

**ECONOMIC GEOLOGY
RESEARCH UNIT**

University of the Witwatersrand
Johannesburg

TRACE ELEMENT TRENDS IN GRANITES AND THE
DISTINCTION BETWEEN PARTIAL MELTING
AND CRYSTAL FRACTIONATION PROCESSES :
CASE STUDIES FROM TWO GRANITES IN
SOUTH AFRICA

L. J. ROBB

INFORMATION CIRCULAR No.164

UNIVERSITY OF THE WITWATERSRAND
JOHANNESBURG

TRACE ELEMENT TRENDS IN GRANITES AND THE DISTINCTION
BETWEEN PARTIAL MELTING AND CRYSTAL FRACTIONATION
PROCESSES : CASE STUDIES FROM TWO GRANITES
IN SOUTH AFRICA

by

L. J. ROBB

(Senior Research Officer, Economic Geology Research Unit)

ECONOMIC GEOLOGY RESEARCH UNIT
INFORMATION CIRCULAR No. 164

October, 1983

TRACE ELEMENT TRENDS IN GRANITES AND THE DISTINCTION
BETWEEN PARTIAL MELTING AND CRYSTAL FRACTIONATION
PROCESSES : CASE STUDIES FROM TWO GRANITES
IN SOUTH AFRICA

CONTENTS

	<u>Page</u>
I. <u>INTRODUCTION</u>	1
II. <u>THE NATURE OF CRYSTAL FRACTIONATION AND</u> <u>PARTIAL MELTING IN GRANITES</u>	1
III. <u>TRACE ELEMENT MODEL CONSIDERATIONS</u>	3
IV. <u>CASE STUDIES FROM TWO GRANITES IN SOUTH AFRICA</u>	5
A. Geological Setting and Previous Work	5
B. Trace Element Trends	7
V. <u>POSSIBLE REASONS AS TO WHY ONE PROCESS MAY</u> <u>PREDOMINATE OVER THE OTHER</u>	11
VI. <u>PARTIAL MELTING AND FRACTIONAL CRYSTALLIZATION IN TERMS</u> <u>OF THE ECONOMIC POTENTIAL OF GRANITES</u>	12
ACKNOWLEDGMENTS	15
APPENDIX	15
REFERENCES	16

————— oOo —————

Published by the Economic Geology Research Unit
University of the Witwatersrand
1 Jan Smuts Avenue
Johannesburg 2001

ISBN 0 85494 796 5

TRACE ELEMENT TRENDS IN GRANITES AND THE DISTINCTION
BETWEEN PARTIAL MELTING AND CRYSTAL FRACTIONATION
PROCESSES : CASE STUDIES FROM TWO GRANITES
IN SOUTH AFRICA

ABSTRACT

Compositional variations in granitoid rocks are generally the result of either crystal fractionation or partial melting processes. Trace elements may assist in distinguishing between the two processes by considering the variation of an element with high (> 1) bulk partition coefficient (D) relative to the variation in one with low (< 1) bulk partition coefficient. Over a wide range in the degree of partial melting a high- D element will remain fairly constant whereas the same element will undergo significant variation during fractional crystallization (Hanson, 1978).

Rb, Sr and Ba inter-relationship in the circa 1100 Ma old Concordia granite (Namaqualand Metamorphic Complex) and the Archaean Boesmanskop syenite pluton (Barberton Mountain Land) are compared with model trends for partial melting and fractional crystallization. The Boesmanskop syenite is shown to represent a cumulus assemblage with compositional variations being the result of crystal fractionation. Variations in the Concordia granite appear to be mainly influenced by progressive partial melting inferring that solidification occurred essentially in an equilibrium mode. The suggestion is made that these differences may be a function of the water vapour pressure in the original magmas and the depth in the crust at which they were generated.

Brief consideration is also given to the importance of crystal fractionation and partial melting processes in the formation of economic deposits associated with granites. If operable, fractional crystallization may be a very efficient mechanism whereby incompatible elements are concentrated into late-stage phases, pegmatites or hydrothermal vein systems. Granites whose compositional variations are predominantly influenced by progressive partial melting are more likely to reflect the nature of the source rocks from which they were derived, and the nature of associated mineralization will tend to depend on the existence of a sedimentary or igneous precursor.

TRACE ELEMENT TRENDS IN GRANITES AND THE DISTINCTION
BETWEEN PARTIAL MELTING AND CRYSTAL FRACTIONATION
PROCESSES : CASE STUDIES FROM TWO GRANITES
IN SOUTH AFRICA

I. INTRODUCTION

Granite bodies are invariably characterized by compositional variations; these variations may be clearly apparent in terms of mineralogy and bulk major element abundances, or more difficult to detect as a minor or trace element zonation. The nature of granites also varies between the extremes of large batholiths comprising a sequence of rock types usually regarded as being genetically inter-related, and much smaller discrete plutons made up essentially of one rock type in which compositional variations are subtle.

In the past it was common, at least within the context of single granite bodies, to attribute compositional variations to marginal assimilation of country rock. This custom was initially challenged by Vance (1961) who suggested that many granites were differentiated *in situ*. Numerous publications, particularly in the last decade, have now established the fact that *in situ* crystal fractionation plays a major role in the genesis of granites in spite of the characteristic high viscosities and slow reaction rates of silicic magmas. However, it is also recognized that magmatic granites are derived by partial melting of pre-existing rock-types which may be mafic, intermediate or felsic in composition, or have had a sedimentary pre-history, and which existed under conditions of variable pressure and temperature. Consequently, it is also feasible that the formation of a given granitoid suite may have been predominantly influenced by progressive partial melting, with crystal fractionation having played a minor or localized role in its formation. In any event it is unlikely that partial melting and crystal fractionation can be entirely divorced in petrogenetic considerations of granites although it is usually necessary to establish which of the two processes was dominant. This paper briefly examines one way in which trace elements can assist in distinguishing between the two processes and also discusses examples where these differences prevail.

II. THE NATURE OF CRYSTAL FRACTIONATION
AND PARTIAL MELTING IN GRANITES

Evidence for crystal fractionation in granites is now abundant and varies from examples of obvious igneous mineral layering to subtle crystallization histories reflected only in detailed trace element distributions. Documented examples of igneous mineral layering, 'cross-bedding' and rhythmic grain size variations are available from the Chebucto Head granite, Nova Scotia (Smith, 1975), granites in southern Greenland (Emeleus, 1963) and the Twin Lakes granodiorite in Colorado (Wilshire, 1968). Most of these reported features are related to flow sorting and collectively suggest that viscosity constraints to differentiation in granitic magmas may not be as severe as previously thought. Many granitoid plutons exhibit well-

defined, concentric zoning with outer dioritic or quartz-dioritic rims, a series of inner zones progressing from tonalite or granodiorite through to granite and, commonly, a central core of granite porphyry or microgranite. Two well-documented examples are the Tuolumne Intrusive Series, California (Bateman and Chappell, 1979) and the Loch Doon pluton, Scotland (Tindle and Pearce, 1981). In the former case, progressive inward nucleation of crystals and differentiation of rest magma was considered to prevail, whilst in the latter case *in situ* crystal accumulation and filter pressing was regarded as the dominant process. Many granite bodies do not, however, display such well preserved *in situ* fractionation processes. This is particularly the case in bodies whose bulk composition falls on or near the cotectic in the 'granite system'. In such cases crystal fractionation will not be characterized by the development of a distinctive sequence of liquidus minerals, but may only be reflected in terms of trace element distributions. Examples of cryptic fractionation in granites are commonplace and include the Opemisca Lake tonalite pluton, Quebec (Wolhuter, 1973) the Malsburg granite pluton, West Germany (Hahn-Weinheimer and Ackermann, 1967), the Nelspruit porphyritic granite, South Africa (McCarthy and Robb, 1978) and the Main granite of the Bushveld Complex, South Africa (McCarthy and Hasty, 1976). In most of these cases the crystallization process can be inferred to have been influenced by a temperature gradient between wall-rock and the core of the magma chamber such that solidification progressed gradually from the margins of the chamber inwards.

