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GEOCHEMICAL STRATIGRAPHY OF THE KLIPRIVIERSBURG  
GROUP VOLCANICS

R.E. MYERS., T.S. MCCARTHY., M. BUNYARD., R.G. CAWTHORN.,  
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by

R.E. MYERS., T.S. MCCARTHY., M. BUNYARD., R.G. CAWTHORN., T.M. FALATSA.,  
T. HEWITT., P. LINTON., J.M. MYERS., K.J. PALMER and R. SPENCER

*(Department of Geology, University of the Witwatersrand,  
P.O. Wits 2050, Johannesburg, South Africa)*

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### ABSTRACT

The results of a stratigraphic geochemical study of the Klipriviersberg Group are reported. The investigation involved sampling and logging or mapping 29 profiles through the Ventersdorp lavas, extending in a 400km arc through Evander, South Rand, Central Rand, West Rand, Klerksdorp, and Welkom. Over 1000 samples were analysed for 24 major, minor, and trace elements. Careful analysis of the data indicated that the most useful stratigraphic information is provided by  $\text{TiO}_2$ , V, Cr abundances and the Ti/Zr ratio. On the basis of these parameters, 9 geochemical units are defined. Units 1 to 4 are developed only along the northern margin of the Klipriviersberg Group basin, while higher units are widespread. Chemical compositions within these units show some spatial variations, notably a trend towards more primitive compositions along the western side of the basin, coincident with a shift of the volcanic centre to this region. The geochemical stratigraphy documented in this study provides a means of locating stratigraphic positions within the very homogeneous Klipriviersberg lavas and of solving structural problems.

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## GEOCHEMICAL STRATIGRAPHY OF THE KLIPRIVIERSBERG GROUP VOLCANICS

### 1. INTRODUCTION

The Klipriviersberg Group lavas of the Ventersdorp Supergroup represent a flood basalt sequence covering in excess of 30000km<sup>2</sup> and typically between 1500m and 2000m in thickness. This volcanic event terminated the Witwatersrand Supergroup sedimentation and, as such, represents an important event in the evolution of the Kaapvaal Craton and the Witwatersrand Basin in particular. A knowledge of the stratigraphy within the Klipriviersberg Group is important in exploration of the Witwatersrand Supergroup because the lavas overlies these sedimentary rocks. A lithostratigraphic subdivision has been developed for the Klipriviersberg Group (Winter, 1976), but the routine implementation of this stratigraphy requires considerable knowledge and skill because of the general homogeneity of the Group. Furthermore, even experienced practitioners err in the implementation of this lithostratigraphy (Linton *et al.*, 1989).

Studies of flood basalt sequences have shown that they are often characterized by a regular, laterally persistent, geochemical stratigraphy (e.g. Mangan *et al.*, 1986; Cox and Hawkesworth, 1985). Previous localized geochemical studies of the Klipriviersberg Group have indicated there are pronounced changes in chemistry with height (Wyatt, 1976). The authors decided to investigate this relationship on a regional basis and a detailed study of the geochemical stratigraphy of the Klipriviersberg Group was initiated.

The study, which began in 1984, involved the sampling of some 29 carefully controlled stratigraphic profiles, both on surface and in borehole core. Samples were obtained from the following areas; Evander, South Rand, Central Rand, West Rand, Klerksdorp, and the Orange Free State.

### 1.1. REGIONAL SETTING

The eruption of the Klipriviersberg Group terminated the deposition of the Central Rand Group sediments. The Klipriviersberg Group is followed, in turn, by the deposition of sediments and volcanics in fault controlled basins during Platburg time.

In recent years there seems to be general agreement that the Central Rand Group was deposited in a compressional tectonic setting (e.g. Burke *et al.*, 1985; Winter, 1988, Myers *et al.*, 1989) although there is no consensus on the cause or structural manifestations of this compressional event. The Platberg has been recognised as a major rifting event (see Burke *et al.*, 1985).

# 111. DISTRIBUTION

The 2700 Ma Klipriviersberg Group flood basalts occur at the base of the Ventersdorp Supergroup (Figure 1) which is distributed over a large area in the west-central portion of the Kaapvaal Craton (Figure 2). Although Ventersdorp sediments and volcanics are found over a very large area, extending from the Northern Cape in South Africa into southern Botswana, the Klipriviersberg Group lavas are found only in the northern to central portion of the rift (Figure 3) and define the eastern 'thumb' of the Ventersdorp distribution (Figure 2). The presently known Klipriviersberg lavas are confined to the immediate vicinity of the Witwatersrand Basin and cover an area of about 30 000km<sup>2</sup>. However, Tyler (1979) has suggested that Klipriviersberg Group lavas may occur to the southeast of Gaborone and recent mapping by the Geological Survey of South Africa suggests that there may be Klipriviersberg lavas preserved to the west of Klerksdorp (Figure 3). If these correlations are correct, then the Klipriviersberg lavas may have originally covered several hundred thousand square kilometres.

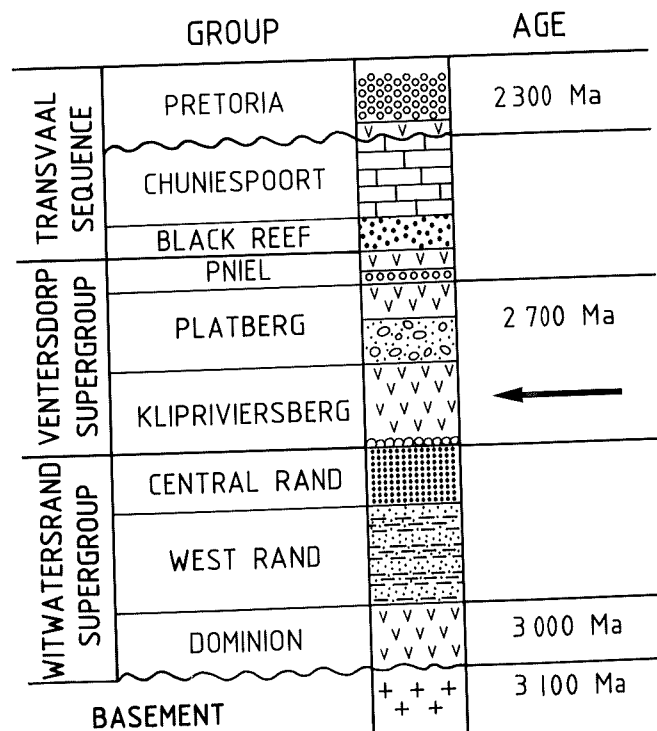


Figure 1: The stratigraphic context of the Ventersdorp Supergroup.

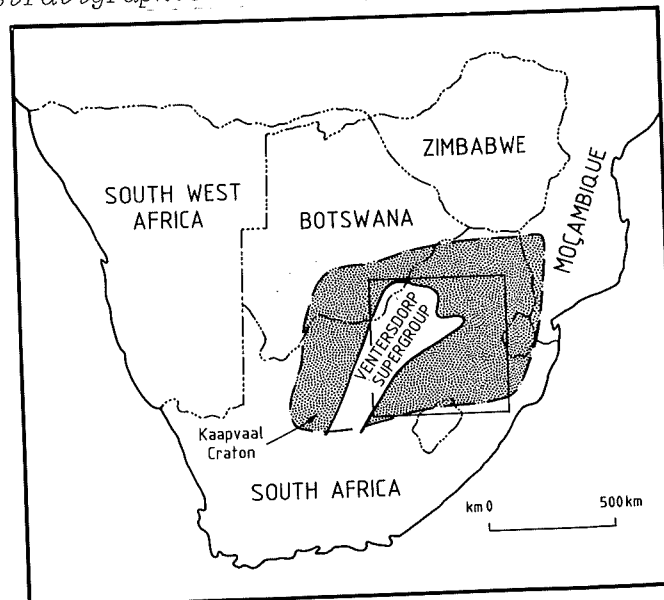


Figure 2. The distribution of the Ventersdorp Supergroup on the Kaapvaal Craton.

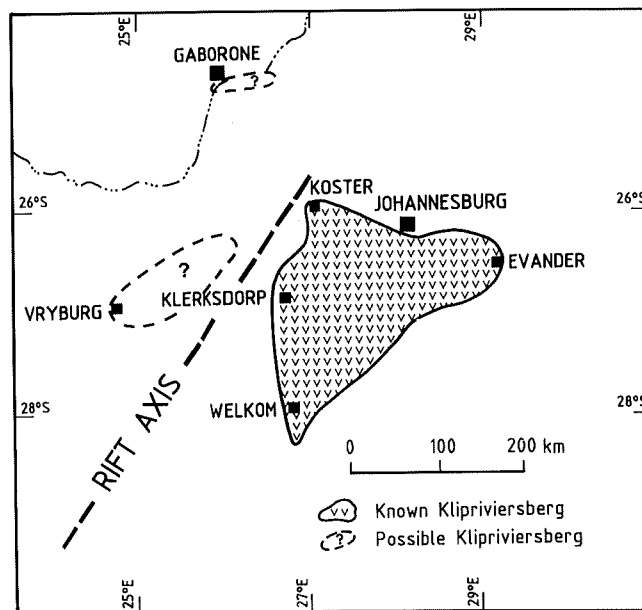


Figure 3: The distribution of the Klipriviersberg Group.

