Correlation Coefficient Patterns and Their Interpretation in Three Basaltic Suites

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Abstract. Single stage magmatic fractionation processes result in igneous rock suites in which correlation coefficients between pairs of elements are generally high. The Tertiary lavas of E. Iceland are used as an illustration of this type of behaviour. When a second process such as fractionation at a different pressure, wall-rock assimilation, or mixing with a different magma, occurs, correlation coefficients are altered in a predictable way if the process and the chemical characteristics of the participating rocks, minerals and liquids are known. A computer program has been devised to simulate complete correlation coefficient matrices for any desired two- or multi-stage process e.g. fractional crystallisation coupled with contamination. Basaltic suites from Mahabaleshwar, India and the Rooi Rand, southern Africa show correlation coefficient patterns characteristic of multi-stage evolution, and these are interpreted with the aid of computer simulation. The Mahabaleshwar suite shows clear evidence of contamination by a granitic component. The Rooi Rand rocks however remain problematic.

Introduction

In many suites of igneous rocks there are poor correlations between concentrations of one element and another. The variation diagrams for pairs of elements show blurred, cloudy or incoherent patterns, in which clear trends are hard to discern. The purpose of the present paper is to investigate and describe variation in suites of this type and to propose ways in which it may have been generated. It is assumed that scattered trends, if analytical error can be discounted, are the result of two or more distinctly different petrogenetic processes operating in sequence on the magmatic system. We shall illustrate this principle by reference to three suites of basaltic rocks which are broadly similar in overall compositional range but which nevertheless show strikingly different properties from the point of view of inter-element correlations. The work can also be viewed as an attempt to develop techniques which make the fullest possible use of sets of analytical data and attempt to ensure that *all* inter-element relationships are consistent with mechanisms proposed. It is an extension of, and complement to, several very well established techniques of which the mixing calculation (Bowen 1928; Bryan et al. 1969; Wright and Doherty 1970) is the most notable, as well as the many variants of trace element modelling calculations based on the work of Gast (1968), for the example the recent study by DePaolo (1981). These methods excel at the simulation of magmatic trends, but do not extract petrogenetic information from the degree to which such trends

may be blurred. In extreme cases they are completely unuseable when inter-element coherence is lacking or slight. As another comparison, many petrogenetic studies have been based on the interpretation of only a small fraction of the potentially available compositional data. These are mainly special cases concerned with isotopes or REE, and while the scientific elegance of these methods is undoubted, and in many cases the conclusions are difficult to refute, it would nevertheless by reassuring to know that other elements did in fact behave according to prediction. Thus the present study attempts to provide a means of confirmation and reinforcement of some existing ideas, and also, as we hope to demonstrate, a means of adding detail to our models of petrogenetic mechanisms.

Single Stage Processes

Before discussing the effects of multi-stage processes on interelement correlations we consider the simple case of the single stage process.

The most idealised single-stage process is the production of a series of magmas by the mixing of two end-members of fixed composition. In *ideal* circumstances (implying amongst other things an absence of analytical error) the resultant suite will show inter-element correlation coefficients which are $+1$, -1, or 0, the latter value being a consequence of one or both elements of a pair having the same concentration in the two end-members. The same arguments would apply to bulk assimilation of a wall-rock of perfectly uniform composition, or to fractional crystallisation or partial melting in the special (and highly unlikely) case of the solid fraction being of constant composition.

In real cases, however, a large number of factors result in correlation coefficients between element pairs being less than unity. In fractional crystallisation and melting, for example, liquid paths in general follow curve trajectories on two-element plots, as the compositions of solid phases and the proportions in which they crystallise or contribute to the melt change with temperature. Although ideally there may exist a curve which all data points fit perfectly the correlation coefficient will be reduced. This is not, however, likely to be a very strong effect in many cases because the departure from linearity of many fractionation curves is small, especially over small to moderate degrees of fractionation. Other factors which in practice serve to reduce the size of correlations are analytical error, small degrees of alteration, and fluctuations in phenocryst proportions and contents which may be effectively random on the scale of the samples analysed. Additional effects, such as, for example, the likely non-uniformity of contaminants or parental magmas,

are considered later because they require description in terms of multi-stage processes (e.g. an extra process is necessary to generate variation in a contaminant).

The degree to which a particular correlation is reduced by the above factors is likely to be highly dependent on the amount of variation shown by individual elements. In an extreme case where one or both elements show no variation, even ideally the correlation will be zero. If the variation in one or both is small, the correlation may ideally be perfect but will become much reduced by even very small random fluctuations in concentrations. In contrast if both elements show large variation the value of the correlation coefficient will not be greatly reduced by such effects.

Thus, a magmatic suite produced by a *near*-ideal single stage process should in principle be recognised by generally high correlations, with the possible exception of those involving elements showing little or no variation. The Tertiary lavas of eastern Iceland described by Wood (1978) provide a suitable example.

In order to provide comparability with the other suites studied we have used the analyses of 16 of these rocks (Tables 2 and 3 of Wood) omitting the four most magnesian samples, the altered sample N47, and those samples more evolved than ferrobasalt. Ranges, means and standard deviations of analytical values are given in Table 1, where the close comparability of these rocks to the other suites, Mahabaleshwar and Rooi Rand, is also evident. The sequence selected has evolved by the fractionation of olivine, clinopyroxene, and plagioclase (Wood, op. cit.). The more evolved rocks are omitted because of the involvement of additional fractionating phases, particularly magnetite, ilmenite, and apatite.

The selected rocks form an excellent example of a tholeiitic iron enrichment trend, produced by the fractionation of the olivine-gabbro assemblage (e.g. see Cox 1980). With increasing Fe/Mg ratio Si shows almost no change and Al shows slight depletion. Other major elements show more variation i.e. strong enrichment in Fe, Ti and K, moderate depletion in Ca, and strong depletion in Mg. Strong enrichment is shown by incompatible minor and trace elements such as P, Ba, Nb, Zr, La, Ce and Hf, while lower degrees of enrichment are seen for elements which are significantly partitioned into clinopyroxene (Y, Zn) or plagioclase (Sr). Strong depletion is of course seen in Ni and Cr which are strongly partitioned into the fractionating ferromagnesian phases.

The inter-element correlation coefficient matrix is given in Table 2, where it is evident that most of the relationships seen here are compatible with the concept of the near-ideal single stage process. The majority of elements show many correlations of high significance (e.g. numerical values >0.8) but several elements already noted as showing less variation than the others, give generally lower values. Amongst these Si is the most prominent, but the effect is also clearly visible for Al, Sr and Zn. There are, however, some exceptions for which no explanation is readily forthcoming in the existing hypothesis. Two elements

Cr, and Ni show somewhat lower correlation coefficients than might be expected, and, because of their occasional very significant correlations with certain critical elements, these can not be explained as simply due to analytical error. For example the coefficient of 0.92 for Ca–Cr and the coefficient of 0.86 for Ni–Mg suggest some sort of mineralogical influence involving clinopyroxene and olivine respectively. Additionally the generally *relatively* low correlation coefficients between Ni, Cr, and the incompatible elements (values mainly <0.8) remain as a slight anomaly, which is not however sufficiently marked to detract from the nearly ideal picture shown by this suite.

