

# A STATISTICAL STUDY OF THE TRACE ELEMENT DISTRIBUTION IN THE MAGMATIC MEMBERS OF SINGHBHUM GRANITE

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Quantitative data for 12 trace elements in 32 granitic rocks belonging to the three magmatic phases of Singhbhum granite have been studied by applying cluster analysis and *R*-mode factor analysis techniques. Cluster groupings obtained by (a) Ramifying Linkage Method, (b) Correlation Profile Method (both on the basis of correlation matrices), and (c) *R*-mode factor analysis, are not similar in all respects. But all of them support a model of substantially different trace element distribution processes for the three different phases of granites.

The four *R*-mode factors in Phases I and II, and five factors in Phase III account for over 85 per cent of the total variance in each phase, but the structures of the rotated factor matrices for the three phases are different. But the invariable associations of the pairs V-Ti and Ga-Mn in the factors for all the three phases are noteworthy.

Assuming that each factor represents a particular process in the crystallisation history of the rocks, the factor analysis suggests the following significant differences in the crystallisation history for the three phases:

In Phase I biotite and plagioclase started crystallising simultaneously and K-feldspar probably formed after biotite ceased to crystallise; in Phase II crystallisation of plagioclase started later than that of biotite but a stage is noted when biotite, plagioclase and K-feldspar crystallised simultaneously; in Phase III at one stage K-feldspar crystallised alone, while at another stage biotite crystallised alone.

## INTRODUCTION

Quantitative spectrochemically-determined trace element data are available for 12 elements (Li, Ua, Ga, U, Zr, V, Cr, Ni, Cu, Sr, Mn and Ti) in 32 samples belonging to the three magmatic phases of Singhbhum Granite in eastern India. These data were reported by the authors in 1968 (Saha *et al.* 1968 *a, b*). Eleven samples each belong to Phases I and III while 10 samples belong to Phase II. The three phases of intrusion have been inferred on the basis of many structural and petrological evidences which have been reported extensively (Saha 1964, 1966 and 1972).

Table I shows the Mean and Standard Deviation for the 12 trace elements in the three phases of granite. Petrographically, the rocks are mainly biotite granodiorite grading to adamellite. Empirical studies of over 700 modal data and trace element data for 37 rocks (Saha, Sankaran and Bhattacharyya 1968 *a, b*) indicate that compositional differences between the three phases of granitic rocks are distinctive (Table II).

TABLE I  
*Mean Trace element contents (in ppm.) in the three phases of intrusions*

Trace element	Phase-I (11 samples)	Phase-II (10 samples)	Phase-III (11 samples)
Li	28.00 (22.98)	22.90 (16.77)	26.42 (22.00)
Ba	209.36 (91.22)	481.00 (206.74)	414.58 (491.96)
Ga	13.82 (1.60)	22.00 (4.06)	19.42 (6.78)
U	4.72 (2.53)	6.10 (3.38)	7.00 (3.36)
Zr	94.73 (59.24)	219.80 (63.15)	181.08 (83.41)
V	23.64 (13.05)	36.70 (7.92)	19.75 (11.43)
Cr	6.82 (4.045)	13.70 (5.48)	6.59 (3.63)
Ni	11.36 (9.43)	22.90 (10.86)	31.50 (26.99)
Cu	12.73 (13.91)	19.90 (14.89)	20.83 (13.25)
Sr	470.00 (151.87)	716.50 (272.39)	452.08 (252.54)
Mn	150.64 (31.83)	284.70 (92.44)	234.67 (91.69)
Ti	999.27 (517.28)	1558.50 (301.79)	1214.00 (561.58)

(Figures in brackets indicate standard deviations)

TABLE II  
*Comparison of composition of granite rocks in three intrusive phases of Singhbhum granite*

Characteristics	Phase I bodies	Phase II bodies	Phase III bodies
	An to An	An to An	An to An
Average composition of plagioclase	18.5 22	15 25	12 17
Average K-feldspar, per cent	6.7, 6.2, 4.0	13.4, 15.9	12.5—29.1
Average colour index, per cent	6.2, 10.7	8.5, 10.2	4.3—6.5
Average epidote, per cent	1.6, 2.8	2.1, 4.1	0.2—1.8
Muscovite, per cent	trace to 0.4	0.1	0.3—1.0
Average alkali content	lowest	Intermediate	highest
CaO	higher than in Phase III	similar to Phase I	low
Trace element characteristics	low Ba, Ga, Y, Zr, Mn, Cu, Ni; high Co/Ni	high Cr and Sr; interme- diate Ni and Co/Ni	high Rb, Pb, Ni; low Co/Ni

Multivariate analysis of variance of the trace element data (converted to  $\log_{10}$  ppm) indicated that the mutual differences among the three phases in their trace element distributions are statistically significant at 95 per cent confidence level (Saha *et al.* 1968 *b*).

