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THE ORIGIN OF THE IVREA-VERBANO BASIC FORMATION (ITALIAN WESTERN ALPS) STATISTICAL APPROACH TO THE PERIDOTITE PROBLEM *****

RIASSUNTO. — L'analisi fattoriale Q-mode viene usata per verificare l'ipotesi che le ultrafemiti della formazione basica Ivrea-Verbano appartengano a due gruppi: 1) peridotiti residue da fusione parziale di materiale del mantello; 2) peridotiti formate per differenziazione gravitativa.

I due gruppi di peridotiti risultano chiaramente discriminati sulla base di tre fattori. L'interpretazione dei tre fattori mostra che il fattore 1 è discriminante tra duniti e ultrafemiti a pirosseno; il fattore 2 esprime una variazione da duniti verso peridotiti a pirosseno e orneblenda, mentre il fattore 3 discrimina sulla base del tenore in ferro dei minerali.

Tra le ultrafemiti appartenenti al mantello, quelle a flogopite, provenienti da Finero, sono distinte da quelle di Baldissero e Balmuccia o per aver subito un meno intenso impoverimento, o a causa di una contaminazione.

I trends mostrati da alcune peridotiti di origine cumulitica hanno il significato di un frazionamento. I clusters raggruppano per lo più campioni raccolti in località con limitato ambito di differenziazione (Rocca di Argimonia, La Balma, Monte Capio, Campello Monti, Cima Cavallo).

ABSTRACT. — The Q-mode factorial analysis is applied in order to evaluate the hypothesis that the ultramafites of the Ivrea-Verbano basic formation belong to two distinct groups: 1) residual material from mantle partial melting; 2) products of gravitative differentiation.

The two peridotite groups result unequivocally discriminated on the basis of three factors. A geochemical interpretation of the three factors shows that factor 1 discriminates between dunites and pyroxene-bearing ultramafites; factor 2 accounts for a variation from dunites to pyroxene (hornblende)-peridotites and factor 3 for the different iron content of the minerals.

The mantle peridotites are discriminated from those of the cumulitic sequence because of the different composition of the minerals. Within the mantle peridotites, the discrimination of the phlogopite-peridotite (Finero) from those of Baldissero and Balmuccia may be due either to a lower depletion or to contamination.

The trends of the cumulitic peridotites have the meaning of fractionation. The clusters group merely samples collected within a limited range of differentiation (Rocca di Argimonia, La Balma, Monte Capio, Campello Monti, Cima Cavallo).

Introduction

It has been recently shown that the Ivrea-Verbano basic formation in the Sesia Valley can be distinguished into two units: 1) a peridotite body (the Balmuccia peridotite) interpreted as residue from mantle partial melting; 2) an ultramafic-mafic layered series formed by gravitative differentiation (RIVALENTI et al., 1975). The

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residual peridotites are harzburgites and lherzolites, rarely dunites. The cumulitic peridotites are dunites and harzburgites, rarely lherzolites.

In the field, the residual peridotites are greysh, while the cumulitic ones are black.

Preliminary geochemical studies have shown that the residual peridotites differ from the cumulitic ultramafites of comparable mineralogy for a lower Fe and Mn content and lower Fe/Fe+Mg ratio. The composition of the minerals in the two peridotite types is also different: in the mantle peridotites, with respect to the others, olivines are more forsteritic, orthopyroxenes more enstatic and less Al-rich, clinopyroxenes more diopsidic and less Al-rich, spinels richer in Al and Mg and lower in Fe and Cr (CAPEDRI et al., 1976, and unpublished data).

In the whole basic formation, which extends from Locarno to Ivrea, there are several ultramafic bodies which, on the basis of simple field criteria and/or univariate parameters (such as the Fe/Fe+Mg ratio), may be ascribed to the residual mantle type or to the cumulitic type. This paper is aimed to check, on the basis of many chemical variables, the consistence of the discrimination between the peridotites attributed preliminarely (and tentatively) to one type or to the other and to point out which are the best discriminating variables. The results of this investigation allow to asses a higher confidence level in the attribution of unknown peridotite bodies of the same formation.