The conclusion that the Tertiary basalts of eastern Iceland approach the ideal single-stage model in their behaviour is plausible. The rocks are relatively fresh, the phenocryst contents are low, and Wood concludes that they have formed by fractional crystallisation in a high-level magma chamber. A complex polybaric evolution has evidently not taken place, and continental crust, a possible contaminant, is absent. In the remaining parts of this paper two continental basaltic suites will be studied for comparison. They show patterns of inter-element correlation which are fundamentally different from the eastern Iceland case. Contamination by granitic materials, complex polybaric fractionation processes, the accumulation of phenocrysts, and source material heterogeneity, are all factors which could be considered as possibly capable of bringing about these changes.

Two-Stage Processes

After a single-stage process has operated to produce inter-element relationships of the type discussed, a second process may act upon the resultant rocks or magmas. It is convenient to think of two processes operating in sequence though in a statistical sense it makes little difference which one takes place first, or indeed if they alternate with each other repetitively, or act simultaneously. The consequences of two-stage processes will be examined with reference to the generalised two-element variation diagrams illustrated in Fig. 1.

In these diagrams the *initial trend* (A–B) is generated by the first process. The second process involves the introduction of a new compositional component, C, which may have a variety of roles. If a solid, C may represent the bulk composition of a contaminant which is added to liquids lying on the initial trend. Alternatively the liquids may accumulate crystals represented by C, or may lose them by fractional crystallisation. If the initial trend is represented by solid rocks of varying composition, C may further represent a residue left after partial melting, in which case new liquids are effectively produced by the removal of C from compositions on the initial trend. Alternatively C may represent the composition of a metasomatising fluid which is added to rocks on the initial trend.

In Fig. 1 three different positions of C are shown, relative to the position of the initial trend. Shaded areas represent the ranges of compositions occupied by resultant rocks or magmas
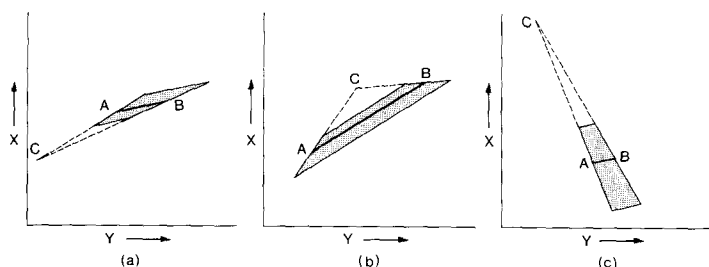

Fig. 1a–c. The geometrical principles of a two-stage fractionation process. X and Y are concentrations of two elements or oxides. *Heavy line A–B* is initial fractionation trend. Shaded areas are fields occupied by rocks or magmas derived by adding or subtracting up to 25 per cent of the third compositional component C

when variable amounts of fractionation of C operate on all of the compositions on the initial trend. The maximum amount of fractionation of C has been taken as 25 per cent in all cases (both addition and subtraction). At the moment we ignore the possibility that C fractionation could operate selectively by affecting one end of the initial trend more than the other. This probably does happen in some cases (see behaviour of Ni in Mahabaleshwar rocks discussed later) but it is not necessary to invoke this effect to explain many observed relationships.

It is evident from inspection of Fig. 1 that the capacity of the second process to blur the initial trend is entirely dependent on the geometrical relationships concerned. In Fig. 1(a) a case is depicted where an initially positive correlation is maintained by the second process. The essential geometry of this diagram is that C lies near the extension of the initial trend and is compositionally significantly displaced from A and B. Figure 1(b) shows how an initial correlation will suffer only limited modification when C is compositionally close to A and B. In contrast the third case, Fig. 1(c), illustrates the way in which the second process can convert an initially positive correlation into a negative one.

It follows from the above that *qualitative* predictions about the behaviour of correlation coefficients can be made for two-stage models in which compositional characteristics are assigned to both the initial trend and to component C. Since many data sets contain ca. 200 element pairs, and since predictions can be made for *all* of these, each specific model may be expected to produce a highly distinctive array of coefficients. The technique explored in this paper thus consists of examining arrays of correlation co-efficients derived from sets of real analytical data, and then trying to simulate them mathematically by means of model two-stage or multi-stage processes, using geologically plausible compositions for A, B, C, and additional components when required.

Correlation Coefficient Patterns

The correlation coefficient matrices for the two other suites under discussion are given in Tables 3 and 4. The Mahabaleshwar rocks are a series of horizontal flood basalts from the Western Ghats escarpment of the Deccan province, India (Najafi et al. 1981). The Rooi Rand rocks are from a dyke swarm in the southern part of the Lebombo Monocline area of the Karoo Province (Armstrong 1978; Bristow 1980). As demonstrated in Table 1 both suites are extremely similar to the eastern Icelandic basalts discussed previously, in terms of the ranges of elemental variation shown. All are tholeiitic suites which show typical tholeiitic iron-enrichment trends. In the case of the Rooi Rand the analyses all represent aphyric rocks. For Mahabaleshwar, where virtually

Table 1. Means, ranges, and standard deviations of major element oxides in the suites studied

Oxide	Mean	Range	Standard deviation	Suite
SiO_2	47.79	44.92–49.37	0.98	E. Iceland
	49.01	47.94–52.02	0.97	Mahabaleshwar
	49.63	47.04–52.11	1.08	Rooi Rand
TiO_2	2.65	1.77–3.96	0.69	E. Iceland
	2.10	1.09–2.94	0.63	Mahabaleshwar
	2.10	1.08–3.46	0.62	Rooi Rand
Al_2O_3	14.52	12.86–15.92	0.97	E. Iceland
	14.00	12.32–15.84	1.10	Mahabaleshwar
	13.37	11.66–15.35	0.77	Rooi Rand
Fe_2O_3 total	14.33	11.95–17.51	1.63	E. Iceland
	15.93	13.81–17.34	1.18	Mahabaleshwar
	15.41	12.52–19.02	1.62	Rooi Rand
MgO	6.41	4.50–7.53	1.04	E. Iceland
	6.16	4.86–7.22	0.68	Mahabaleshwar
	5.84	4.28–7.11	0.83	Rooi Rand
CaO	10.89	9.03–12.52	1.13	E. Iceland
	9.53	7.67–10.90	0.95	Mahabaleshwar
	10.34	8.52–12.04	0.91	Rooi Rand
Na_2O	2.55	2.03–3.28	0.38	E. Iceland
	2.43	1.94–3.68	0.46	Mahabaleshwar
	2.44	2.16–2.89	0.20	Rooi Rand
K_2O	0.36	0.09–0.73	0.21	E. Iceland
	0.37	0.14–0.83	0.18	Mahabaleshwar
	0.40	0.16–1.04	0.23	Rooi Rand

all the rocks are porphyritic, the most phenocryst-poor specimens have been selected for the present study (total olivine + clinopyroxene + plagioclase < 8 per cent).

A correlation coefficient pattern is a diagrammatic representation of the coefficients between a particular element and a series of other elements. In Fig. 2 we focus attention on the correlation behaviour of K in the three suites, as it relates to other incompatible and semi-incompatible elements. The correlation coefficient for Rb is omitted from the East Iceland diagram since some Rb values given by Wood (1978) are below detection limits. The elements are arranged in a somewhat arbitrary order, which is as much a matter of convenience as anything else, as will become apparent.