Examples of where compositional variations in granites can be dominantly attributed to partial melting rather than crystal fractionation processes are not common. One reason for this may be that anatexis is viewed primarily as the fundamental process behind initial magma generation, with any subsequent compositional modifications occurring during movement, cooling and solidification of the magma. Despite this, cases do exist where consideration has been given to the generation of a cogenetic granitoid suite by progressively increasing degrees of partial melting. An example is the Proterozoic gabbro-tonalite-trondhjemite suite of south-west Finland described by Arth *et al.* (1978). In this suite factors such as the volumes of rock observed (i.e. trondhjemite > tonalite > gabbro) were considered suggestive of progressive partial melting, whereas other criteria were regarded as being ambivalent in terms of distinguishing between the two processes. Arth *et al.* (1978) pointed out that the presence of some cumulate rocks suggests that crystal fractionation must have occurred, and it is possible, therefore, that both the latter and partial melting were operative. Other examples of a possible predominance in the role of partial melting processes stem from studies of Archaean tonalite and trondhjemite gneiss plutons. These rocks are generally regarded as having been derived by melting of pre-existing mafic crust although doubt exists as to the depth at which anatexis occurred and, more specifically, whether amphibole or garnet was the key residual mineral (Arth and Hanson, 1975; Arth and Barker, 1976). Recent studies of tonalite and trondhjemite gneisses in the Barberton Mountain Land of South Africa suggest that trace element variations may be the result of partial melting processes at differing depths in the Archaean crust and that crystal fractionation processes appear to have been relatively subdued (Robb and Anhaeusser, 1983).

Some of the best documented examples of granites owing their compositional variations to partial melting processes come from south-eastern Australia where granitoid batholiths are shown to have been derived from both

igneous and sedimentary precursors (Chappell and White, 1974; Hine *et al.*, 1978). The recognition of I-type and S-type granites in this region is mainly dependant on the differing nature (i.e. meta-igneous or metasedimentary) of cognate xenoliths in the two types. Appreciation of the nature of these xenoliths in granites (a topic initially studied by the French school, e.g. Didier and Lameyre, 1969) has important implications, not only in assessing the source region from which they were derived, but also in understanding their compositional variations. White and Chappell (1977), for example, have suggested that compositional variations in certain granites are the result of variable proportions of retained restite within the melt and are not necessarily due to control by a liquid-line-of-descent. Thus, they distinguish between compositional variations evident as linear "mixing" lines and those controlled either by crystal fractionation or progressive partial melting. White and Chappell (1977) point out that in Harker-type diagrams, for example, melt-restite situations result in linear variation trends which extend between the limits of pure melt and final residue, whereas granites formed by fractional crystallization will tend to form curved variation trends.

III. TRACE ELEMENT MODEL CONSIDERATIONS

With the continued improvement in knowledge of mineral/melt distribution or partition coefficients (K_d 's), trace elements have become an indispensable tool in petrogenetic studies of igneous rocks. In addition, the development of mathematical equations which model the behaviour of trace elements during a variety of crystal and liquid fractionation processes has resulted in a better understanding of the mechanics of compositional variation in these rocks. In particular, the study of granites has benefitted because their mineralogical nature does not facilitate recognition of features such as cumulus/intercumulus relations which are often more readily apparent in mafic rock types.

Theoretical considerations indicate that trace elements may provide an indication of whether a cogenetic granitoid suite has been derived by partial melting or crystal fractionation processes. Hanson (1978) has pointed out that this distinction can best be made by considering trace elements with large (i.e. significantly greater than unity) *bulk* distribution coefficients (D) with respect to the mineral assemblage in question. Hanson stated that, "If the concentration of the element remains relatively constant throughout the suite, the main process is partial melting. If the element with a large D has a large variation, the main process is differentiation." This statement can be demonstrated in a plot of the type shown in Fig. 1. Here model curves for partial melting and fractional crystallization are calculated for two elements (in this case rubidium and strontium as these are commonly used in petrogenetic studies of granites), one of which is assumed to have $D = 0.25$ and the other to have $D = 3.0$. In the case of partial melting, the model was constructed by considering the effects of batch melting (i.e. where melt and solid residue are in equilibrium until the melt is removed — equations after Shaw, 1970; see Appendix) on a rock initially comprising 100 ppm Rb and 200 ppm Sr. The process of crystal fractionation is modelled by considering the effects of perfect fractional crystallization (i.e. where crystals are immediately removed from the effects

