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THE USE OF DISCRIMINANT FUNCTION ANALYSIS FOR THE STRATIGRAPHIC CLASSIFICATION OF KLIPRIVIERSBERG GROUP AND ALLANRIDGE FORMATION SAMPLES

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by

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August, 1992

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ABSTRACT

The Klipriviersberg Group and Allanridge Formation volcanics are frequently encountered during exploration for the reefs of the Witwatersrand Supergroup. The generally uniform and similar appearances of these volcanics makes identification difficult, yet it is vitally important to be able to distinguish between the two units, and to establish stratigraphic position within the Klipriviersberg Group.

A geochemical stratigraphy exists within the Klipriviersberg Group but its application requires analyses of many samples in stratigraphic order. A technique has been developed for the stratigraphic classification of single Klipriviersberg Group volcanic samples. The technique has also been extended to include the Allanridge Formation.

Using data for the Klipriviersberg Group on the Central Rand, where a complete succession of eight geochemical units is encountered, discriminant function analysis was employed to discriminate between the geochemical units. It was found that a combination of TiO_2, Y and Zr is the most effective for discrimination. The two functions derived are:

$$\text{Function 1} = 15.1483 \times TiO_2 - 0.12907 \times Y - 0.01643 \times Zr - 11.9865$$

$$\text{Function 2} = -9.60491 \times TiO_2 - 0.14676 \times Y + 0.14589 \times Zr - 4.43084$$

Data for profiles from the Klerksdorp South and Evander areas were used in order to define the field boundaries, and the accuracy of the technique was then tested using data from stratigraphically subdivided profiles from across the entire extent of the Witwatersrand Basin, which were treated as unknowns. It was found that the accuracy of the technique varies between 81.5 and 96%. Systematic and random misclassifications occur, of which the systematic account for $\pm$70%. The numerically most important systematic misclassification between Unit 1 and Units 6 and 7 can be corrected for, and when this was done the accuracy of the technique was increased to $>$87.1% in all cases.

Seventy five Allanridge Formation samples were similarly tested, and virtually no overlap between the Klipriviersberg Group and the Allanridge Formation was observed. The discriminant function analysis can be supplemented by a Cr-Zr plot to further enhance the discrimination between these suites.

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

ISBN 1 86838 026 2

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INTRODUCTION

The lavas of the Klipriviersberg Group overlie extensive areas of the Central Rand Group sediments. Due to their proximity to the gold-bearing reefs, the lavas have been subjected to a number of stratigraphic studies over the years. These studies have been based either on lithological criteria (e.g. Matthysen, 1953; Pienaar, 1956; Winter, 1965, 1976), or on the chemistry of the lavas (eg. Palmer *et al.*, 1986; Bowen *et al.*, 1986; Myers *et al.*, 1990). It has been shown that a lithostratigraphy for the Klipriviersberg Group is prone to misinterpretation, and moreover does not allow for long-range correlation (Linton *et al.*, 1990). In contrast, the geochemical stratigraphy appears to have potential for solving exploration-related stratigraphic and structural problems as it can be easily applied, and is consistent over the entire extent of the Witwatersrand Basin.

Palmer *et al.* (1986) and Bowen *et al.* (1986) used binary plots to erect a geochemical stratigraphy for the Klipriviersberg Group. On these plots, the different geochemical units define discrete fields. These plots are based on the absolute values of indicator elements, and are thus susceptible to any factors which may cause variations in the absolute values (eg. fractionation, analytical uncertainty). Myers *et al.* (1990) chose to plot their indicators against stratigraphic height, which has the effect of emphasising relative differences in the values of the indicators, as the patterns produced on these plots rather than the absolute values of the indicators, are important. Myers *et al.* (1990) showed that a combination of TiO_2, V, Cr and the Ti/Zr ratio provides the most effective method for defining a geochemical stratigraphy. On the basis of these indicators, they were able to distinguish eight definite geochemical units, and indicated that a further two units may occur at the top of the sequence. These two units were not shown on any of their profiles, however, and so for the purposes of this study have been ignored.

Two basic uses are envisaged for the geochemical stratigraphy. The first is to estimate depth to reef during exploration drilling thus permitting earlier decision making regarding the continuation of the hole. The second basic use is in solving structural problems such as stratigraphic duplication due to reverse faulting or folding, and stratigraphic loss due to normal faulting.

In cases where long intersections are available, the geochemical stratigraphy can be applied directly by constructing stratigraphic height plots of TiO_2, V, Cr and Ti/Zr. There is, however, no method at present for the stratigraphic classification of single samples. This becomes especially important if sampling does not intersect a geochemical break, or where budgetary constraints limit the amount of sampling possible. From an academic standpoint, it would also be useful to be able to classify samples where no stratigraphic control exists (e.g. from dykes or pebbles in later sediments), into their correct stratigraphic unit. The writers therefore set out to establish a technique for single sample classification.

It was considered desirable to include the Allanridge Formation volcanics of the Ventersdorp Supergroup in the classification scheme because they resemble the Klipriviersberg Group lavas macroscopically and can, superficially, appear similar on chemical grounds as well. The ability to distinguish between them is vital in exploration.

Bowen (1984) showed that Discriminant Function Analysis (DFA) could be successfully applied to stratigraphic classification of samples within the volcanics of the Witwatersrand Triad. It was thus decided to use DFA to attempt to construct a method for classifying samples within the Klipriviersberg Group and the Allanridge Formation. Although DFA provides essentially a binary plot, the shortcomings of the binary plot technique are reduced considerably as discriminant function analysis is a multivariate technique, and the increased number of variables provides tighter constraint on the position of the fields. However, radical changes in the concentrations of the variables can produce appreciable field shifts.

DISCRIMINANT FUNCTION ANALYSIS (DFA)

Discriminant function analysis is a non-parametric multivariate statistical technique which performs two basic functions:

1. to discriminate between groups of observations on the basis of a number of variables, and

2. to classify observations and unkown samples into the correct group on the basis of the variables used to define the discriminant functions.