Peridotites examined and their preliminary attribution

The chemical data used in this paper are partly taken from the literature and partly are new analyses (Tab. 1).

Table 2 sets out the general characteristics of the peridotites examined and their preliminary attribution, references and locality.

While most peridotites can be easily classified on the basis of the criteria exposed in the introduction, the Finero body deserves some discussion.

According to LENSCH (1971) and VOGT (1962) the Finero body is distinguished in an inner part constituted by a phlogopite peridotite and an outer zone constituted by hornblende peridotites and gabbros. They consider both as mantle. More recently CAWTHORN (1975) re-examined the complex and interpreted both peridotites as formed by fractional crystallization from two pulses of hydrous magma: one rich in K which gives the phlogopite type, and another low in K which gives the hornblende type. Our field inspection has shown that:

1) the phlogopite type matches with the characters of the mantle peridotites of the Ivrea-Verbano formation, except for the presence of phlogopite. (Phlogopite however, is underformed, while the other minerals are, and this may support a possible late crystallization for phlogopite);
2) the hornblende peridotites are similar to the cumulitic peridotites;
3) the composition of the minerals (LENSCH, 1971; CAWTHORN, 1975) does not contrast with the possibility that the hornblende peridotite is cumulitic and the phlogopite

peridotite is residual as they show the same variations found in the two peridotite tipes of the Sesia Valley (RIVALENTI et al., 1975).

Results of the Q-mode multivariate analysis

The statistical approach chosen for grouping and discriminating the peridotites is the Q-mode multivariate method, introduced in the geological literature by IMBRIE and PURDY (1972). The method is reported in several brooks of statistical mathematics and in numerous papers (see e.g.: HARMAN, 1970; DAVIS, 1973; SHAW & HARMAN, 1975).

TABLE 1

Chemical analyses of peridotites

See Table 2 for location and attribution

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O+	Cr	Ni
Mo296	44.58	.84	6.10	21.53	.31	21.00	4.31	.37	.00	.01	.95	277	1370
Mo297	41.87	.62	4.59	19.76	.28	28.92	2.52	.38	.00	.01	1.06	150	1450
Mo298	40.45	.57	4.27	20.11	.27	29.45	3.27	.48	.00	.02	1.11	318	1510
Mo299	42.07	.27	2.17	13.31	.19	38.84	.65	1.14	.00	.01	1.35	1490	1950
Mo901	39.99	.02	1.04	12.09	.18	44.32	.83	.26	.03	.01	1.23	920	2300
Mo903	36.60	.01	4.80	11.90	.16	43.26	.14	.02	.00	.00	.67	11300	2193
Mo897	39.79	.07	1.16	13.10	.18	44.06	.74	.12	.01	.00	.78	5600	2410
Mo898	40.10	.05	2.25	12.55	.17	42.57	1.17	.15	.00	.01	.97	5000	2045
Mo900	41.41	.03	.55	11.91	.19	43.95	1.09	.08	.00	.00	.78	1600	1825
Mo913	40.53	.10	1.50	16.68	.22	38.72	1.04	.14	.02	.01	1.03	2200	1013
Mo916	38.39	.06	1.10	16.16	.21	42.22	.55	.30	.01	.00	.99	4310	1033
Mo923	38.14	.05	.92	16.28	.21	42.81	.52	.07	.01	.00	.99	3800	954
Mo925	39.28	.07	1.12	17.04	.22	39.73	1.40	.08	.01	.00	1.05	3650	1028
Mo926	38.77	.07	.99	17.09	.22	40.37	1.34	.08	.01	.00	1.07	3750	1039
Mo927	39.07	.08	1.45	15.95	.21	40.98	1.17	.09	.01	.01	.97	3800	1132
Mo928	40.41	.14	1.92	17.66	.22	36.80	1.62	.15	.03	.01	1.03	3250	1010
Mo891	43.46	.06	1.85	9.52	.14	42.20	1.58	.15	.00	.00	1.03	2190	2284
Mo892	44.76	.09	2.59	9.31	.15	38.63	2.85	.25	.00	.00	1.37	2820	2030
Mo893	44.31	.07	2.15	9.38	.15	40.77	2.42	.23	.00	.00	.53	2900	2210
Mo894	44.23	.06	2.25	9.04	.14	41.16	2.26	.22	.00	.00	.63	3080	2185
Mo895	44.59	.07	2.30	9.46	.15	40.23	2.40	.25	.00	.00	.54	2950	2095
Mo896	44.61	.07	2.41	9.41	.15	39.95	2.66	.21	.00	.00	.54	3200	2130
Mo906	42.42	.05	.53	8.84	.13	46.94	.19	.11	.13	.01	.67	2570	2638
Mo907	40.85	.04	.73	9.25	.14	46.96	.39	.07	.20	.01	1.35	3200	2693
Mo908	40.94	.01	.16	9.09	.14	48.87	.06	.15	.04	.00	.53	2620	2718
Mo909	43.52	.02	.32	8.90	.14	43.83	2.69	.06	.00	.01	.52	4150	2528