In an attempt to elucidate the interrelationships in the trace element distributions of the three phases in more detail, *R*-mode factor analysis and cluster analysis (both on the basis of the factor loadings as well as on the multiple correlations) were attempted.

TABLE III  
*R*-Matrices of the trace-elements in the three phases

	Li	Ba	Ga	U	Zr	V	Cr	Ni	Cu	Sr	Mn	Ti
(a) Phase I												
Li	—											
Ba	.352	—										
Ga	.063	.184	—									
U	.137	.710*	.134	—								
Zr	.021	-.266	-.514	-.308	—							
V	.335	.544	-.487	-.632*	.385	—						
Cr	.649*	.224	-.206	.190	.424	.595*	—					
Ni	.128	.381	-.479	.511	.337	.858*	.605*	—				
Cu	.798*	-.082	-.142	-.221	.509	.263	.607*	.126	—			
Sr	.085	.258	.187	.596	-.401	.099	.248	.136	-.233	—		
Mn	-.039	.302	.611*	.512	-.360	.102	-.025	.237	-.201	.183	—	
Ti	.371	.278	-.389	.289	.757*	.808*	.699*	.662*	.549	.061	.010	—
(b) Phase II												
Li	—											
Ba	-.091	—										
Ga	.160	-.141	—									
U	.192	.232	-.267	—								
Zr	.254	-.566	.315	-.507	—							
V	.089	.686*	.325	.134	-.291	—						
Cr	-.381	.493	-.025	.290	-.724*	.180	—					
Ni	-.328	.355	.313	-.293	-.150	.318	.534	—				
Cu	.160	.169	.637*	-.324	.425	.579	-.227	.536	—			
Sr	.425	.253	.648*	-.440	.336	.607*	-.147	.469	.840*	—		
Mn	.101	-.038	.837*	-.609*	.417	.206	.067	.542	.631*	.770*	—	
Ti	-.070	.340	.624*	-.091	.009	.811*	-.062	.229	.614*	.582	.419	—
(c) Phase III												
Li	—											
Ba	.144	—										
Ga	.380	.285	—									
U	.468	.272	.528	—								
Zr	.352	.375	.882*	.325	—							
V	.259	.263	.688*	.308	.484	—						
Cr	.401	.346	.407	.239	.295	.300	—					
Ni	-.185	-.095	.365	.392	.194	.077	.042	—				
Cu	.005	-.000	.608*	-.008	.505	.607*	.322	.098	—			
Sr	.027	.174	.603*	.101	.496	.694*	.169	-.031	.658*	—		
Mn	.133	.119	.928*	.408	.771*	.670*	.254	.505	.518	.560	—	
Ti	.423	.407	.844*	.443	.778*	.824*	.339	.029	.605*	.698*	.721*	—

\*Indicates significant correlations

#### CLUSTER ANALYSIS BASED ON CORRELATION COEFFICIENTS

The correlation-coefficient matrices (*R*-matrices) for the 12 trace elements in the three phases, are shown in Table III. Since in the present case we have

10-11 samples in each phase only the  $r$  values  $>0.60$  or  $<0.60$  may be considered statistically significant at 95 per cent confidence level (Snedecor 1957).

The significant intercorrelations ( $>.60$  and  $<-.60$ ) of the trace elements are represented diagrammatically also in Fig. 1, which clearly brings out the distinctive pattern of mutual correlations in the three phases. The only constant feature is the high V-Ti and Ga-Mn correlations in all the three phases.