DFA weights and combines variables into a linear equation that forces groups of observations to be as different as possible. The general form of the equation is :

$$D_i = c_{i1}v_1 + c_{i2}v_2 + \ldots.. + c_{ip}v_p + N$$

where: D_i is the value of the i^{th} discriminant function

c_i are the coefficients of the variables for the i^{th} discriminant function

v_p are the values of p discriminating variables

N is a numeric constant

DFA discriminates between groups of observations in multi-dimensional space on the basis of the variables used. It does this by locating the centres of the ellipsoids formed by the groups in multi-dimensional space, and then comparing the distances between them. The coefficients are calculated so that the distances between the ellipsoid centres are maximised. Initially, a data set for which the groupings are known is used to define the discriminant functions. All the varaibles within the data set may be used for DFA, or the variables may be selected according to the degree of variation they display between groups. DFA generates either as many functions as there are groups, or one less function than the number of variables, depending on which is the smaller number. The discriminatory power and significance of the discriminant functions are expressed by means of a number of statistics pertaining to the functions. Details of the statistics of the discriminant function are not given here, and the reader is referred to Koch and Link (1971).

In order to employ the discriminant functions for the classification of unknown samples, the simplest method is to select the two most powerful discriminant functions and to plot the results generated in the form of a binary plot. Individual groups define fields on the plot, but as the field boundaries are not defined by DFA, they must be selected by inspection. Once the field boundaries have been selected, the values of the variables in the unknown samples can be substituted into the discriminant functions, and plotted. The classification of each sample can thus be effected depending on the field in which it plots.

APPLICATION OF DFA TO THE KLIPRIVIERSBERG GROUP

Central Rand Profile

In order to define the discriminant functions, the Central Rand profile of Myers *et al.* (1990) has been chosen as it contains all eight geochemical units, as opposed to profiles from other areas which contain a maximum of five units. The geochemical stratigraphy of the Klipriviersberg Group on the Central Rand is shown in Fig. 1.

The selection of the variables for DFA is limited by a number of factors. The Klipriviersberg Group suffered a post-eruption alteration event during which many elements were redistributed. Transition elements, and in particular the High Field Strength group, appear not to have been affected by this process. However, Myers *et al.* (1990) showed that fractionation has produced strong regional variations in the concentrations of the compatible elements (MgO, Cr and Ni) in Units 7 and 8. As mentioned earlier, radical shifts in the concentration of variables will add uncertainty to DFA. The incompatible HFS elements TiO_2, P_2O_5, Y and Zr thus appear to offer the best possibilities.

After examining all possible combinations of the four incompatible elements, it became clear that a combination of TiO_2, Y and Zr provided the most effective discrimination between units. The two functions defined are:

$$Fn1 = 15.1483 \times TiO_2 - 0.12907 \times Y - 0.01643 \times Zr - 11.9865$$

$$Fn2 = -9.60491 \times TiO_2 - 0.14676 \times Y + 0.14589 \times Zr - 4.43084$$

Figure 2 shows a plot of discriminant function 1 vs. discriminant function 2 for the Central Rand. In general, the units are well separated on the plot. The only exception to this are two Unit 4 samples that plot amongst the Unit 5 samples, and one Unit 6 sample that plots amongst the Unit 7 samples. This amounts to three misclassified samples out of a total of sixty-two. The sample population is not sufficiently large for the field boundaries to be accurately drawn, however.

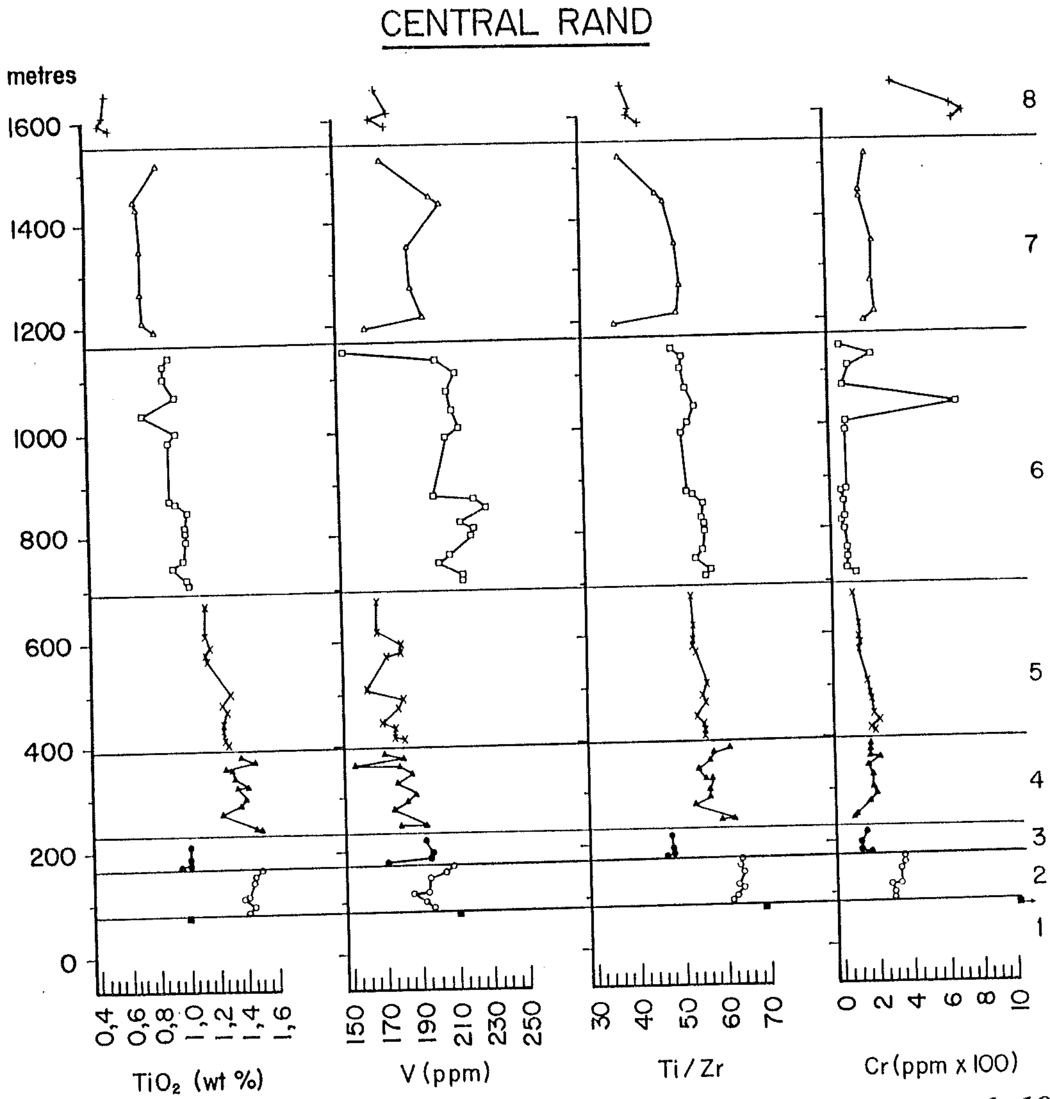

Figure 1: Stratigraphic height plot for the Central Rand profile (after Myers et al., 1990).

