

**ECONOMIC GEOLOGY  
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**GEOCHEMISTRY AND METAMORPHIC  
PETROLOGY OF DOMINION GROUP  
METAVOLCANICS IN THE VREDEFORT AREA,  
SOUTH AFRICA**

**M.C. JACKSON**

**INFORMATION CIRCULAR No. 256**

UNIVERSITY OF THE WITWATERSRAND  
JOHANNESBURG

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DOMINION GROUP METAVOLCANICS IN THE VREDEFORT AREA,  
SOUTH AFRICA**

by

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## **ABSTRACT**

A thin sequence of amygdaloidal mafic metavolcanics occurs as the basal supracrustal unit above the Outer Granite Gneiss in the circular collar of the Vredefort Dome structure, South Africa. These volcanics have been correlated with the Dominion Group, a supracrustal assemblage underlying the Witwatersrand Supergroup, since the 1930's (Nel, 1934). Recent petrographic and geochemical studies confirm this correlation, specifically identifying the Vredefort "basal amygdaloid" with the middle mafic volcanic unit, the Rhenosterhoek Formation, of the Dominion Group in the type area near Klerksdorp. The Dominion Group appears to pinch out in the northeastern part of the Vredefort Dome, this and the lack of clastic sedimentary and felsic volcanic units, present in the type area, are consistent with a distal environment of deposition. The geochemistry of the bulk of the mafic lavas in the Vredefort area is similar to the more primitive Dominion Group mafic lavas found in the type area in their high compatible and low incompatible trace element contents. However, they have lower alkali and higher CaO contents. These geochemical differences are attributed to the higher metamorphic grade implying different alteration histories. The hornblende + quartz + Ca-plagioclase + FeTi oxide metamorphic mineral assemblage implies higher temperature burial metamorphism for the Vredefort-area amphibolites compared to Klerksdorp-area greenschist facies metavolcanics.

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# **GEOCHEMISTRY AND METAMORPHIC PETROLOGY OF DOMINION GROUP META VOLCANICS IN THE VREDEFORT AREA, SOUTH AFRICA**

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# GEOCHEMISTRY AND METAMORPHIC PETROLOGY OF DOMINION GROUP VOLCANICS IN THE VREDEFORT AREA, SOUTH AFRICA

## INTRODUCTION

In the annular collar of the dome-shaped Vredefort structure, in the southern Transvaal and northern Orange Free State Provinces, South Africa, dark grey, amygdaloidal, metavolcanic amphibolite comprises the basal unit of the Archaean supracrustal sequence unconformably overlying granitoid basement in the core of the structure (Figure 1). A thin, but widespread, unit in the collar, the amphibolite provides information on the nature of the eastern extent of the Dominion Group, conditions preceding deposition of the overlying economically important Witwatersrand Supergroup, and metamorphic conditions at the centre of the Witwatersrand Basin, as well as information relating to the Vredefort structural event.

### **Dominion Group**

A recent review of the Dominion Group was provided by Jackson (1991). Initially considered the basal unit of the Witwatersrand sequence, this unit was called the "basal amygdaloid" by Hall and Molengraaff (1925) and Nel (1927), and was later correlated with the "Dominion Reef Series" of Molengraaff (1905) by Nel (1934). It is now known as the Dominion Group and is the first of three semi-conformable sequences making up the Witwatersrand triad (SACS, 1980). The Dominion Group overlies granitoid basement with erosional nonconformity and conformably underlies the Witwatersrand Supergroup in the western part of the Witwatersrand Basin. The third member of the triad is the mainly volcanic Ventersdorp Supergroup which disconformably overlies the Witwatersrand succession.

The Dominion Group is divided into three formations in the type area near Klerksdorp: (1) at the base is the locally developed Rhenosterspruit Formation (incorrectly called the Rhenosterhoek Quartzite Formation in SACS, 1980; see Bowen *et al.*, 1986, and discussion in Jackson, 1991), composed of clastic sediments and interbedded volcanics, about 60 m thick, locally containing gold and uranium in two conglomeratic reefs; (2) the overlying Rhenosterhoek Formation is a widespread, but poorly exposed, sequence of amygdaloidal mafic lavas and subordinate tuffs, about 1 km thick; and (3) the uppermost Syferfontein Formation is composed mainly of massive felsic volcanic rocks and feldspar and quartz-feldspar porphyry, with subordinate intercalated mafic to intermediate flows and tuffs, up to 1.5 km thick.

Recent precise radiometric dating by U/Pb isotopic analysis of zircons, shows that the Witwatersrand triad represents an age span of about 360 Ma. The granitoids underlying the Dominion Group, which have been dated by this method, range from 3250 Ma to 3096 Ma (Drennan *et al.*, 1990; Robb *et al.*, 1991). The Outer Granite Gneiss underlying the Dominion Group in the Vredefort area has been dated at 3080 ( $\pm$  20) Ma by the Rb/Sr method (Hart *et al.*, 1981). Granite beneath the Dominion Group in the Klerksdorp area was

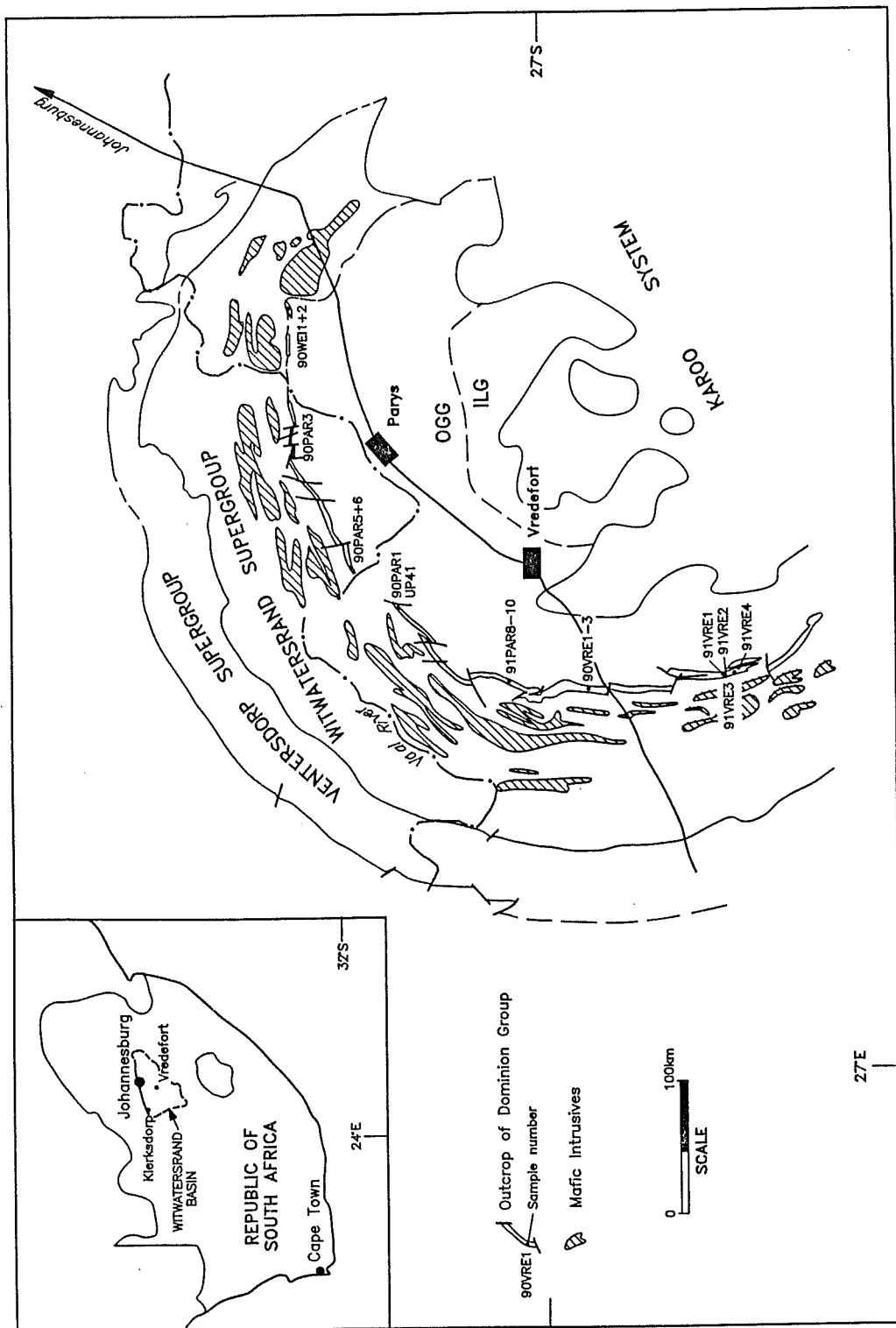


Figure 1: Generalized geologic map showing outcrop of the Dominion Group and sample locations, other members of the Witwatersrand triad supracrustal rocks forming the collar and granitoid basement (OGG-Outer Granite Gneiss; ILG - Inlandsee Leucogranofels) of the Vredefort Dome, and overlying Karoo Sequence cover strata, after Nel (1927) and Geological Survey (1986). Note the numerous mafic intrusives within the Wits SG. Inset shows central location of Vredefort within the Witwatersrand Basin.

dated at 3120 Ma, and a felsic volcanic sample, within the Syferfontein Formation, has been dated at 3074 ( $\pm$  6) Ma; the Klipriviersberg Group, at the base of the Ventersdorp volcanics has an age of 2714 Ma (Armstrong *et al.*, 1991). The 3074 Ma age of the Syferfontein felsic volcanics is consistent with the youngest age of detrital zircons in the Rhenosterspruit sediments implying a maximum age of deposition of 3105 Ma (Robb *et al.*, 1990) for the base of the Dominion Group.