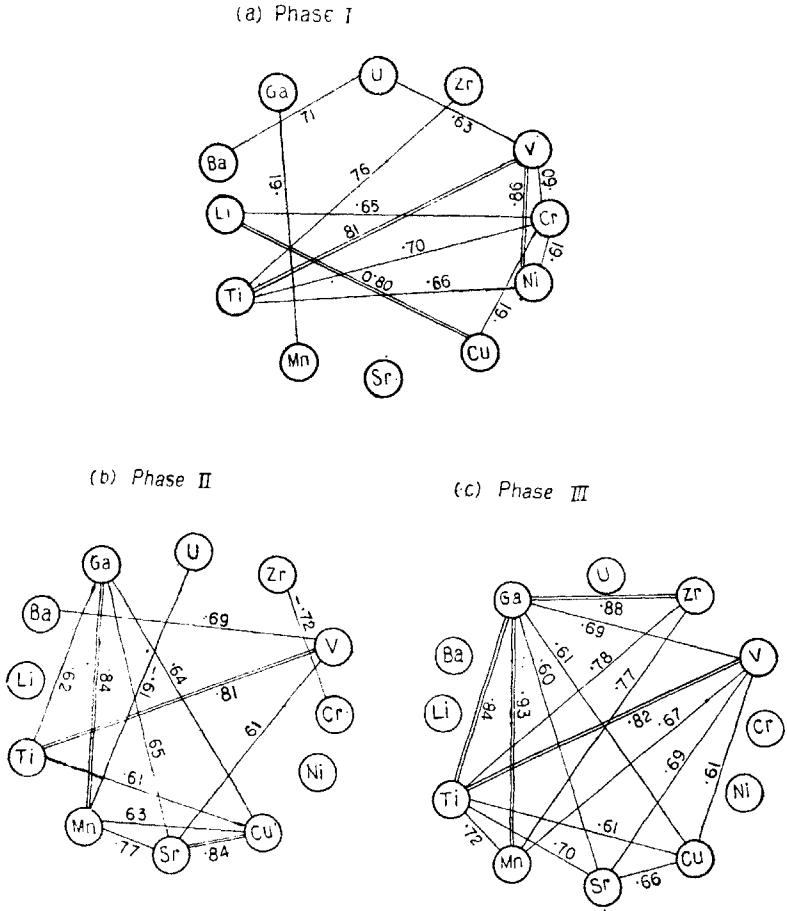


FIG. 1. Corellegrams showing significant correlations ( $\geq .60$  &  $\leq -.60$ ) in the three phases. (a) Phase I, (b) Phase II, (c) Phase III; single bar indicates correlations  $\geq .6$  and  $\leq -.6$  double bar indicates correlations  $\geq .8$

Cluster analysis was carried out on the basis of the  $R$ -matrices using two methods:

1. Ramifying Linkage Method, and
2. Correlation Profile Method.

*Ramifying linkage method*

Using the procedure described by Miller and Kahn (1962) all possible clusters (with  $r > 0.6$ ) were extracted from the three  $R$ -matrices and the preliminary cluster grouping is presented in Table IV.

TABLE IV  
*Preliminary cluster grouping by Ramifying Linkage Method*

Phase I	Phase II	Phase III
(i) Li-Cu-Cr	(i) Ba-V	(i) Ga-Mn-Zr
(ii) Ba-U	(ii) Ga-Mn-Cu-Sr	(ii) V-Ga-Sr-Cu-Ti
(iii) Ga-Mn	(iii) U-Mn	(iii) V-Mn
(iv) Zr-Ti	(iv) Zr-Cr	(iv) Ti-Zr
(v) U-V	(v) V-Ti	(v) Mn-Ti
(vi) V-Ni-Cr-Ti	(vi) V-Sr	
	(vii) Cu-Ti	
	(viii) Ga-Ti	

Next an attempt is made to list all the 'basic pairs' in each *R*-matrix. The basic pair is defined as that pair of measurements such that each is more highly correlated with the other than any of the remaining measurements in the matrix. The basic pairs in the three *R*-matrices are listed in Table V.

TABLE V  
*Basic pairs in the three phases*

Phase I	Phase II	Phase III
(i) Ba-U	(i) V-Ti	(i) Ga-Zr
(ii) Ga-Mn	(ii) Ga-Mn	(ii) V-Ti
(iii) V-Ti	(iii) Sr-Cu	
(iv) Li-Cu	(iv) Zr-Cr	

Then all the groups in Table IV which do not contain one or more basic pairs are rejected and any member common to several groups is assigned to that group which has the highest basic pair link with the common member. Using these two principles, we get the final groupings in the clusters as shown in Table VI.