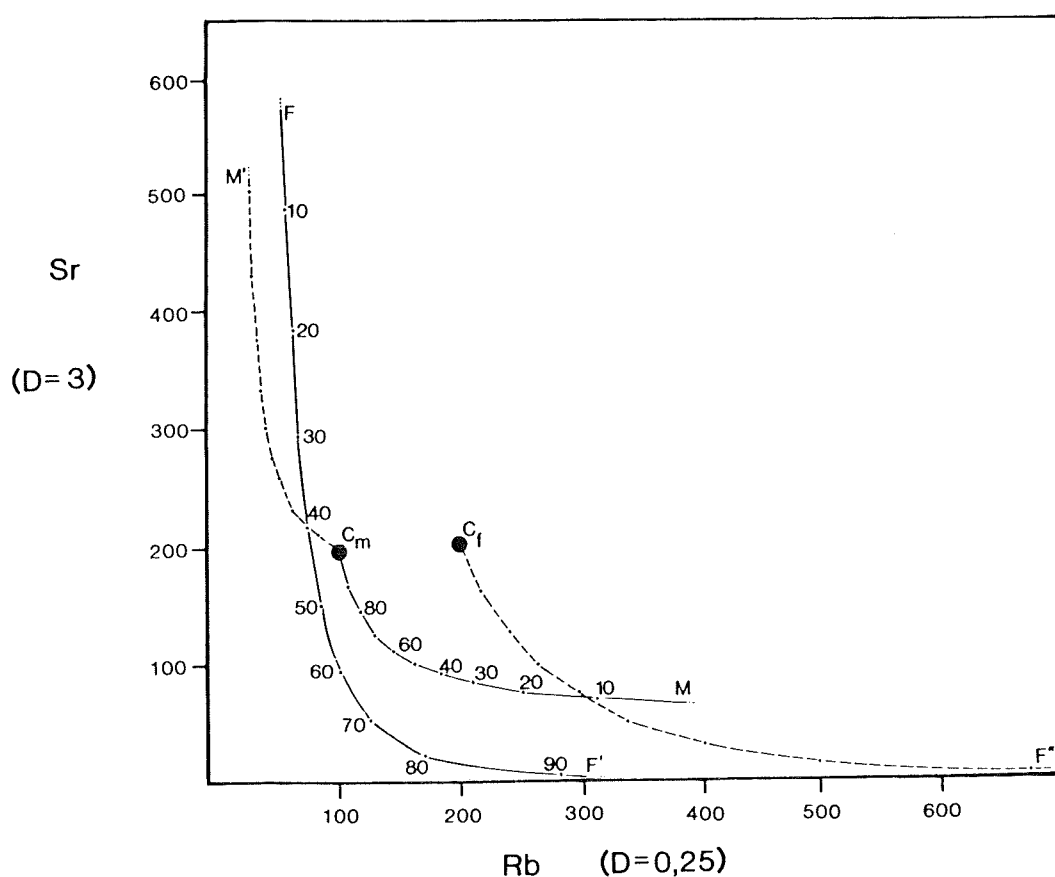


Figure 1 : Model plot showing the theoretical variations in two elements such as Rb and Sr (i.e. one with $D < 1$ and the other with $D > 1$) during batch melting and fractional crystallization. Melting is considered to have occurred from a parental assemblage at C_m in which $D_{Rb} = 0,25$ and $D_{Sr} = 3,0$. Fractional crystallization is considered to have occurred from an initial magma at C_f , with the crystallizing assemblage also having $D_{Rb} = 0,25$ and $D_{Sr} = 3,0$. Trace element abundances of the partial melt vary along $M-C_m$, whilst those of the solid residue vary along C_m-M' . Trace element abundances of the fractionating solid phases vary along $F-F'$, whilst those of the residual liquid vary along C_f-F'' . The equations used to calculate these curves are presented in the Appendix (note that in the case of the anatectic model, modal melting is assumed such that $D_m = D_p$ in Shaw's (1970) equation). The values of D chosen here are arbitrary but not unrealistic for typical granitoid assemblages. The values 10, 20, 30 etc. refer to percentage melting or crystallization.

of continued equilibration with the liquid from which they formed — equations after Neumann *et al.*, 1954; see Appendix) on a magma initially comprising 200 ppm Rb and 200 ppm Sr. In the case of the evolving partial

melt (trend M-C_m, Fig. 1) it is apparent that, at least for the first $\approx 80\%$, the process is characterized by a small variation with respect to the high-D element (i.e. Sr) and a subhorizontal trend. In contrast, during fractional crystallization the crystallizing assemblage (trend F-F', Fig. 1) is characterized by a marked variation with respect to the high-D trace element and a sub-vertical trend. Conversely, it is significant to note that a significant range occurs in the abundance of the low-D element (i.e. Rb) during progressive partial melting whereas fractional crystallization has little effect on the concentration of this element until the final stage of solidification.

The above considerations demonstrate that it should be possible to distinguish between crystal and liquid fractionation processes by plotting against each other trace elements which have contrastingly high (> 1) and low (< 1) bulk partition coefficients with respect to the rock-type in question. Two points are worthy of consideration in this regard. The first is that absolute abundances are of little significance and that distinctions should be made by considering the variation in the one element relative to the variation in the other. The second is that differences between partial melting and fractional crystallization may, in reality, be accentuated because neither process is likely to proceed to completion. It is apparent in Fig. 1 that the extremes of either process (i.e. greater than about 80% solidification or melting) result in marked changes with respect to the general orientation of the main trends. However, because the extremes of fractional crystallization are usually evident in discrete late-stage phases (i.e. pegmatites, aplites, etc.) and partial melting does not proceed to completion because of increases in liquidus temperatures accompanying progressive dehydration of residues, it is unlikely that trends produced by real data will be confused one for the other.

IV. CASE STUDIES FROM TWO GRANITES IN SOUTH AFRICA

A. Geological Setting and Previous Work

In the following section two granitoid (*sensu lato*) bodies from South Africa are described and their trace element characteristics discussed in the light of the above considerations.

The first example is the *Concordia granite* which makes up one of three granite types in the Spektakel Suite of the *circa* 1100 Ma-old Namaqualand Metamorphic Complex in the north-western Cape Province (Fig. 2). The Concordia granite intrudes a suite of high-grade quartzo-feldspathic gneisses and intermediate granulites (Clifford *et al.*, 1975) and occurs as a sheet-like body underlying large tracts mainly to the north, west and south of the town of Springbok. The data discussed in the following section were derived from samples all collected from the "type-area" shown in Fig. 2, although occurrences of Concordia granite are also reported from elsewhere in Namaqualand.

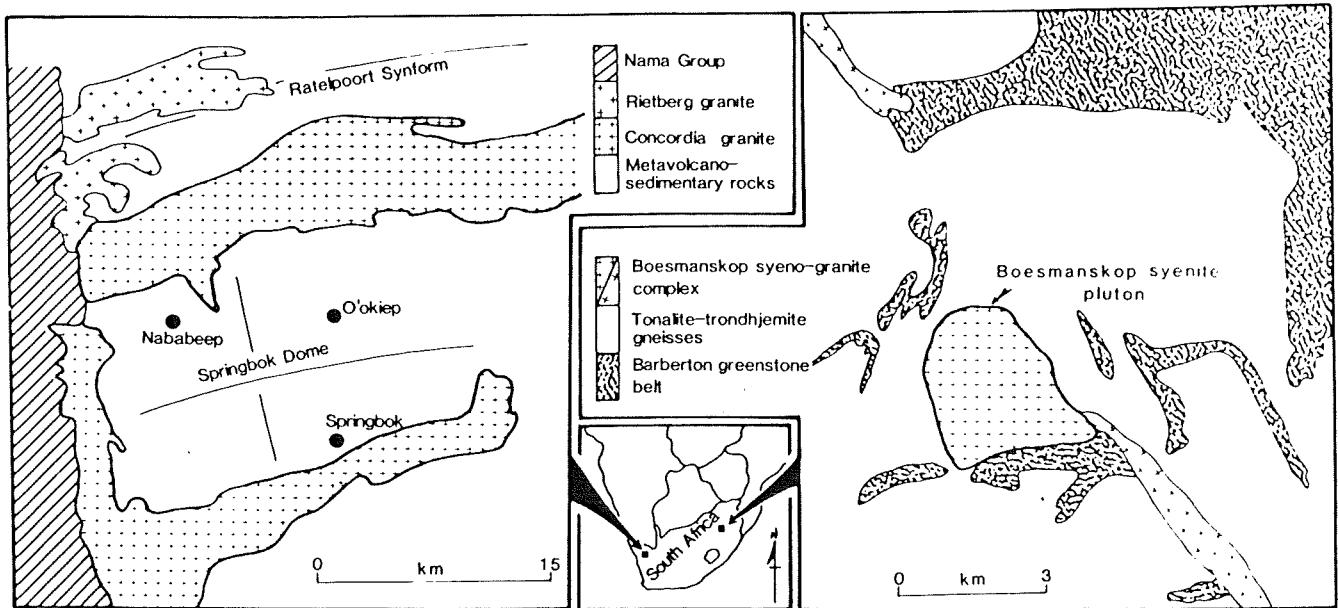


Figure 2 : Locality map and simplified geological sketches showing the distribution of the Concordia granite in the Namaqualand Metamorphic Complex (left) and the Boesmanskop syenite pluton in the Barberton Mountain Land (right).