The Q-mode analysis structures a variance-covariance matrix of a multivariate population by extraction of eigenvalues and eigenvectors from a similarity matrix. Each of the so obtained « factors » is a vector which account for a percentage of the total desired variance of the original statistical sample. Table 3 sets out the general statistics of the untrasformed data. Table 4 shows the weight of the various oxides over each factor, variance and relative cumulative variance. It can be seen that three factors account for about 97 % of total variance, which is a sufficient level for the present case.

TABLE 2

General characteristics, references and preliminary attribution of the peridotites examined

Locality	Samples	References
VALSESIA	Ol-Pyroxenites: Mo296,	This paper
Lower Layered Group (LLG)	Lherzolites: Mo 297, Mo298,	This paper
	Mo44, Mo57, Mo90,	Rivalenti & al., (1975)
	Harzburgites: Mo299,	This paper
	Mo16, Mo17,	Rivalenti & al., (1975)
	Dunites: Mo43, Mo51, Mo52, Mo56, Mo58, Mo59,	Rivalenti & al., (1975)
ROCCA D'ARZIMONIA (RdA)	Harzburgites: Mo898,	This paper
	2570, 2572,	Lensch, (1971)
	Dunites: Mo897, Mo900,	This paper
	2234,	Lensch, (1971)
CIMA CAVALLO (CC)	Dunite: 2582,	Lensch, (1971)
CAMPELLO MONTI (CM)	Ol-Pyroxenites: Q266,	Bertolani, (1968)
	Harzburgites: Q268,	Bertolani, (1968)
LA BALMA - MONTE CAPIO	Harzburgites: Mo913, Mo927, Mo928,	This paper
(BMC)	Dunites: Mo916, Mo923, Mo925, Mo926,	This paper
	2596,	Lensch, (1971)
FINERO HORNBLENDE (FH)	Harzburgites: 2228, 2531, 2540,	Lensch, (1971)
	Dunites: Mo901, Mo903,	This paper
	1447, 2205, 2226, 2522, 2527, 2532,	
	2533, 2539,	Lensch, (1971)
	MANTLE PERIDOTITES	
BALMUCCIA (B)	Lherzolites: Mo4, Mo5, Mo6, Mo7, Mo13, Mo14,	
	Mo15, Mo64, Mo65, Mo66, Mo67, Mo69,	
	Mo72, Mo73,	Rivalenti & al., (1975)
	1444, 2254, 2276, 2597, 2884, 2885,	Lensch, (1971)
	Harzburgites: Mo8, Mo9, Mo10, Mo74,	Rivalenti & al., (1975)
BALDISSERO (BA)	Lherzolites: Mo891, Mo892, Mo893, Mo894,	
	Mo895, Mo896,	This paper
	2230, 2231, 2232, 2233, 2558, 2886,	
	2887,	Lensch, (1971)
FINERO PHLOGOPITE (FP)	Lherzolites: Mo909,	This paper
	Harzburgites: Mo906,	This paper
	2840, 2841, 2842, 2847, 2848,	Lensch, (1971)
	Dunites: Mo907, Mo908,	This paper
	1446, 1450,	Lensch, (1971)