The nature and extent of the Dominion successions and possible correlatives, is discussed in Jackson (1991). SACS (1980) designated three areas of outcrop as Dominion type localities: (1) around the town of Ottosdal in the western Transvaal; (2) between Ottosdal and Klerksdorp, in the vicinity of the old Dominion Reefs Mine with scattered exposures extending northeast toward Ventersdorp; and (3) west and north of Vredefort and Parys, in the collar of the Vredefort Dome. Although all of these occurrences are part of the Dominion succession, and borehole intersections indicate a greater subsurface areal extent to the north and south (Figure 1), there are important differences in the lithological-stratigraphic and geochemical nature of the group in each of these areas. The structure, stratigraphy, age, and petrology of the Group are best known in the Klerksdorp area, samples of which have been studied by numerous workers (Bowen *et al.*, 1986; Crow and Condie, 1987; Marsh *et al.*, 1989) as well as dated (Armstrong *et al.*, 1991). Therefore it seems preferable to designate the Klerksdorp area as the type area in order to facilitate comparisons with other occurrences.

### Basal Amygdaloid

Nel (1927) originally considered this unit to be the basal unit of the Hospital Hill Series of the Witwatersrand Supergroup. He described it as a "dark diabasic-looking rock", petrographically a "hornblende granulite", with common quartz-filled amygdales up to 15 cm in diameter. The unit occurs between the "Old Granite" and the Orange Grove Quartzite, surrounding the granite on the north and west sides of the Vredefort Dome. Its stratigraphic thickness varies, according to Nel (1927, p. 30), from a maximum of about 250 m, in the southwest, to only 90-120 m in the northeast. While its extent to the south was unknown, due to its disappearance under the cover of Karoo rocks, Nel believed that it naturally pinched out to the northeast, and that this diminution in thickness was due to a distal location with respect to the volcanic vent(s) located further to the west.

Nel's (1927) conclusions are supported by this study which verifies the correlation of the basal amygdaloid with the Rhenosterhoek Formation mafic lavas of the Dominion Group in the Klerksdorp area, based on geochemistry. Furthermore, the presence of a much greater thickness of Dominion strata in the Klerksdorp area, including felsic volcanics and proximal coarse clastic sediments, supports this as the main locus of volcanic vents from which fluid mafic lavas may have issued and spread to the east as far as the Vredefort area. Alternatively, vents which produced only mafic lavas may have been located in the Vredefort area.

This paper describes the nature of the Dominion succession in the Vredefort area in comparison to the better known Klerksdorp area occurrence. Future contributions will deal

with the Group in the Klerksdorp, Ottosdal and other areas. It is shown that the Dominion rocks in the Vredefort area comprise primitive mafic lavas similar to the upper parts of the Rhenosterhoek Formation in the Klerksdorp area. These lavas were probably derived by partial melting of sub-continental lithospheric mantle sources which had been modified by previous melting and enrichment processes. Volcanism probably occurred in a continental rift zone setting. The metamorphic petrology indicates conditions of moderate pressure and temperature with regional amphibolite-facies metamorphism probably due to burial under up to 10-12 km of overlying Witwatersrand triad strata.

## RESULTS

Samples were collected from Dominion Group exposures in the collar of the Vredefort Dome, for petrographic and geochemical analysis, at the locations shown in Figure 1. Most samples are dark-grey amphibolites with variable amounts of quartz-filled amygdalites. The amphibolite is locally deformed, as shown by the stretching of amygdalites, and the local occurrence of coarser-grained gneissic texture. This texture is defined by quartz lenses and stringers and amphibole blades up to 5 mm long, seen in narrow highly amygdaloidal zones which accommodate most of the deformation. Small quartz veinlets are ubiquitous, and irregular black pseudotachylite veins are common. Very rare interbeds of micaceous, schistose metasediment or tuff occur within the amphibolite and some garnetiferous zones were noted by Nel (1927, p. 32). The maximum outcrop width of the unit occurs west of Vredefort, e.g. on the farm Bakenkop. However, in this and other areas the unit is almost certainly repeated by faulting.

The attitude of the Dominion succession in the Vredefort collar is conformable with overlying clastic sediments of the West Rand Group which are overturned to subvertical, dipping moderately to steeply south to east towards the centre of the Vredefort Dome.

## Analytical Methods

Major elements were determined by X-ray fluorescence spectrometry on fused discs by the method of Norrish and Hutton (1969). The trace elements - Ba, Rb, Sr, Nb, Y, Zr, V, Cr, Co, Ni, Cu and Zn - were determined on undiluted sample powder briquettes using standard XRF techniques. XRF analyses were done on a Philips 1400 spectrometer at the Department of Geology, University of the Witwatersrand. More detailed discussion of XRF analytical methods and precision of the data can be found in Myers *et al.*, (1990).

Comparison of XRF results for this study and those for Dominion samples analysed by Marsh *et al.*, (1989) is made in Table 1A for splits of the same samples from Klerksdorp-area boreholes. Data are in general agreement between the two laboratories. For the major elements, the Witwatersrand data have slightly higher  $TiO_2$ , and lower  $Fe_2O_3$ ,  $MgO$  and  $CaO$ , but the differences are within the precision of the analyses (about 5% relative). Among the trace elements, there are systematic differences between the two laboratories in lower Y, Ni, Co, V and Cu, and higher Zr and Nb for the Witwatersrand analyses. Again these differences are mainly within precision limits (about 10% relative) except for Co and

TABLE 1A. XRF analyses of Dominion Group samples. New data for samples from Klerksdorp-area boreholes and splits analysed at University of Witwatersrand and Rhodes University

Lab Sample	Wits DB251	Rhodes DB251	Wits DB278	Rhodes DB278	Wits DB68	Rhodes DB68	Wits DB248	Wits DB255
SiO <sub>2</sub>	54.14	54.52	54.84	55.35	56.76	56.39	53.63	53.29
TiO <sub>2</sub>	0.68	0.66	1.28	1.25	1.19	1.14	0.78	0.63
Al <sub>2</sub> O <sub>3</sub>	15.56	15.89	15.41	15.79	14.24	14.16	12.82	15.00
Fe <sub>2</sub> O <sub>3</sub> *	9.28	9.46	10.91	11.28	11.51	11.76	11.05	9.84
MnO	0.15	0.15	0.17	0.18	0.14	0.14	0.20	0.16
MgO	6.51	6.76	5.73	5.93	4.58	4.69	8.34	7.94
CaO	7.10	7.39	4.84	5.01	6.22	6.33	10.04	9.09
Na <sub>2</sub> O	5.30	3.93	5.57	3.99	3.88	3.98	1.69	3.06
K <sub>2</sub> O	1.08	1.08	0.87	0.83	1.12	1.07	1.29	0.89
P <sub>2</sub> O <sub>5</sub>	0.16	0.17	0.38	0.38	0.36	0.33	0.15	0.09
L.O.I.	1.99	2.02	1.87	1.86	1.46	1.54	2.26	2.17
Mg#	58.1	58.6	51.0	51.0	44.1	44.1	59.9	61.5
Ba	653	662	407	416	405	386	570	295
Rb	17	17	11	12	41	36	26	25
Sr	426	441	193	203	491	485	310	370
Nb	4.1	3.4	7.9	8.1	6.5	8.0	5.0	4.2
Y	15	19	28	34	26	32	17	15
Zr	106	97	191	185	181	168	95	87
Ni	202	216	101	115	83	93	292	259
Co	35	57	40	61	30	57	48	49
Cr	315	299	45	47	40	52	986	716
V	169	180	249	276	224	244	214	186
Cu	50	57	39	48	58	78	64	72
Zn	84	81	126	132	115	108	95	83

Fe<sub>2</sub>O<sub>3</sub>\* - All Fe as Fe<sub>2</sub>O<sub>3</sub>. L.O.I. - Loss on Ignition wt%

Mg# = 100Mg/Mg+Fe assuming all Fe as FeO

DB251, DB278 & DB68 - New analyses (Wits) of splits of samples of primitive low Ti/V, primitive high Ti/V, and evolved high Ti/V mafic lava types, respectively, from Klerksdorp-area boreholes previously analysed (Rhodes) by Marsh et al. (1989)

DB248 & DB255 - New samples from Klerksdorp area borehole DRH-14 not previously analysed

Major element oxides in weight percent. Trace element values in parts per million

Major and trace elements recalculated to 100% without Loss On Ignition (L.O.I.)

TABLE 1B. XRF analyses (except Pt) of Dominion Group samples from the collar of the Yredfont Dome compared to mean primitive low Ti/V type in the Klerksdorp area boreholes.