TABLE VI  
*Final grouping in the clusters by Ramifying Linkage Method*

Phase I	Phase II	Phase III
(i) Li-Cu-Cr	(i) V-Ti	(i) Ga-Mn-Zr
(ii) Ba-U	(ii) Ga-Mn-Cu-Sr	(ii) V-Ti-Cu-Sr
(iii) Ga-Mn	(iii) Zr-Cr	
(iv) V-Ni-Ti		

It is evident that the structure patterns of the clusters in the three phases are different except that V-Ti on one hand and Ga-Mn on the other, are linked in all the three phases.

*Correlation Profile Method*

A more rigorous and elaborate method of cluster analysis starting from *R*-matrix has been described by Miller and Kahn (1962). In this method cluster analysis is carried out on the basis of *Z* matrix where  $Z = \frac{1}{2} \ln \frac{(1+r)}{(1-r)}$ .

Using the procedure of Miller and Kahn (1962), we obtain the final cluster grouping for the three phases as shown in Table VII.

TABLE VII  
*Final cluster groups by Correlation Profile Method*

Phase I	Phase II	Phase III
(i) Ba-U-V-Ni	(i) Ga-Zr-Ni-Sr-Mn-Ti	(i) Zr-V-Cu-Sr-Mn-Ti
(ii) Zr-Cr-Ti	(ii) Ba-V-Cr	(ii) Li-Ba-U-Cr
(iii) Ga-Mn	(iii) Li	(iii) Ga
(iv) Li	(iv) Cu	(iv) Ni
(v) Cu	(v) U	
(vi) Sr		

The distinctive correlation profiles for the four clusters in Phase III are illustrated in Fig. 2.

The cluster groups obtained using the correlation profile method are somewhat different from those obtained by the ramifying linkage method. The Ga-Mn and V-Ti linkages which were found to be common to the three phases by ramifying linkage method are here found in only two phases (Phases I and II) and one phase (Phase III), respectively. On the other hand Zr-Ti linkage which is common to all the three phases in the correlation profile method is absent in the ramifying linkage method.

#### FACTOR ANALYSIS OF THE TRACE ELEMENT DATA

*R*-mode factor analysis was carried out on the log-transformed trace element data (32 samples) using the FORTRAN II Programme by Sampson (1968), with slight modifications. The computations consist of several stages as follows :

1. Computing the matrix of correlations (*R*-matrix) between all possible pairs of the variables (in this case, 12 trace elements).
2. Computing the eigen values and eigen vectors corresponding to the principal components matrix.
3. Computing the desired number of rotated orthogonal factors.

In the case of combined factor analysis of 32 trace element data (i.e. all the three phases together), it was found that as many as nine factors would be needed in order to account for at least 85 per cent of the total eigen values (Table VIII). None of the factors account for more than 15 per cent of the total variance. Since it is not possible to investigate the genetic interrelationship on the basis of so many factors, it was considered not worthwhile to compute the rotated factor matrix. This failure to extract a sufficiently small number of factors out of the combined trace

