crustal granitoid masses of the « Lake series » zone, that partly were transformed in orthogneisses during metamorphic phase of 325 m.y., and partly melted and a higher levels injected, or also deposed on surface, in the late-Hercynian orogenic events. The ternary relation Rb-Ba-Sr between investigated granites and « Scisti dei Laghi » horneblende-bearing or horneblende-free orthogneisses and « Strona-Ceneri » augen-gneisses (data in BORIANI et al., 1982-83) agrees with this hypothesis (see, fig. 6).

REE, LILE and Zr-Hf evolution trends give credit to the unity of the Biellese granite massif. The structural effects of the peripheral cooling granitic body against comagmatic volcanites are in harmony with the antecedence of extrusive products (BALCONI, 1963; BALCONI & ZEZZA, 1965; ZEZZA, 1977).

Nevertheless radiometric measurements are necessary to describe exactly the age of the emplacement of the comagmatic units in the Biellese area, where the primary direct contact between late-Hercynian granites and volcanites is well-exposed in several places.

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