Sample	Pt										Pt				MEAN DB#1	
	90PAR1	90PAR3	90PAR5	90PAR6	90PAR8	91PAR9	91PAR10	90VRE1	90VRE2	90VRE3	91VRE1	91VRE2	91VRE4	90VRE1	UP41	
Si02	55.22	53.70	53.58	52.28	51.38	55.11	54.51	57.23	56.35	54.14	56.55	54.47	50.60	55.23	53.35	53.01
Ti02	0.67	0.74	0.60	0.84	0.40	1.07	0.78	1.07	1.00	0.92	1.08	0.74	0.75	0.74	0.79	0.70
Al2O3	13.69	15.23	17.71	14.22	15.09	14.49	13.23	14.83	14.58	15.84	14.40	13.61	15.91	13.90	13.56	14.02
Fe2O3*	11.46	10.42	10.53	12.04	11.61	12.81	11.05	11.62	11.78	12.20	12.98	12.01	12.60	10.99	10.84	11.69
MnO	0.14	0.14	0.21	0.19	0.17	0.27	0.15	0.13	0.14	0.17	0.15	0.23	0.23	0.26	0.19	0.17
MgO	6.81	6.60	4.51	7.70	8.04	3.18	8.36	4.01	4.30	4.05	3.87	7.42	5.80	7.40	6.42	7.74
CaO	10.65	11.88	12.22	10.92	11.36	10.54	9.59	9.43	9.53	10.44	9.21	8.96	13.28	8.88	12.96	9.31
Na2O	1.08	0.88	0.34	1.52	1.77	2.09	1.89	1.33	2.05	2.33	1.49	2.30	2.30	0.58	2.41	0.53
K2O	0.15	0.24	0.10	0.21	0.17	0.25	0.25	0.09	0.10	0.09	0.02	0.11	0.10	0.13	0.17	0.08
P2O5	0.13	0.15	0.20	0.08	ND	0.19	0.18	0.24	0.20	ND	0.25	0.16	0.13	0.13	0.16	0.16
L.O.I.	1.17	0.86	0.36	1.18	ND	0.41	0.52	0.34	0.31	ND	0.25	0.53	0.50	0.56	0.97	0.59
Mg#*	54.1	55.7	45.9	55.9	57.8	33.0	60.0	40.6	42.0	39.7	37.1	55.0	47.7	57.2	54.0	56.7
Ba	132	96	63	159	ND	89	125	172	129	ND	95	32	50	100	44	149
Rb	13	20	12	23	ND	6	14	11	6	ND	12	3	6	6	22	9 [4]
Sr	611	623	431	248	ND	503	434	827	854	ND	802	558	255	575	767	552 [7]
Nb	4.8	5.2	4.7	4.9	ND	6.4	5.5	6.8	3.6	ND	7.3	4.4	4.5	3.6	5.2	3.7 [1]
Y	15	17	16	19	ND	25	18	25	22	ND	23	16	18	14	21	16 [1]
Zr	93	100	77	65	ND	149	111	163	140	ND	166	95	98	95	107	95 [1]
Ni	315	293	257	134	ND	39	279	41	54	ND	45	270	363	294	367	306 [1]
Co	57	52	55	49	ND	56	50	44	39	ND	46	50	64	51	67	52 [7]
Cr	855	821	696	358	ND	19	784	11	18	ND	11	917	890	892	945	851 [26]
Y	196	212	181	270	ND	295	201	273	246	ND	285	216	254	214	222	211 [29]
Cu	58	62	27	109	ND	20	83	53	98	ND	72	51	6	75	26	116 [5]
Zn	86	85	64	85	ND	107	88	100	90	ND	107	94	93	81	84	85 [1]

Fe2O3\* - All Fe as Fe2O3. L.O.I. - Loss on Ignition wt%. ND - Not determined

Mg# = 100Mg/(Mg+Fe assuming all Fe as FeO)

Pt - average of 3 to 7 defocused-beam probe analyses of pseudotachylite veins; FeO\* converted to Fe2O3\* for comparison to XRF data.

MEAN DB#1 - Average of ten analyses of primitive low Ti/V type mafic lavas from the Klerksdorp-area boreholes from Marsh et al. (1989, table 1)

Major element oxides in weight percent. Trace element values in parts per million; UP41 average of duplicate analyses for trace elements (except Ba) with standard deviation in brackets

Major and trace elements recalculated to 100% without Loss On Ignition (L.O.I.)

All XRF analyses (except MEAN DB#1) done at Department of Geology, University of the Witwatersrand, V.P. Govender analyst

Y (lower by 4-6 ppm for Witwatersrand data) and Nb (about 1 ppm higher for Witwatersrand data).

Selected samples were analysed for trace elements (As, Au, Sb, Hf, Sc, Ta, Th, U) and the rare earth elements (REE), by instrumental neutron activation analysis at the Schonland Centre, University of the Witwatersrand, Johannesburg. Discussion of this procedure can be found in Erasmus *et al.*, (1977). Four samples were analysed for the REEs by the method of gradient ion chromatography (described in Le Roex and Watkins, 1990) at the University of Cape Town. A comparison of REE results by the two methods can be seen for three samples in Table 2.

Minerals were analysed using a Cameca electron microprobe at the University of Cape Town. Counting times of 10 seconds were used for all elements and the data were reduced using the Bence-Albee method. Precision and accuracy of the probe data are estimated to be 2-4% relative based on replicate analyses of standard minerals.

### Petrography

M.P. Bowen (1984) described the petrography of Dominion Group mafic lavas in the Klerksdorp area boreholes. He stated that the lavas were largely recrystallized, fine-grained, and allotriomorphic, composed of albitic plagioclase, chlorite, calcite, epidote, clinzoisite, quartz and amorphous sphene with some samples showing dispersed fibrous amphibole.

Nel (1927) described "basal amygdaloid" samples from the Vredefort area composed of hornblende, quartz and feldspar with accessory titanite (sphene), ilmenite and apatite. Actual mineral compositions have not been previously reported for Dominion Group samples from either area.

In thin section, Vredefort-area Dominion Group metabasalts are fine to medium-grained, granular to faintly foliated, hornblende amphibolites composed of green hornblende (60-70%), quartz (20-30%), plagioclase (10-15%) and opaques (2-5%), with minor sphene. A few samples contain dark brown biotite (2-3%), probably of secondary origin. The main opaque mineral is ilmenite, often in needle-like crystals, but minor pyrite is also present. Some samples contain a colourless amphibole, probably tremolite.

Pseudotachylite, a dark grey to black, friction-generated glass, occurs in irregular, discontinuous veins and networks from less than 1 mm to several centimetres wide in most outcrops.

### Geochemistry

Major and trace element analyses for bulk-rock samples determined by XRF are shown in Table 1B. Major element data for pseudotachylite veins in two samples, determined by defocussed-beam microprobe analysis, are also shown. For a detailed comparison of Vredefort-area lavas with those from the Klerksdorp type area, analyses of Dominion Group mafic lava samples from the boreholes studied by Bowen *et al.* (1986) and

TABLE 2. Trace element determinations (ppm, except Au = ppb) for Vrededorp-area Dominion samples by neutron activation analysis (NAA) and gradient ion chromatography (GIC)

Method	NAA	GIC	NAA	GIC	NAA	GIC	NAA	GIC	NAA	GIC	GIC	GIC	GIC	GIC	GIC	NAA
Sample	90PAR1	90PAR3	90PAR5	90PAR6	90PAR8	90PAR9	91PAR10	91PAR11	90YRE1	90YRE3	90YRE12	UP41	DB251	DB278	DB68	MEANDB#1
La	9.38	10.5	10.5	5.2	6.04	14.1	26.9	26.6	25.2	12.5	13.2	25.7	8.90	9.53	11.0	
Ce	20.3	23.1	22.3	10.0	16.2	30.6	32.8	51.1	54.3	42.1	26.4	28.8	56.5	53.1	23.2	21.5
Pr	ND	3.59	ND	1.37	ND	4.07	ND	6.27	ND	ND	ND	3.94	7.67	7.45	2.96	2.80
Nd	12.0	14.7	12.5	6.25	10.3	16.5	16.7	25.2	27.2	26.0	22.2	13.4	15.9	31.2	29.3	11.9
Sm	2.90	3.25	3.13	1.58	2.56	3.71	3.42	5.16	4.65	4.82	4.67	3.20	3.54	6.84	6.31	3.51
Eu	0.98	1.16	1.05	0.59	1.06	1.19	1.25	1.63	1.64	1.67	1.31	1.08	1.25	2.04	1.98	1.11
Gd	3.15	3.34	3.30	1.87	3.12	3.46	3.58	4.73	4.30	4.57	4.56	3.34	3.43	6.28	5.78	3.29
Tb	0.51	0.52	0.49	0.31	0.52	0.54	0.57	0.67	0.70	0.72	0.70	0.54	0.49	0.68	0.82	0.51
Dy	ND	3.06	ND	1.96	ND	3.02	ND	3.93	ND	ND	ND	2.89	4.99	4.73	2.91	2.41
Ho	0.58	ND	0.60	ND	0.63	ND	0.65	ND	0.73	0.76	0.84	0.61	ND	ND	ND	ND
Er	ND	1.65	ND	1.08	ND	1.61	ND	2.11	ND	ND	ND	1.42	2.26	2.25	1.49	1.21
Yb	1.34	1.29	1.23	1.18	1.42	1.43	1.32	1.64	1.49	1.71	2.04	1.25	0.99	1.59	1.45	1.12
Lu	0.20	ND	0.18	ND	0.22	ND	0.19	ND	0.22	0.25	0.30	0.18	ND	ND	ND	0.23
As	0.10	ND	0.13	ND	0.09	ND	0.08	ND	0.09	0.14	0.07	0.19	ND	ND	ND	ND
Au	0.23	ND	BD	ND	0.21	ND	0.19	ND	BD	0.43	0.19	0.23	ND	ND	ND	ND
Sb	0.03	ND	0.07	ND	0.09	ND	BD	ND	0.04	BD	0.07	0.05	ND	ND	ND	ND
Hf	2.21	ND	1.95	ND	1.84	ND	2.78	ND	3.77	4.17	4.01	2.41	ND	ND	ND	2.05
Sc	21.2	ND	20.7	ND	28.7	ND	21.3	ND	21.3	21.5	18.5	21.4	ND	ND	ND	ND
Ta	0.19	ND	0.19	ND	0.22	ND	0.24	ND	0.36	0.38	0.39	0.23	ND	ND	ND	ND
Th	0.50	ND	0.44	ND	0.83	ND	0.60	ND	1.71	1.81	0.51	0.55	ND	ND	ND	0.33
U	0.39	ND	0.32	ND	0.35	ND	0.34	ND	0.47	0.52	0.32	ND	ND	ND	ND	ND