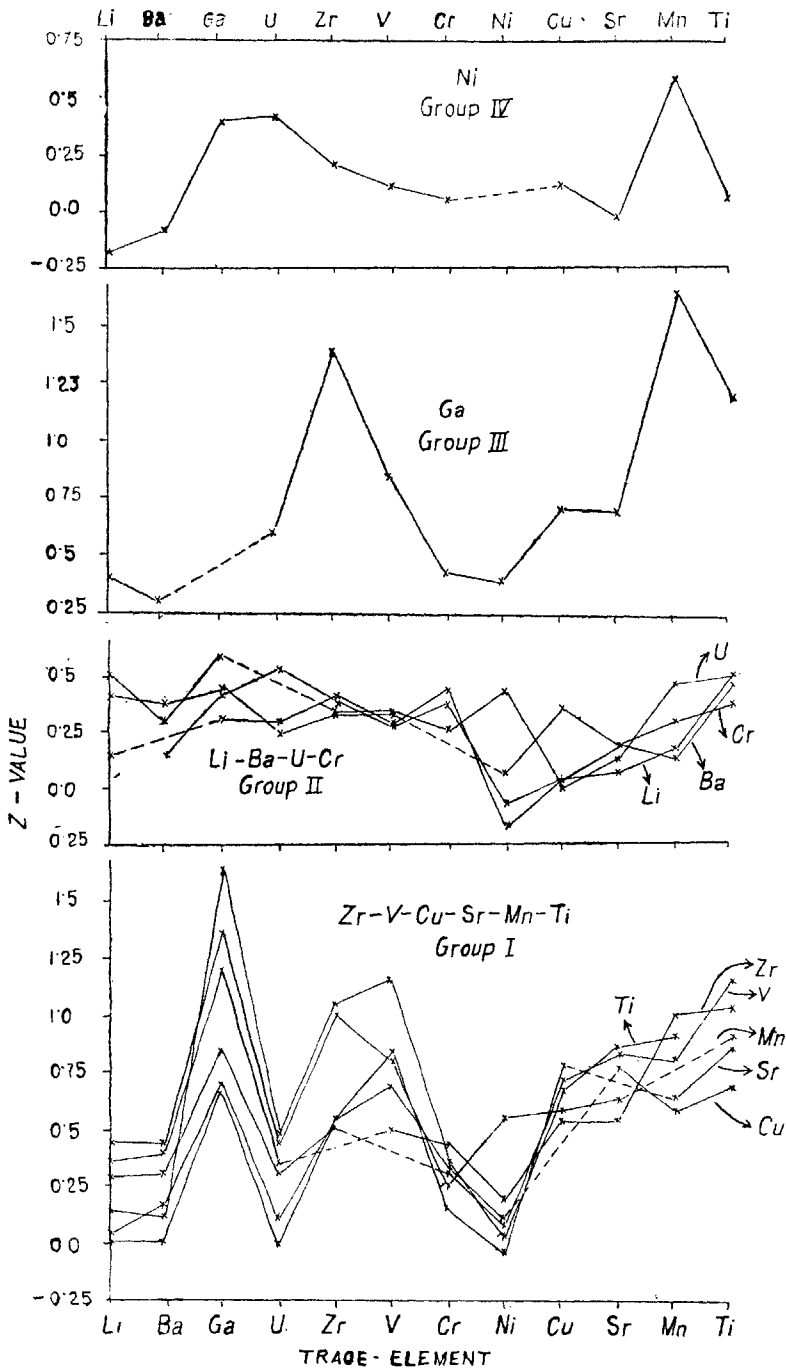


FIG. 2. Final clustering in Phase III by Correlation Profile Method : Group I — Zr-V-Cu-Sr-Mn-Ti ; Group II — Li-Ba-U-Cr ; Group III — Ga ; Group IV — Ni.

element data indicates a rather random distribution of the correlation vectors and a lack of clustering of the trace elements among the three phases.

TABLE VIII  
*Unrotated factor matrix (nine factors) for the combined trace element data*

Trace element	1	2	3	4	5	6	7	8	9
Li	.00	.00	.00	.05	.00	.99	.00	.00	.00
Ba	.06	.00	.00	.81	.43	-.03	.00	.12	-.44
Ga	.06	.00	.00	.82	-.37	-.03	.00	-.11	.46
U	.35	.00	.00	.03	.57	.00	.00	.55	.38
Zr	.40	.00	.00	.03	-.72	.00	.00	.54	-.20
V	.88	-.01	-.04	.00	.03	.00	.18	.25	.00
Cr	.79	.01	.04	.00	.03	.00	.19	-.25	.00
Ni	.01	.15	.42	.00	.00	.00	.85	.00	.00
Cu	.00	-.28	.95	.00	.00	.00	-.36	.00	.00
Sr	.00	.92	-.14	.00	.00	.00	-.22	.00	.00
Mn	.00	.64	.34	.00	.00	.00	.02	.00	.00
Ti	.00	.47	.32	.00	.00	.00	-.02	.00	.00
Cumulative per cent eigen values	14.0	27.2	40.3	51.4	61.1	69.5	77.5	83.7	88.7

Next, *R*-mode factor analysis of the trace element data for the individual phases was attempted on the same lines. In this case it was found that for phases I and II only the first four of the principal components together account for over 85 per cent of the corresponding eigen values, while for phase III five principal components were needed (Table IX). Also for all the phases, the first two of the principal components between themselves account for at least 61 per cent of the eigen values. The first five of the principal components in each case were chosen and subjected to varimax rotation in order to yield five factors each. The rotated factor matrices for the three phases are shown in Table X.

As will be noted from Table X the loadings for most of the variables in the individual factors are of a low order. Following the conventional procedure, only the variables having loadings  $>.70$  or  $<-.70$  may be considered to contribute significantly to the corresponding factor. When this is done, we find distinctive clustering pattern of the elements in the different factors of the three phases (Table XI).