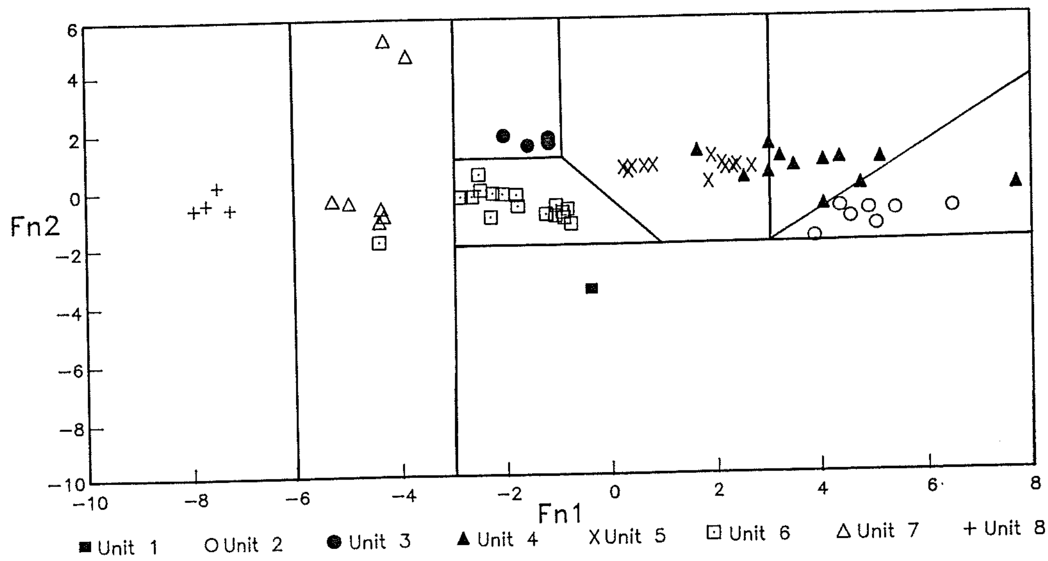

Figure 2: Discriminant function plot for the Central Rand profile.

Evander and Klerksdorp South Profiles

In order to define the field boundaries, two areas with large sample densities have been chosen, viz. Klerksdorp South (83 samples) and Evander (168 samples). These two areas are also useful in that Unit 7 and 8 compositions are highly primitive in the Klerksdorp area, and evolved in the Evander area (Myers *et al.*, 1990), and hence the effects of fractionation will be included. The stratigraphic plots of profiles from Evander and Klerksdorp South are shown in Figs. 3 and 4. It can be seen that in the Evander profile Units 2, 3 and 4 are absent, while in the Klerksdorp South profile Units 1, 2, 3 and 4 are absent. In addition to the profile from Evander shown, data from a further three profiles in the area (R. Myers, 1990) have been incorporated into the DFA.

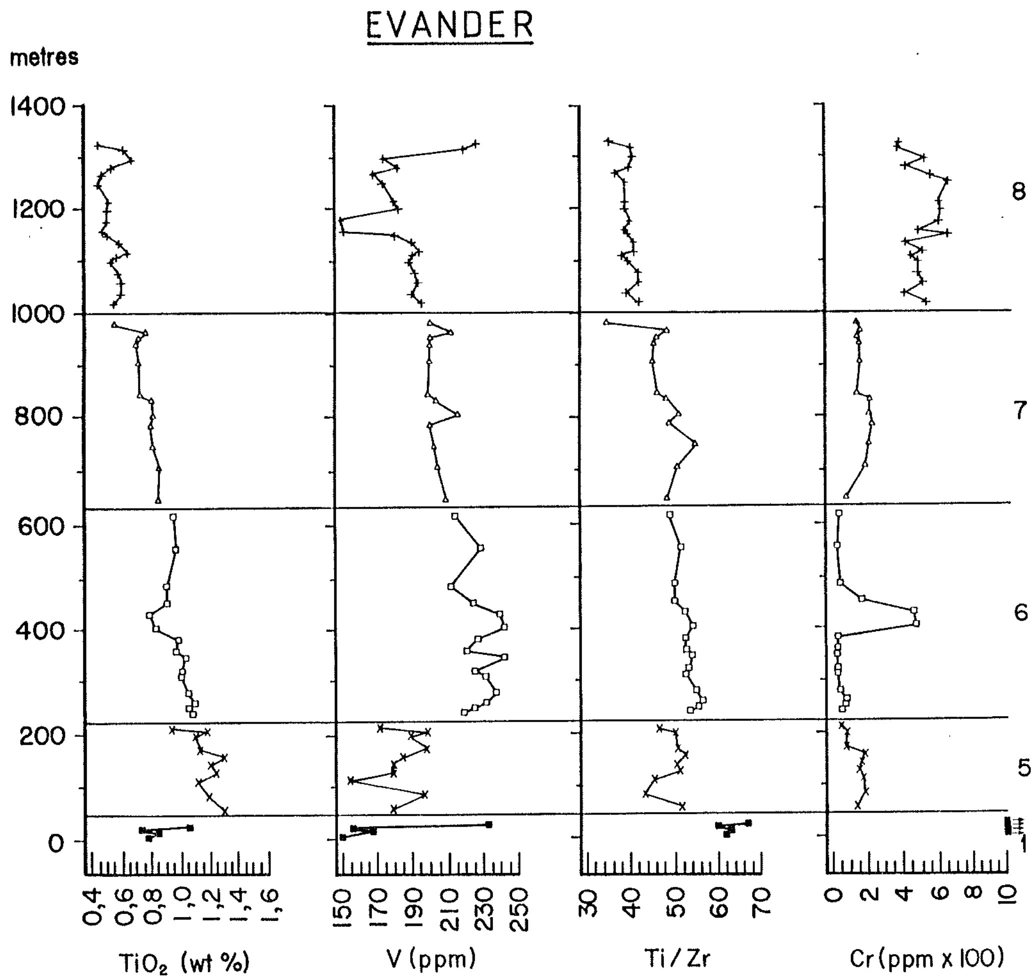

Figure 3: Stratigraphic height plot for an Evander profile (after Myers et al., 1990).