BD - Below detection limit

ND - Not determined

DB251, DB278 &amp; DB68 - New analyses of splits from samples of primitive low TiW, primitive high TiW, and evolved high TiW mafic lavas, respectively, from Klerksdorp-area boreholes previously analysed by Marsh et al. (1988; tables I &amp; II)

DB248 &amp; DB255 - New samples from Klerksdorp area borehole DRH-4 not previously analysed

MEAN DB#1 - Mean of six samples from Klerksdorp area boreholes analysed by Marsh et al. (1988)

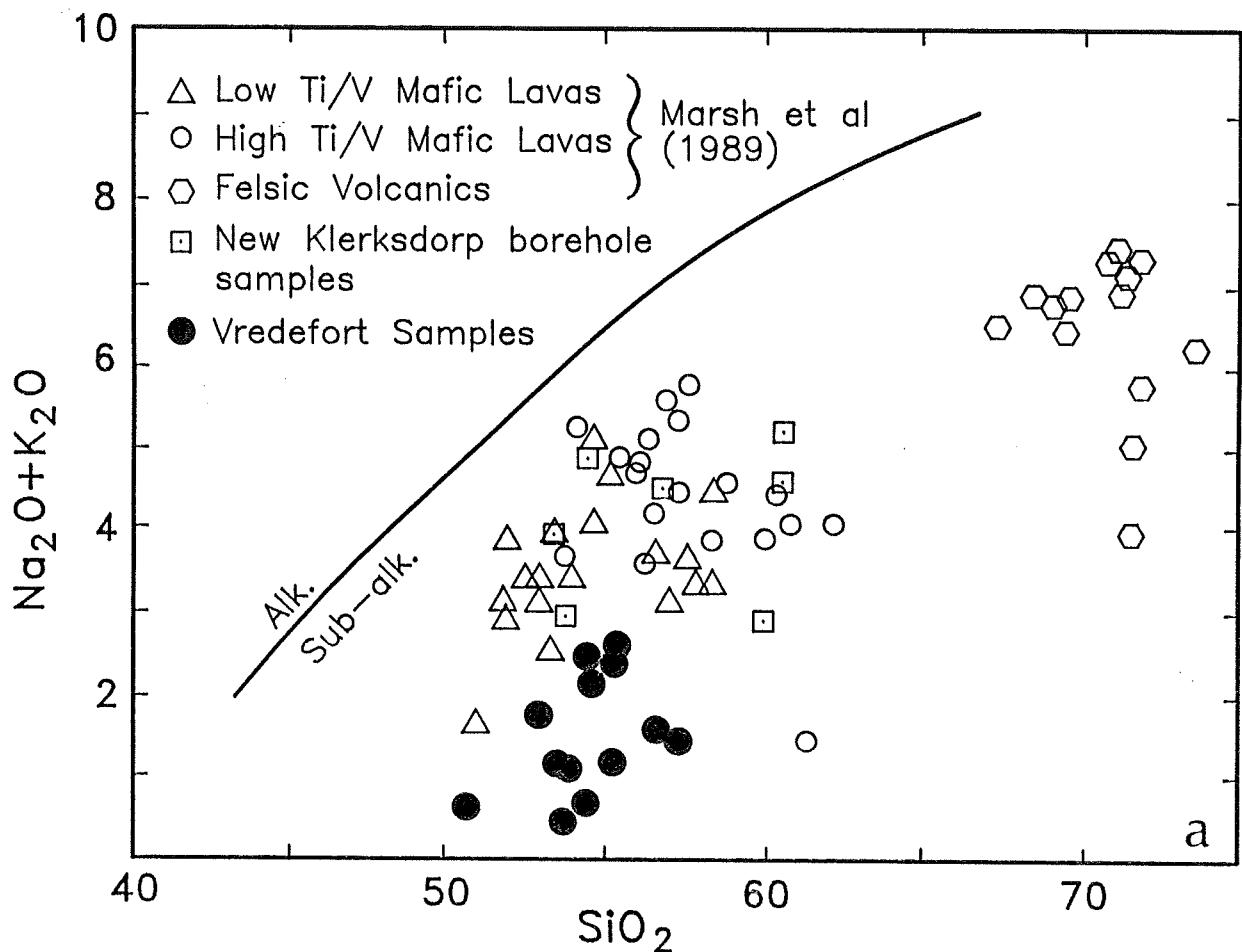


Figure 2: Total alkalies ( $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ) versus  $\text{SiO}_2$  diagram with dividing line between alkaline and sub-alkaline series after Irvine and Baragar (1971). Data for Dominion Group volcanics from Marsh *et al.* (1989) plotted along with new samples from the same Klerksdorp-area boreholes and surface samples from the Vredefort area (locations shown on Figure 1).

Marsh *et al.* (1989) are shown in Table 1A. Samples DB248 and DB255 are from borehole DRH-14 and were not previously analysed, whereas analyses DB251, DB278 and DB68 are from splits of sample powders previously analysed (data reported in Marsh *et al.*, 1989). A comparison of these newly analysed samples with those from the Vredefort area avoids possible interlaboratory bias.

Vredefort-area Dominion Group amphibolites are subalkaline tholeiitic basalts to andesites (Figure 2). Most samples are relatively primitive in terms of low  $\text{FeO}^*/\text{MgO}$  (high Mg#), very low alkalies, and relatively high Ni and Cr contents.  $\text{SiO}_2$  contents are high for basalts, putting them in the range of basaltic andesites ( $\text{SiO}_2 > 52$  wt. %; Cox *et al.*, 1979). This is a common trait of Dominion mafic lavas (see Bowen *et al.*, 1986) and may be due,

at least in part, to silicification during alteration, or, in the case of the Vredefort area samples especially, it may be due to the ubiquitous presence of quartz-filled amygdales, many of which are microscopic in size and could not be avoided in selecting sample material for crushing (as was noted by Hall and Molengraaff, 1925). On the other hand, high  $\text{SiO}_2$  may be a primary characteristic due to crustal contamination or other source or process-related factors.

Compared to the range of compositions reported for Dominion mafic lavas in the Klerksdorp area, most Vredefort-area samples are relatively primitive and have low  $\text{TiO}_2$  (< 0.8 wt%) and very low alkalies (Figures 2 and 3) and higher  $\text{CaO}$  and  $\text{CaO}/\text{Al}_2\text{O}_3$ . A few samples are more evolved with higher  $\text{FeO}^*/\text{MgO}$  and  $\text{TiO}_2$  contents up to 1.1 wt%. Major oxides are plotted against  $\text{FeO}^*/\text{MgO}$  in Figure 4 with Vredefort-area samples compared to the data for the Klerksdorp area published by Marsh *et al.*, (1989). The degree of scatter observed in these variation diagrams is probably largely due to alteration for some elements, e.g.  $\text{CaO}$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$ , but may also be ascribed to different liquid lines of descent from various primitive parental liquids as shown by Marsh *et al.* (*ibid*). Allowing for scatter due to alteration, the general trends of increasing  $\text{K}_2\text{O}$  and  $\text{P}_2\text{O}_5$ , as well as  $\text{TiO}_2$ , and decreasing