The purpose of *R*-mode factor analysis is to resolve an array of correlation coefficients into a form that can be interpreted more easily in terms of processes thought to have been responsible for the correlations. Viewed in this light each of the factors should be indicative of a particular group of processes responsible for causing parts of the total variance in the data matrix. Substantially different structures of the factors in the different populations would indicate significant differences in the causative processes.

In the present case it is found that V and Ti have got high loadings with the first factors for all the three phases, which suggest that the combination has had an



TABLE IX  
Unrotated factor matrices for the trace element data for the three phases

Trace element	Factor I	Factor 2	Factor 3	Factor 4	Factor 5
(a) PHASE-I					
Li	.554	.006	.768	-.194	-.204
Ba	.432	.667	.056	-.010	-.515
Ga	-.433	.520	.566	.364	.123
U	.433	.834	-.169	-.063	-.042
Zr	.541	-.692	-.190	.246	.175
V	.915	.184	-.281	-.019	-.159
Cr	.828	-.044	.304	.115	.317
Ni	.808	.196	-.401	.095	.106
Cu	.563	-.473	.632	.045	.000
Sr	-.098	.631	.043	-.577	.472
Mn	.021	.699	.110	.620	.248
Ti	.911	-.169	-.068	.201	.064
Cumulative per cent eigen values	37.454	63.318	77.712	86.190	92.688
(b) Phase-II					
Li	.159	-.339	.680	.605	-.129
Ba	.207	.822	.197	-.029	-.364
Ga	.802	-.147	-.049	.146	.541
U	.461	.446	.535	.221	.321
Zr	-.342	-.860	-.016	-.099	-.102
V	.618	.590	.442	-.198	-.039
Cr	-.076	.796	-.421	.353	.169
Ni	.560	.434	-.562	.162	-.197
Cu	.900	-.054	.099	-.085	-.145
Sr	.935	-.048	.160	.180	-.226
Mn	.849	-.180	-.348	.251	.131
Ti	.731	.273	.285	-.435	.303
Cumulative per cent eigen values	39.002	64.275	78.571	86.308	93.022
(c) Phase-III					
Li	.390	.693	-.193	-.514	-.079
Ba	.370	.442	-.277	.753	-.049
Ga	.965	.013	.176	-.037	.001
U	.502	.555	.432	-.058	-.206
Zr	.842	.040	.039	.087	-.084
V	.816	-.160	-.189	-.053	-.103
Cr	.463	.393	-.197	.006	.745
Ni	.255	-.106	.893	.123	.206
Cu	.672	-.497	-.201	-.137	.299
Sr	.711	-.431	-.297	.031	-.129
Mn	.864	-.195	.352	-.002	-.025
Ti	.931	.027	-.194	-.008	-.191
Cumulative per cent eigen values	47.458	61.201	73.657	81.005	87.755

TABLE X  
Rotated factor matrices for trace element data

Trace element	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
(a) Phase-I					
Li	.025	.064	.943*	-.018	-.287
Ba	.150	.074	.133	.156	-.911*
Ga	-.535	.071	.111	.786*	-.069
U	.337	.460	-.104	.298	-.702*
Zr	.691	-.362	.206	-.239	.438
V	.831*	.053	.163	-.105	-.493
Cr	.604	.304	.660	.022	.024
Ni	.877*	.153	-.012	.016	-.283
Cu	.238	-.210	.895*	-.076	.182
Sr	-.016	.965*	.001	.089	-.160
Mn	.117	.096	-.133	.928*	-.215
Ti	.861*	-.107	.384	-.025	-.080
Recalculated cumulative per cent eigen values	29.5	41.8	61.8	75.8	92.8
(b) Phase II					
Li	.028	.109	.224	.956*	.085
Ba	.647	-.086	-.577	.072	-.356
Ga	.268	-.220	.062	.090	.922*
U	.057	.800*	-.361	.243	-.111
Zr	-.160	-.393	.784*	.145	.245
V	.946*	-.027	-.225	.107	.090
Cr	-.048	.004	-.965*	-.174	.082
Ni	.194	-.693	-.555	-.145	.188
Cu	.597	-.552	.181	.176	.353
Sr	.545	-.605	.079	.433	.358
Mn	.119	-.660	-.021	.113	.701*
Ti	.858*	-.016	.089	-.173	.444
Recalculated cumulative per cent eigen values	23.8	44.2	64.8	75.9	93.0
(c) Phase-III					
Li	.129	.907*	-.195	-.020	.251
Ba	.155	.078	-.049	.960*	.161
Ga	.797*	.337	.407	.134	.177
U	.141	.696	.480	.240	-.026
Zr	.712*	.275	.254	.264	.100
V	.833*	.172	.011	.098	.079
Cr	.176	.207	.047	.185	.923*
Ni	.040	-.059	.958*	-.080	.032
Cu	.804*	-.206	.019	-.204	.341
Sr	.878*	-.107	-.102	.057	-.018
Mn	.761*	.151	.552	.028	.041
Ti	.864*	.353	.026	.252	.069
Recalculated cumulative per cent eigen values	38.9	53.7	68.2	78.4	87.7