#### 1V. GENERAL GEOLOGY

Because the Klipriviersberg Group directly overlies the auriferous Witwatersrand sediments it has undergone considerable study and various lithostratigraphic subdivisions have been suggested (Jacobsen, 1943; Pienaar, 1956; Winter, 1965; Wyatt, 1976; Winter, 1976; SACS, 1980). The lithostratigraphic sequence shown in Figure 4 is based on Winter (1976) with the subdivisions of the Alberton Formation taken from Wyatt (1976).

The Westonaria Formation is distinguished by its ultramafic nature which, after low grade metamorphism, gives the lavas a talcose character. The Alberton Formation is characterized by plagioclase phenocrysts which may be up to 50mm in length but are generally <2cm. The Orkney and Jeanette Formations have characteristic flow top breccias while the Loraine and Edenville Formations have distinctive amygdales and alteration zones around the amygdales (see Winter, 1976). Although most workers have been able to recognize a lithostratigraphy, there is still considerable debate over the usefulness for regional correlation of some of the stratigraphic 'markers'. One of the primary objectives of this study has been to verify and refine the lithostratigraphic subdivisions of the Klipriviersberg Group.

The thickest sections of Klipriviersberg Group lavas encountered by drilling anywhere in the Witwatersrand Basin are in the order of 2 km. However, the true thickness remains unknown because, almost without exception throughout the basin, the top of the sequence is defined by erosional unconformities.

One of the most striking features of the Klipriviersberg Group, and of considerable importance for stratigraphic studies such as this one, is the almost total absence of sediments within the flood basalt sequence. Minor sand and 'lithic' tuff horizons occur in the lowermost Westonaria Formation (Wyatt, 1976) and Winter (1965) reported two minor occurrences of sediments in the uppermost Edenville Formation (Figure 4). Apart from these minor occurrences, no other sediments have been reported in the Klipriviersberg Group. There appear to be no major or minor disconformities within the sequence.

LITHO-STRATIGRAPHY		GEOCHEM. STRAT.
KLIPRIVIERSBERG GROUP	EDENVILLE FM.	10
		9
	LORAINÉ FM.	8
	JEANETTE FM.	7
	ORKNEY FM.	6
	ALBERTON FM	5
		4
		3
		2
	WESTONARIA FM.	1
		B A

Figure 4: The lithostratigraphic subdivisions of the Klipriviersberg Group. The geochemical subdivisions established in this study are shown on the right.

Within the Klipriviersberg Group, a wide variety of chemical compositions are represented, ranging from the picritic lavas of the Westonaria Formation to the highly differentiated compositions of the Alberton and Orkney Formations (Table 1). Most of the Klipriviersberg liquids are highly evolved resulting in almost uniform trace element compositions. In general the FeO/MgO ratio is greater than 1,7. The lavas of the Jeanette and Loraine Formations are more primitive, however, containing between 7 and 15% MgO (Table 1).

The entire Klipriviersberg sequence has undergone lower greenschist grade metamorphism resulting in the development of a chlorite, actinolite, Na-feldspar,  $\pm$  epidote, zoisite, sphene, pyrite, quartz assemblage. Occasionally, remnant clinopyroxene is preserved, but in general the assemblage seems to have totally re-equilibrated. In spite of metamorphism original igneous textures are generally well preserved.

The effects of metamorphism on the geochemistry are evident in the alkali and alkaline earth elements (Ca, Na, K, Ba, Rb, Sr) as well as in Si, rendering these key elements almost useless for petrogenetic studies (Palmer *et al.*, 1986). In addition, Armstrong *et al.* (1986) showed that the Rb/Sr isotopic system appears to have re-equilibrated during this metamorphic event. The Pb-Pb model ages of  $\sim 2350$  Ma (Armstrong *et al.*, 1986) may thus represent the age of metamorphism.



TABLE 1

KLIPRIVERSBERG GROUP  
AVERAGE COMPOSITIONS FOR GEOCHEMICAL SUBDIVISIONS

Unit	1	2	3	4	5	6	7	8	9
SiO <sub>2</sub>	45.36	53.98	55.71	53.36	53.19	53.62	53.24	54.37	55.40
TiO <sub>2</sub>	.87	1.44	.99	1.41	1.16	.98	.72	.52	0.68
Al <sub>2</sub> O <sub>3</sub>	5.26	13.65	14.29	14.44	14.58	14.18	13.64	13.68	14.30
Fe <sub>2</sub> O <sub>3</sub>	14.53	11.92	10.40	11.89	11.20	12.06	11.07	9.97	9.94
MnO	.21	.15	.15	.12	.13	.15	.16	.14	1.14
MgO	18.19	5.36	5.41	4.72	4.53	4.88	6.39	7.69	5.07
CaO	6.63	6.65	6.28	5.46	7.25	6.69	7.60	6.81	6.90
Na <sub>2</sub> O	.08	3.23	4.25	2.88	3.20	3.22	3.02	2.44	3.48
K <sub>2</sub> O	.06	1.60	.76	2.06	1.41	1.35	1.39	1.65	1.44
P <sub>2</sub> O <sub>5</sub>	.08	.18	.13	.19	.16	.12	.09	.08	.11
LOI	7.82	1.43	1.30	3.07	2.39	2.10	2.12	2.06	1.61
TOTAL	99.12	99.69	99.68	99.39	99.22	99.37	99.43	99.41	99.09
Zr	82	138	125	150	135	113	91	80	99
V	139	197	189	1.89	174	210	196	172	185
Cr	1608	308	118	179	128	49	292	503	146
Ni	1326	191	113	128	146	131	169	176	106

## V. METHODOLOGY

This study represents the combined work of several M.Sc and B.Sc Honours studies carried out at the University of the Witwatersrand since January, 1984. Individual projects were limited to specific areas and at least two detailed profiles were analysed in each study to verify the lateral continuity of the stratigraphy in each area. In addition to the Witwatersrand University studies, analytical data from boreholes south of Klerksdorp, studied by M. Bowen (1984) and T. Bowen (1984) have been examined. These data are generally consistent with the results presented here. A total of 29 profiles through the Klipriviersberg Group have been investigated covering most of the periphery of the Witwatersrand Basin (Figure 5).

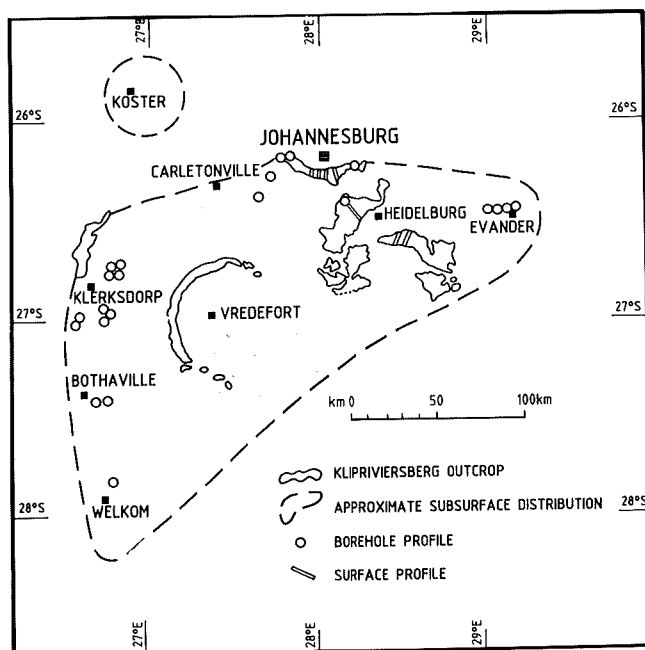


Figure 5: The location of sample profiles used in this study.

An important aspect of each project has been to log or map each profile so that the geochemical data can be related to well-defined geology. With this geological control it has been possible to relate the lithostratigraphy to the geochemical stratigraphy. The good geological control on sampling has also permitted corrections to be made for faulting within the Klipriviersberg succession.

Geochemical samples were selected so as to exclude those with visible alteration effects, and only the homogeneous central portions of the flows were sampled. All samples were analysed by X-ray fluorescence spectrometry on a Philips 1400 spectrometer. Calibration curves were constructed using 30 international standards. Major elements were determined using the fusion method of Norrish and Hutton (1969), while trace elements were determined on undiluted sample powder briquettes using standard techniques. Internal controls covering the entire working range have been used to monitor and adjust for between-run calibration differences. Typical analytical precision obtained in a single run for elements used in this study are shown in Table 2. The analytical precision obtained over a period of four years on check samples covering the full range of Klipriviersberg compositions is shown in Figure 6. These results reflect total precision, including sample preparation and run to run variability.

TABLE 2

WITHIN-RUN ANALYTICAL PRECISION

	Mean	s.d.	cv
MgO (%)	10.88	0.031	0.28
	28.46	0.45	1.57
TiO <sub>2</sub>	0.979	0.0005	0.05
	0.262	0.006	2.29
V (ppm)	112	1.9	1.70
	190	1.4	0.74
Cr (ppm)	3143	27	0.86
	1964	7.6	0.39
Zr (ppm)	24	0.59	2.46
	90	0.78	0.87

In spite of the massive size of the data set (>1000 samples) the writers have chosen not to adopt a statistical approach to our data analysis. In each profile the data have been plotted against stratigraphic height so that geochemical discontinuities can be directly related to the geological log. Although initially every element was plotted against stratigraphic height, it soon became apparent that a combination of TiO<sub>2</sub>, V, Zr, and Cr was the most effective in defining the stratigraphic sequence although many elements show some stratigraphic variations. The stratigraphic variation pattern exhibited by TiO<sub>2</sub> is identical to the patterns shown by the incompatible elements Zr, Y, and P. The semi-compatible element V shows a surprising degree of variation independent of both Fe and Ti. Cr, a highly compatible element, varies in the same way as Ni and MgO, but appears to be more sensitive to small degrees of differentiation than Ni, and consequently shows more pronounced breaks. The Ti/Zr ratio shows unexpected shifts which correspond to specific stratigraphic units. For this reason it has been added to the profiles presented here. Variations in this ratio indicate that one or both of these elements is not behaving in a completely incompatible manner. Representative analyses of each of the geochemical units are shown in Table 3.