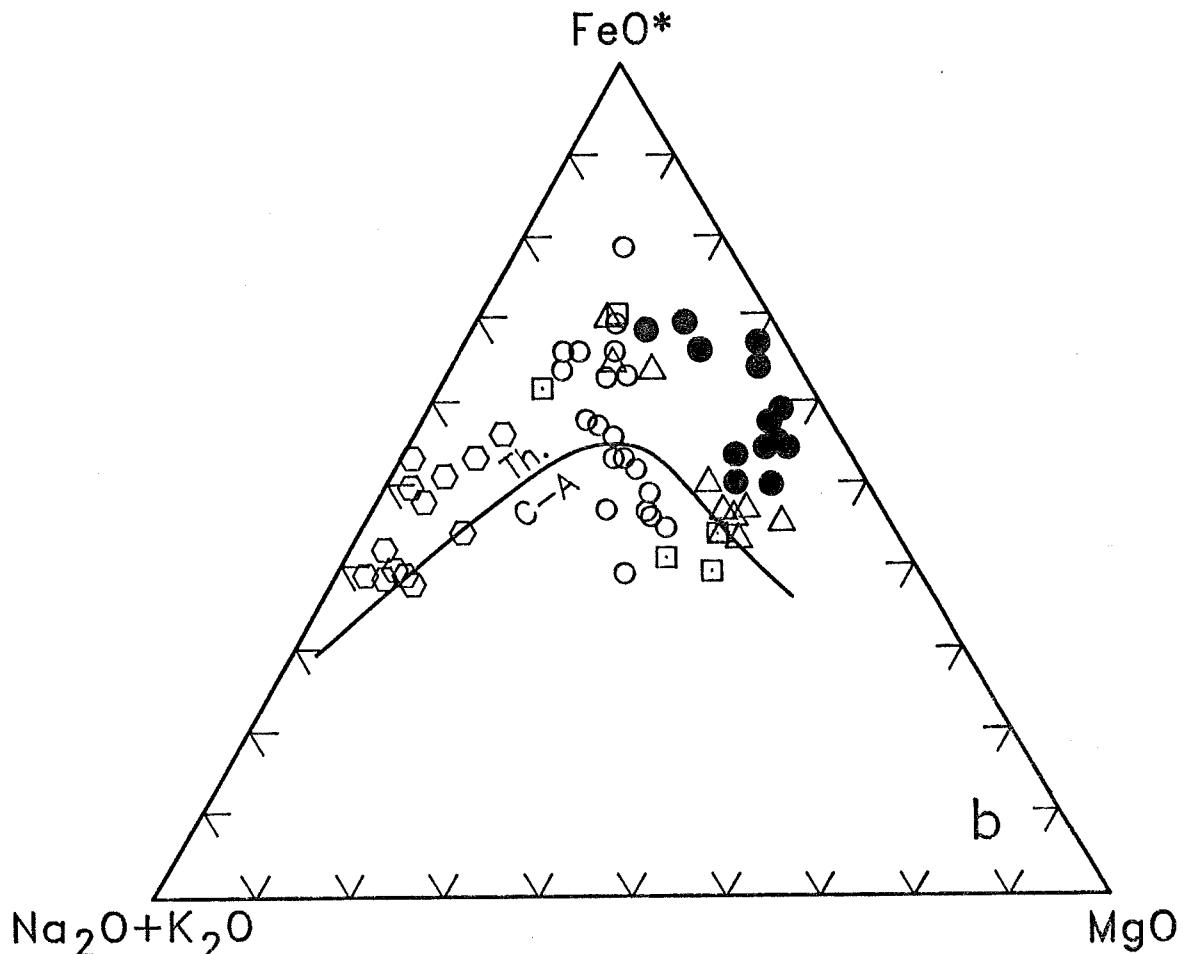


Figure 3: AFM diagram:  $A = \text{Na}_2\text{O} + \text{K}_2\text{O}$ ,  $F = \text{total Fe}$ ,  $M = \text{MgO}$ , with dividing line between tholeiitic (Th) and calc-alkaline (C-A) series after Irvine and Baragar (1971). Symbols as in Figure 2.

CaO and  $\text{Al}_2\text{O}_3$  with increasing  $\text{FeO}^*/\text{MgO}$  are those of a tholeiitic suite. In the Vredefort-area data set,  $\text{Al}_2\text{O}_3$  increases initially up a value of  $\text{FeO}^*/\text{MgO} = 2$ , and then decreases, suggesting a change in fractionating phase assemblage from ferromagnesian-mineral dominated to plagioclase dominated.

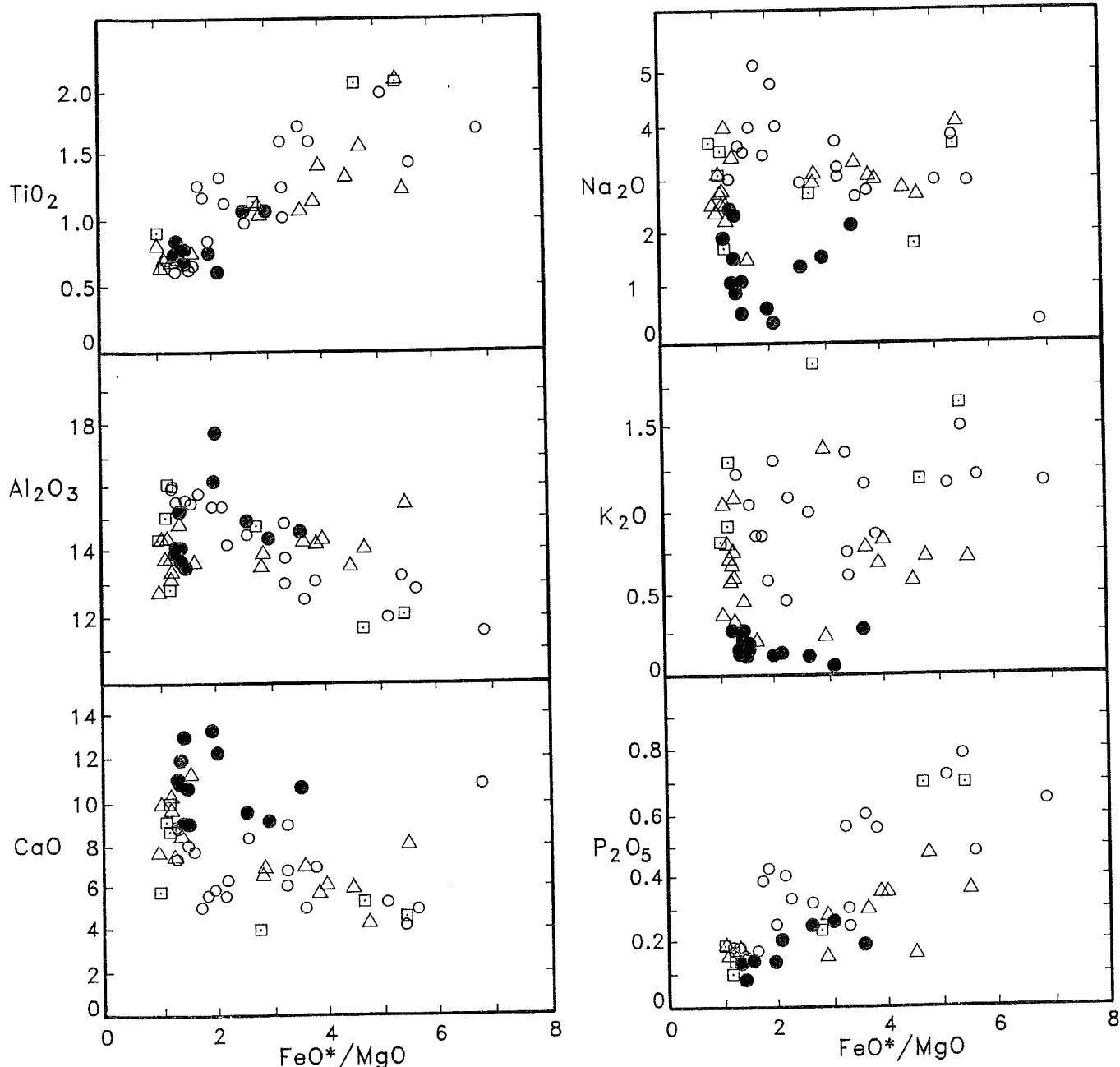


Figure 4: Major oxides plotted against  $\text{FeO}^*/\text{MgO}$  ( $\text{FeO}^*$  = total Fe as  $\text{FeO}$ ). Symbols as in Figure 2. Note the relatively low alkali and high  $\text{CaO}$  and  $\text{Al}_2\text{O}_3$  contents of Vredefort-area samples compared to those from the Klerksdorp area but similarity in immobile incompatible elements Ti and P.

### Pseudotachylite

Dark-grey aphanitic melt rock, known as pseudotachylite, occurs as irregular and discontinuous veins, without apparent preferred orientation, from less than 1 mm to several centimetres in width, in many Dominion Group exposures around the Vredefort Dome. This rock type is widespread in most lithologies comprising the core and collar of the structure and is generally attributed to formation by dynamic deformation at the time of dome formation, whether by endogenous or exogenous (meteorite impact) processes (Reimold, 1991).

Analyses were made of pseudotachylite in two Dominion Group samples by electron microprobe using a defocussed beam (Table 1B). Compared to their host rocks (bulk rock analyses by XRF) these analyses show that pseudotachylite is very similar to bulk host rock composition, but shows some consistent differences in certain elements.  $\text{SiO}_2$  and  $\text{FeO}^*$  (total iron as  $\text{FeO}$ ) are slightly lower and  $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$  and  $\text{Na}_2\text{O}$  are slightly higher in pseudotachylite compared to bulk host rock. However, these differences, in the range of 2 to 15% relative, are not much greater than that which can be attributed to analytical error and the use of different analytical techniques.  $\text{K}_2\text{O}$  contents are variable being lower than the host rock in one pseudotachylite but higher in the other. This can be explained by analytical errors at these low concentrations (less than 0.2 wt%) and the susceptibility of potassium to alteration.  $\text{TiO}_2$  shows a large difference between pseudotachylite and host rock in one sample (90PAR6) which exceeds that of possible analytical error and cannot be easily explained by alteration processes.

Reimold (1991) made a similar comparison of pseudotachylite and host-rock composition, determined by microprobe and XRF respectively, for a number of rock types in the core and collar (2 samples) of the Vredefort Dome. He found that pseudotachylites and host rocks were very similar in composition for all host-rock types with a few significant chemical differences but a lack of consistent trends. No Dominion samples were analysed by Reimold (1991), but gabbroic intrusive rocks of similar composition were studied. The chemical differences in pseudotachylite/gabbroic host rock pairs differed from those found in Dominion samples in the present study. However, the general conclusion of Reimold (1991) that pseudotachylite formed by selective melting of its adjacent host rock is in agreement with the Dominion Group data. Pseudotachylite appears to represent a close approach to a simple melt of crystalline Dominion mafic lava, but the lower  $\text{TiO}_2$  content in sample Pt-90PAR6 remains unexplained.