\*Indicates significant loadings.

TABLE XI  
Trace element clusters in the rotated factors for the three phases

Phase I	Phase II	Phase III
Factor 1 Ni-Ti-V	V-Ti	Sr-Ti-V-Cu-Ga-Zr-Mn
Factor 2 Sr	U	Li
Factor 3 Li-Cu	Cr-Zr	Ni
Factor 4 Mn-Ga	Li	Ba
Factor 5 Ba-U	Ga-Mn	Cr

important role to play in all the three phases of granites. As will be evident from the *R*-matrices (Table III), V and Ti are highly correlated in all the three phases ( $r > +0.8$ ). Also the association of Ga and Mn in the same factor in all the three phases is significant. Ga-Mn pair has high loadings with factor 1 in Phase III (their mutual correlation is  $>0.9$  in this phase) and with the fourth and fifth factors respectively in Phases I and II (mutual correlation is more than 0.6 in both the phases). Apart from the invariable presence of these two pairs (V-Ti and Ga-Mn), there is no other similarity in the structure of the factors in the three phases. These results are to be expected if the members of the three phases of intrusion crystallised under substantially different conditions as regards P, T, fluid pressures, rate of cooling, etc.

#### INTERPRETATION OF ROTATED FACTORS

Identification of the source or cause which is responsible for the parts of the total variability in data array which is reflected in the individual factor is the first step in the interpretation of the results of factor analysis. Each factor represents a part of the total variability, and for this part of the total variability the variables with high loadings in the factor must be responsible. In other words, the particular cause or causes responsible for the variability of the particular variables are represented by the particular factor.

In the present case all the three phases of granite are known to be of magmatic origin from structural and petrographic evidences and we find that in the different factors for each phase certain trace elements are strongly correlated to the respective factors. There is no evidence of appreciable post-crystallisation changes in the bulk composition of these rocks though some mineralogical changes are evident viz., partial saussuritisation and sericitisation of plagioclase, and chloritization of biotite and some epidotisation. Thus, the bulk of the variations in the trace element distribution in the total rocks must have been caused by the various processes (or various stages) involved during magmatic and deuteric crystallisation. Also the 12 trace elements considered here are contributed by the following minerals—plagioclase, K-feldspar, biotite, chlorite, epidote, sphene and opaque ore (contribution of quartz being considered negligible). On the basis of the available semiquantitative data on the trace element composition of these minerals (Saha *et al.* 1968 *b*) and also on the basis of our knowledge of the trace element contents

TABLE XII  
*Mineralogical interpretation based on the significant rotated factor loadings*