Since the object of this study concerned the identification of systematic changes in chemistry with height, the authors considered that it was essential to examine variability in chemistry caused by local geological variables such as within-flow crystal accumulation, open-system metamorphism or alteration, and so forth. Several individual flows were sampled at regular intervals in borehole core. The results of these flows

TABLE 3

REPRESENTATIVE ANALYSES OF EACH OF THE GEOCHEMICAL UNITS

Area	No.	Unit.	TiO <sub>2</sub> (%)	MgO (%)	Zr	V ppm	Cr
CR	HB65	8	.490	8,89	57	159	751
EV	R316	8	.572	7,82	66	178	503
KS	KL157	8	.420	14,24	41	171	2299
KB	KL155	8	.510	11,22	63	153	1287
CR	HB57	7	.734	6,26	74	169	206
EV	R324	7	.693	5,44	75	187	149
EV	R327	7	.802	5,94	83	190	219
KN	H309	7	7.48	6,02	74	165	245
KN	H346	7	.651	9,40	60	175	976
KS	KL151	7	.640	5,23	75	182	156
KS	KL143	7	.610	8,32	56	214	482
KS	KL140	7	.540	9,91	45	201	783
KS	KL135	7	.490	13,62	43	171	2086
CR	HB38	6	1.015	5,12	96	194	18
EV	R336	6	.898	4,38	93	157	40
EV	R339	6	.833	8,28	77	227	480
EV	R344	6	1.006	5,19	102	218	23
KN	H338	6	.931	4,65	92	191	30
KN	H318	6	.983	4,96	97	193	63
KS	KO126	6	.925	5,47	96	209	26
KS	KO111	6	1.097	5,79	109	259	72

TABLE 3 (continued)

Area No.		Unit	TiO <sub>2</sub>	MgO (%)	Zr	V ppm	Cr
CR	HB33	5	1.125	4,77	121	161	90
CR	HB29	5	1.242	4,43	134	151	183
EV	R349	5	.936	4,29	109	161	40
EV	R355	5	1.223	5,03	133	167	156
KN	H331	5	1.107	4,58	115	160	139
KS	KA104	5	1.075	4,95	124	169	66
KS	KA101	5	1.080	5,69	119	192	143
CR	HB15	4	1.276	4,31	130	137	152
CR	HB12	4	1.395	4,72	145	168	156
KN	H329	4	1.443	4,77	145	183	187
KN	H322	4	1.400	4,65	137	174	179
CR	HB18	3	1.012	5,33	122	173	106
CR	HB5	3	1.003	5,18	119	175	77
CR	HB8	2	1.468	5,61	135	183	358
CR	HB2	2	1.449	5,39	136	173	289
CR	HB1	1	1.000	13,71	74	189	2687
EV	R360	1	.729	21,84	56	145	2158
EV	R362	1	.766	18,20	58	96	1214

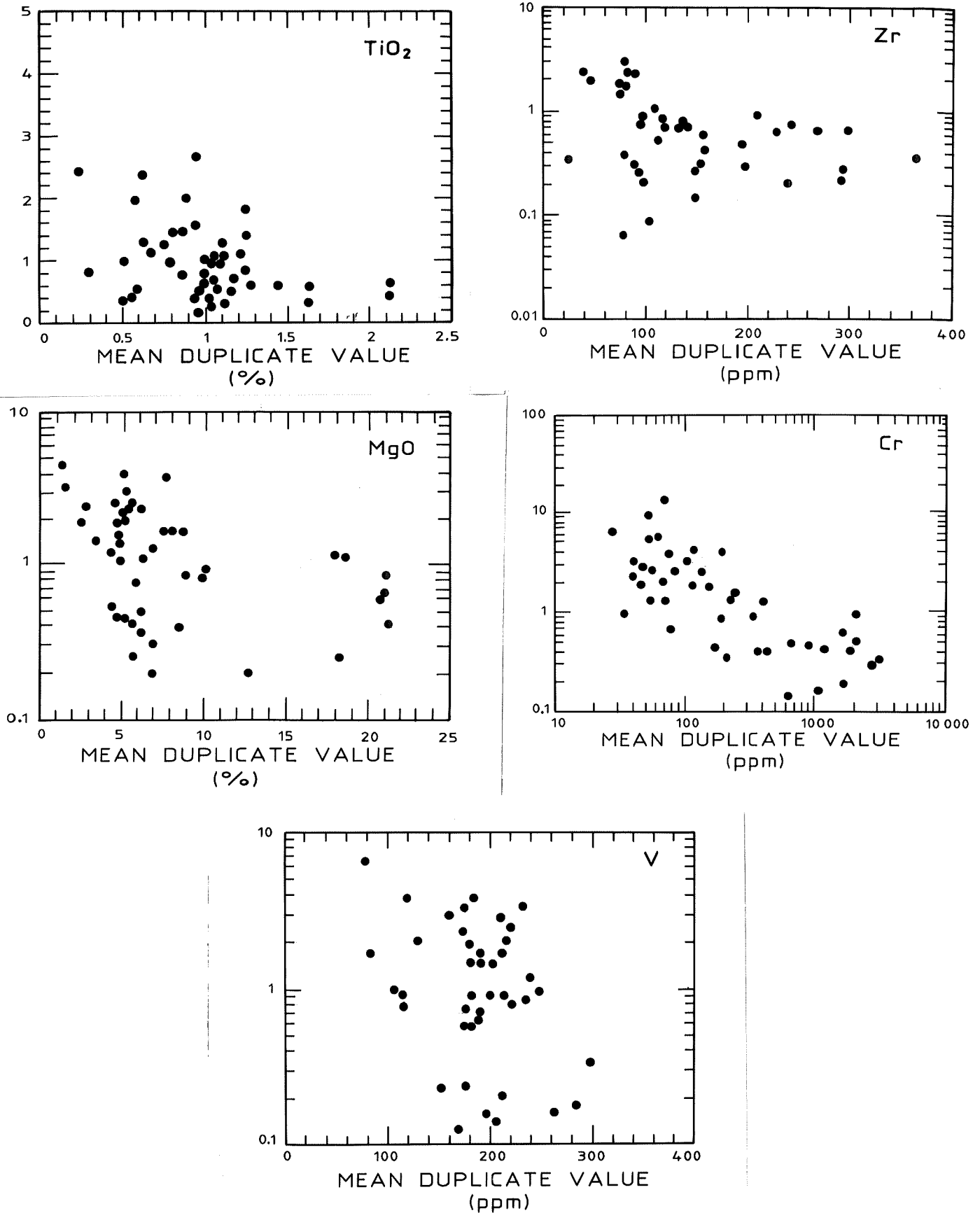


Figure 6: Diagram illustrating the analytical precision (co-efficient of variation) as a function of mean concentration over the working range of this study. Each point represents the value obtained by repeated analysis (normally 4 times) of individual samples over a period of four years.

are listed in Table 4. The variability is somewhat greater than analytical precision, as might be expected, but is generally of the same order of magnitude. On the basis of these observations and on the basis of the uniform changes in composition with height which is discussed below, the authors conclude that extraneous variables are not a major source of chemical variability for the elements and ratio used in this study. It is, however, important to remember that the samples used here were carefully selected and these conclusions might not apply to a less rigorously selected sample set (e.g. amygdaloidal or visibly altered samples).

## V1. GEOCHEMICAL STRATIGRAPHY

The profiles illustrated in the following discussion represent actual profiles rather than composite sections. Representative analyses for each unit from several profiles are given in Table 3. Each data point on these profiles represents a single lava flow.

It must again be emphasized that the stratigraphy represented in each section has been verified by at least one, but usually more additional sections in the same area. Although this study is based on 29 geochemical sample profiles, only a few of them are used here for the sake of brevity.

### A. Central Rand Profile

The Central Rand profile (Figure 7), a surface profile taken south of Johannesburg (Figure 5), may be regarded as a type section and geochemical unit names are defined from this area. Unit 1 (U1) at the base of the sequence is characterized by extremely high Cr (>1500ppm) and correlates with the ultramafic Westonia Formation. The break between U1 and U2 is defined by a sharp increase in  $TiO_2$  and pronounced decreases in Cr and the Ti/Zr ratio. The break between U2 and U3 is marked by a dramatic decrease in  $TiO_2$ , Ti/Zr, and Cr. The U3-U4 boundary is marked by an increase in  $TiO_2$  and Ti/Zr with no apparent change in Cr. In the Central Rand the U4-U5 break is not very pronounced but is characterized by a slight decrease in  $TiO_2$ . The break between U5 and U6 is the most clearly defined break is defined by a dramatic increase in V and Ti/Zr as well as a decrease in  $TiO_2$  and Cr. The break between U5 and U6 is the most clearly defined in the entire sequence and has formed the basis of the regional correlation. The U6-U7 change is defined by a sharp increase in Cr and a decrease in  $TiO_2$  with minor changes in V and Ti/Zr. The U7-U8 break is defined by a sharp decrease in  $TiO_2$  and an increase in Cr. The top of the Central Rand profile is defined by an unconformity beneath the Transvaal Sequence.