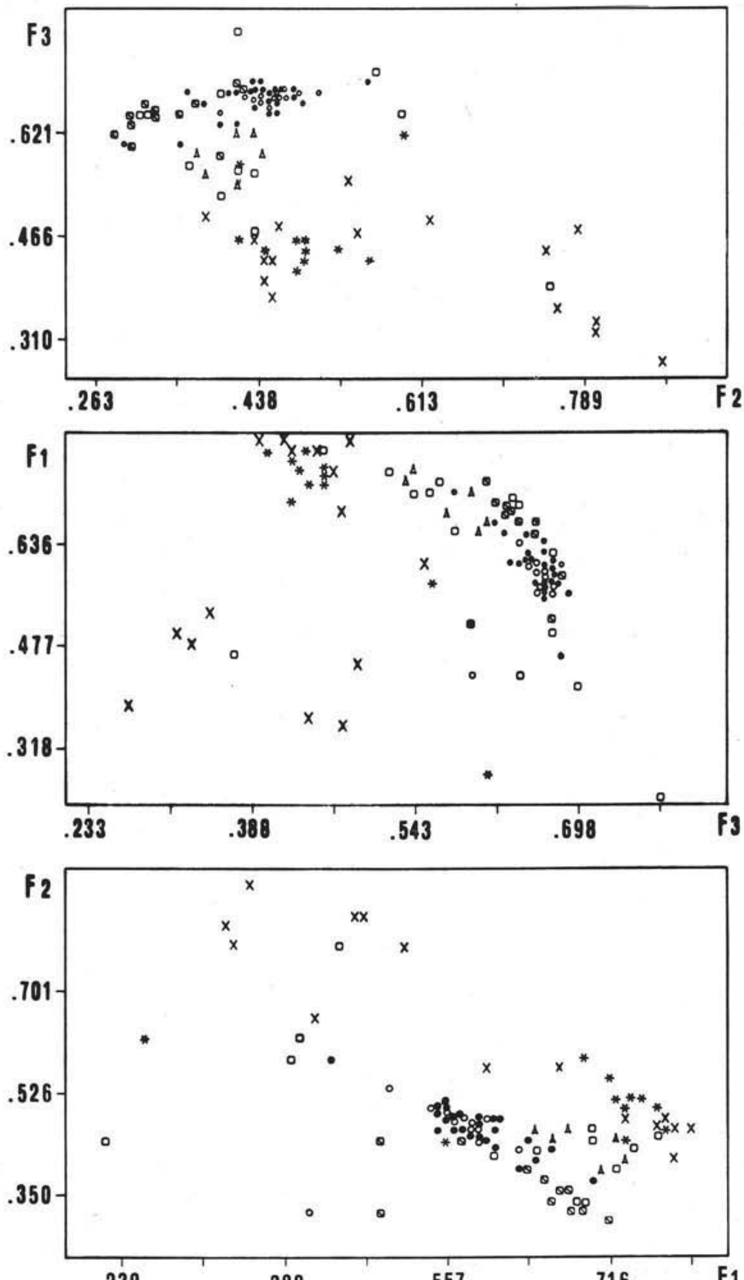

Fig. 1. — Reciprocal plots of the three main factors F1, F2 and F3. Symbols: Balmuccia peridotite = =dots; Baldissero peridotite = open circles; phlogopite peridotite of Finero = squares with a diagonal; hornblende peridotite of Finero = squares; Rocca di Argimonia peridotites = triangles; peridotites from Balma, Monte Capio, Cima Cavallo and Campello Monti = flowers; Ultramafites from LLC and ULG in Sesia Valley = crosses.

The diagrams of Fig. 1 are reciprocal plots of the sample loadings of the orthogonal factors. The peridotites of the two groups result discriminated in all cases, but the discrimination is more powerfull in the plots F1 vs F2 and F2 vs F3. Moreover, the samples of the cumulitic series from RdA, BMC-CC-CM in most cases form two distinct clusters, while those from LLG define a trend of variation. Some overlapping between mantle and cumulitic peridotites occurs only for three FH samples. Within the mantle peridotites, FP samples cluster in a distinct position with respect to B and BA (see Table 2 for abbreviations).