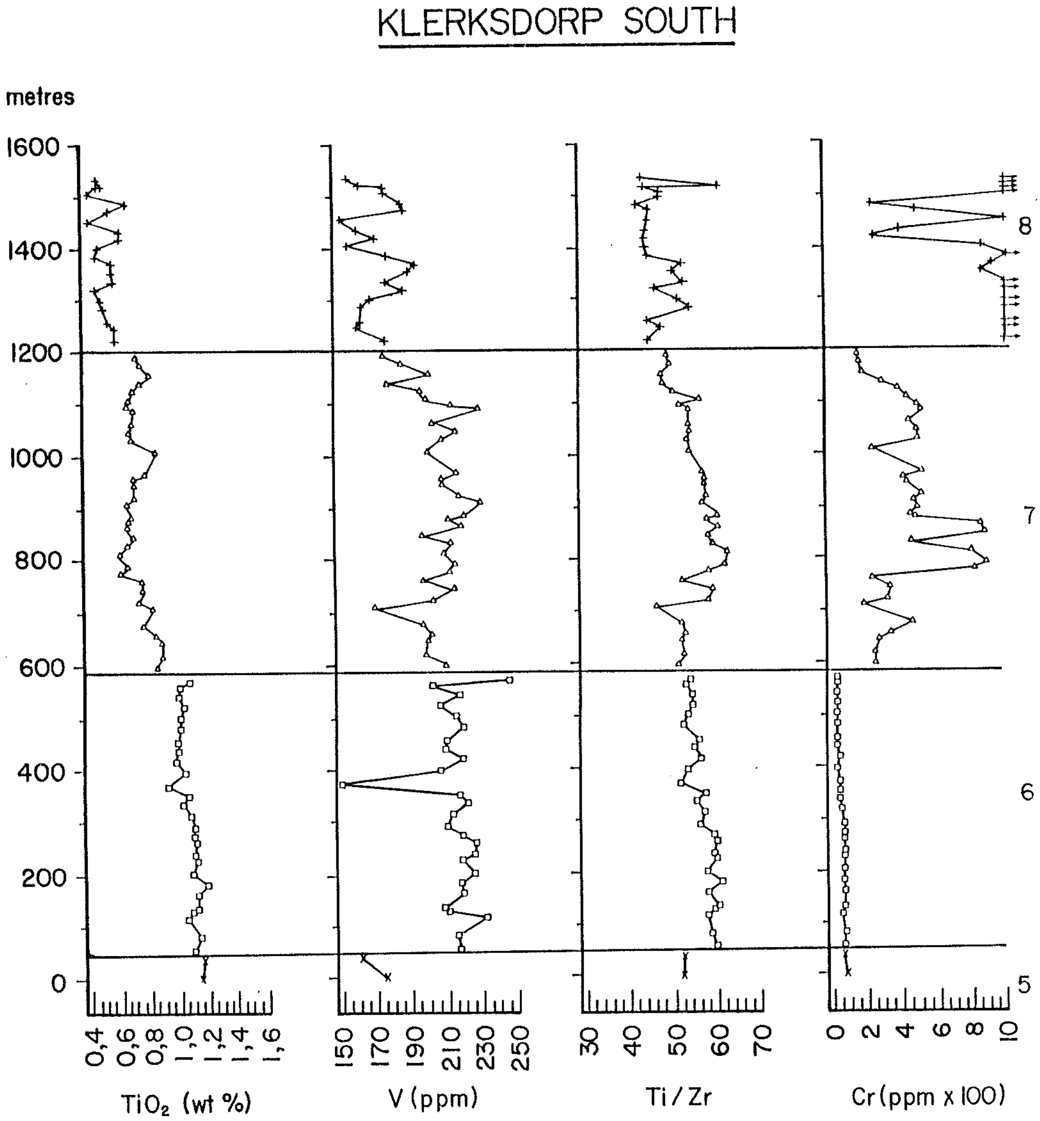

Figure 4: Stratigraphic height plot for the Klerksdorp South profile (after Myers et al., 1990).

The plots of discriminant function 1 vs. discriminant function 2 for the two areas are shown in Figs. 5 and 6. On the plot for Evander (Fig. 5), there are a number of misclassifications evident; however, except for the slight overlap between Units 5 and 6, and the six Unit 6 samples which plot with the Unit 7 samples, there are no systematic misclassifications, and only isolated samples plot incorrectly. On the plot for Klerksdorp South (Fig. 6), the separation between the units is good.

Taking all three plots in conjunction, the sample population is sufficiently large to draw in the field boundaries. This has been done in a manner that minimises the degree of misclassification. The resulting plot is shown in Fig. 7. By applying the field boundaries to the Central Rand, Evander, and Klerksdorp South plots, the degree of misclassification

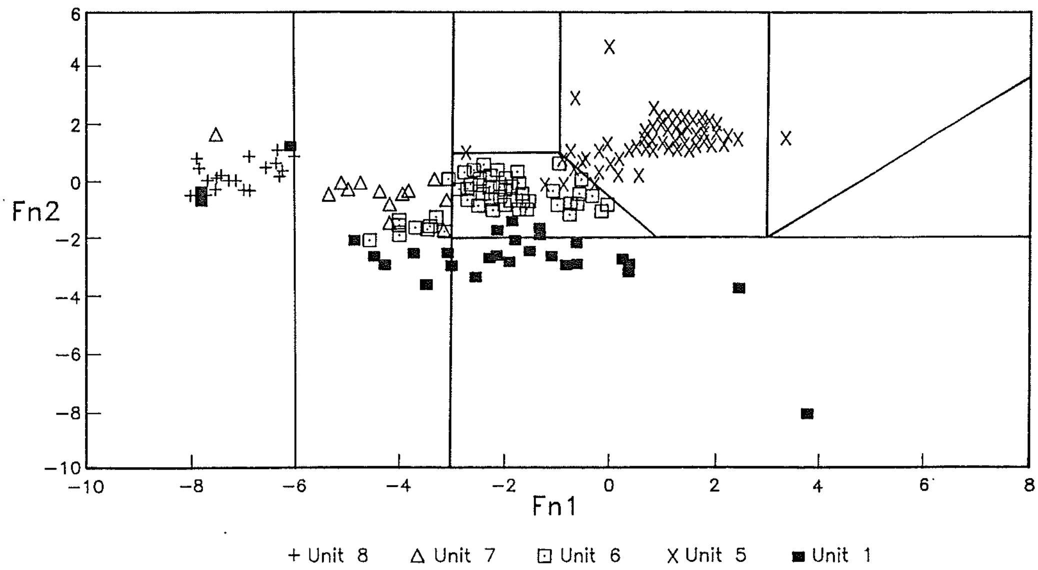

Figure 5: Discriminant function plot for the Evander profiles.