The distinctive nature of the three patterns is obvious, and if it is accepted that the eastern Icelandic suite was generated by a single-stage process involving the removal of olivine, clino-
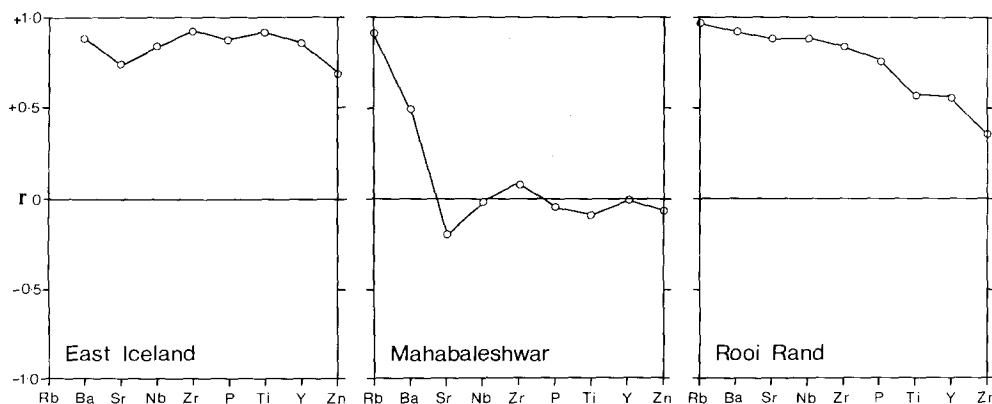
Fig. 2. Correlation coefficient patterns showing how K correlates with other incompatible and semi-incompatible elements in three contrasted basaltic suites

Table 2. Correlation coefficients for 16 samples of E. Iceland basalts

	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Sr
SiO_2	−0.11	−0.41	−0.17	0.01	−0.24	0.19	−0.36	−0.20	−0.29	−0.55
TiO_2		−0.72	0.94	0.78	−0.90	−0.95	0.82	0.92	0.87	0.72
Al_2O_3			−0.76	−0.81	0.77	0.60	−0.37	−0.58	−0.41	−0.15
Fe_2O_3				0.88	−0.85	−0.93	0.78	0.81	0.74	0.64
MnO					−0.75	−0.74	0.53	0.61	0.63	0.33
MgO						0.86	−0.72	−0.76	−0.73	−0.52
CaO							−0.90	−0.90	−0.86	−0.76
Na_2O								0.80	0.83	0.82
K_2O									0.88	0.74
P_2O_5										0.81

	Ba	Nb	Zr	Y	Ni	Cr	Zn	La	Ce	Yb	Hf
SiO_2	−0.21	−0.19	−0.11	0.13	−0.37	0.07	−0.11	−0.18	−0.14	0.18	0.11
TiO_2	0.93	0.94	0.97	0.90	−0.74	−0.86	0.79	0.95	0.97	0.88	0.95
Al_2O_3	−0.54	−0.56	−0.62	−0.70	0.79	0.60	−0.57	−0.59	−0.63	−0.79	−0.75
Fe_2O_3	0.83	0.85	0.87	0.80	−0.70	−0.87	0.85	0.87	0.88	0.83	0.84
MnO	0.65	0.73	0.70	0.79	−0.73	−0.71	0.77	0.68	0.71	0.85	0.70
MgO	−0.82	−0.84	−0.88	−0.90	0.86	0.84	−0.76	−0.84	−0.87	−0.89	−0.92
CaO	−0.90	−0.91	−0.95	−0.84	0.61	0.92	−0.87	−0.92	−0.94	−0.84	−0.89
Na_2O	0.83	0.83	0.81	0.67	−0.41	−0.83	0.72	0.84	0.82	0.65	0.72
K_2O	0.89	0.84	0.93	0.83	−0.58	−0.74	0.69	0.88	0.91	0.78	0.88
P_2O_5	0.92	0.93	0.91	0.83	−0.61	−0.76	0.68	0.89	0.91	0.75	0.81
Sr	0.86	0.78	0.75	0.47	−0.38	−0.66	0.53	0.83	0.79	0.38	0.65
Ba		0.95	0.93	0.79	−0.72	−0.79	0.70	0.98	0.97	0.71	0.89
Nb			0.94	0.86	−0.71	−0.81	0.75	0.96	0.97	0.81	0.90
Zr				0.91	−0.72	−0.87	0.81	0.94	0.97	0.86	0.96
Y					−0.77	−0.76	0.76	0.80	0.86	0.96	0.89
Ni						0.64	−0.55	−0.71	−0.73	−0.74	−0.80
Cr							−0.85	−0.83	−0.84	−0.80	−0.83
Zn								0.74	0.77	0.79	0.77
La									0.99	0.75	0.92
Ce										0.82	0.95
Yb											0.87

pyroxene, and plagioclase in approximately fixed proportions, then it follows that the other two were generated in significantly different ways. Since these suites nevertheless still have much in common with the east Iceland rocks (particularly with regard to major elements) the most obvious possibility is that they too have undergone gabbro fractionation but that other processes have also operated i.e. they may be multi-stage suites. However, before discussing these problems in more detail a number of general points should be made.

Firstly, we have assumed that the data sets have a normal distribution in calculating the *significance* of a correlation coefficient, which is usually expressed in terms of confidence level e.g. 95 per cent, or more commonly 99 per cent. Most of our data approximate to this criterion but occasionally an outlying value may impart a strong skew to the distribution and under these circumstances a spurious correlation coefficient may result. We shall point out examples as they arise.

Secondly, the term significant has to be employed both in its statistical sense, and in its more ordinary linguistic sense for many petrogenetic purposes. For example if two elements are normally expected to correlate strongly e.g. Zr and Nb, and a particular data set produces a correlation coefficient of 0.00, this is a relationship of extreme significance in the ordinary sense of the word. Some process must have operated (even if it is only analytical error) to produce such an unusual result.

Thirdly, it is important to know in the discussion which follows whether two correlation coefficients *differ* from each

other significantly. *Standard errors* of coefficients are calculated approximately as:

$$\text{standard error} = \frac{1 - r^2}{n}$$

where r is the correlation coefficient and n the number of samples. As examples of the magnitudes of such errors, for the Mahabaleshwar and E. Iceland data sets, in which $n = 16$, the standard errors on correlation coefficients of 0.9, 0.5 and 0.1 are 0.05, 0.19 and 0.25 respectively. For the Rooi Rand data $(n = 23)$ these figures are correspondingly slightly reduced. Reference to Fig. 2 will show that the pattern differences for K between the three suites are mainly outside the standard errors, though the differences between the East Iceland and Rooi Rand patterns are only small.

Finally, the place of correlation coefficient patterns within the general concept of data presentation in igneous geochemistry deserves some comment. The particular advantages of two-element plots (variation diagrams) in the investigation of inter-element relationships and the construction of petrogenetic hypotheses have already been argued by Wright (1974) and by Cox et al. (1979). However, for a data set where analyses of, say, 20 elements have been obtained there are 190 such plots potentially available. The characteristics, but not the details, of the diagrams may be generalised by the calculation of regression lines, intercepts of regression lines, and correlation coefficients. The latter tell us roughly speaking how scattered each

Table 3. Correlation coefficients for 16 samples of Mahabaleshwar basalts

	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Rb	Sr
SiO_2	-0.46	-0.39	-0.46	-0.43	0.02	-0.07	0.52	0.75	-0.24	0.85	-0.48
TiO_2		-0.44	0.78	0.43	0.08	-0.63	-0.39	-0.08	0.58	-0.26	0.43
Al_2O_3			-0.46	0.02	-0.16	0.41	-0.05	-0.38	-0.42	-0.30	0.06
Fe_2O_3				0.50	-0.25	-0.59	-0.22	-0.09	0.69	-0.34	0.61
MnO					-0.28	-0.30	0.05	-0.17	0.01	-0.24	0.33
MgO						0.03	-0.49	-0.34	-0.03	-0.31	-0.35
CaO							-0.16	-0.41	-0.61	-0.21	-0.46
Na_2O								0.59	-0.10	0.71	0.11
K_2O									-0.04	0.91	-0.20
P_2O_5										-0.14	0.53
Rb											-0.26