The stratigraphic units in the Central Rand are defined using chemical discontinuities. In this approach to correlation the actual chemical compositions of the units, i.e. the absolute element concentrations, are not as important as the relative changes from unit to unit. Systematic lateral compositional changes within individual units are therefore readily accommodated. This approach differs from those used previously (Palmer *et al.*, 1986; Bowen *et al.*, 1986) which utilize binary variation diagrams or multi-variate statistical methods and in which lateral compositional changes could reduce sensitivity.

The single sample with extremely high Cr near the top of U6 is worth comment. Because this sample is anomalous there is a real

TABLE 4

VARIABILITY OF COMPOSITION THROUGH INDIVIDUAL LAVA FLOWS

<u>Flow A: (37m thick)</u>		%	ppm			
Sample		TiO <sub>2</sub>	V	Cr	Zr	Ti/Zr
1		1.175	193	43	108	65
2		1.075	173	44	100	65
3		1.054	169	39	98	64
4		1.111	177	45	101	66
5		1.125	178	43	100	67
6		1.075	175	42	99	65
7		<u>1.098</u>	<u>182</u>	<u>46</u>	<u>101</u>	<u>65</u>
Mean		1.102	178	43	101	65
s.d		0.040	7.7	2.3	3.3	0.95
c.v.		3.6	4.3	5.4	3.3	1.5

<u>Flow B: (67m thick)</u>		%	ppm			
Sample		TiO <sub>2</sub>	V	Cr	Zr	Ti/Zr
1		0.973	185	13	90	65
2		0.955	187	13	88	65
3		0.963	185	13	91	63
4		0.952	190	14	91	63
5		0.928	179	17	90	62



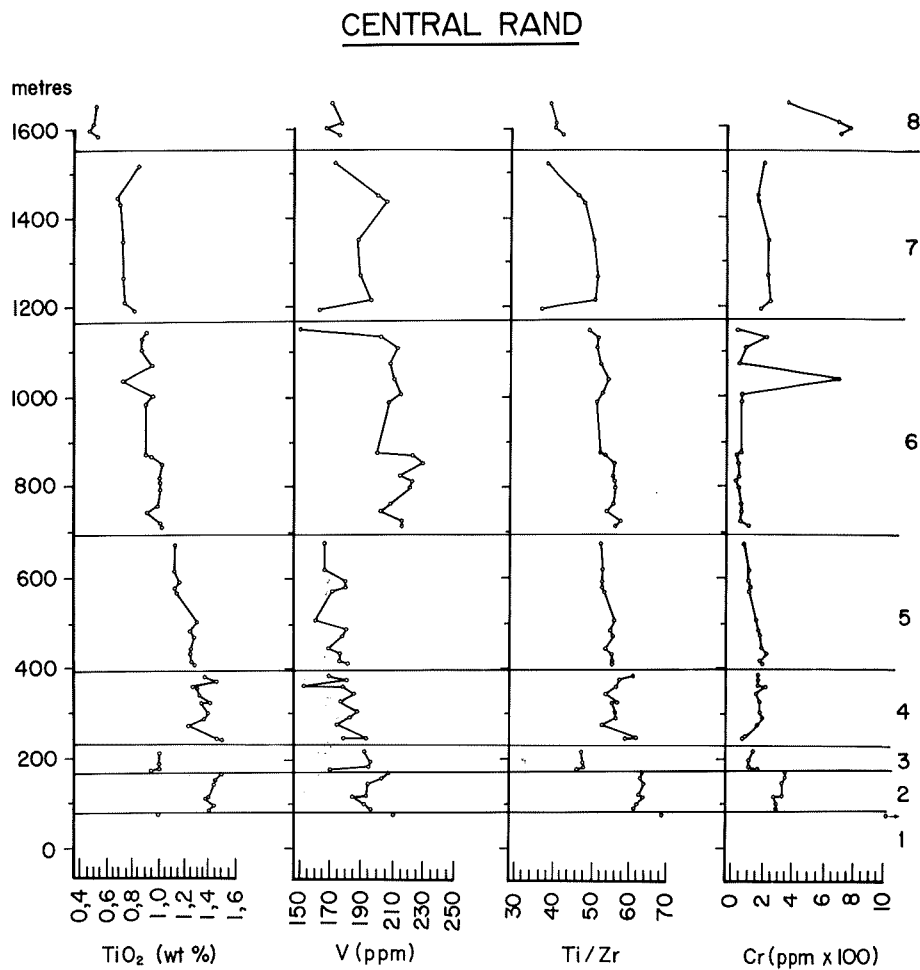


Figure 7: Geochemical profile on the Central Rand.

temptation to discard it as a dyke. However, because the sample was collected with careful geological control it cannot be thoughtlessly discarded. In two other profiles (West Rand and South Rand) single samples with anomalously high Cr values have been found near the top of U6 while in the Evander area a high Cr unit was clearly defined (Figure 8). If the anomalous samples were discarded from each profile, the fact that there is an anomalous unit at the same stratigraphic position in three areas would not have been recognized and a possibly important event overlooked.

#### B. Evander Profile

The Evander profile (Figure 8) is a vertical borehole from the eastern side of the Evander Basin (Figure 5). In order to compare this section with the Central Rand similar chemical breaks must be identified.

In the Evander area the distinctive U5-U6 boundary, characterized by a sharp increase in V and the Ti/Zr ratio, can be easily recognized near the base of the sequence. To verify that this correlation is correct the chemical break at the top of the high V unit must be compared to the U6-U7

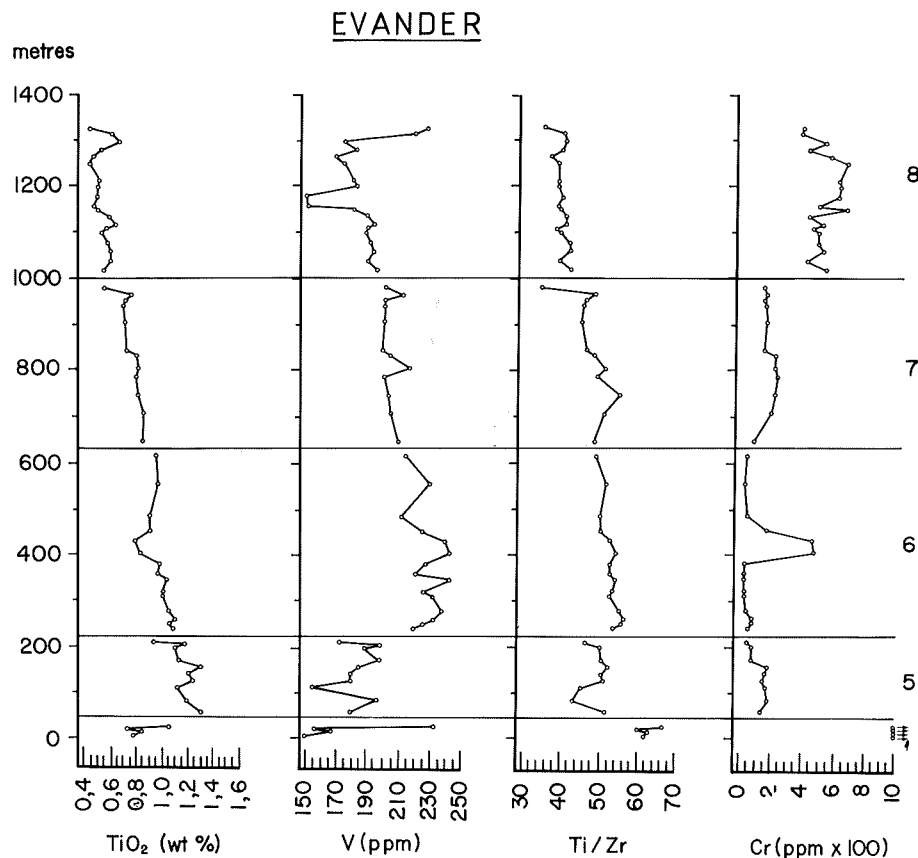


Figure 8: Geochemical profile at Evander.

boundary in the Central Rand. In the Central Rand this break is characterized by a sharp increase in Cr and a decrease in  $\text{TiO}_2$ . In the Evander profile the same type of changes occur thus confirming the initial U5-U6 correlation. The U7-U8 break is clearly marked by an increase in Cr. The top of this profile is defined by the pre-Transvaal unconformity. Comparing the sequence beneath the U5-U6 boundary in Evander with the Central Rand, it is clear that the sequence in Evander is attenuated. The high  $\text{TiO}_2$  values characteristic of U2 and U4 are absent as are the relatively high Cr values of U2. The low Ti values of U3 are also missing. It thus appears that U2, U3, and U4 were not deposited in the Evander area. However, at the base of the sequence the high Cr and Ti/Zr values characteristic of ultramafic U1 are present, a correlation which the geological logs verify.