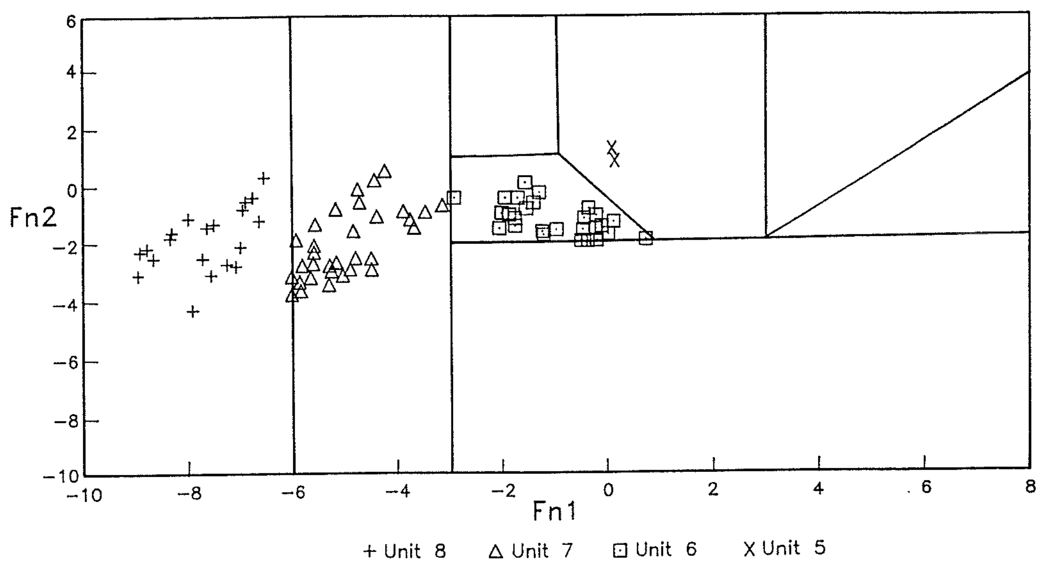

Figure 6: Discriminant function plot for the Klerksdorp South profile.

be quantified. The results are shown in Table 1. It can be seen that although the separation of units in the Klerksdorp South profile is good, the construction of the field boundaries results in two Unit 7 samples that plot in the Unit 8 field. However, if the field boundary were chosen so as to remove these misclassifications, a number of Unit 8 samples in the Evander profiles would be misclassified. The overall accuracy for the Klerksdorp South profile is 96%. In the Evander profiles, there are a number of Unit 1 samples that plot in the

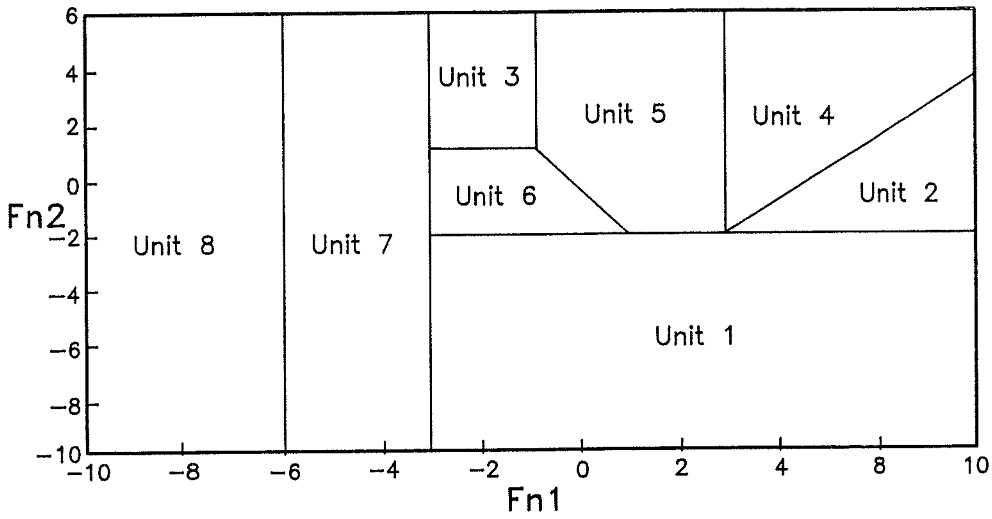

Figure 7: Discriminant function plot for the Klipriviersberg Group.

Unit 6 and Unit 7 fields. The overall accuracy for these profiles is relatively low at 81.5%. The Central Rand profile remains unchanged, and the accuracy is 94.5%.

DFA Tested on Other Profiles

In order to assess the accuracy of the DFA, data for the South Rand (two profiles) (Spencer, 1992), Klerksdorp North (three profiles) (J. Myers, 1990), Carletonville (two profiles) (Quadling, 1991), Welkom (one profile), and Edenville (one profile) areas have been used. These profiles have been selected so as to supply cover across the entire Witwatersrand Basin. These profiles were first stratigraphically subdivided according to the method of Myers *et al.* (1990), and the data were then plotted onto discriminant function plots. The results are shown in Fig. 8 (a-e).

Using the field boundaries, it is possible to quantify the accuracy of the technique. Table 1 shows the number of samples correctly classified in each unit in each profile relative to the total number of samples in each case. From Table 1, it can be seen that the accuracy is generally very good. The lowest accuracy occurs in the Welkom and South Rand profiles (less than 83%), while the others are all above 90%. In the case of the Welkom and South Rand profiles, the problem is a systematic misclassification of Unit 6 samples which fall into the Unit 1 field. As mentioned earlier, the Evander profile also has a low accuracy (81.5%), and in this case it is due to a systematic misclassification of Unit 1 samples which plot in the Unit 6 and Unit 7 fields. The other overlaps that may occur are between Units 2 and 4 in the Klerksdorp North profile, and Units 7 and 8 in the Edenville profile.