Instead of a reciprocal plot of the orthogonal factors, it is also possible to plot the samples in a triangular diagram the apexes of which represent the three main factors after rotation from the original orthogonality and normalization so that the contribution of each factor to the cumulative variance is of comparable order. The new factor scores and variance are reported in Table 5.

TABLE 3

Gen. statistics for the untrasformed data

VARIABLE	AVERAGE	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE
SiO_2	41.8215	2.8378	35.4300	47.5000
TiO_2	.1115	.1575	.0100	.8400
Al_2O_3	2.3057	1.5395	.1600	10.7000
MnO	.1642	.0412	.0500	.3100
MgO	40.3195	4.9112	21.0000	48.8700
CaO	2.1570	1.7735	.0600	14.0000
Na_2O	.1851	.1593	0.0000	1.1400
K_2O	.0315	.0867	0.0000	.7000
Fe_2O_3tot	11.8645	3.5303	5.1000	21.5300
Cr	3401.3763	3137.7964	150.0000	30100.0000
Ni	2055.3978	1927.3949	472.0000	18070.0000

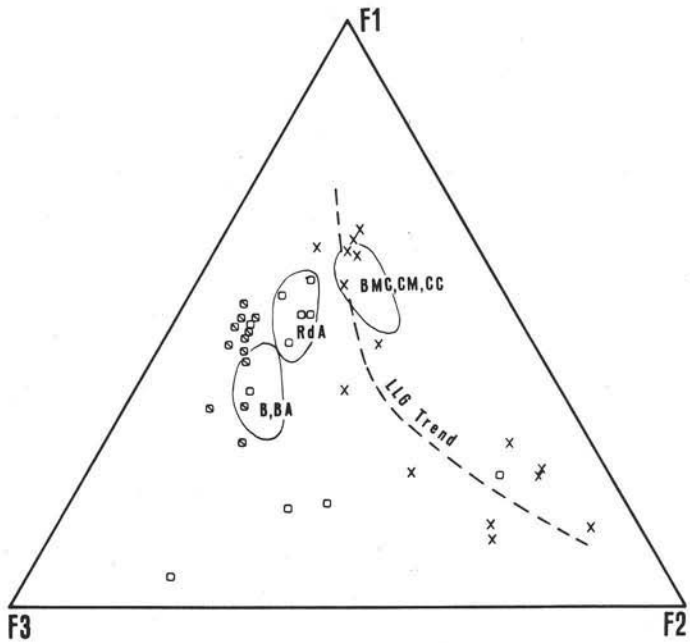

Fig. 2. — Triangular plot of the three main factors F1, F2 and F3, after rotation from the original orthogonality and normalization. Symbols as in Fig. 1.

The small differences in weight of the variables, if compared to Table 4, are a consequence of the rotation. The discrimination results improved and the samples have the same characteristics of clustering and trend as in the other cases (Fig. 2).

Interpretation

The discrimination, clustering and trends resulting from the Q-mode analysis must depend on the geochemistry of the peridotite population. A geochemical interpretation, however, is complicated by the high number of the variables involved.

The problem can be tackled by trying to clarify the meaning of the single factors and, then, of the clusters and trends of the diagrams.

TABLE 4
Scaled principal factor score matrix, variance of each factor and relative cumulative variance

	F1	F2	F3	F4	F5
SiO_2	1.986	- .270	1.087	- .469	- .174
TiO_2	.267	2.027	- .096	.694	- .705
Al_2O_3	.472	1.198	1.222	- .038	2.219
MnO	1.180	.516	-1.261	- .831	- .653
MgO	1.874	-1.498	.094	.704	- .410
CaO	.341	.693	1.467	1.221	- .542
Na_2O	.350	1.116	.770	1.031	-1.439
K_2O	.093	- .153	.325	2.560	.314
Fe_2O_3tot	1.219	.959	-1.921	.190	1.052
Cr	.250	- .390	.231	- .066	1.005
Ni	.249	- .224	.350	.150	.609
VARIANCE	93.64	2.09	1.55	.72	.61
CUM. VARIANCE		95.73	97.28	98.00	98.61

The variables which weight more over F1 (factor 1) are SiO_2, MgO, Fe_2O_3tot and MnO in order of decreasing importance (Tab. 4). This factor should therefore be suitable for distinguishing between dunites and pyroxene-bearing ultramafites. It must be expected that the F1 values of mantle peridotites are intermediate between the cumulitic dunites and cumulitic ultramafites richer in pyroxene.