#### C. South Rand Profile

The South Rand profile is based on surface mapping (Figure 5). Careful documentation of structure enabled estimation of stratigraphic thickness. The lowermost unit sampled belong to U5, characterized by high  $\text{TiO}_2$ , low V, and moderate Cr (Figure 9). The U5-U6 boundary is marked by a sudden rise in V and decreases in  $\text{TiO}_2$  and V. The U7-U8 boundary is marked by a further rise in Cr. The uppermost rocks in this profile differ from normal U8 and appear to constitute a distinctive group, probably a Unit 9, characterized by somewhat higher  $\text{TiO}_2$  and lower Cr than U8. Although not represented on this profile, a basal ultramafic unit is developed in the South Rand (U1 equivalent).

-15-  
SOUTH RAND

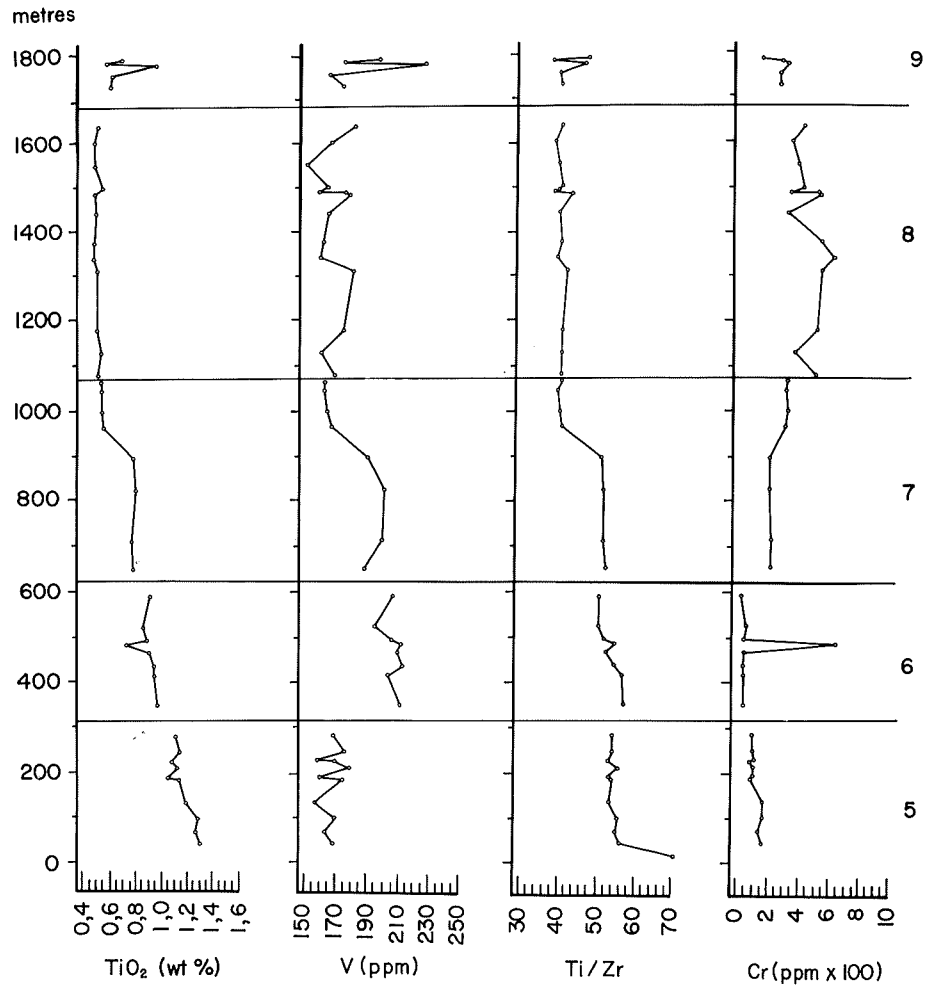


Figure 9: Geochemical profile on the South Rand.

D. Klerksdorp North Profile

The Klerksdorp North section (Figure 10) is a vertical borehole about 15km north of Klerksdorp (Figure 5). In this area the U5-U6 boundary, with its distinctive increase in V and Ti/Zr, can be identified allowing a direct correlation with the Central Rand profile. The U6-U7 break is also evident with a marked increase in Cr and a decrease in TiO<sub>2</sub>. The top of the profile is defined by the Platberg Group unconformity and the U7-U8 boundary is not preserved. Beneath the U5-U6 boundary only one chemical break is evident, defined by a sharp increase in TiO<sub>2</sub>. Comparing the Cr values in the high Ti unit with those of U2 and U4 in the Central Rand (Figure 7) it appears that the lowermost unit in Klerksdorp North probably correlates with U4 in the Central Rand. This indicates that U1, U2, and U3 were never deposited in this area.

E. Klerksdorp South Profile

The Klerksdorp South profile (Figure 11) is from a vertical borehole drilled some 30km southwest of Klerksdorp. Units 1 to 4 are absent from this borehole. The U5-U6 boundary is again marked by increases in V concentration and Ti/Zr ratio. The U6-U7 boundary is marked by a fall in TiO<sub>2</sub> accompanied by a rise in Cr content. In this particular area, it may be possible to further sub-divide U7. The top of the section is again marked by an unconformity so the full succession is not developed.

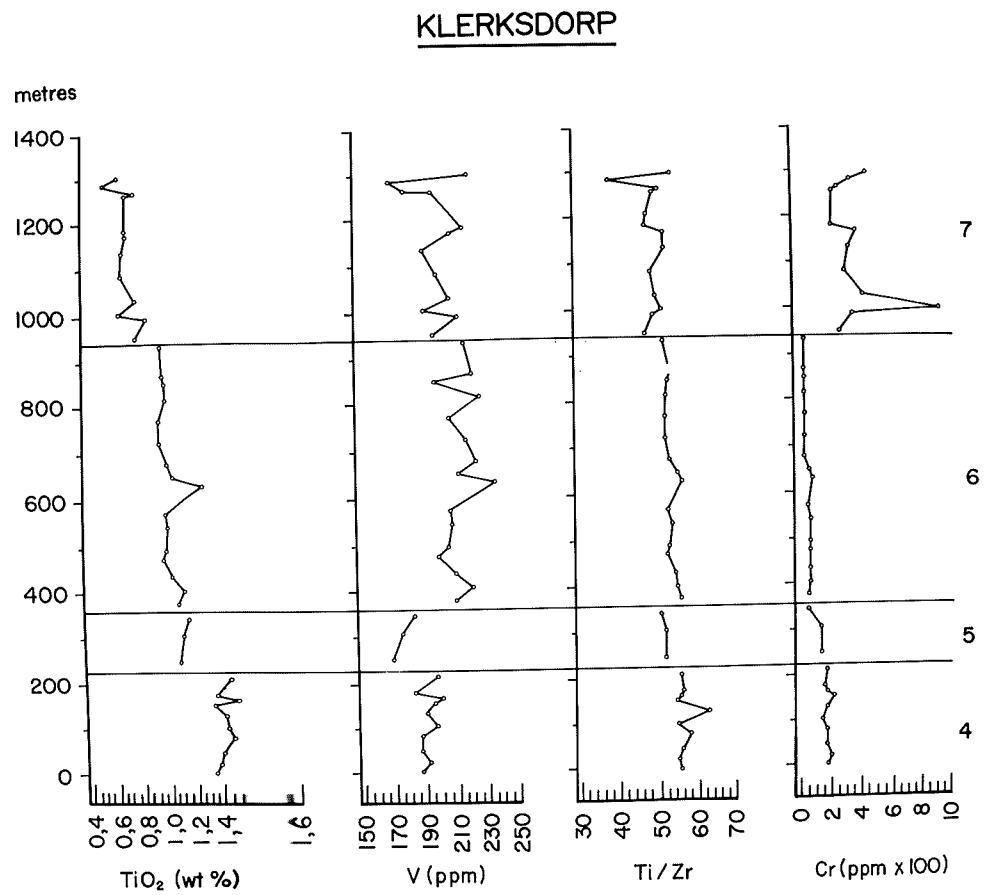


Figure 10: Geochemical profiles north of Klerksdorp.