	Ba	Nb	Zr	Y	Ni	Cr	Co	V	Zn	Cu
SiO_2	0.37	-0.32	-0.32	-0.41	0.52	0.61	-0.39	-0.69	-0.49	-0.51
TiO_2	0.33	0.55	0.66	0.76	-0.67	-0.69	0.27	0.76	0.74	0.56
Al_2O_3	-0.36	-0.12	-0.16	-0.21	0.06	0.16	-0.02	-0.10	-0.18	-0.10
Fe_2O_3	0.19	0.73	0.76	0.81	-0.65	-0.70	0.01	0.63	0.71	0.70
MnO	-0.10	0.44	0.36	0.41	-0.24	-0.32	0.25	0.48	0.50	0.58
MgO	0	-0.48	-0.41	-0.34	0.10	0	0.33	-0.23	-0.37	-0.37
CaO	-0.67	-0.60	-0.71	-0.68	0.51	0.29	0.27	-0.26	-0.54	-0.41
Na_2O	0.21	0.11	-0.01	-0.13	0.30	0.54	-0.42	-0.18	0.08	0.04
K_2O	0.49	-0.01	0.07	-0.01	0.17	0.33	-0.37	-0.27	-0.07	-0.24
P_2O_5	0.35	0.59	0.67	0.66	-0.59	-0.46	-0.08	0.46	0.58	0.62
Rb	0.40	-0.10	-0.09	-0.19	0.32	0.51	-0.36	-0.35	-0.16	-0.32
Sr	0.19	0.88	0.80	0.72	-0.72	-0.54	-0.40	0.52	0.77	0.56
Ba		0.45	0.45	0.33	-0.08	0.07	-0.49	-0.07	0.32	0.13
Nb			0.94	0.86	-0.65	-0.50	-0.45	0.52	0.85	0.71
Zr				0.96	-0.80	-0.62	-0.38	0.60	0.83	0.69
Y					-0.84	-0.72	-0.17	0.71	0.85	0.75
Ni						0.88	0.05	-0.64	-0.66	-0.45
Cr							-0.20	-0.65	-0.55	-0.40
Co								0.33	-0.06	0.09
V									0.84	0.73
Zn										0.83

diagram would look, and, if a discernible trend exists, whether it represents a sympathetic or antipathetic relationship. A set of 20 correlation coefficient patterns will thus provide a large part of the petrogenetic information potentially derivable from the 190 diagrams. The method, then, provides a convenient way of looking at the 'internal structure' of clouds of data points. There may be much debate about the way such structures should be interpreted, but they still require explanation of some sort.

## Basalts of Mahabaleshwar, Deccan Traps

The Mahabaleshwar section of the Deccan Traps consists of a relatively monotonous flat-lying sequence of tholeiite flows, 1.5 km thick, forming part of the impressive escarpment of the Western Ghats. Details of the geology and geochemistry are given by Deshmukh et al. (1977), Najafi (1979), Najafi, Cox and Sukheswala (1981) and Mahoney et al. (in press). The range of compositional variation is similar to that of the Icelandic lavas discussed previously (see Table 1) and, similarly, the phenocrysts present are olivine, clinopyroxene, and plagioclase.

However in contrast with the Icelandic lavas the major element relationships are scattered and incoherent. Because of these complexities and because work is continuing on this suite, it is not intended to analyse these rocks in detail at present. Attention is restricted largely to the incompatible and semi-incompatible element which show patterns of behaviour strikingly different from those of the Icelandic lavas and which can be explained neither in terms of phenocryst accumulation nor in terms of polybaric fractionation. The relationships have been ascribed by Najafi et al. (1981) to crustal contamination, a model which is rediscussed and elaborated here.

In order to minimise possible complexities caused by porphyritic rocks, correlation coefficients calculated here (Table 3) refer only to 16 rocks from the original data set, selected as having less than 8 per cent total phenocrysts. The sample set is biased towards the lower and middle parts of the sequence. It is apparent from Fig. 3, compared with Fig. 2 and Table 2, that the correlation coefficient matrix for the incompatible and semi-incompatible elements differs grossly from that derived from the Icelandic rocks. Many values have extremely low significance levels, and there are even some negative coefficients between pairs of elements for which a positive correlation would normally be expected.

As an approach to the interpretation of the patterns we note that the most obvious feature of the collection is the way in which groups of elements show similarities of pattern-shape. K, Rb, and Si form one group, characterised by a rapid fall to the right, between Ba and Sr. Ba has a distinctive pattern which is almost flat, while the other elements Sr, Nb, Zr, P, Ti, Y, Cu, Zn and Fe, have patterns which slope to the left. Alternatively expressed, positive correlations within the first group of elements are good, as they are also within the last
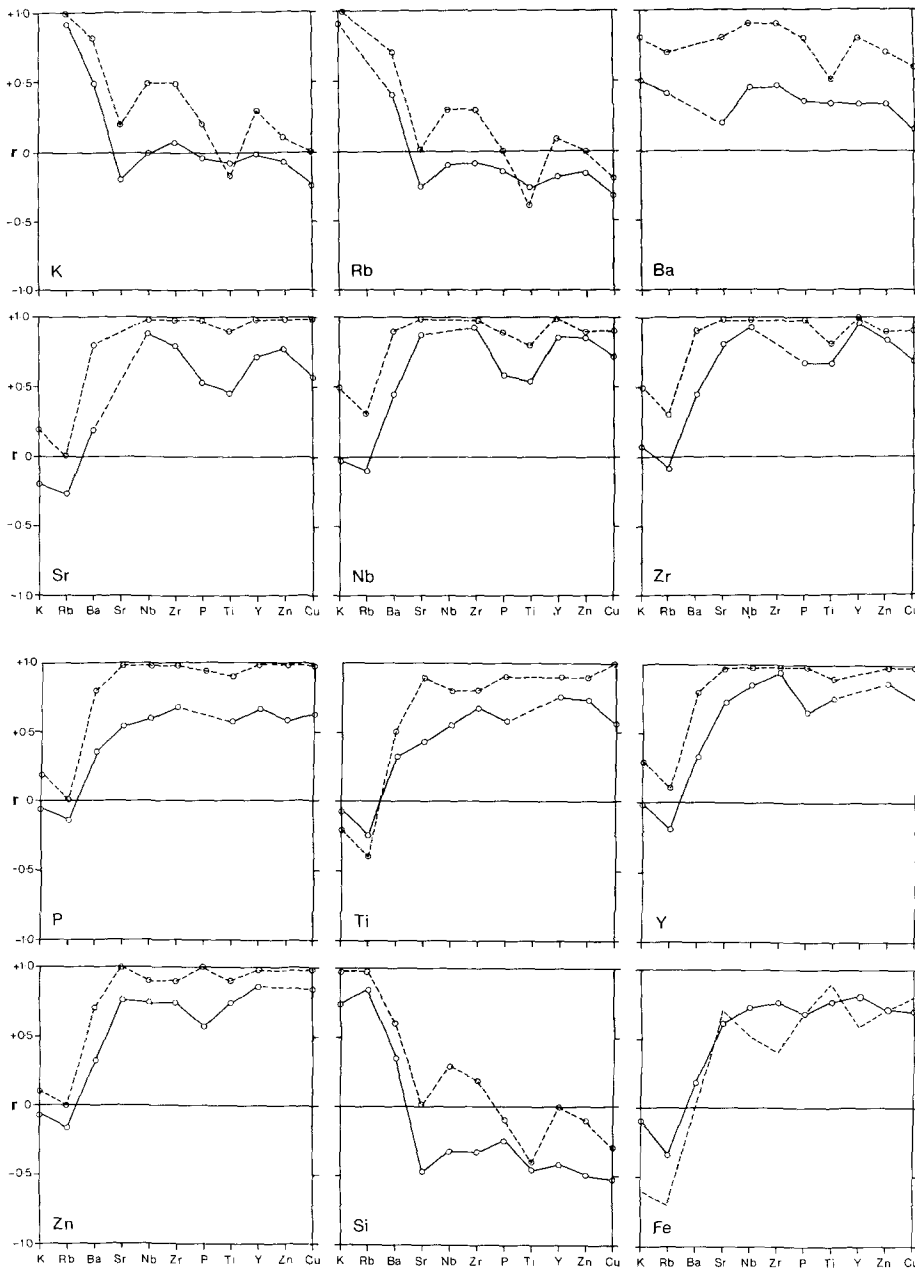
Fig. 3. Correlation coefficient patterns for Mahabaleshwar rocks (see Table 3 for complete matrix). *Solid line* joins points in *observed* pattern, the *broken portion* indicates where the correlation coefficient between each element and itself has been omitted. *Continuously broken lines* are patterns *calculated* using DARWIN, the specific model consisting of a 0–100 per cent mixture of MRR1 and MRR2 (Table 5) giving the initial trend, followed by the addition of 0–40 per cent of "Granite B" (Table 5)