F2 (factor 2) accounts for an inverse relationship between MgO from one side and TiO_2, Al_2O_3 and Na_2O from the other (Tab. 4). The Mg-richer mineral is olivine, while TiO_2 is concentrated in hornblende and to a lesser degree in pyroxenes, Al_2O_3 in spinels and subordinately in pyroxenes and hornblende, Na_2O in hornblende and subordinately in pyroxenes.

As hornblende and spinels are the last phases to crystallize in the present rocks (RIVALENTI et al., 1975), the variation in F2 assumes the meaning of an igneous differentiation from dunites to hornblende-spinel-bearing ultramafites through pyroxene-ultramafites.

The variables which weight more over F3 (factor 3) are, in order of decreasing influence, Fe_2O_3tot and MnO (negative), and Al_2O_3, CaO and SiO_2 (positive) (Tab. 4). The above mentioned Al-bearing minerals are richer in Al_2O_3 in the cumulitic ultramafites. The amount of CaO depends on the composition of clinopyroxene, endiopsides, in the mantle peridotites and generally iron-salites in the others. On this basis it is expected that F3 is suitable for the discrimination of the mantle and cumulitic peridotites. The variation of the F3 value in the cumulitic group, from low to high, corresponds mainly to an increase in iron content. In the light of the meaning of the various factors, an interpretation of the features shown in the diagrams can now be attempted.

In the plot F1 vs F2 the mantle peridotites are discriminated because, for a given F1 value, they result lower in F2.

This accounts mainly for the more magnesian composition of the mantle minerals, and also for the relatively small spinel content of the mantle peridotites and for lower Al_2O_3 content in their pyroxenes. The FP samples, many of which are practically devoided of pyroxenes, have in fact the lowest F2 values, even if compared with the RdA rocks, which are dunites with some orthopyroxene. The FP samples with some orthopyroxene plot together with the other mantle peridotites.

The rather poor discrimination of the plot F1 vs F3 can be explained in a similar way: for a given mineralogical composition (F1) the mantle rocks are poorer in F_2O_3tot.

TABLE 5
Scaled varimax factor scores, variance of each factor and relative cumulative variance

	F1	F2	F3
SiO_2	.661	.625	2.091
TiO_2	- .606	1.906	- .436
Al_2O_3	- .995	1.167	.895
MnO	1.359	1.125	- .368
MgO	1.747	- .415	1.595
CaO	-1.029	.643	1.130
Na_2O	- .742	1.076	.501
K_2O	- .090	- .117	.340
Fe_2O_3tot	1.632	1.588	- .955
Cr	.168	- .240	.426
Ni	.022	- .106	.472
VARIANCE	38.677	23.219	35.386
CUM. VARIANCE		61.896	97.283

The plot F2 vs F3 discriminates mainly on the basis of F3.

The trend given by the cumulitic peridotites has the meaning of an increase, toward high F2, of orthopyroxene, clinopyroxene and hornblende with respect to olivine. It is worth noting that also single rock types (dunites or lherzolites) spread over the trend: this is clearly due to the different composition of the minerals in relation to the structural level of fractionation (RIVALENTI et al., 1975).

For what concerns the triangular plot of Fig. 2, the weight of the variables over the factors, although purified from some redundant information (such as, for instance, the disappearance of SiO_2 in F1), has overall the same meaning already discussed. So F1 accounts for variation of olivine with respect to Ca-bearing minerals, F2 for the decrease of MgO content (and increase of Fe_2O_3tot content) of pyroxene at increasing spinels and amphiboles, and F3 mainly for variations in the Fe/Mg ratio. It is therefore expected that mantle peridotites plot distinctly from the others. The trend of cumulitic peridotites has the same meaning as in the plot F2 vs F3.