### Trace Elements

Trace element variation is apparently affected by both alteration and igneous processes. Ni decreases rapidly, Co decreases slightly, and V increases, with increasing  $\text{FeO}^*/\text{MgO}$  (Figure 5). Cr also decreases with increasing  $\text{FeO}^*/\text{MgO}$  (not shown) but shows more scatter than the other metals. The rapid decreases in Ni and Cr and decreasing Co with increasing  $\text{FeO}^*/\text{MgO}$  are consistent with olivine  $\pm$  pyroxene  $\pm$  Cr-spinel fractionation; the increasing V indicates a lack of magnetite fractionation up to an  $\text{FeO}^*/\text{MgO}$  of about 5 where it levels off.

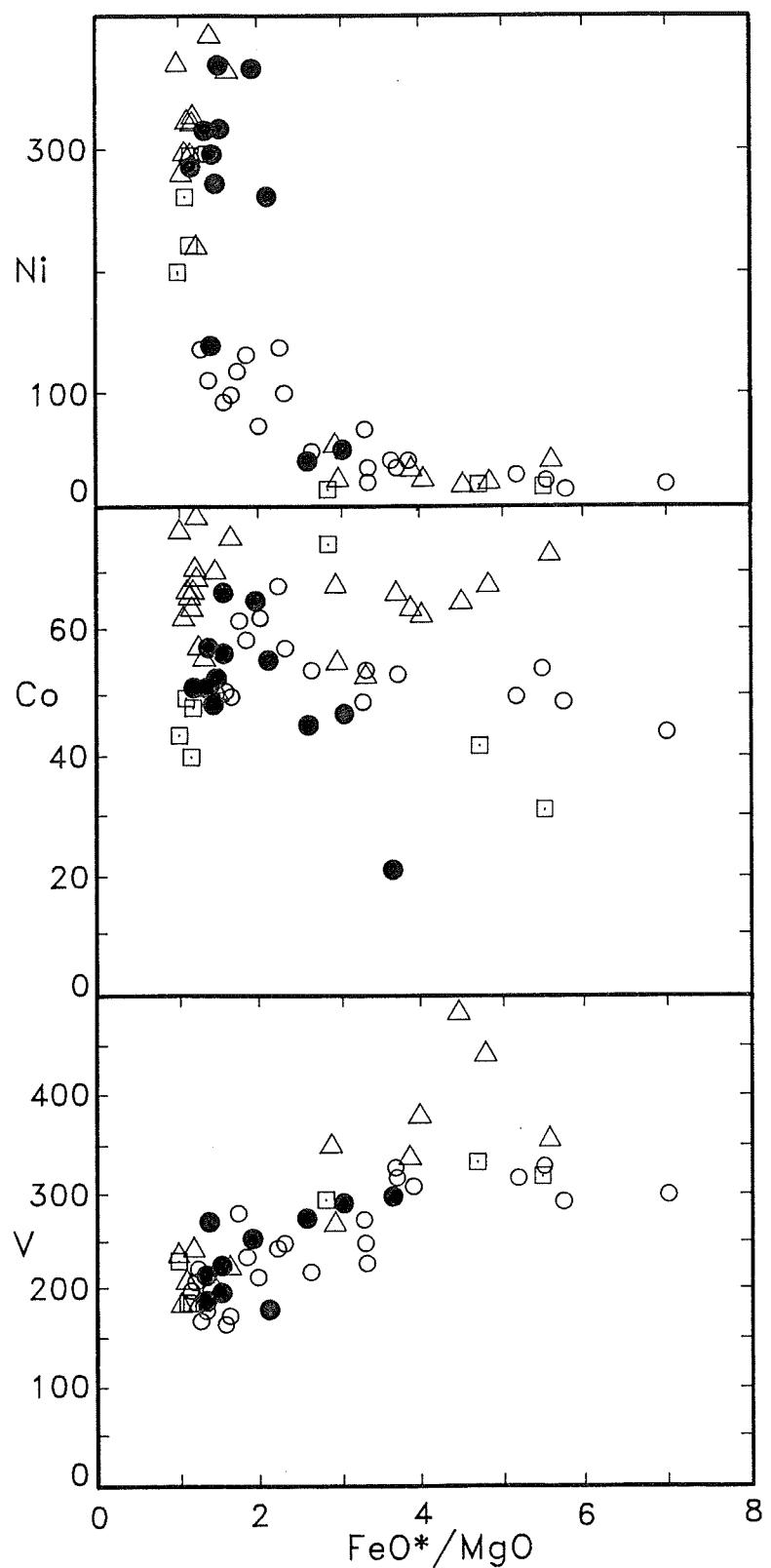


Figure 5: Transition metals, Ni, Co and V versus  $\text{FeO}^*/\text{MgO}$ . Symbols as in Figure 2. Note compatible behaviour (decrease) of Ni and Co but incompatible behaviour of V (increase) with fractionation.

Large-ion lithophile elements, Ba, Rb and Sr, show scattered variation against Zr, reflecting alteration, whereas the high-field strength elements, Nb, Y and Ce (and other REEs), show good correlations with Zr (Figure 6) indicating a lack of mobility during alteration. General increases in Ba and Rb, as well as the immobile trace elements indicate that these elements behaved incompatibly during fractionation, whereas a general decrease in Sr in the evolved Klerksdorp-area samples indicates compatible behaviour suggesting fractionation of plagioclase. However, there is no decrease in Sr in the Vredefort-area samples, instead an increase in Sr is seen in the evolved lavas.

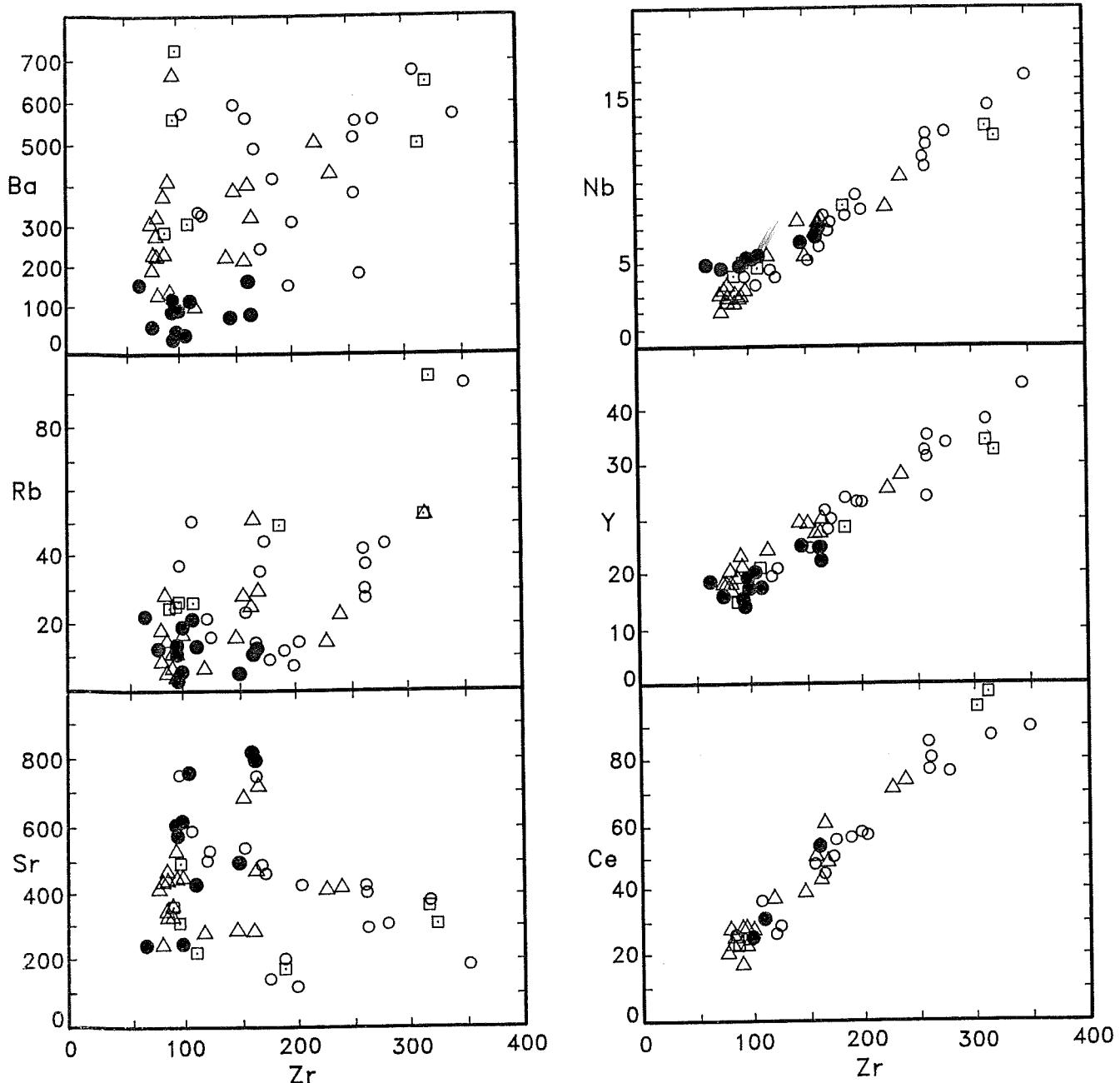


Figure 6: Large-ion lithophile and high-field strength elements versus Zr. Symbols as in Figure 2. Note scatter of points in Ba, Rb and Sr diagrams, probably due to redistribution of these elements by alteration, compared to good correlation of immobile elements Nb, Y and Ce with Zr.