The Concordia sheet is typically granitic (*sensu stricto*) in composition with quartz, microcline-perthite, plagioclase and biotite representing the main rock-forming minerals. Garnet may occur, particularly in the lower portions of the sheet, in close proximity to metasedimentary schists (Clifford *et al.*, 1975). The lower portions of the Concordia sheet are strongly foliated, whilst structurally upwards the foliation disappears and a prominent lineation persists. The upper portions also become progressively coarser-grained and even porphyritic at the top of the sheet (Clifford *et al.*, 1975; Robb, 1982).

The Concordia granite is similar, and closely related in the field, to the Rietberg granite (Fig. 2) which, however, displays no obvious planar fabric and, on average, is slightly more ferromagnesian than the Concordia body (McCarthy, 1978). Although, in terms of field relationships, the Rietberg granite is recognized as having post-dated the Concordia granite, the two bodies are isotopically indistinguishable and together yield a single Rb-Sr whole-rock isochron age of 1166 ± 26 Ma with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7080 ± 0.0010 (Clifford *et al.*, 1975). Isotope and geochemical studies by McCarthy (1976) indicate that both the Concordia and Rietberg granites appear to have been derived by partial melting of a granulite of intermediate composition at lower crustal depths.

The second example is the Boesmanskop syenite pluton which forms the major component of an Archaean syeno-granite complex in the Barberton Mountain Land, Eastern Transvaal (Fig. 2). The syeno-granite complex has been emplaced along a north-westerly-trending tectonic lineament and intrudes tonalite-trondhjemite gneisses and xenolithic remnants of the Barberton greenstone belt. The complex has yielded an U-Pb mineral age of 3130 Ma and

a Rb-Sr whole rock age of 2848 ± 31 Ma with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of $0,7040 \pm 0,004$ (Anhaeusser *et al.*, 1983).

The syeno-granite complex occurs as a number of discrete intrusions (Fig. 2) and yields rocks ranging from syenitic to granitic (*sensu stricto*) compositions. The Boesmanskop syenite pluton itself, however, comprises mainly syenites with lesser quartz-syenites. The syenites consist mainly of microcline-perthite, plagioclase, hornblende and biotite with abundant accessory minerals including apatite, magnetite, epidote, zircon and sphene (Anhaeusser *et al.*, 1983). The quartz syenites contain a small proportion of free quartz at the expense of the ferromagnesian minerals. The Boesmanskop pluton is massive and coarse-grained-to-porphyritic in texture, although in places tabular feldspars may be aligned as a result of flow sorting in the original magma.

Compositional variations in the Boesmanskop syenite pluton, and indeed in the syeno-granite complex as a whole, are reflected in a trend from the thermal maximum (i.e. the Ab-Or tie-line) in the "granite system" towards silica-oversaturated compositions (Anhaeusser *et al.*, 1983). Geochemical considerations suggest that most of the rocks in the complex represent cumulates formed by fractionation of both major and accessory minerals. In addition, the authors suggest that the original syenitic magma was derived by melting of an intermediate or dioritic parent at deep crustal levels where high pressures ($P_{\text{H}_2\text{O}} = P_{\text{Total}}$) result in minimum-melt compositions in the granite system being depleted in quartz.

B. Trace Element Trends

The present case-studies are based on a compilation of previously published Rb, Sr and Ba data for the Boesmanskop syenite and the Concordia granite, as well as a number of new analyses of the latter body. The data represent a wide sample cross-section of both bodies and is presented in Table 1 as well as in the form of Rb v Sr and Rb v Ba plots in Figs. 3 and 4.

It is apparent in these plots that inter-element variations between the Concordia and Boesmanskop bodies are markedly different. In the Rb v Sr plot (Fig. 3) strontium abundances in the Concordia granite remain remarkably constant in comparison to much higher concentrations and more marked variations for the Boesmanskop syenite pluton. Conversely, the Rb values are, on average, lower and more constrained in the Boesmanskop data whereas they vary by a factor of two in the Concordia granite. Similar patterns are evident in the Rb v Ba plot (Fig. 4) although barium abundances in the Concordia granite are more variable.

The trace element trends evident in Figs. 3 and 4 can be modelled in the light of the discussion in the previous section. Both the Rb v Sr and Rb v Ba diagrams represent cases where a trace element with high bulk partition coefficient is plotted against one with low bulk partition coefficient for typical granitoid assemblages. With respect to the relevant distribution coefficients and mineral modes presented in the Appendix it is apparent that the value of D_{Rb} for both the Concordia granite and Boesmanskop syenite are significantly less than unity (i.e. between 0,3 - 0,4), whereas values of D_{Sr} and D_{Ba} are much larger, being in the order of 2-3. Consequently, a

TABLE 1

TRACE ELEMENT ABUNDANCES IN THE CONCORDIA GRANITE,
NAMAQUALAND METAMORPHIC COMPLEX, AND THE
BOESMANSKOP SYENITE PLUTON, BARBERTON MOUNTAIN LAND

DATA SOURCE	CONCORDIA GRANITE			DATA SOURCE	BOESMANSKOP SYENITE		
	Rb	Sr	Ba		Rb	Sr	Ba
McCarthy (1978)	400	95	664		140	2000	2350
	436	81	391		190	1620	1750
	242	53	133		180	1800	2000
	333	105	453		140	1950	1950
	340	98	438		210	1320	1350
	317	62	309		210	1390	1650
	362	80	362		230	1530	1700
					280	1120	1250
	226	143	630	Anhaeusser	238	1046	-
	230	81	362	<i>et al.</i>	229	693	-
	299	101	462	(1983)	200	577	-
	269	136	584		205	994	-
Robb (1982)	274	69	314		231	1108	-
	300	75	339		247	965	-
	331	89	446		222	995	-
	248	327	1124		239	359	-
	333	60	245		183	1372	-
	257	61	254		164	370	-
					240	325	-
Clifford <i>et al.</i> (1975)	359	95	-				
	432	85	-	Mean	209	1133	1750
				Std. Dev.	37	518	356
Clifford <i>et al.</i> (1981)	365	85	717				
Mean	318	99	457				
Std. Dev.	63	58	226				

(All values as ppm)