Phase	Factor	Variables with significant loadings	Recalculated per cent eigen values accounted for	Interpretation
I	1	Ni, Ti, V, (Ga*, Zr, Cr)	29.5	probably an early phase of crystallisation when biotite and opaque ore started to crystallise, accompanied by plagioclase, plagioclase crystallised alone, probably accompanied by some K-feldspar, a phase of crystallisation in which biotite was crystallising along with plagioclase, crystallisation of plagioclase accompanied by some biotite, crystallisation of K-feldspar along with accessories (sphene and allanite). The negative correlation of Ba and positive correlation of U with this factor indicate with progressive crystallisation Ba decreases and U increases.
	2	Sr	12.3	
	3	Li, Cu, (Cr)	20.0	
	4	Mn, Ga	14.0	
	5	Ba*, U	17.0	
II	1	V, Ti, (Ba)	23.8	a phase of crystallisation when biotite, plagioclase and K-feldspar were crystallising simultaneously, crystallisation of sphene along with plagioclase and biotite, when U increased Sr, Ni and Mn decreased with progressive crystallisation, crystallisation of biotite and zircon simultaneously. With progressive crystallisation Cr decreased and zirconium increased, crystallisation of biotite along with some plagioclase, crystallisation of plagioclase mainly, probably along with a little biotite,
	2	U, (Sr*, Ni*, Mn*)	20.4	
	3	Cr*, Zr	20.6	
	4	Li	11.1	
	5	Ga, Mn	17.1	
III	1	Sr, Ti, V, Cu, Ga, Mn, Zr	38.9	crystallisation of biotite along with plagioclase, K-feldspar and zircon, crystallisation of biotite with some accessories like sphene and apatite, crystallisation of biotite accompanied by some plagioclase, crystallisation of K-feldspar, probably alone, crystallisation of biotite alone.
	2	Li, (U)	14.8	
	3	Ni, (Mn)	14.5	
	4	Ba	10.2	
	5	Cr	9.3	

Variables in brackets have minor loadings

\*indicates negative loadings

of granitic minerals in general, it appears that the chief contributors (in order of importance) of each trace element in the total rock are, as follows :

- Li — Biotite, chlorite, plagioclase (minor)  
 Ba — K-feldspar, plagioclase (notably in phase II)  
 Ga — mainly plagioclase  
 U — sphene, allanite  
 Zr — zircon (mainly inclusions in biotite and chlorite)  
 V — biotite, chlorite, plagioclase, opaque ore  
 Cr — biotite, chlorite, plagioclase (minor)  
 Ni — biotite, chlorite  
 Cu — chlorite, biotite, plagioclase  
 Sr — plagioclase, K-feldspar (in Phase III)  
 Mn — plagioclase, chlorite, biotite  
 Ti — chlorite, biotite, plagioclase, opaque ore.

The role of chlorite has been apparently secondary as biotite is the chief primary mineral in these rocks and chlorite is derived from it by metamorphism. So the trace elements in chlorite belonged mostly to the original biotite.

As already noted, each factor may be considered to represent a particular process of magmatic or (deuteric) crystallization. We may identify such processes as the

TABLE XIII  
*Influence of different minerals on the factors for the three phases*

Factors Minerals	1	2	3	4	5
(a) Phase—I					
Biotite	×	—	×	×	—
K-feldspar	—	×	—	—	×
Plagioclase	×	×	×	×	—
Sphene, allanite	—	—	—	—	×
Opaques	×	—	—	—	—
(b) Phase—II					
Biotite	×	×	×	×	—
K-feldspar	×	—	—	—	—
Plagioclase	×	×	—	×	—
Sphene	—	×	—	—	—
Opaques	—	—	—	—	—
Zircon	—	—	×	—	—
(c) Phase—III					
Biotite	×	×	×	—	×
K-feldspar	×	—	—	×	—
Plagioclase	×	—	×	—	—
Sphene, apatite	—	×	—	—	—
Opaques	—	—	—	—	—
Zircon	×	—	—	—	—

crystallisation of the minerals or groups of minerals containing the trace elements having high loadings on the particular factor. The interpretation of the rotated factors was made on this basis (Table XII).

From Table XII it appears that in Phase I biotite and plagioclase started crystallising simultaneously as the structure of no factor suggests crystallisation of biotite alone. In Phase II plagioclase crystallisation started later than that of biotite but it appears that at one stage biotite, plagioclase and K-feldspar were crystallising simultaneously. In phase III, on the other hand, biotite appears to have started crystallising alone in the early stages, followed by the simultaneous crystallisation of biotite, plagioclase and K-feldspar and at a later stage there is evidence of K-feldspar crystallising alone. The presence or absence influence of different minerals in the different factors of the three phases is shown in Table XIII.

### CONCLUSIONS

The differences in the cluster groupings, as observed in different methods, are bound to occur as the three methods follow different assumptions in the grouping techniques. The correlation profile method is rather more subjective than the ramifying linkage method and factor loadings method and the cluster groupings obtained by the former are probably not as reliable. But the important point to be noted is that the cluster groups for the three phases are found to be substantially different in all the three methods. This supports a model of substantially different processes of trace element distribution during the crystallisation of the rocks belonging to the three phases.

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