Trace elements determined by neutron activation analysis and gradient ion chromatography on selected samples are shown in Table 2. A spider diagram (Figure 7) illustrates the chondrite-normalized variation in incompatible trace elements for three representative Vredefort-area samples compared to the average Klerksdorp area group I (primitive low Ti/V mafic lava) composition from Marsh *et al.* (1989). This diagram, constructed by the method of Thompson (1982), corrects for the effects of fractionation by "double-normalizing" each spidergram to a chondrite-normalized Yb value of 10. Thus elements with similar partition coefficients to Yb should plot on a horizontal line on this diagram. It is clear that most of the elements plotted are more incompatible than Yb with the possible exception of Ti and P in the most depleted sample (90PAR6). The effects of alteration are shown by the irregular crossing patterns for Ba, Rb, and K. A relative depletion in Nb and Ta, as well as Ti, compared to the other high-field strength elements (Hf and Zr) is apparent as was previously noted by Marsh *et al.* (1989). Large enrichments in the light rare earth elements (LREE) and Sr occur in the most evolved samples (e.g. 90VRE1).

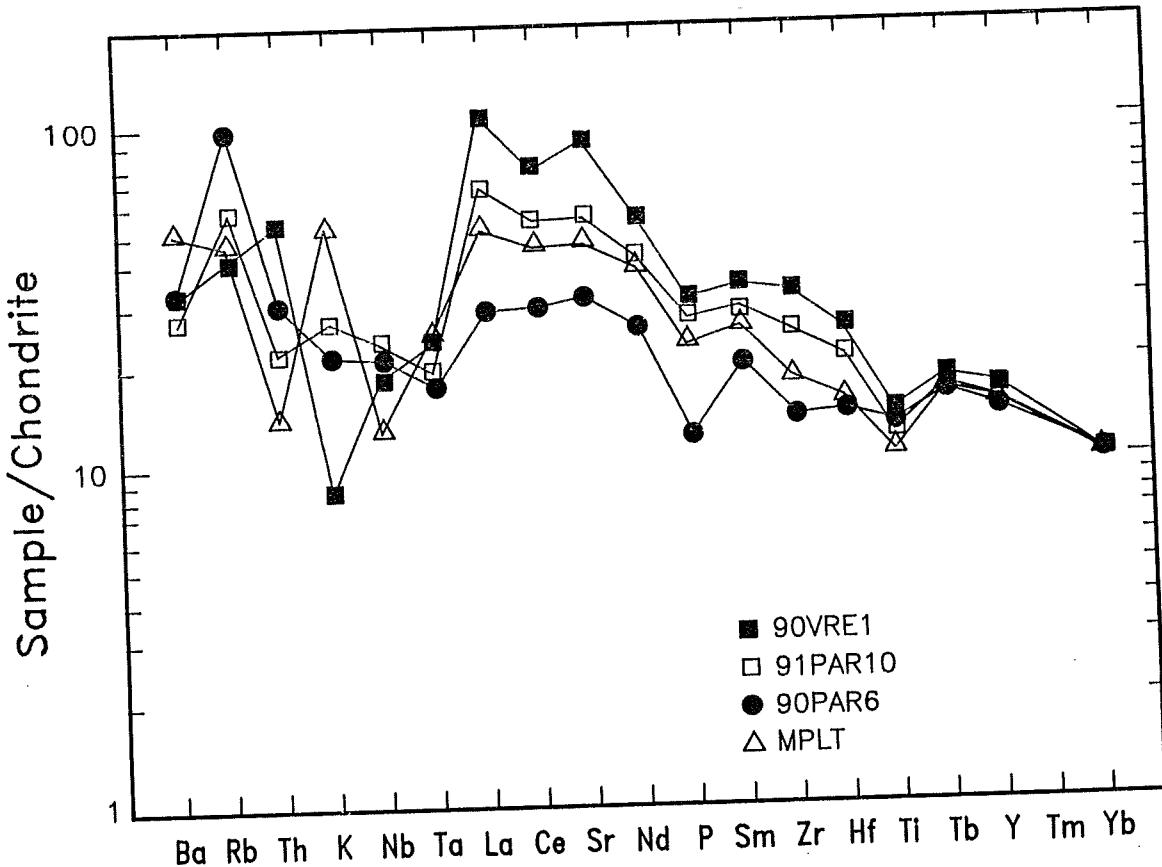


Figure 7: Spider diagram for three Dominion Group mafic lavas from the Vredefort area, representing the range in incompatible elements from most depleted (90PAR6) to most enriched (90VRE1) lavas, compared to the average ( $N=7$ ) primitive low Ti/V group I (MPLT) composition from Marsh *et al.* (1989). Trace elements arranged in order of increasing compatibility with mid-ocean ridge basalt from left to right; double-normalized to chondritic values (except Rb, K and P which are normalized to "undepleted mantle") and a normalized Yb value of 10, after the method of Thompson (1982).

Chondrite-normalized patterns show REE systematics in more detail in Figure 8. REE contents are low and generally increase with increasing fractionation (e.g. Ce vs. Zr, Figure 6). LREEs are enriched over heavy rare earth elements (HREE) and LREE/HREE increases with fractionation. Normalized Ce/Yb ( $Ce_N/Yb_N$ ) values range from about 5 to 10 and increase with increasing fractionation (Figure 9). REE patterns of Vredefort-area samples are similar to the average group I Dominion mafic lava type in the Klerksdorp area, from the data of Marsh *et al.* (1989), and to sample DB255 from one of the same boreholes (Figure 8).

## Mineral Chemistry

Compositions of amphibole, plagioclase, oxide and sphene are shown in Tables 3 to 5. Amphiboles are calcic with low Na, K and Ti contents, and range from magnesio-hornblende to ferro-hornblende in the terminology of Leake (1978). One sample (91VRE2) shows a continuous range of amphibole compositions from hornblende to actinolite (Figure 10). Hornblendes are relatively rich in the tschermakitic component with Si cations = 6.5-7.0 and low Si/Al ratios compared to actinolite. For comparison, a few representative analyses of actinolites from Dominion mafic lavas in the Klerksdorp area are shown in Table 3.

The composition of amphibole is related both to metamorphic grade and to bulk rock composition. On plots of  $Si/Al^{total}(Al^{IV+VI})$  vs. Mg# ( $Mg/Mg+Fe^{2+}$ ) amphibole (Figure 10) and Mg# amphibole vs. Mg# bulk rock (Figure 11) Dominion samples from the Vredefort area are distinct from those from the Klerksdorp area over a range of Mg#.

Na content of amphibole is related to pressure during metamorphism (Laird and Albee, 1981). The low Na/(Ca+Na) ratios of Vredefort-area Dominion samples are similar to metabasites from low to medium pressure terranes (Figure 12). The trend of increasing  $Al/(Si+Al)$  in hornblendes may be related to increasing temperature of metamorphism at constant pressure (Laird and Albee, 1981; Spear, 1981a).

Plagioclases in Vredefort-area amphibolites are calcic bytownites to anorthites  $An_{88-92}$  with negligible  $K_2O$ ,  $FeO$  and  $MgO$  contents, whereas feldspar in greenschist facies mafic lavas are albites accompanied by minor alkali feldspar (Table 4 and Figure 13).

Compositions of oxides and sphene are shown in Table 5. The analysed oxides are ilmenites with about equal Ti and Fe contents.

## DISCUSSION

In a detailed petrological study of Dominion Group volcanic samples from seven boreholes in the Klerksdorp area, Marsh *et al.*, (1989) identified four types of mafic lavas: primitive low Ti/V (group I), evolved low Ti/V (group II), primitive high Ti/V (group III), and evolved high Ti/V (group IV). Group I are the most primitive type with high Mg#, Ni and Cr contents and low incompatible element and REE contents. Groups II-IV are more evolved, group IV ranging to siliceous andesites with up to 60 wt%  $SiO_2$ ,  $TiO_2$  up to 2 wt%,