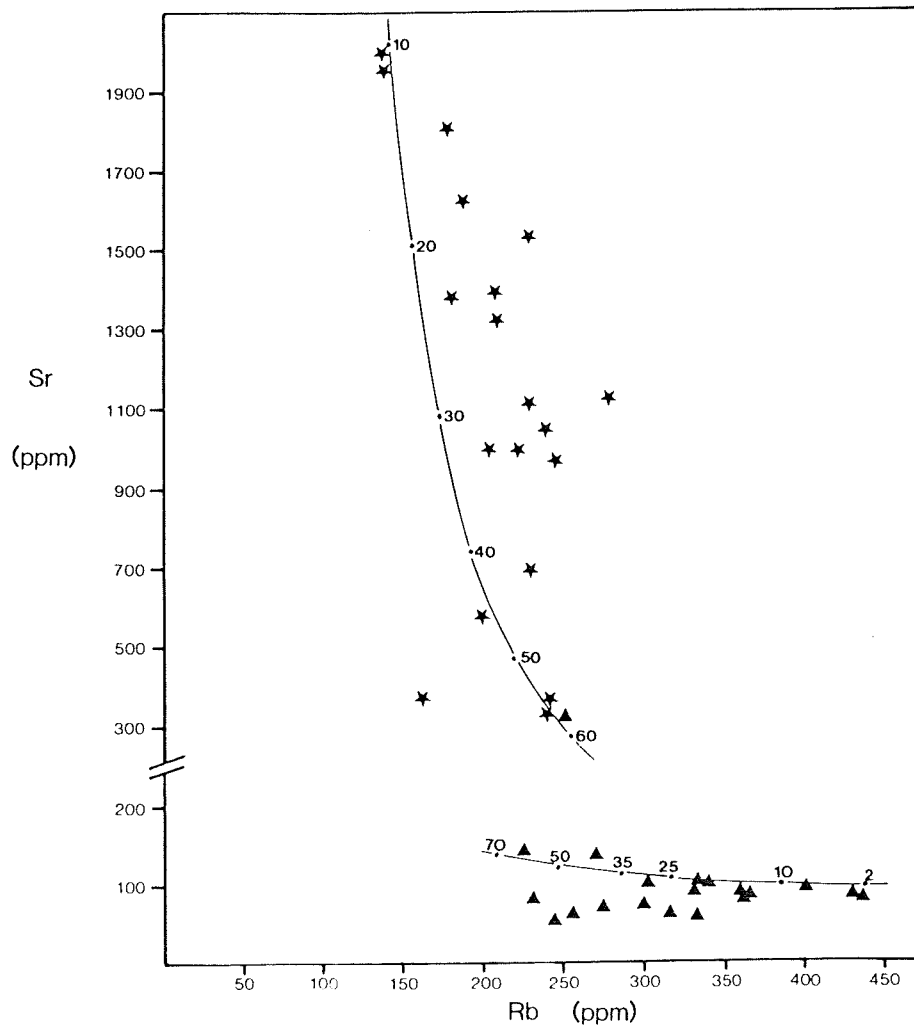


Figure 3 : Plot of Rb v Sr for data from the Concordia granite (triangles) and the Boesmanskop syenite pluton (stars). Also shown are model curves which attempt to account for trace element trends in the two bodies. The sub-horizontal trend of the Concordia granite is best simulated by a model reflecting progressive partial (batch) melting, whereas the sub-vertical trend of the Boesmanskop syenite pluton is very similar to a cumulus assemblage derived by fractional crystallization. The parameters used in the calculation of both curves are presented in the Appendix. The values 2, 10, 20, etc. refer to the percentage melting or crystallization.

consideration of progressive partial (batch) melting, in accordance with the parameters outlined in the Appendix, results in a sub-horizontal model curve which is not dissimilar to the Concordia granite trend (see Figs. 3 and 4). In contrast, the Boesmanskop trend is better simulated by considering a fractional crystallization model (the model parameters are provided in the Appendix) which results in a sub-vertical trace element trend. The above considerations suggest that compositional variations in the Concordia granite

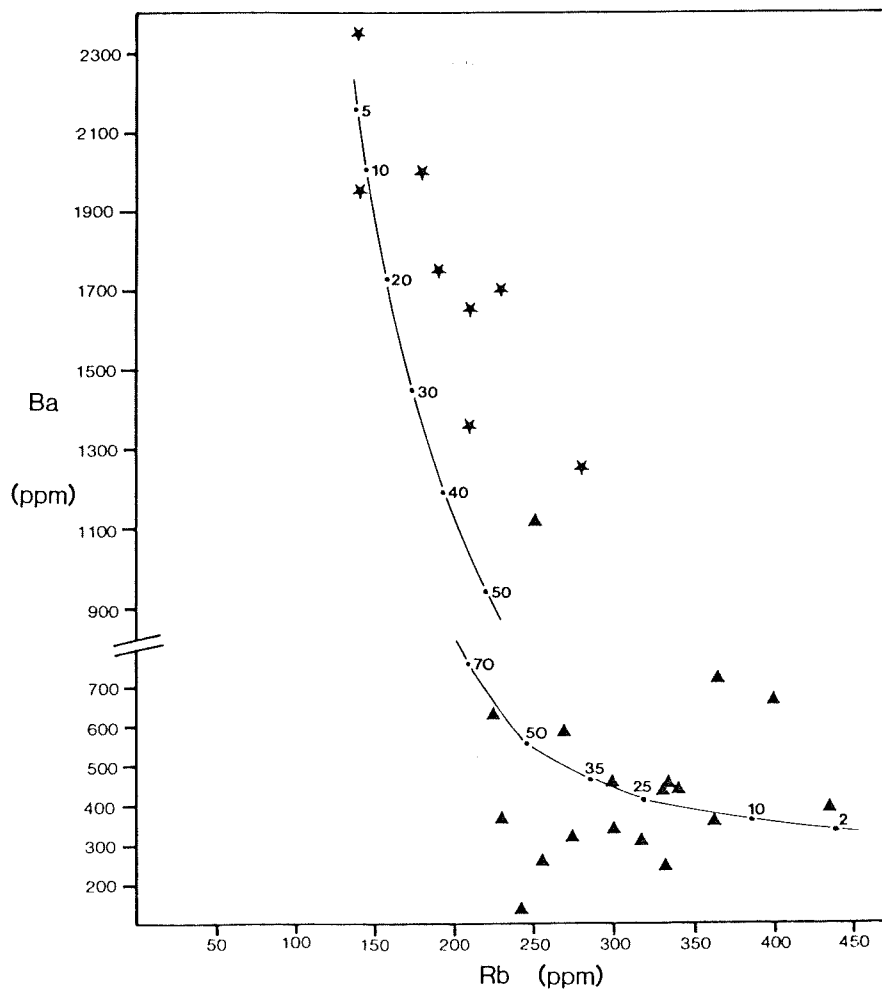


Figure 4 : Plot of Rb v Ba for the Concordia granite (triangles) and Boesmanskop syenite pluton (stars). The explanation for this diagram is the same as that for Fig. 3.

as a whole were predominantly influenced by a process of progressive partial melting and imply, therefore, that solidification of the body occurred in an essentially equilibrium mode. In contrast, the Boesmanskop syenite pluton appears to represent a cumulate assemblage which formed in response to a process of marked crystal fractionation. Naturally these statements are based only on Rb, Sr and Ba inter-relationships and need to be more rigorously tested. Nevertheless, it is apparent that consideration of these particular trace elements raise a number of interesting petrogenetic possibilities which are not necessarily evident from other sources.