group. Correlations between elements in different groups are in contrast poor, or may even be negative. Reference to Table 2 will show that in the East Iceland suite all the correlations of these elements, with the exception of Si, are strongly positive. Si in the Icelandic rocks does show negative correlations but the pattern is flat except for a strong negative Sr peak, quite unlike the strongly inflected Mahabaleshwar pattern.

Simulation of Patterns

To allow the simulation of complete correlation coefficient matrices resulting from the mixing of random amounts of designated compositions as many times as desired we have designed a computer program, Darwin, details of which are given in the appendix. A typical operation, for example, might consist of a first step in which a mixing line is generated between two basaltic compositions in order to simulate a desired basaltic fractionation trend. All correlations at this stage are +1.0, −1.0 or, if a compositional parameter has the same value in the two end-

members, 0.0. A second stage might then consist of the random addition of up to any desired amount of, say, plagioclase, to the existing series, and the correlation matrix for the resultant series is calculated. The calculation thus attempts to reproduce the correlation coefficient patterns to be expected in a fractionated basaltic series which had undergone subsequent plagioclase accumulation. The flexibility of the program is such that large numbers of options can be tested in a short time. Like any modelling operation the results can be used to confirm the feasibility of a proposal, but more importantly can be used to exclude other hypotheses positively. It is important to stress that the operation is not designed to match observed correlation coefficient patterns *exactly* but simply to discover the ranges or types of models which match *qualitatively,* and to exclude those which do not so match. Multi-stage operations with progressive refinement of input data will no doubt lead to exact matches if they are desired, but such are the artificialities of the calculation that there is absolutely no guarantee that the results would be more realistic than those of less exact calculations.

Table 4. Correlation coefficients for 23 samples of aphyric Rooi Rand dolerites (original data from Armstrong (1978) and Bristow (1980))

	K	Rb	Ba	Sr	Nb	Zr	P	Ti	Y	Zn	Cu
Rb	+0.97										
Ba	+0.92	+0.94									
Sr	+0.88	+0.89	+0.89								
Nb	+0.89	+0.92	+0.90	+0.82							
Zr	+0.84	+0.86	+0.81	+0.69	+0.94						
P	+0.77	+0.79	+0.72	+0.61	+0.85	+0.93					
Ti	+0.57	+0.40	+0.29	+0.17	+0.53	+0.70	+0.81				
Y	+0.56	+0.58	+0.50	+0.29	+0.71	+0.88	+0.86	+0.83			
Zn	+0.35	+0.40	+0.31	+0.27	+0.57	+0.65	+0.58	+0.84	+0.71		
Cu	+0.35	+0.36	+0.22	+0.09	+0.47	+0.70	+0.71	+0.81	+0.91	+0.71	
Si	+0.52	+0.52	+0.68	+0.65	+0.41	+0.21	+0.18	−0.30	−0.14	−0.17	−0.43
Fe	+0.21	+0.21	+0.08	+0.06	+0.48	+0.57	+0.48	+0.84	+0.80	+0.76	+0.83
Na	+0.38	+0.36	+0.36	+0.38	+0.30	+0.30	+0.13	+0.14	+0.14	+0.41	+0.05
Al	−0.41	−0.40	−0.28	−0.17	−0.53	−0.70	−0.59	−0.86	−0.83	−0.84	−0.80
Ca	−0.86	−0.88	−0.86	−0.69	−0.92	−0.95	−0.85	−0.75	−0.82	−0.63	−0.60
Mg	−0.78	−0.80	−0.76	−0.62	−0.85	−0.90	−0.79	−0.78	−0.81	−0.74	−0.62
Ni	−0.66	−0.68	−0.72	−0.61	−0.69	−0.67	−0.50	−0.47	−0.53	−0.56	−0.30
Cr	−0.67	−0.66	−0.72	−0.50	−0.63	−0.65	−0.56	−0.45	−0.58	−0.35	−0.33
Co	−0.34	−0.31	−0.45	−0.26	0.00	−0.16	−0.26	−0.25	−0.16	+0.17	−0.03
Sc	−0.76	−0.73	−0.67	−0.74	−0.67	−0.56	−0.48	−0.38	−0.22	−0.32	−0.09

Application to Mahabaleshwar Basalts

The minor and trace element geochemistry of the Mahabaleshwar basalts lead Najafi et al. (1981) to suggest that the suite had been affected by the addition of a granitic contaminant rich in K, Rb and Ba. This would create strong positive correlations between these elements and destroy or diminish positive correlations which they might previously have had with other incompatible elements such as P, Zr, Nb, and semi-incompatible elements such as Ti, Y, Zn and Cu. Existing correlations between elements of the latter two groups e.g. Zr vs. Nb or P vs. Ti would however be retained because the contaminant contained approximately the same amount of these elements as the uncontaminated magmas.

We have made a more comprehensive test of this proposal using Darwin, and are able to illustrate the behaviour of the important major elements Si and Fe in addition to the trace elements. The first step in the calculations employed was to generate a plausible Fe-enriched tholeiite fractionation trend to simulate the behaviour of the Mahabaleshwar magmas before contamination. The considerable range of Fe and Ti concentrations, the presence of olivine, clinopyroxene, and plagioclase phenocrysts, and the absence of phenocrysts of an opaque phase, all suggest that the evolution of the Mahabaleshwar suite involved the fractionation of a gabbroic (olivine + clinopyroxene + plagioclase) assemblage likely to have produced such a trend. An Fe-poor and an Fe-rich representative analysis of the Rooi Rand dolerite suite (see later section) termed MRR1 and MRR2 (see Table 5) were therefore selected as end members for mixing. We have already seen (Table 1) that the Mahabaleshwar and Rooi Rand suites are closely similar, and the latter has been described as a typical Fe-enriched tholeiite suite ascribable to gabbro fractionation (Cox 1980).