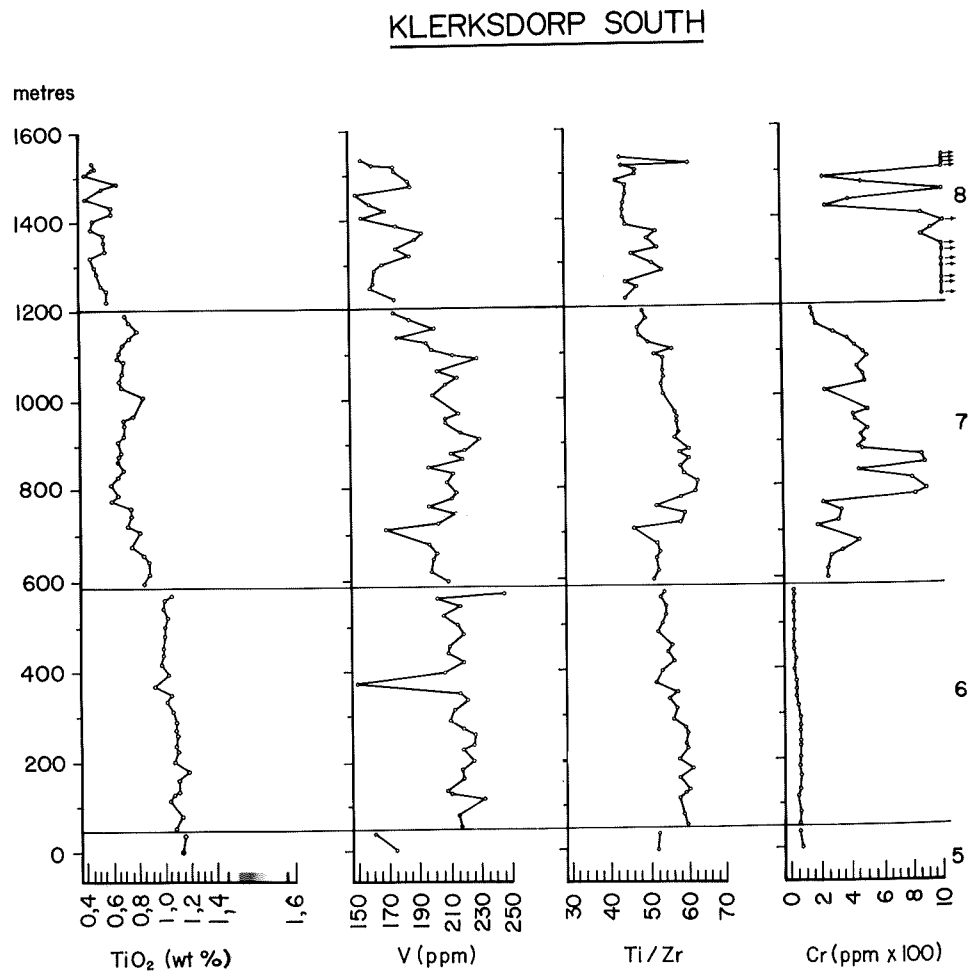


Figure 11: Geochemical profiles south of Klerksdorp.

# F. Welkom Profile

A profile taken from a borehole drilled immediately north of Welkom is shown in Figure 12. In this borehole, units 1 to 5 are absent. As in other areas, U6 is characterized by very low Cr and the U6-U7 boundary is marked by a rise in Cr which rises further at the U7-U8 boundary. As in all other profiles studied, the top of the Klipriviersberg Group in the Welkom area is marked by an erosional unconformity.

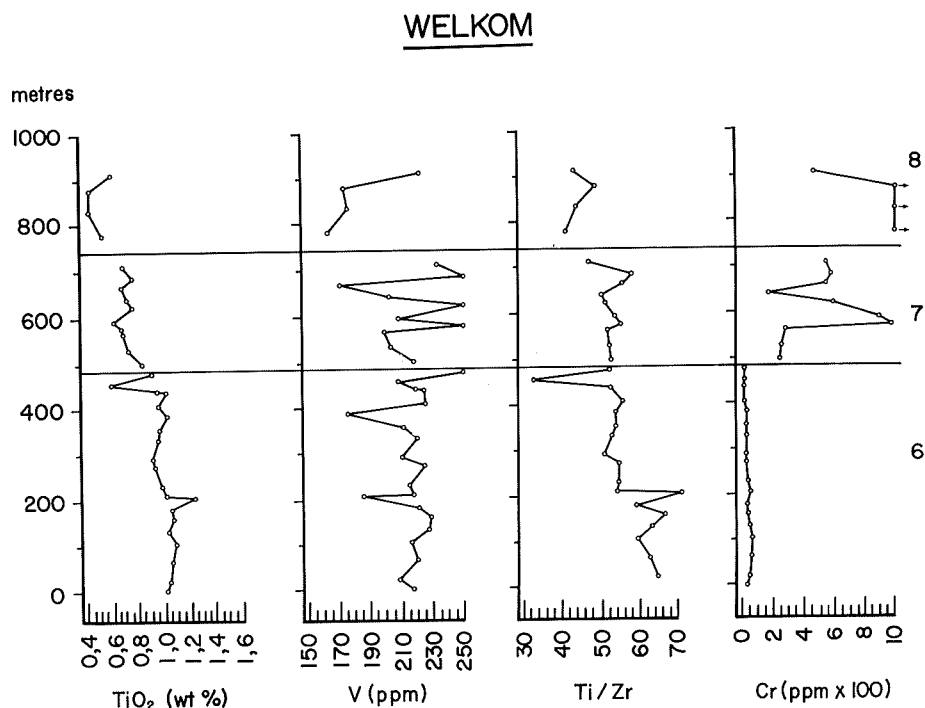


Figure 12: Geochemical profiles at Welkom.

## V11. BETWEEN-UNIT VARIATIONS

The composition versus stratigraphic height diagrams in Figures 7 to 12 illustrate that a well-defined geochemical stratigraphy can be traced over the entire extent of the Klipriviersberg Group - an arc of some 400km. This stratigraphy is characterized not so much by distinctive absolute abundances, but rather by definite and distinctive changes in chemical abundances as a function of stratigraphic height.

One of the more striking features is the discrete nature of each of the stratigraphic units. The unit boundaries are abrupt and occur between successive lava flows. There is no indication of sediment or palaeoregolith at these breaks. It is remarkable that once the break occurs, the previous composition never re-appears. There is no indication of mixing or of inter-digitation of magma units at the unit boundaries. These features imply that the switch to a new magma type must have been quite abrupt and must have occurred more or less simultaneously over the entire Klipriviersberg volcanic province, an area in excess of 30000km<sup>2</sup>.

Each geochemical unit thus represents a discrete and separate batch of magma. A full discussion of the petrogenetic implications of the chemistry is beyond the scope of this publication. However, it is of note that these magma batches do not appear to have been derived in a simple way from a homogeneous source as both Cr and  $\text{TiO}_2$  decrease with height up to unit 6, whereafter they become decoupled and while  $\text{TiO}_2$  continues to decrease, Cr increases. Furthermore, the Ti-Zr ratio shows abrupt and erratic changes between successive units.

#### V111. REGIONAL WITHIN-UNIT VARIATIONS

Within the individual units defined by the regional correlation there is a considerable amount of variation both in the composition and the internal structure of the unit. The best example of a regional variation in composition is found in U7, where the Cr concentration increases from 200ppm in Evander and the Central Rand to over 500ppm in Klerksdorp South (Figure 13). The fact that  $\text{MgO}$  shows the same regional variation, from 6% in the east to over 8% in the west (Figure 14), suggests that this regional variation is due to significant differences in the degree of

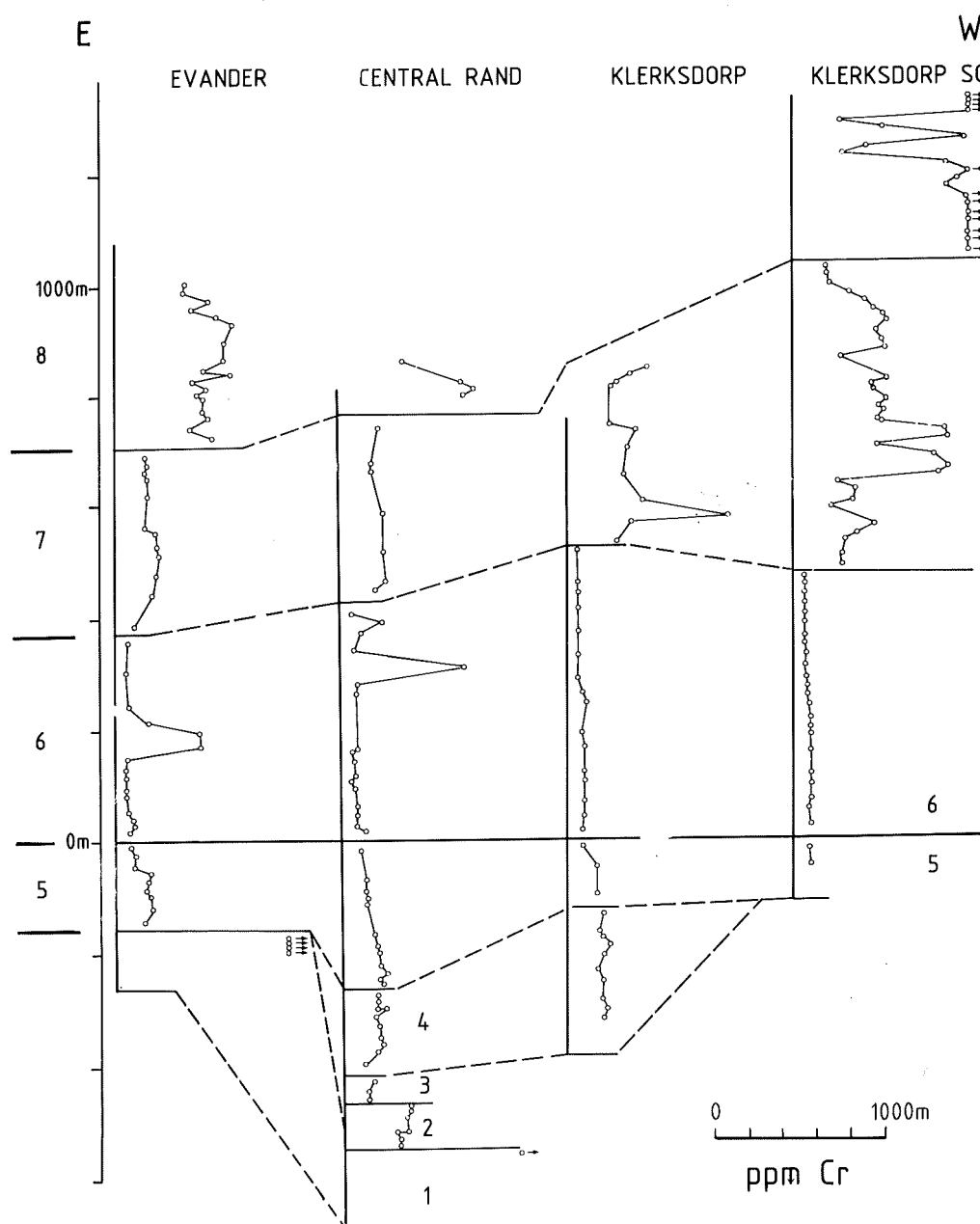


Figure 13: Lateral variation in the chromium content across the Klipriviersberg Group basin.