V. POSSIBLE REASONS AS TO WHY ONE PROCESS
MAY PREDOMINATE OVER THE OTHER

An obvious question which arises out of the above considerations relates to why certain granites appear to be affected by pronounced crystal fractionation, whereas in others this process is only weakly developed. Furthermore, clarification is required on whether it is in the latter category that one might logically expect to see compositional variations resulting from progressive partial melting. One factor pertinent to this problem is the water vapour pressure of a granitic melt at its site of generation and the distance it can rise in the crust. As Cann (1970) has demonstrated, dry granitic melts move much higher in the crust than wet melts, this being a consequence of the negative slope of the wet melting curve for granites. Granitic melts in which the ratio of water vapour pressure to total pressure is low will rise adiabatically until the relevant solidus is intersected. At this point the melt can only cross the solidus by undergoing partial solidification such that the rest magma becomes residually enriched in water-vapour. Such a process may continue until the melt intersects the water-saturated solidus, at which point the body solidifies completely. The evolution of such a melt obviously contrasts with one initially characterized by near-water saturation where upward movement and concomitant crystal fractionation will be constrained by rapid intersection with the wet melting curve. Consequently, and with all other factors being equal, it is inferred that dry magmas will be more prone to compositional variations by crystal fractionation than their wet equivalents. Although this mechanism of crystal fractionation is a direct consequence of the upward movement of magma, the process may nevertheless appear to have occurred *in situ* because of the entrainment of early crystals by viscous silicic liquid. On the other hand, wet granitoid magmas can be expected *not* to exhibit pronounced differentiation and consequently, compositional variations may more readily reflect progressive partial melting. The latter process will be particularly evident in the cases where the degree of anatexis has been relatively low (i.e. < 30%) such that variations in the abundances of, for example, incompatible trace elements, are particularly severe (see curve M-C_m, Fig. 1).

With respect to the Concordia granite and Boesmanskop syenite, the trace element data presented above cannot obviously be used alone in making inferences about the depth in the crust at which they crystallized or the relative ratios of water vapour pressure to total pressure in either body. It is pertinent, however, to emphasize again the inherent lower quartz and higher ferromagnesian contents of the syenite body in relation to those of the granite. Such differences could be explained by the fact that the original Boesmanskop syenite magma was probably derived at a deeper crustal level, and from a source that was, consequently, drier, than that from which the Concordia magma was derived. This feature is inferred from the fact that eutectic melts at high pressures are relatively SiO₂-poor in comparison to melts derived from similar source material at lower pressures (Luth *et al.*, 1964). In the light of the above considerations, therefore, the Boesmanskop magma (and later crystal mush) may have been capable of moving a significant distance upwards in the crust, a phenomenon which would rationalize the suggestion that crystal fractionation played the dominant role in compositional variations within the body. Conversely, if the Concordia magma was derived at a shallower level in the crust and was originally wetter, it could not

have moved as far upwards in the crust, thereby explaining solidification in an essentially equilibrium mode and compositional variations reflecting progressive partial melting. Although these comments remain speculative it is nevertheless a measure of the usefulness of the trace element data that they can be made at all.

VI. PARTIAL MELTING AND FRACTIONAL CRYSTALLIZATION IN TERMS OF THE ECONOMIC POTENTIAL OF GRANITES

The economic potential of granites is a subject which has received considerable attention from a number of different points of view. Two features have been particularly prominent amongst these and include (i) the overall geochemical signature of a granite (i.e. particularly the abundance of elements such as Le, Sn, Be, B, S, F, Cu, Pb, U, Th, Ta, Na and the REE's) which is ultimately related to the nature of the source rock from which the granite was derived, and (ii) the tectonic setting of the granite, in particular its proximity to presently active or fossilized plate margins and/or subduction zones. These features have become evident by virtue of the fact that granitoids of known economic potential exhibit combinations of the characteristics mentioned above. For example, greisen and certain pegmatite-related ore deposits are usually characterized by high abundances of B and F and contain varied combinations of a mineral suite comprising cassiterite, tantalite-columbite, beryl and lepidolite amongst others. Porphyry copper and molybdenum deposits are associated with granitoid magmas that must originally have been characterized by high contents of S. Furthermore, porphyry copper and molybdenum stocks of the circum-Pacific belt are almost invariably associated with a particular tectonic setting, namely that of a still active subduction zone. The tin granites of the Malaysian peninsula, too, are considered to have been generated by subduction processes occurring during late Palaeozoic - early Mesozoic times.

A third feature, essentially independent of either the source material from which a granite is derived or the tectonic setting within which it is generated, is also, however, extremely important in assessing the economic potential of a granite. The effectiveness of *in situ* crystal fractionation processes and/or the nature and degree of partial melting processes must, in the light of work in the last decade, now be considered as highly relevant to the understanding of mineralization associated with granites. The fact that important tin mineralization is associated with the intra-cratonic Bushveld granite, for example, is an indication that tectonic setting is not necessarily the only factor influencing the formation of stanniferous granites. As shown by Groves and McCarthy (1978) the effectiveness of fractional crystallization may be the dominant control in tin mineralization processes in both orogenic and anorogenic granitoids. The object of this brief section is to emphasize the role which both crystal and liquid fractionation processes can play in the concentration of incompatible elements in granitic rocks.

Fractional crystallization, in any magma, can be a very efficient mechanism by which incompatible elements are concentrated into late-stage or differentiated rocks. McCarthy and Hasty (1976) and Groves and McCarthy (1978) have demonstrated that for granitic magmas pronounced concentration of incompatible elements only occurs very late in the crystallization history. Hence the tendency for incompatible elements such as Be, Li, U, Th, Ta, Nb and Sn to be associated with the late stage aqueous vapour phase in granites and to crystallize out together with hydrothermal veins or pegmatitic phases. The degree of concentration of an incompatible element in a fractionally crystallizing granitic magma is a function of both the amount of solidification that has occurred and the efficiency of the mechanism (i.e. the amount of intercumulus melt that is trapped between crystals — McCarthy and Hasty, 1976). These features are demonstrated in Fig. 5 where a theoretically calculated enrichment factor for a "perfectly" incompatible element is plotted as a function of the percentage of crystallization. It is evident here that the original concentration of an incompatible element in a granitic magma is not nearly as important a factor in potential mineralization processes as the efficiency with which such an element can be concentrated during its solidification.

The process of partial melting can, to a certain extent, be regarded as the reverse of crystal fractionation. Thus, whereas incompatible elements are concentrated into the late-stage products of a crystallizing magma, the same elements will be readily taken up by incipient melts during anatexis. The smaller the degree of partial melting the higher the concentration of incompatible elements in the melt and, logically, as the volume of melt increases so the concentration of such elements will become progressively diluted. It is evident within this simplistic scenario that a factor related to the efficiency of the partial melting process does not have the same impact on the concentration of incompatible elements as it did in the case of crystal fractionation (i.e. the influence of intercumulus liquid in the latter process, for example). Hence, the concentration and nature of incompatible elements, or the geochemical signature, of the source material from which the melt is being derived is a much more important criterion in the anatectic framework than it is in that of crystal fractionation. It is at least partly for this reason that an association is often evident between the envisaged source area of a granitic magma and its metallogenic character. Ishihara (1980) has demonstrated that ilmenite-series granitoids tend to be associated with Sn and W mineralization whereas porphyry-type Cu and Mo deposits are generally associated with magnetite-series granitoids. This subdivision can be related to the genetic classification of Chappel and White (1974), described in an earlier section of this paper, in that magnetite-series granitoids are generally I-type in origin whereas those of the ilmenite-series have, with some exceptions, S-type affinities (Takahashi *et al.*, 1980). Consequently, the Cu-Mo porphyry-type granitoids appear generally to have been derived by partial melting of an igneous source rock whereas Sn-W granitoids have an origin related to anatexis of sedimentary precursors. Melting of sedimentary, as opposed to igneous, source rocks obviously influences the nature and content of incompatible elements in the parental magma of a granitic rock and, in addition, affects the oxidation state of that magma (Ishihara, 1980).