The geochemical interpretation of the Q-mode analysis given above may explain also the behaviour within the mantle and cumulitic peridotites. The clustering of the mantle peridotites into two groups is a consequence of the differential mineralogical composition of FP samples with respect to those of B and BA. The behaviour of FP samples might be interpreted either as the consequence of lower depletion of the mantle at this locality or as contamination.

Within the cumulitic group, the trend shown by the LLG ultramafites may be the consequence of the fractionation of Ol-Opx-Cpx-(Ho, Sp) in the order, as already discussed by RIVALENTI & al. (1975) on the basis of other criteria.

The clusters formed by RdA and BMC-CC-CM are due to the small interval of fractionation represented in the sampling at these localities. The BMC-CC-CM cluster behaves as the early differentiates of the LLG series and therefore follows the same differentiation scheme. The cluster of RdA, which in most cases plots in an intermediate position between mantle peridotites and early cumulitic members, might indicate a more primitive composition of the RdA peridotites, with olivine and orthopyroxene more magnesian with respect to the LLG minerals. Possibly, this feature is a consequence of fractionation at a deeper crustal level, which might lack (or was not found) in Sesia Valley because of the intense tectonism.

For what concerns the FH ultramafites, the Q-mode analysis supports the hypothesis that they are, with the exception of three samples, more similar to the cumulitic peridotites than to the mantle type. A possible factor which may account for the anomalous behaviour of the three samples is their erroneous assignement: they have been taken from literature where the distinction between mantle and cumulitic ultramafites had not been made.

Conclusions

Multivariate factor analysis has proven to be a useful method for distinguishing peridotites of different origin and strictly associated in the same area. Not only mantle peridotites have been unequivocally distinguished from those formed by fractionation and cumulus, but it has also been possible to point out geochemical differences that would have been otherwise difficult to be seen. The trends of variation shown in the factorial space are geochemical consequences of the fractionation that occurred in the peridotite formation.

Appendix

— Chemical analyses have been carried out by XRF, according to FRANZINI and LEONI (1972); H_2O has been determined gravimetrically, and Na_2O by emission spettroscopy.

— The Q-mode Fortran program used in this paper is a modified version of the Klovan and Imbrie program (KLOVAN & IMBRIE, 1971).

REFERENCES

CAPEDRI S., GOMES C. B., RIVALENTI G. & RUBERTI E. (1976) - *Pyroxenes and Olivines as Indicators of the Petrological Evolution of the Ivrea-Verbano Basic Formation (Italian Western Alps)*. Tschermaks Min. Petr. Mitt., 23, 175-190.

CAWTHORN R. G. (1975) - *The amphibole peridotite-metagabbro complex, Finero, Northern Italy*. Journ. of Geol., 83, 437-454.

DAVIS J. C. (1973) - *Statistics and data analysis in Geology*. John Wiley, New York.

FRANZINI M., LEONI L. (1972) - *A full matrix correction in X-ray fluorescence analysis of rocks samples*. Atti Soc. Tosc. Sc. Nat. Mem., 79 A, 719-734.

HARMAN H. H. (1970) - *Modern factor analysis*. The Univ. of Chicago press, Chicago and London.

IMBRIE J., PURDY E. G. (1972) - *Classification of modern Bhamian Carbonate sediments*. Ann. Assoc. Petroleoum Geologist Mem., 1, 253-272.

LENSCH G. (1971) - *Die Ultramafite der Zone von Ivrea*. Ann. Univ. Saraviensis, 9, 5-146.

KLOVAN J. E., IMBRIE J. (1971) - *An algorithm and Fortran IV program for large scale Q-mode factor analysis and calculation of factor score*. 3, I.

RIVALENTI G., GARUTI G. & ROSSI A. (1975) - *The origin of the Ivrea-Verbano basic formation (Western Italian Alps)-Whole rocks geochemistry*. Boll. Soc. Geol. It., 94, 1194-1186.

SHAW D. M., HARMAN R. S. (1975) - *Factor analysis of elemental abundances in chondritic and achondritic meteorites*. Meteorites, 10, III, 253-282.

VOGT P. (1962) - *Geologische-petrographische Untersuchung im Peridotitstock von Finero*. Schweiz. Min. Petr. Mitt., 48, 165-173.