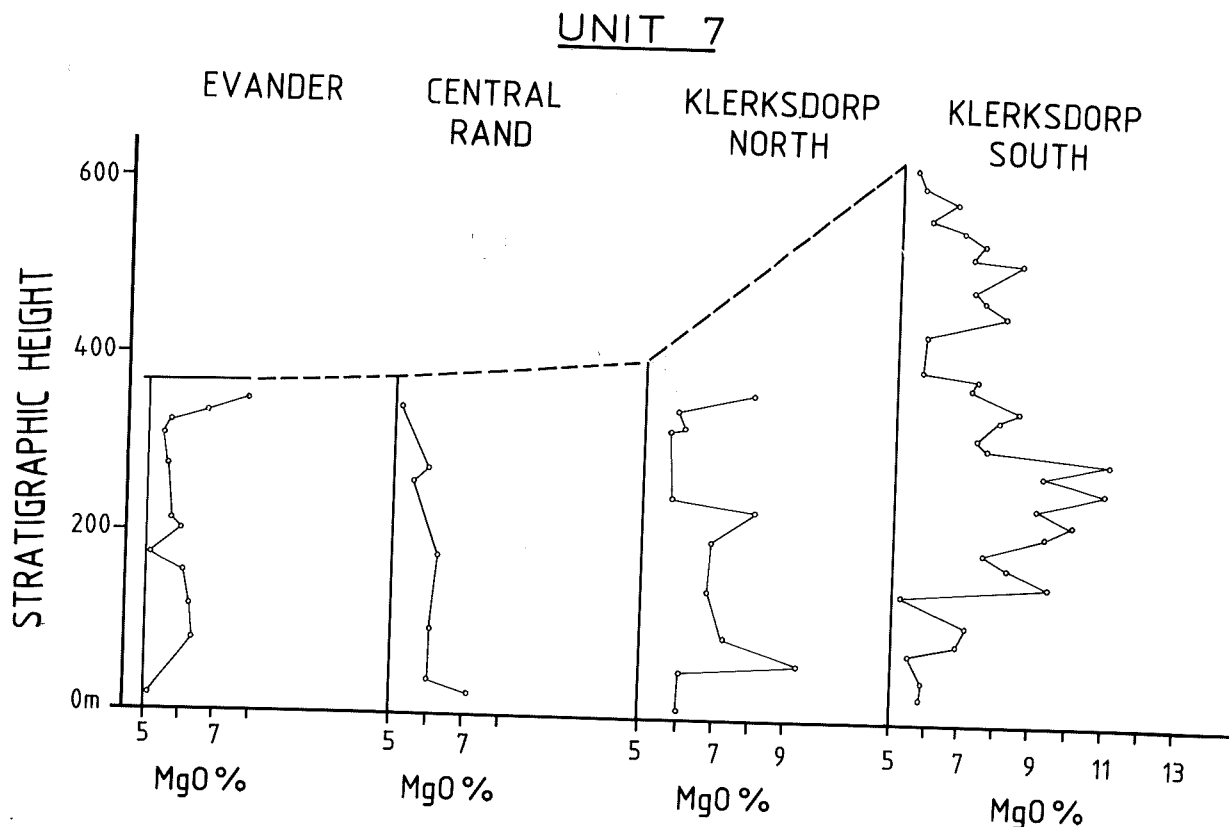


Figure 14: Variation in the magnesium content in Unit 7 across the Klipriviersberg Group basin.

differentiation rather than simply crystallization of a minor Cr phase such as chromite. A similar argument can be made for U8 (Figure 13) although at present the data on U8 are limited. These lateral variations in abundance mean that the use of absolute concentrations to establish stratigraphic position must be done with considerable caution. If this is to be done, it is recommended that a local type stratigraphy be established first.

#### 1X. REGIONAL CORRELATION

Using the method discussed above a regional correlation of the Klipriviersberg geochemical stratigraphy has been erected (Figure 15) which can be followed for over 400km, from Evander in the east to Klerksdorp in the west and south to Welkom (Figure 5).

On the fence diagram (Figure 15) representative profiles from each area are illustrated. Although illustrated sections (Figures 7-12) enable the writers to define a sequence extending generally to U8 and in one case to U9, studies currently in progress near Bothaville (Figure 5) confirm the existence of U9 and suggest the existence of an additional unit (U10) in this area (Pearton, Pers. Comm. May 1987). Unfortunately these data are confidential at present.

One of the most difficult problems encountered in this study was the correlation of the established lithostratigraphy with the newly defined geochemical stratigraphy. In each area examined in this study, an independent lithostratigraphic subdivision of the Klipriviersberg was established. In general, these could be related to the subdivisions of Winter (1976). In most instances, the lithological breaks could be related directly to chemical breaks. The presence of local chemical sub-units

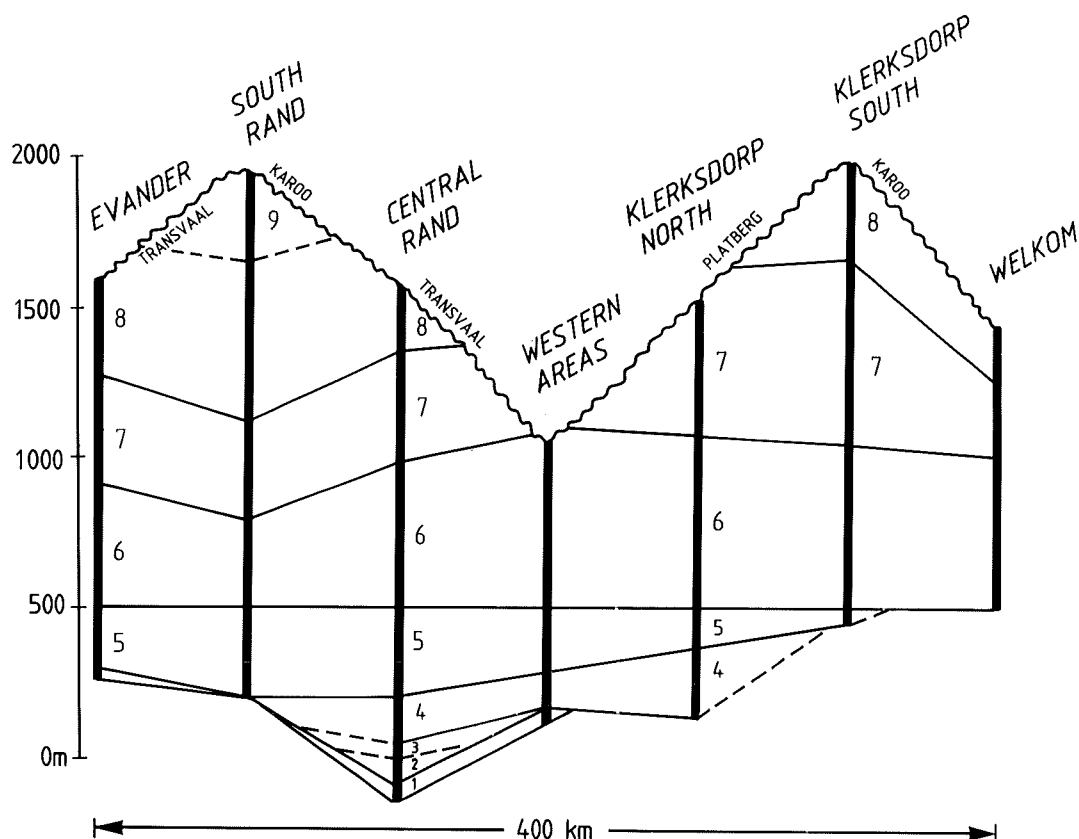


Figure 15: Fence diagram showing regional correlation of the geochemical units.

(e.g. U7 Figure 11) resulted in considerable confusion during early correlation attempts. Once the regional correlation was established it became clear that different stratigraphic names had been assigned to the same geochemical unit in different areas. The final correlation between the lithostratigraphy and the geochemical stratigraphy which the authors have adopted is shown in Figure 4.

#### X. SPATIAL DISTRIBUTION

Using regional correlation across the profiles analysed in this study it is possible to define the spatial distribution of each unit (Figure 16). Unit 1 appears to have covered a large area in the northeastern portion of the basin. Following the U1 event the areas covered by U2 and U3 retreated back to a relatively small area on the Central Rand. The area covered by U4 shows a distinct E-W orientation with the southern limits well defined at Klerksdorp and Heidelberg. The centre of eruption for U4 appears to have shifted to the west relative to U1. U5 was the first to cover the entire basin, followed by U6, U7, and U8.

From the combination of stratigraphic data and spatial distributions the minimum volume of each unit can be estimated (Table 5). The volume erupted initially as U1 was large, followed by a smaller volume in U2 and a still smaller volume in U3. Unit 4 marks the beginning of a period in which each successive unit has a greater volume than its precursor. This cycle of increasing volume continues through U6 after which the volume erupted appears to stabilize (the thickness of U8 is poorly constrained).