The efficiency of crystal fractionation on the one hand and the degree of partial melting and nature of the source rock on the other, are factors of considerable importance in evaluating the economic potential of

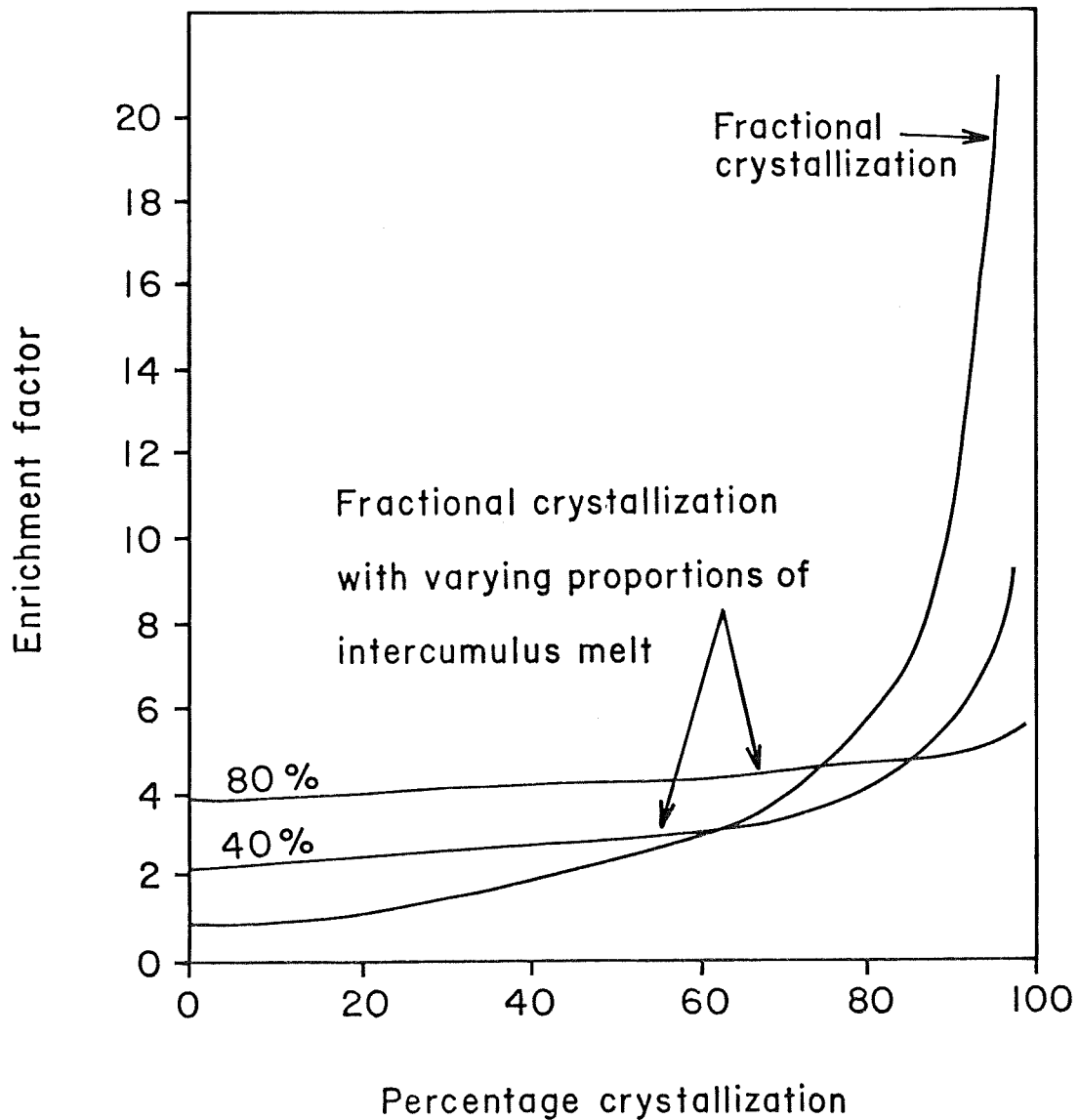


Figure 5 : Theoretically calculated enrichment of a "perfectly" incompatible element (i.e. bulk partition coefficient = 0) during progressive fractional crystallization (modified after McCarthy and Hasty, 1976). The curve for fractional crystallization shows marked enrichment in the incompatible element only after a significant degree of crystallization. Other curves show the effect that varying proportions of intercumulus melt (40% and 80%) would have on reducing the degree of enrichment at any given stage of crystallization. This is, in effect, a measure of the "efficiency" of the fractionation process. The two latter curves are shown to commence their crystallization history with higher incompatible element contents, thereby illustrating the fact that efficiency of the concentration process is more important than the original magma content.

granites. Although it may be possible to distinguish between granites owing their compositional variations to crystal fractionation from those influenced largely by progressive partial melting, there seem to be no criteria for establishing a preferential economic potential on the basis of one or the other process being dominant. The formation of ore-deposits associated with granitoid rocks is a complex, interactive process and attention is only drawn here to the fact that the way in which granites crystallize and/or the nature and extent of melting in the source rocks from which they were derived, are but two of the perhaps previously underestimated parameters affecting the economic potential of these rocks.

ACKNOWLEDGMENTS

This paper was written whilst the author was in receipt of an Alexander von Humboldt Fellowship at the University of Cologne, West Germany. Professor T.S. McCarthy, University of the Witwatersrand, Johannesburg, kindly read and suggested useful improvements to a draft version of the paper.

APPENDIX

1. Mineral/melt distribution coefficients (Kd's) used :

	Quartz	Plagioclase	K-feldspar	Biotite
Rb	0,00	0,04	0,66	3,00
Sr	0,00	2,80	3,60	0,10
Ba	0,00	0,40	6,00	6,00

(after compilations by McCarthy, 1976 and Hanson, 1978)

2. Mineral modes used :

(a) *Concordia granite*

parental assemblage-	Quartz	20%	K-feldspar	10%
	Plagioclase	60%	Biotite	10%
derived melt-	Quartz	35%	K-feldspar	30%
	Plagioclase	30%	Biotite	5%

(b) *Boesmanskop syenite pluton*

fractionating phases-	Plagioclase	45%	Hornblende	5%
	K-feldspar	35%	Biotite	10%
	Quartz	5%		

APPENDIX (Continued)

3. Initial trace element abundances :

(a) Partial melting model -	Rb	175	ppm
	Sr	200	ppm
	Ba	500	ppm
(b) Fractional crystallization model -	Rb	450	ppm
	Sr	750	ppm
	Ba	1000	ppm