The second stage consisted of mixing a variety of average rhyolites and granites from the literature with the suite so formed. A little experimentation resulted in the calculated patterns illustrated in Fig. 3 which were derived by using a composition 'Granite B' shown in Table 5, and which are obviously qualitatively similar to the observed patterns. Most of the discrepancies consist of calculated correlation coefficients having a higher level of significance than observed ones, a result which

Table 5. Input analyses for calculation of simulated Mahabaleshwar patterns

	MRR1	MRR2	'Granite B'
SiO$_2$	49.02	51.3	74.12
TiO$_2$	1.55	2.85	0.30
Al$_2$O$_3$	14.03	12.4	13.58
Fe$_2$O$_3$	12.96	16.02	3.33
MnO	0.22	0.25	0.07
MgO	6.98	4	0.50
CaO	11.32	8.6	2.02
Na$_2$O	2.17	3.1	3.88
K$_2$O	0.19	0.80	3.12
P$_2$O$_5$	0.08	0.38	0.08
Rb	2.5	18.5	131
Sr	150	245	165
Ba	35	245	350
Zr	60	225	154
Nb	2	14	10
Y	24	52	29
Zn	76	144	67
Cu	160	425	21
Ni	85	30	6

'Granite B' is the average of the analyses given by Ewart in his Table 4A (orogenic rhyolites). However, in order to fit the Ba and Nb patterns to their equivalents in the Mahabaleshwar data the concentrations of these elements were adjusted by trial and error, Ba from 597 ppm to 350 ppm and Nb from 23 ppm to 10 ppm

is not surprising in view of the relative simplicity of the model used.

In Table 6 the compositional input parameters to the calculation have been arranged in appropriate sequence to illustrate the three pattern-types which have so far been discussed. What may be termed the K-type pattern (shown by K, Rb, and Si) is generated when the element concerned is strongly enriched during gabbroic fractionation, and when the contaminant is even more enriched. The Ti-type pattern on the other hand is generated by enrichment during gabbroic fractionation followed by the addition of a contaminant absolutely depleted in the element concerned (strong versions of the pattern e.g. Ti, Fe) or at least

Table 6. Dependence of correlation coefficient pattern-type on relative values of input parameters

Pattern type	Element	Value in MRR1	Value in MRR2	Value in Granite B
K-type	K_2O	0.19	0.80	3.12
	Rb	2.50	18.50	131
	SiO_2	49.02	51.30	74.12
Ba-type	Ba	35	245	350
Ti-type	TiO_2	1.55	2.85	0.30
	Fe_2O_3	12.96	16.02	3.33
	MnO	0.22	0.25	0.07
	Sr	150	245	165
	Nb	2	14	10
	Zr	60	225	154
	P_2O_5	0.08	0.38	0.08
	Y	24	52	29
	Zn	76	144	67
	Cu	160	425	21
Mg-type	MgO	6.98	4.00	0.50
	CaO	11.32	8.60	2.02
	Ni	85	30	6
Al type	Al_2O_3	14.03	12.40	13.58

Fig. 4. Calculated and observed pattern for Al in Mahabaleshwar rocks. Symbols as in Fig. 3

depleted relative to the most enriched basalts (weaker pattern e.g. Zr, Nb). The Ba-type pattern can be seen to be intermediate between the K- and Ti-types, and is generated by strong enrichment in the first stage and slight enrichment in the second stage. The geometrical principles given in Fig. 1 can readily be applied to the data in Table 6 to confirm the validity of the statements above.

Of the elements so far not discussed Mg, Ca and Ni form a group whose calculated patterns are all negative since these elements are depleted in both stages. Of these, Ni produces a discrepant observed pattern which illustrates one of the pitfalls of the technique. Reference to Table 3 shows that Ni correlates *positively* with both K and Rb and only slightly negatively with Ba. Calculated coefficients for these elements are however respectively -0.8, -0.6 and -1.0. Reference to the original data set shows that two of the most Ni-rich samples are also amongst the most enriched in K, Rb and Ba. The Ni values for these samples form outlying points in the set, and hence the data are obviously not normally distributed. Elimination of just one sample, that showing the most extreme Ni value, results in correlation coefficients of -0.4, -0.3 and -0.3 with K, Rb and Ba. This illustrates the strong effects which outlying values can have when data distribution is not normal. We have found it useful to calculate gamma, the coefficient of skewness, when deriving correlation coefficients to direct attention towards non-normal data sets. In the case discussed it seems likely that the more basic (Ni-rich) rocks of the suite are over-represented amongst the apparently most contaminated samples, with the consequent generation of positive correlations between Ni and the K, Rb, Ba group.

The remaining element of interest, Al, again produces an observed pattern which is very different from that calculated (see Fig. 4). The calculated pattern is a mirror image (imagining the $r=0$ line as the mirror) of the Ti-type which is a consequence of the fall of Al during the postulated gabbroic fractionation event followed by a slight rise during contamination. However from a consideration of the Ba-type pattern it is evident that if the granitic contminant used had contained slightly less Al than the most evolved basalt, then the calculated pattern would
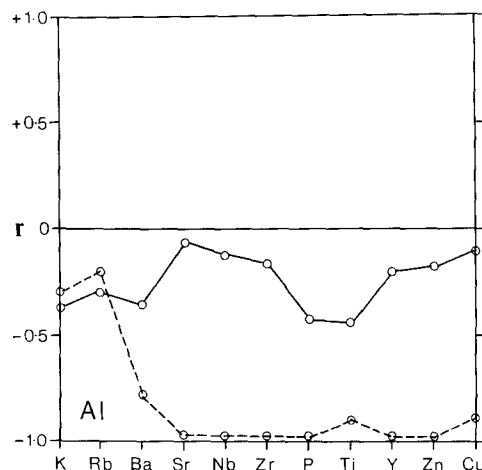
have been a mirror image of the Ba-pattern, and would therefore have matched the observed pattern fairly well. The low level of significance of all of the Al correlations is of course to be expected since the variation in Al is much lower than in any of the other elements considered. In these circumstances calculated patterns are ultra-sensitive to values placed on input parameters, and hence discrepant results may be expected.

Summarising the Mahabaleshwar results, the behaviour of most elements is consistent with an evolution dominated by fractionation of the olivine+clinopyroxene+plagioclase gabbroic assemblage together with contamination by broadly granitic material. Specifically, the contaminant can be identified as enriched in Si, K, and Rb relative to basalt, and impoverished in Fe, Ti, Sr, Nb, Zr, P, Y, Zn and Cu. The contaminant would appear to have about the same content of Al and Ba as the basalt. The low contents of Sr, Nb, Zr, P and Y relative to basalt point to an evolved (low-temperature) granitic composition and thus suggest that contamination may have been caused by the extraction of a low-temperature melt from the country rocks (cf. Patchett 1980) rather than by wholesale assimilation.

As an addendum, C.J. Hawkesworth (pers. comm.) has recently determined $^{87}Sr/^{86}Sr$ ratios on a number of Mahabaleshwar samples and discovered that significant positive correlations exist between the values obtained and the concentrations of K, Rb and SiO_2. Mahoney et al. (in press), on the basis of isotopic data, have also suggested that crustal contamination affects at least the lower part of the Mahabaleshwar sequence.