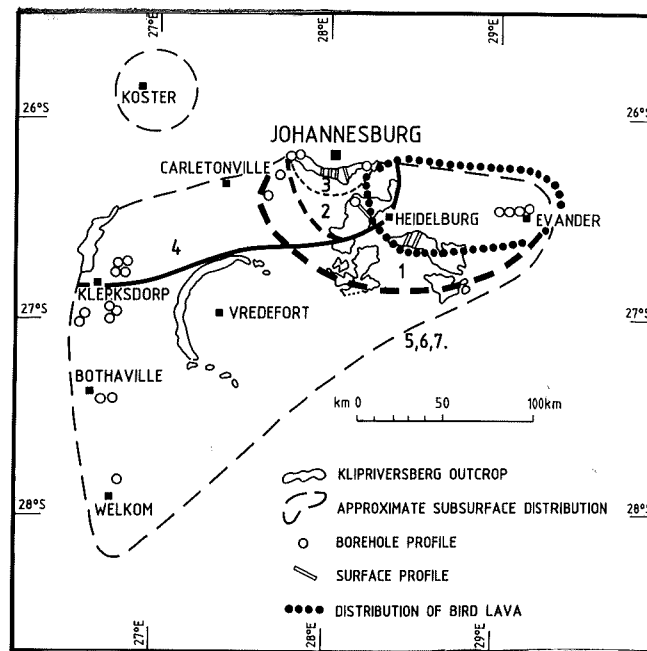


Figure 16: The regional distribution of the various geochemical units.

TABLE 5

ESTIMATED MINIMUM VOLUMES FOR EACH STRATIGRAPHIC UNIT IN THE  
KLIPRIVIERSBERG GROUP

Unit	Area (km <sup>2</sup> )	Thickness (m)	Volume (km <sup>3</sup> )
1	12000	50	600
2	2400	90	200
3	600	50	30
4	8000	170	1400
5	30000	200	6000
6	30000	480	14000
7	30000	370	11000
8	30000	400	12000
			45230 km <sup>3</sup>

## X1. DISCUSSION

The recognition of a geochemical stratigraphy which can be correlated over the entire known Klipriviersberg basin provides a potentially useful tool with a multiplicity of uses. The most important area of potential application is undoubtedly in exploration. It is now possible to establish and to monitor reliably the stratigraphic positions

of boreholes within Klipriviersberg lavas. This can be done in a fast, but approximate, manner using only the  $\text{TiO}_2$  content or more precisely using the full range of elements used in this study. For accurate application it is necessary to calibrate the method in the area where drilling is underway so that unit thicknesses can be established. Once these are known, absolute positions of core samples can be readily established. Furthermore, fault offsets involving Klipriviersberg lavas can now also be quantified, providing additional data for the solution of structural problems in the underlying Central Rand Group.

The geochemical stratigraphy is based on relative changes and because of regional, within-unit, compositional changes, absolute abundances must be used with great care. The most reliable method of application is to select several samples from known relative stratigraphic positions spanning at least 150 m. Abundance versus height plots for these samples can be compared with type profiles from the same area in order to locate the position of the samples. The most accurate positioning is obtained if the lavas sampled span a geochemical unit boundary.

The routine use of geochemistry as a stratigraphic aid requires careful sampling. The results obtained in this work were based on homogeneous samples from the centres of flows, which were free of veining, brecciation, or other visible alteration. Logically, the better the quality of the sample material the better the chance of obtaining meaningful results.

In general the element concentration changes between stratigraphic units are more than one order of magnitude greater than the single run analytical uncertainty and pose little problem for stratigraphic work. The authors found, however, that between-run calibration variations, in bad cases, may be of the same order as the between-unit geochemical variations. If this is not monitored the geochemical signature of each unit will be masked and correlation problems can arise. The between-run variations can be effectively neutralized if the data is interpreted stratigraphically, and all samples from a given profile are run on a single batch. However, the authors recommend actually correcting for the between-run variation through the use of reference samples.

The geochemical stratigraphy of the Klipriviersberg volcanics also provides exceptional opportunities for more fundamental research. It provides some insight into the mechanics of the flood basalt generation and production. The between-unit changes probably reflect large-scale events and are influenced by factors such as the depth and degree of melting, the rate of melt extraction, the residence time of the melts in intermediate level magma chambers, and the degree of mixing in such chambers (e.g. O'Hara and Matthews, 1981; Cox, 1988). The more subtle within-unit variations possibly reflect the processes involved in the extraction of the lavas from the magma chambers and their migration to the surface.

The initial event, U1, which consists of very magnesian compositions, must have erupted directly from the mantle, while later magmas, particularly up to unit U6, are much more evolved, and presumably reflect eruption from a tabular, intermediate, magma chamber in the lower crust (e.g. Cox, 1980). Chemically uniform, highly differentiated magma compositions, which erupted over areas of greater than 30000 km<sup>2</sup> (e.g. U5) indicate that the volume of the magma chamber in which evolution occurred must have been very large. The discrete nature of the compositional breaks

over such large areas indicates that a single magma chamber was involved as multiple chambers would almost certainly have produced some interfingering of compositions. It seems likely that a magma chamber of great size would be compositionally stratified (Huppert and Sparks, 1980). In such a stratified chamber, a complex set of processes involving episodic addition of new magma, periodic mixing and continual crystallization (Cox, 1988) probably produced the complex inter-relationships of chemical elements seen in the Klipriviersberg volcanics. Each pulse of surface eruption may be the response to injection of new magma into the chamber. A full discussion of this aspect of the study is beyond the scope of this paper.

The regional variations in the degree of differentiation observed in U7 and U8 may, in part, reflect differentiation *en route* to the surface from the magma chamber. This type of variation might be expected if, for instance, the magma chamber was located beneath Klerksdorp and melts were translated 280km to Evander via dykes. In this case the most differentiated liquid would probably be found farthest from the magma chamber or the main centre of eruption. Although it is possible for a lava to differentiate as it flows, the large within-unit compositional differences observed in U7 have not been reported even in the Columbia River Basalt Group where lavas are inferred to have flowed for hundred of kilometres (Mangan *et al.*, 1986). It is therefore unlikely that within-flow differentiation can explain the U7 variation. Furthermore, geochemical studies of individual flows failed to reveal any significant within-flow differentiation (Table 4). The authors infer, therefore, that the differentiation which gave rise to this variation probably occurred in the subsurface *en route* to the site of eruption.

The spatial distribution of the geochemical units indicates that the centre of eruption migrated westward with time. U1 is found only in the northeast portion of the basin. Following the initial widespread eruption of U1 the centre of eruption retracted to the Central Rand. This retraction may be related to the initial formation of the magma chamber in which later units evolved, following which widespread eruption occurred. This time, however, the centre of eruption shifted to the northwest. Because U5 and U6 cover the entire basin, the principal centre of eruption cannot be determined. However, the fact that U7 and U8 at Klerksdorp are much less differentiated than U7 and U8 in Evander and the Central Rand is consistent with the inferred movement of the eruption centre.

The spatial distribution of the Klipriviersberg geochemical units has important tectonic implications. The early eruptions took place in an E-W trending belt along the northern margin of the basin (Figure 16). Spatially, these early eruptions occurred in close proximity to that region of the basin affected by major wrench faults (Myers *et al.*, 1987; Stanistreet *et al.*, 1986) which are inferred to have been active as transpressional features during Witwatersrand time. It is significant that the distribution of the Bird lavas is almost identical to that of Unit 1 of the Klipriviersberg lavas suggesting a similar structural control. With time, the centre of eruption migrated westward and by U7 time was located on the western margin of the Witwatersrand Basin close to the principal axis of the Ventersdorp Rift. The fact that the earliest Klipriviersberg eruptions are spatially related to Central Rand Group events and the last Klipriviersberg eruptions are spatially related to Platberg events suggests that the Klipriviersberg was erupted during and possibly as a response to the transition from Witwatersrand-style tectonics to Platberg-style tectonics. The possible causes and implications of this change are discussed at length elsewhere (Myers *et al.*, 1989; McCarthy *et al.*, 1989).

## X11. CONCLUSIONS

This study, which has involved the collection, documentation, and careful analysis of thousands of samples of lavas, has revealed that a regular, correlatable, geochemical stratigraphy exists within the Klipriviersberg Group which can be traced over 400km of strike. This stratigraphy offers a useful tool in exploration in that detailed, accurate, stratigraphic analysis in these otherwise homogeneous lavas is now possible. With reasonable care in sampling and analysis, reliable results can be obtained quickly and cheaply.

The eruption of the Klipriviersberg flood basalts appears to have been controlled by episodic melt generation, with melts undergoing extensive differentiation in a large laterally homogeneous, but possibly stratified magma chamber. The model favoured to explain the cause and effect relationship of the eruptive cycles is one in which old differentiated liquid is pushed out of the magma chamber by new injections of melt. The detection of significant regional variations in composition and structure within a given stratigraphic unit indicates that the lavas in each area were erupted from local centres.

The positions of the earliest Klipriviersberg eruptions coincide with major Witwatersrand-age wrench faults (Stanistreet *et al.*, 1986) rather than the position of the Ventersdorp rift axis. However, the eruptive centres migrated to the west with time to reach near coincidence with the position of the rift. The flood basalts therefore appear to have developed during the transition from regional compression to craton-scale rifting.

This paper emphasizes the more practical aspects of the study. However, it is clear that the database created offers the opportunity to elucidate details of the mechanisms of generation and emplacement of this important flood basalt assemblage.

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