4. Equations used :

(a) Partial melting model -

$$C_l = C_0/D_p + F(1 - D_m) \quad \text{after Shaw (1970)}$$

$$C_s = C_l \cdot D_p$$

(b) Fractional crystallization model -

$$C_s = C_0 \cdot D_f \cdot (1 - F)^{D_f - 1} \quad \text{after Neumann et al. (1954)}$$

$$C_l = C_s/D_f$$

where $C_{l,s}$ - abundances of trace elements in liquid or solid
 C_0 - initial trace element abundance
 $D_{p,m,f}$ - bulk distribution coefficients in parent, melt or fractionating phases
 F - weight fraction of melt/liquid

REFERENCES

- Anhaeusser, C.R., Robb, L.J., and Barton, J.M. Jr. (1983). Mineralogy, petrology and origin of the Boesmanskop syeno-granite complex, Barberton Mountain Land, South Africa. *Spec. Publ. geol. Soc. S. Afr.*, 9, 169-184.
- Arth, J.G., Barker, F., Peterman, Z.E., and Friedman, I. (1978). Geochemistry of the gabbro-diorite-tonalite-trondhjemite suite of southeast Finland and its implications for the origin of trondhjemite-tonalite magmas. *J. Petrol.*, 19, 289-316.
- Arth, J.G., and Hanson, G.N. (1975). Geochemistry and origin of the early Precambrian crust of northeastern Minnesota. *Geochim. Cosmochim. Acta*, 39, 325-362.
- Bateman, P.C., and Chappell, B.W. (1979). Crystallization, fractionation and solidification of the Tuolumne Intrusive Series, Yosemite National Park, California. *Bull. geol. Soc. Amer.*, 90(1), 465-482.

- Cann, J.R. (1970). Upward movement of granitic magma. *Geol. Mag.*, 29, 335-340.
- Chappell, B.W., and White, A.J.R. (1974). Two contrasting granite types. *Pacif. Geol.*, 8, 173-174.
- Clifford, T.N., Gronow, J., Rex, D.C., and Burger, A.J. (1975). Geochronological and petrogenetic studies of high grade metamorphic rocks and intrusives in Namaqualand, South Africa. *J. Petrol.*, 16(1), 154-188.
- Clifford, T.N., Stumpf, E.G., Burger, A.J., McCarthy, T.S., and Rex, D.C. (1981). Mineral - chemical and isotopic studies of Namaqualand granulites, South Africa : a Grenville analogue. *Contr. Miner. Petrol.*, 77, 225-250.
- Didier, J., and Lameyre, J. (1969). Les granites du Massif Centrale francs : étude comparée des leucogranites et granodiorites. *Contr. Miner. Petrol.*, 24, 219-233.
- Emeleus, C.H. (1963). Structural and petrographic observations on layered granites from southern Greenland. *Spec. Pap. Mineral. Soc. Amer.*, 1, 22-29.
- Groves, D.I., and McCarthy, T.S. (1978). Fractional crystallization and the origin of tin deposits in granitoids. *Mineral. Deposita*, 13, 11-26.
- Hahn-Weinheimer, P., and Ackermann, H. (1967). Geochemical investigations of differentiated granite plutons of the southern Black Forest. *Geochim. Cosmochim. Acta*, 37, 2197-2228.
- Hanson, G.N. (1978). The application of trace elements to the petrogenesis of igneous rocks of granitic composition. *Earth Planet. Sci. Lett.*, 38, 26-43.
- Hine, R., Williams, I.S., Chappell, B.W., and White, A.J.R. (1978). Contrasts between I- and S-type granitoids of the Kosciusko batholith. *J. geol. Soc. Aust.*, 25(4), 219-234.
- Ishihara, S. (1980). Significance of the magnetite-series and ilmenite-series of granitoids in mineral exploration. *Proc. 5th. Quad. IAGOD Symp., Stuttgart*, 309-312.
- Luth, W.C., Jahns, R.H., and Tuttle, O.F. (1964). The granite system at pressures of 4 to 10 kilobars. *J. Geophys. Res.*, 69, 759-773.
- McCarthy, T.S. (1976). Chemical interrelationships in a low pressure granulite terrain in Namaqualand, South Africa, and their bearing on granite genesis and the composition of the lower crust. *Geochim. Cosmochim. Acta*, 40, 1057-1068.
- McCarthy, T.S. (1978). *Geochemical studies of selected granitic terrains in South Africa*. Ph.D. thesis (Unpubl.) Univ. Witwatersrand, Johannesburg, 268 pp.

- McCarthy, T.S., and Hasty, R.A. (1976). Trace element distribution patterns and their relationship to the crystallization of granitic melts. *Geochim. Cosmochim. Acta*, 40, 1353-1358.
- McCarthy, T.S. and Robb, L.J. (1978). On the relationship between cumulus mineralogy and trace and alkali element chemistry in an Archaean granite from the Barberton region, South Africa. *Geochim. Cosmochim. Acta*, 42, 21-26.
- Neumann, H., Mead, J., and Vitaliano, C.J. (1954). Trace element variation during fractional crystallization as calculated from the distribution law. *Geochim. Cosmochim. Acta*, 6, 90-99.
- Robb, L.J. (1982). A review of magmatic differentiation in granites and its influence on the distribution of uranium and thorium in these rocks - preliminary application to chemical trends and U-Th mineralization in alaskites and in the Concordia granite from the Springbok region, Namaqualand. *Int. Rep. Atomic Energy Board*, Pretoria, South Africa, 61 pp.
- Robb, L.J., and Anhaeusser, C.R. (1983). Chemical and petrogenetic characteristics of Archaean tonalite-trondhjemite gneiss plutons in the Barberton Mountain Land. *Spec. Publ. geol. Soc. S. Afr.*, 9, 103-116.
- Shaw, D.M. (1970). Trace element fractionation during anatexis. *Geochim. Cosmochim. Acta*, 34, 237-243.
- Smith, T.E. (1975). Layered granitic rocks at Chebucto Head, Halifax County, Nova Scotia. *Can. J. Earth Sci.*, 92, 456-463.
- Takahashi, M., Aramaki, S., and Ishihara, S. (1980). Magnetite-series/ilmenite-series versus I-type/S-type granitoids. *Spec. Issue Min. Geol.*, 8, 13-28.
- Tindle, A.G., and Pearce, J.A. (1981). Petrogenetic modelling of in situ fractional crystallization in the zoned Loch Doon pluton, Scotland. *Contr. Miner. Petrol.*, 78, 196-207.
- Vance, J.A. (1961). Zoned granite intrusions - an alternative hypothesis of origin. *Bull. geol. Soc. Amer.*, 72, 1723-1728.
- White, A.J.R., and Chappell, B.W. (1977). Ultrametamorphism and granitoid genesis. *Tectonophysics*, 43, 7-22.
- Wilshire, H.G. (1968). Mineral layering in the Twin Lakes granodiorite, Colorado. *Mem. geol. Soc. Amer.*, 115, 235-261.
- Wolhuter, L.E. (1973). Major and trace elements in the Opemisco Lake granite pluton, Quebec, Canada. *Spec. Publ. geol. Soc. S. Afr.*, 3, 387-409.