The Rooi Rand Dolerites

The Rooi Rand dolerites have been taken as one of the best available examples of the Fe-enriched tholeiitic trend during recent studies of the Karoo province (Cox 1980). Nevertheless, a study of correlation coefficient patterns suggests complexities in their evolution which are not explained by a simple model of gabbro fractionation. A matrix of selected correlation coefficients for aphyric dolerites is given in Table 4 and selected patterns are illustrated in Fig. 5. Compared with Mahabaleshwar distinctive patterns are less well-developed. It is clear however that as in the latter suite the patterns for K, Rb and Si are similar to each other and display the same slope to the right, though without the pronounced Mahabaleshwar inflection. Unlike Mahabaleshwar, though, the same type of pattern is displayed by Ba and Sr, and to a slight extent by Al and Nb. In the Rooi Rand case P and Zr show the flat positive pattern
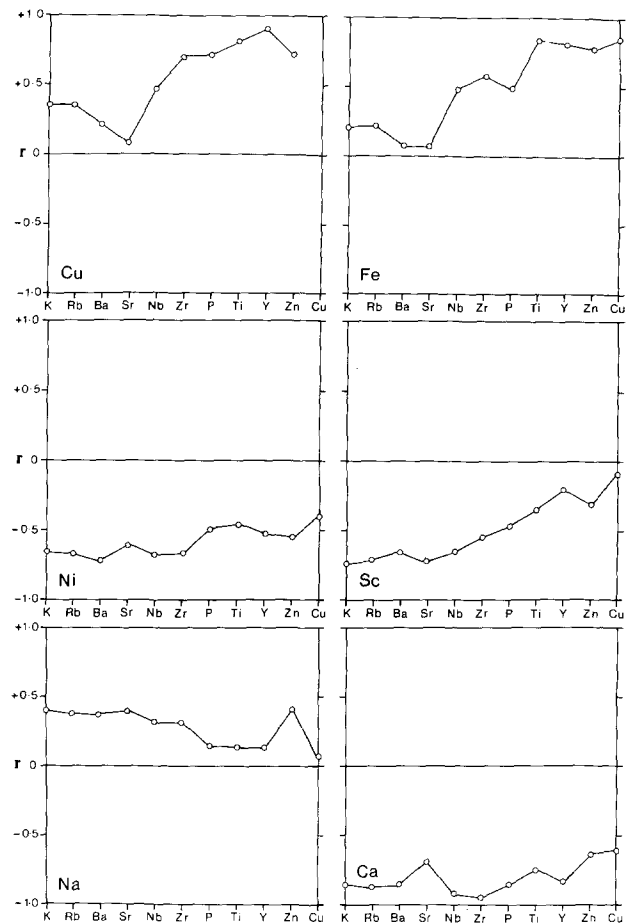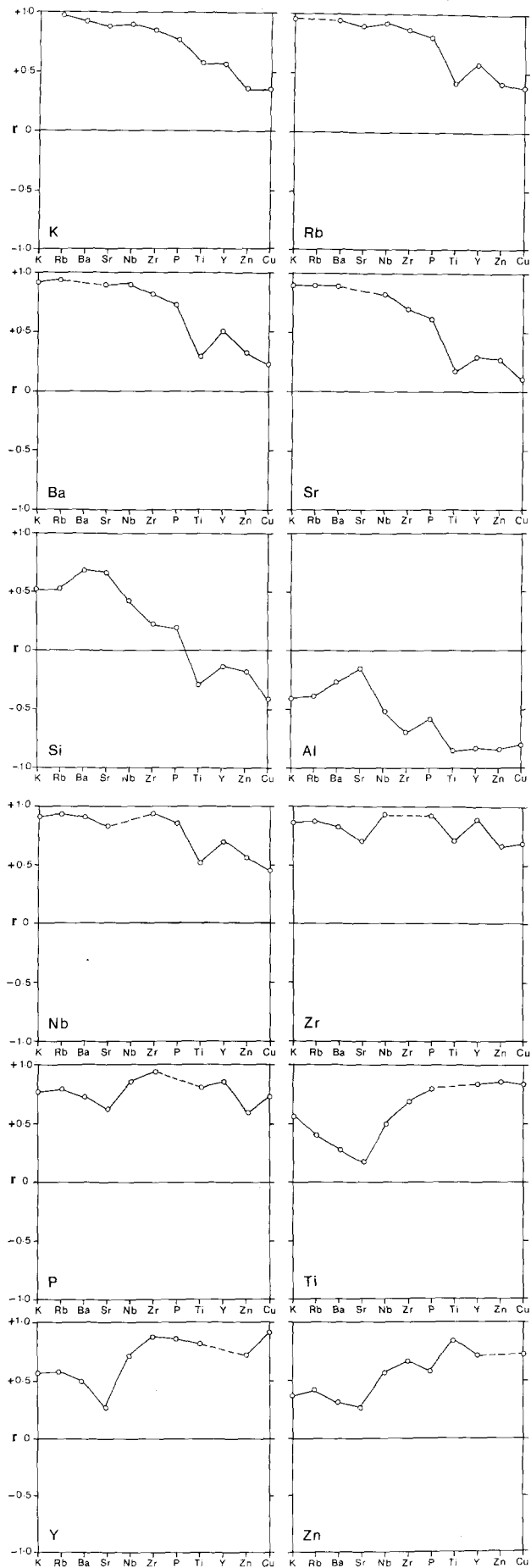
Fig. 5. Observed correlation coefficient patterns for Rooi Rand dolerites

(cf. Ba in Mahabaleshwar), while Fe, Ti, Y, Zn and Cu show patterns sloping to the left as they do in Mahabaleshwar. Thus the groupings of elements in the Rooi Rand data are significantly different from the Mahabaleshwar case. The interpretation of the Rooi Rand, as will be seen, is however distinctly problematic.

The first attempts to simulate observed patterns by calculation using DARWIN were based on the possibility of mineralogical controls in which pyroxene and plagioclase were allowed to play independent roles during fractionation. This idea arose from the fact that the elemental groupings were to some extent the elements concentrated into feldspars (K-type patterns), pyroxenes (Ti-type patterns), or excluded from both (P-type patterns). Independent fractionation could be visualised as a possible polybaric effect, as the proportions in which plagioclase and pyroxene crystallised varied with pressure. However after a large number of attempts, in which pyroxene and plagioclase proportions and compositions were varied through wide limits, nothing resembling the observed patterns was achieved. In general the models consisted of using MRR1 (Table 5) as a parent magma, mixing with MRR2 to produce the essential outlines of the observed fractionation trend, and then removing plagioclase and/or clinopyroxene separately. Other variants consisted of removing olivine, clinopyroxene and plagioclase from MRR1 in varying proportions, together and separately. Although some elements of the observed patterns could be reproduced, problems were usually encountered with Sr and Si. The distribution coefficient for Sr in plagioclase (e.g. Korringa and Noble 1971; Sun et al. 1974) is so much larger than those for K, Rb, and Ba that calculated patterns maintaining the coherence of all four ele-

ments are impossible to obtain if significant amounts of plagioclase are used. On the other hand if large amounts of clinopyroxene are incorporated in the fractionating assemblage it becomes impossible to separate the K group from P and Zr, and moreover, with most reasonable pyroxene compositions the behaviour of the Si pattern tends to be the reverse of that observed.

This is not a problem that can be satisfactorily resolved at the present time, though the acquisition of more analytical data in the future might be helpful. However, as a speculation it is worth considering that the Rooi Rand magmas might have become contaminated, that is mixed with an additional component, as appears to be the case in Mahabaleshwar. By analogy with arguments already made we can read off some of the compositional characteristics of the postulated contaminant.