Discussion on Misclassifications

In many cases, misclassifications are not systematic, and isolated samples are misclassified. Petrographically, these samples are no different to other samples from the

Table 1: Number of correctly classified samples relative to the total number of samples in each geochemical unit in each of the areas studied

AREA	GEOCHEMICAL UNIT									
	U1	U2	U3	U4	U5	U6	U7	U8	Total	%
Central Rand	1/1	7/7	3/3	9/12	12/12	16/17	6/6	4/4	58/62	93.6
Evander	15/27	-	-	-	47/57	44/52	12/13	19/19	137/168	81.6
Klerksdorp South	-	-	-	-	2/2	28/29	30/32	20/20	80/83	96.4
South Rand	-	-	-	3/3	6/7	7/18	11/11	39/42	66/81	81.5
Carletonville	-	-	-	5/5	35/41	30/31	9/9	-	79/86	91.9
Klerksdorp North	-	-	-	20/26	22/24	39/41	36/39	-	117/130	90.0
Edenville	-	-	-	-	11/12	13/13	14/17	-	38/42	90.5
Welkom	-	-	-	-	-	16/22	9/10	4/4	29/36	80.6
Total	16/28	7/7	3/3	37/46	136/156	193/223	127/137	86/89	605/689	87.8

Klipriviersberg Group, and thus cannot be simply dismissed as dykes. It is more likely that these samples either represent zones of intense alteration in which TiO_2, Y and Zr abundances have been changed; or may be related to faulting which is often difficult to distinguish unequivocally.

Some isolated misclassifications can be explained. The Unit 6 sample that plots in the Unit 7 field on the Central Rand diagram is enriched in compatible elements and depleted in incompatible elements relative to other Unit 6 samples. The flow that this sample comes from is easily recognisable on the stratigraphic plot (Fig. 1), and can be traced as far west as Vredefort. This flow is misclassified on the Central Rand and Carletonville plots (Fig. 2 and Fig. 8(b). Myers *et al.* (1990) recognised this flow but did not advance any reasons for its unusual chemistry relative to the surrounding flows.

Systematic misclassifications are highly significant in that they account for $\pm$70% of all misclassified samples. On all the plots, Units 7 and 8 are well separated. As discussed earlier, with the construction of the field boundary, some misclassification has resulted since, as anticipated, the effects of fractionation have caused the positions of the Unit 7 and 8 samples to shift slightly on a regional basis. In the case of the Klerksdorp South and Edenville profiles, the boundary could be drawn at -6.25 on the x-axis, while in the case of the South Rand profile the boundary could be drawn at -5.5. The extent of the problem can be minimised if this shift is anticipated.

In the Klerksdorp North profile, a number of Unit 4 samples plot in the Unit 2 field. The distribution of Unit 2 is highly restricted, and it occurs only on the Central Rand (Myers *et al.* 1990). Thus any sample plotting in the Unit 2 field from areas beyond the Central Rand will probably be from Unit 4. There is also slight overlap between Units 4 and 5, and Units 5 and 6. The stratigraphic error introduced by this is minor, however.

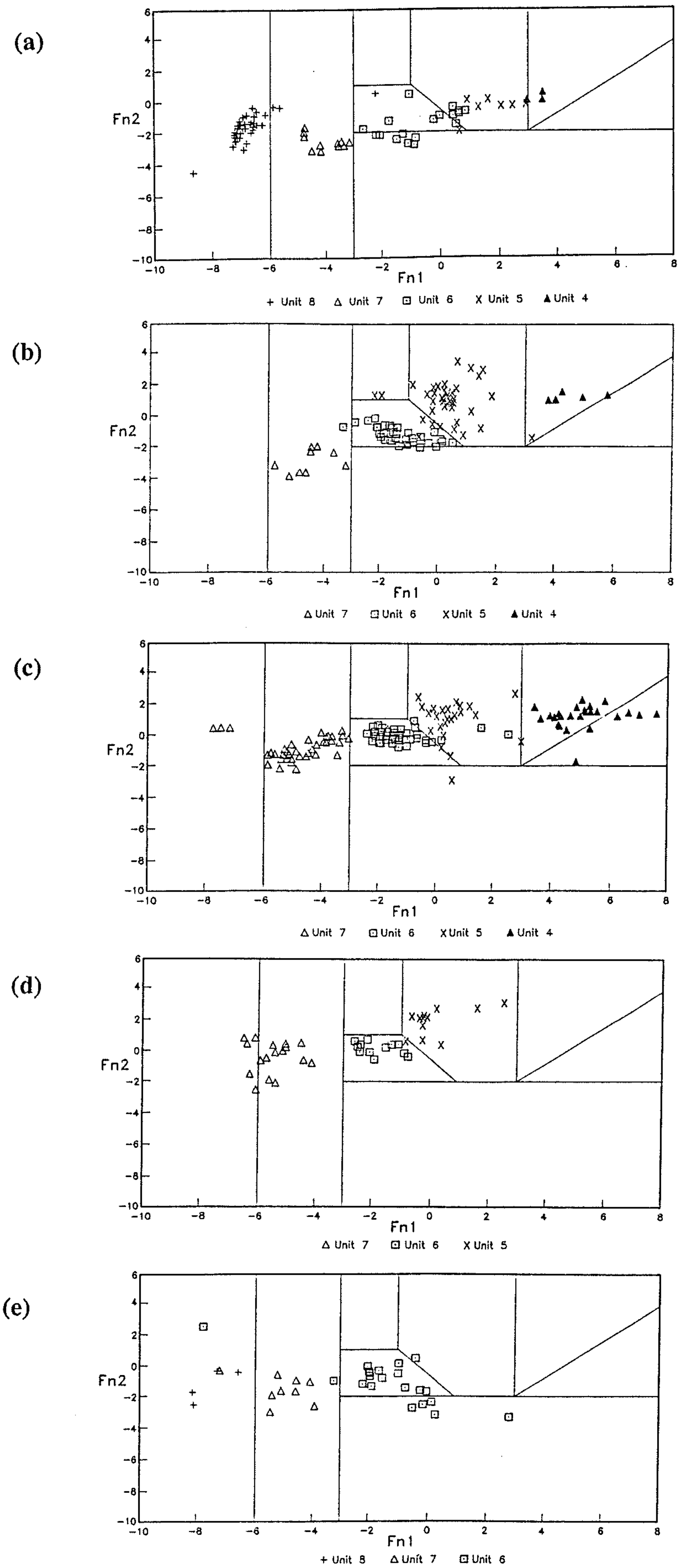

Figure 8: Discriminant function plots for profiles from the South Rand (a), Carletonville (b), Klerksdorp North (c), Edenville (d), and Welkom (e).