Relative to the original magmas the contaminant must be enriched in K, Rb, Ba, Sr, Si and Al, impoverished in Fe, Ti, Zn, Cu and Y, and must have about the same amount of P and Zr. Nb is perhaps slightly enriched in the contaminant.

$^{87}Sr/^{86}Sr$ ratios determined for the Rooi Rand rocks (Bristow 1980) show very little variation when age-corrected to 190 Ma. Seven of the samples analysed have initial ratios in the very small range 0.70350 to 0.70396. One sample, A.117, which also happens to be the most Si, K and Rb enriched rock, has a slightly higher ratio at 0.70432. This suggests that the contaminant, if such existed, had an $^{87}Sr/^{86}Sr$ ratio only very slightly above that of the dolerite magma.

Thus compared with Mahabaleshwar the postulated Rooi Rand contaminant appears to have had a more dioritic than granitic air, since this is the best way of explaining the high Sr, Zr and P. This is a not implausible idea since most of the pre-Cambrian crust in the region is, if not dioritic, at least tonalitic (A. Kröner, pers. comm.) and has generally low Rb/Sr and $^{87}Sr/^{86}Sr$. The Ancient Gneiss Complex in Swaziland for example contains high Sr and Zr rocks with present day $^{87}Sr/^{86}Sr$ as low as 0.703–0.705 in some cases. Another possible candidate at the moment seems to be some sort of rather basic Karoo rhyolite magma. Karoo rhyolites are developed in enormous volumes in the immediate vincinity of the Rooi Rand dyke swarm and may have a similar age. They have initial $^{87}Sr/^{86}Sr$ ratios of ca. 0.704 (Manton 1968) and it is postulated that they were formed by the remelting of basic rocks emplaced slightly earlier in the Karoo cycle (Betton and Cox 1979). However, the rocks so far analysed (e.g. Cleverly 1977) are all somewhat too evolved in their trace element compositions (e.g. too Sr depleted) to satisfy the requirements of the postulated contaminant.

As an alternative to the above hypotheses, Bristow (1980) has postulated trace element heterogeneity in the mantle source. If this is so, the characteristics ascribed above to the contaminant might alternatively apply to one end member of a range of primary partial melts. A heterogeneous mantle containing domains enriched in K, Rb, Ba and Sr would be appropriate and with approximately constant degrees of partial melting could produce a range of liquids with some of the required correlation patterns built in. The melting process would however also effect correlations. For example, if the trace-element enriched domains were also hydrous, then the correlation between Si and the enriched elements would be added at this stage, rather than being an inherent property of the source.

Finally it is intriguing to note that primitive Rooi Rand magmas (see Fig. 6) are comparable to mid-ocean ridge basalts (MORB) in most of their incompatible elements, but contain higher concentrations of K, Rb, Ba, and Sr, precisely that group of elements which we require to correlate together as a partially independent group. This does not *prove* that the source has
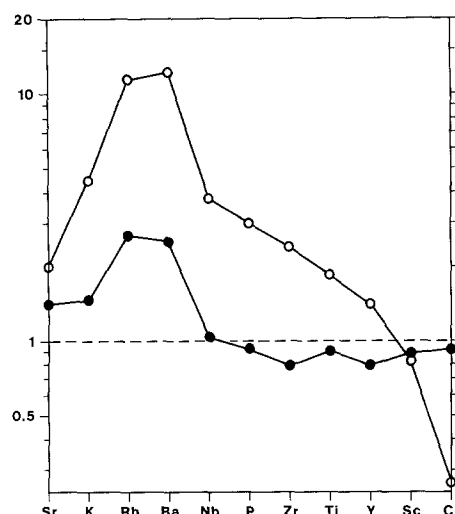

Fig. 6. Primitive Rooi Rand dolerites (*black symbols*) and evolved Rooi Rand dolerites (*open symbols*) normalised against average MORB of Pearce et al. (1981). The primitive rocks are represented by the average of 5 primitive (i.e. Fe-poor and Mg-rich) dolerites, the evolved by the average of the three most Fe-rich samples. Data are from Armstrong (1978) and Bristow (1980). Changes of pattern in evolved dolerites relative to primitive dolerites are consistent with gabbro fractionation

been affected by an enrichment process involving these elements but it is consistent with it. It would appear to suggest however that, whatever the enrichment process was, the source of the dolerites was originally similar to the source of MORB. K, Rb, Ba and Sr were then either added to magmas by contamination in the crust, or were added to domains within the mantle before melting took place. In the latter case, because the enrichment in Rb is much greater than that in Sr, it follows that the enrichment process must have taken place only shortly before magma generation, otherwise the range of Rb/Sr ratios would have generated an obvious isotopic signature.

Conclusions

Correlation coefficients may be used to describe many of the most important properties of analytical data sets which produce scattered variation diagrams. Computer simulation of the correlation coefficient matrix using multi-stage mixing calculations can in some cases lead to plausible hypotheses of complex magmatic evolution. The technique encourages the consideration of all available analytical data in the construction of hypotheses, and extracts information which normally lies concealed and unappreciated. Of the cases discussed in the present work, the Rooi Rand dolerites can not so far be uniquely explained, but even here the technique identifies problems and possibilities which might otherwise have been undetected.

Appendix. The Program DARWIN

The advent of inexpensive interactive computing systems has meant a change in the way in which data are analysed. Stiatistical procedures are no longer restricted to providing a single definitive analysis produc-

ing the best fit or explanation. With interactive systems it is possible to obtain a feel for the types of hypotheses which are consistent with the data. This is particularly important when a variety of hypotheses have been postulated. With these considerations in mind we have produced a program which will rapidly sythesise the effects of multi-stage petrogenesis. The input data are the compositions of a parent rock and a variety of contaminants and crystal phases. The user may cause a suite of rocks to evolve by specifying which compositions are to be added to or extracted from the parent and by how much. The correlation coefficient variation diagrams are then displayed along with the mean composition and the standard deviations of the elements in the suite if required. At any stage a new composition may be specified and added to or extracted from the current suite.

Specifically the computer updates a variance-covariance matrix Σ, giving variances and covariances of elements in the suite. It also updates μ the mean vector, giving the average composition of rocks in the suite. At stage n of the evolution, a composition, C_n is selected by the user to be either added to or extracted from the current distribu-tion of compositions in the suite. If the composition is to be added, an arbitrary upper bound, b_n, to the percentage added, can be set by the user. The program then calculates the effect of adding a random amount of C_n uniformly distributed between 0 and b_n to each rock in the suite. Let Σ_n and μ_n be the variance-covariance matrix and the mean vector after n stages, then

$$\Sigma_n = \Sigma_{n-1}\{\sigma_n^2 + (k - \tfrac{1}{2}b_n)^2\} + (C_n - \mu_{n-1})(C_n - \mu_{n-1})^T$$

and

$$\mu_n = \mu_{n-1}(1\ 1\ \tfrac{1}{2}b_n) + \tfrac{1}{2}b_n C_n$$

where

$$\sigma_n^2 = b_n^2/12.$$

The process of extraction is similar, although in this case there will be a limit to the amount which can be extracted. This is determined by the most depleted elements in the current suite. The program keeps a record of the extreme compositions and will not allow impossible amounts to be extracted. At stage zero Σ_0 is set equal to zero and μ_0 is set equal to the parent rock.

From the variance-covariance matrix, the variances, standard de-viations and correlations can be determined. The correlations diagrams are drawn by means of a low resolution graphics routine. Numerical values of means and standard deviations are printed on request.

The program is written in BASIC language and implemented on an RML 380Z. A limited number of copies are available from the senior author on request.

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