The source of the bulk of the misclassifications is provided by Unit 1. In the Evander profiles, several Unit 1 samples plot in the Units 6 and 7 fields. In the South Rand and Welkom profiles, a number of Unit 6 samples plot in the Unit 1 field. This can be overcome by employing the Ni and Cr contents of the sample. Samples from Unit 1 (which is correlatable with the komatiitic Westonaria Formation) have >1500ppm Cr and >1000ppm Ni. In contrast, the Cr content of Unit 7 samples is generally 200-600ppm, and that for Unit 6 samples is <100ppm, while the Ni contents are 150-300ppm and 100-150ppm respectively.

If this additional screening criterion is applied to the data set, the effects of this misclassification are removed. This results in a further seven Unit 6 samples being correctly classified in the South Rand profiles, and similarly a further four Unit 6 samples in the Welkom profile. This raises the accuracy for these areas to 91% and 93.5% respectively. In the case of the Evander profiles, the Unit 1 samples can effectively be removed from the DFA., which results in the accuracy increasing to 87.1%.

ALLANRIDGE FORMATION

The Allanridge Formation forms the uppermost unit of the Ventersdorp Supergroup. Generally, it is possible to distinguish between the Allanridge and Klipriviersberg lavas on the basis of stratigraphic position. However, in certain cases, there may be no stratigraphic control, and it may be difficult to separate the two lava sequences, particularly as they are texturally similar. Cases could include highly faulted areas, or areas to the north of the Witwatersrand Basin where Allanridge lava is observed resting on conglomerates of the Bothaville Formation, which in turn rest on basement. In this case, it is particularly important to resolve whether the sequence represents the Bothaville and Allanridge Formations, or whether it represents the Ventersdorp Contact Reef and Klipriviersberg Group.

Bowen *et al.* (1986) showed that the Klipriviersberg and Allanridge lavas could be discriminated between using a Zr/P-P/Ti plot. It is important however, that the D.F.A defined in this study should also be able to discriminate between the two lava sequences. For this purpose, a total of seventy-five Allanridge Formation samples were tested using the DFA. These samples were drawn from the work of Bowen (1984) and Falatsa (1988).

Figure 9 shows the Allanridge Formation samples plotted on a discriminant function plot. On the plots for the Klipriviersberg Group, only one Unit 5 sample in the Evander profile has a value for function 2 of greater than 4. By contrast, only two Allanridge samples have a value for discriminant function 2 of less than four, and so a boundary between the two lava suites can be drawn at this point. A further test can be made using a Cr-Zr binary plot (Figure 10). On this diagram, the Allanridge samples are compared to samples from Units 2 to 6 (which display similarly evolved compositions to the Allanridge Formation) for profiles along the northern margin of the Witwatersrand Basin. From this plot it can be seen that the Allanridge Formation has much higher Zr concentrations than the Klipriviersberg Group, except for a few samples which overlap. There should be no confusion on this plot with the other mafic volcanics in the Ventersdorp Supergroup, viz. the Rietgat and Goedgenoeg lavas, as they invariably have >200ppm and often >300ppm Zr. This plot should never be used alone for the reasons discussed earlier, but must be used in conjunction

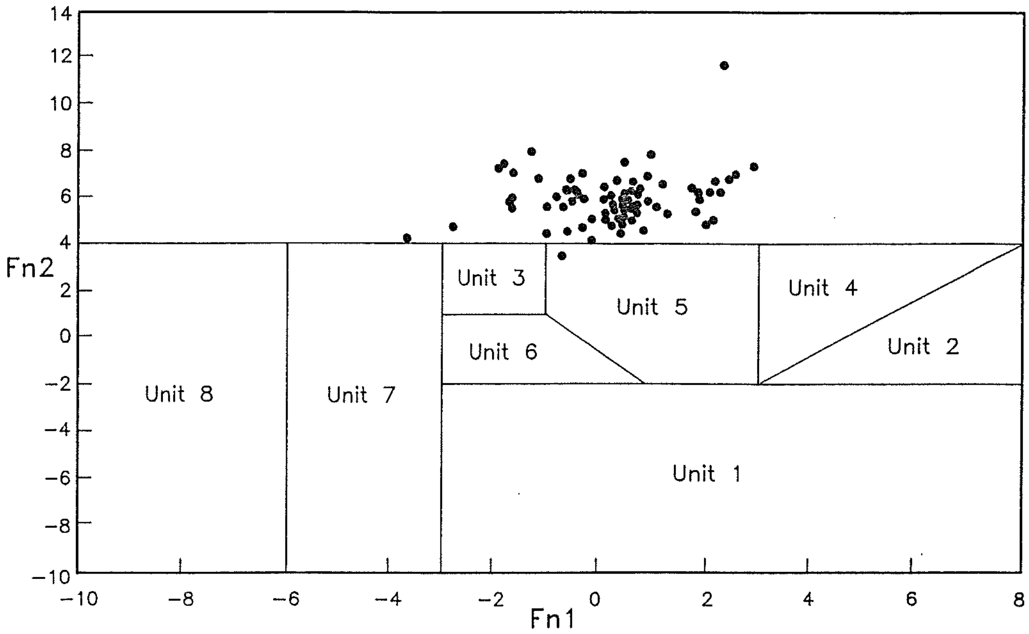

Figure 9: Discriminant function plot for the Allanridge Formation.

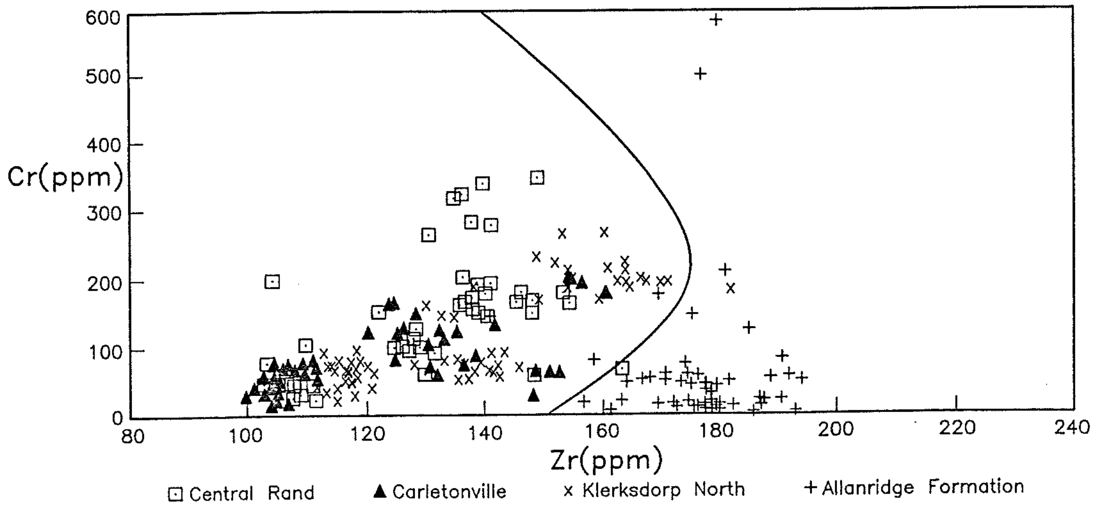

Figure 10: Zr-Cr plot showing the difference between the Allanridge Formation and Units 2 to 6 of the Klipriviersberg Group.

with the discriminant function plot.

CONCLUSIONS

DFA provides a useful tool for the stratigraphic classification of Klipriviersberg Group samples, and is especially useful in cases where no stratigraphic control exists. Caution must be exercised, however, as misclassifications do occur. The bulk of the misclassifications are systematic. The actual stratigraphic error introduced by the overlap between Units 4 and 5, and Units 5 and 6 is small, and thus not critical. By selecting a reasonably sized sample population this error will be overcome to a large extent. In cases where samples from outside the Central Rand plot in the Unit 2 field, these samples will probably belong to Unit 4. The overlap between Unit 1 and Units 6 and 7 is easily overcome by simply studying the Cr and Ni contents of the samples concerned. Due to the effects of fractionation, the boundary between Units 7 and 8 shifts slightly on a regional scale. The accuracy of the technique is at least 81.5%, but this lower level is raised to 87.1% when the overlap between Unit 1 and Units 6 and 7 is corrected for. Discriminant function analysis is extremely efficient for distinguishing between the Klipriviersberg Group and the Allanridge Formation, and if used in conjunction with a Cr-Zr plot, and the Zr/P - Ti/Y plot of Bowen et al. (1986), discrimination between the two suites will be extremely good.

ACKNOWLEDGEMENTS

Funding for this work was provided by the Foundation for Research and Development. Technical support from Lyn Whitfield, Di du Toit and Nellie Day is gratefully acknowledged.

REFERENCES

Bowen, T.B. (1984). *The geochemical stratigraphy of the volcanic rocks of the Witwatersrand Triad in the Klerksdorp area, Transvaal.* M.Sc thesis (unpubl.), Rhodes Univ., Grahamstown.

Bowen, T.B., Marsh J.S, Bowen M.P. and Eales, H.V. (1986). Volcanic rocks of the Witwatersrand Triad, South Africa. I: Description, classification and geochemical stratigraphy. *Precambrian. Res.*, **31**, 297-324.

Falatsa T.M. (1988). *The geochemical stratigraphy of the Allanridge Formation (Pniel Group) and the Klipriviersberg Group volcanics south-west of Klerksdorp.* Hons. thesis (unpubl.), Univ. Witwatersrand, Johannesburg.

Koch, G.S. and Link, R.F. (1971). *Statistical Analysis of Geological Data, Vol. II.* John Wiley and Sons, New York, 438pp.

Linton, P.L., McCarthy, T.S. and Myers, R.E. (1990). A geochemical reappraisal of the stratigraphy of the Klipriviersberg Group in the type borehole LL1 in the Bothaville area. *S. Afr. J. Geol.*, **93**, 239-244.

Matthysen, J.L. (1953). *'n Nuwe stratigrafiese indeeling van die Ventersdorp-Sisteem.* M.Sc thesis (unpubl.), Univ. Pretoria.

Myers. J.M. (1990). *The stratigraphy and geochemistry of the Klipriviersberg and Platberg Groups of the Ventersdorp Supergroup in the Klerksdorp area, Western Transvaal.* M.Sc thesis (unpubl.), Univ. Witwatersrand, Johannesburg.

Myers, R.E. (1990). *The geology of the Godwan Basin, eastern Transvaal.* Ph.D thesis (unpubl.), Univ. Witwatersrand, Johannesburg.

Myers, R.E., McCarthy, T.S., Bunyard, M., Cawthorn, R.G., Falatsa, T.M., Hewitt, T., Linton, P., Myers, J.M., Palmer, K.J. and Spencer, R. (1990). Geochemical stratigraphy of the Klipriviersberg Group volcanic rocks. *S. Afr. J. Geol.*, **93**, 224-238.

Palmer, K.J., Spencer, R.M., Hewitt, T. and McCarthy, T.S. (1986). The geochemical stratigraphy of the Klipriviersberg lavas as a stratigraphic guide in the Witwatersrand Basin. *Abstr. Geocongr. '86*, Geol. Soc. S. Afr., Johannesburg, 171-174.

Pienaar, P.J. (1956). *Stratigraphy and petrography of the Ventersdorp System in the Orange Free State Goldfield.* M.Sc thesis (unpubl.), Queens Univ., Kingston, Ontario, Canada.

Quadling, K. (1991). *Geochemical stratigraphy of the Klipriviersberg Lavas in the Western Deep Levels area.* Hons. thesis (unpubl.), Univ. Witwatersrand, Johannesburg.

Spencer, R. (1992). *Late Archaean tectonics and sedimentation of the South Rand area, Witwatersrand Basin.* Ph.D thesis (unpubl.), Univ. Witwatersrand, Johannesburg.

Winter, H. de la R. (1965). *The stratigraphy of the Ventersdorp System in the Bothaville district and adjoining areas.* Ph.D thesis (unpubl.), Univ. Witwatersrand, Johannesburg.

Winter, H. de la R. (1976). A lithostratigraphic classification of the Ventersdorp Succession. *Trans. geol. Soc. S. Afr.*, **79**, 31-48.

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