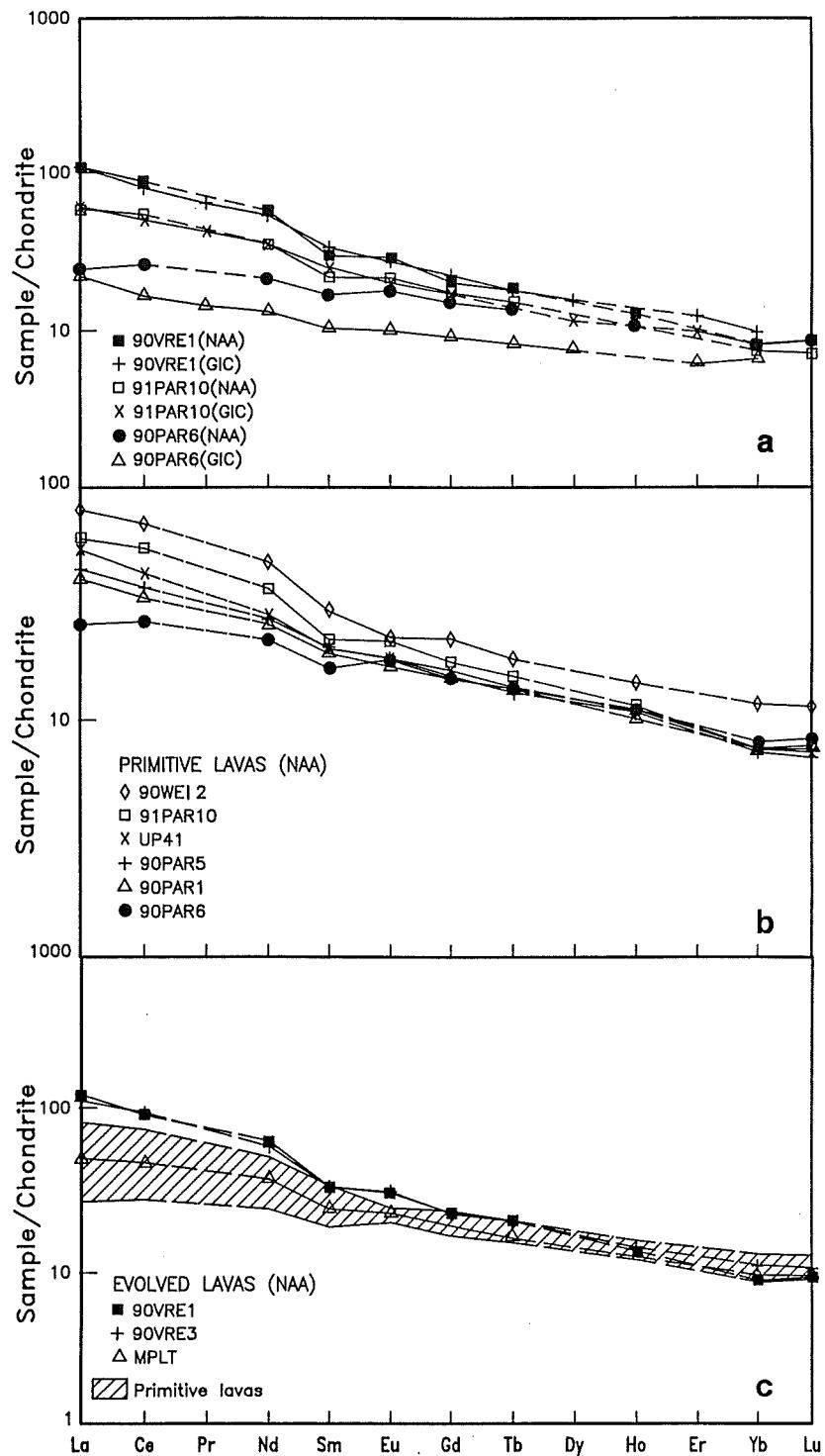
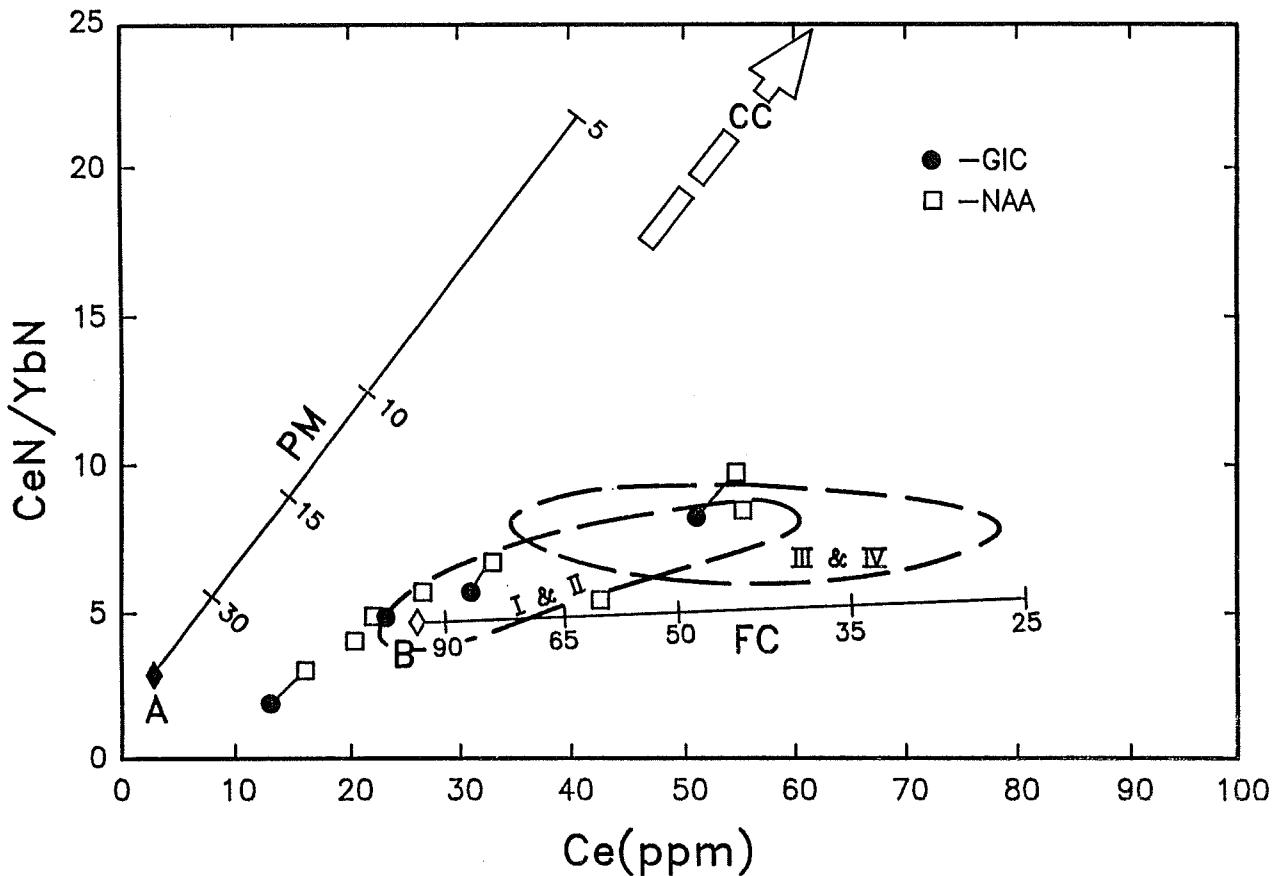


Figure 8: Chondrite-normalized rare earth element diagram. Chondritic normalization values from Sun and McDougall (1989). 8a - comparison of GIC and NAA data for three samples. 8b - NAA data for primitive mafic lavas. 8c - NAA data for two evolved lavas compared to field for primitive lavas and mean primitive low Ti/V (MPLT) composition from Klerksdorp area from Marsh et al. (1989).



*Figure 9: Chondrite-normalized  $Ce_N/Yb_N$  versus  $Ce$  (ppm) diagram. Vredefort-area DG samples plotted, REE determinations by both GIC and NAA with values for the same sample by the two methods joined by tie-lines. Modelled trends for equilibrium fractional crystallization (FC) and batch partial melting (PM). Numbers at tick marks on each trend indicate fraction of liquid (F) in percent, i.e. degree of melting for PM and amount of liquid left after crystallization for FC. Source composition for PM model (A) is garnet peridotite xenolith in kimberlite from Roberts Victor Mine, South Africa (#187, Philpotts et al., 1972, table 1). Assumed modal composition of source is the average of 23 garnet lherzolite xenoliths from South Africa (Mathias et al., 1970): 66% olivine (Ol), 25% orthopyroxene (opx), 6% garnet, 3% clinopyroxene (cpx). Parental liquid composition for FC model (B) is average of seven group I DG mafic lavas from Marsh et al. (1989), table IV. Fractionating assemblages are:  $F=90 - 10\%$  ol;  $F=65 - 15\%$  ol, 20% cpx;  $F=50 - 25\%$  ol, 25% cpx, 10% plagioclase (pl);  $F=35 - 15\%$  ol, 30% cpx, 20% pl;  $F=25 - 25\%$  ol, 35% cpx, 40% pl. Partition coefficients shown in Table 7. Fields for Klerksdorp area mafic lavas from Marsh et al. (1989), low Ti/V groups (I and II) and high Ti/V groups (III and IV). CC - vector for crustal contamination (see text).*

TABLE 3. Compositions of amphiboles in Dominion Group metavolcanics from the Vredfort area

Sample #	90%FE3										90%FE2A										90%FE3									
	1	2	3	4	5	6	7C	7R	8C	8R	1	2	3	4	5C	5R	1	2	3	4	5	6C	6R	1	2	3	4	5	6	7
N	3	3	4	3	1	2	2	1	1	1	2	2	2	2	3	4	1	2	2	2	3	5	4	1	2	2	2	3	5	4
Si	43.95	44.17	44.04	43.85	45.12	43.48	43.68	44.18	44.36	42.89	46.01	45.48	44.44	42.68	44.80	43.96	43.47	43.46	42.78	46.66	46.41	47.74	47.53	47.51	48.33	47.67				
Al[Ni]	0.42	0.45	0.41	0.41	0.45	0.45	0.41	0.28	0.44	0.39	0.38	0.40	0.39	0.32	0.45	0.46	0.50	0.51	0.43	0.36	0.55	0.40	0.45	0.43	0.36	0.42	0.36			
Al[Cr]	14.04	14.06	13.60	13.93	12.51	14.50	14.56	13.84	13.87	15.39	9.52	11.20	10.81	16.34	13.23	13.77	13.68	13.70	15.51	10.65	10.04	8.98	9.07	9.06	8.97	8.80	8.80			
Cr[203]	BD	BD	BD	BD	BD	BD	BD	BD	BD	0.05	BD	0.15	0.18	0.17	0.12	0.12	0.12													
Fe[80*]	20.18	19.83	20.20	20.31	19.44	20.25	19.63	19.78	19.67	19.55	20.41	21.12	20.55	20.85	20.71	20.97	20.96	20.38	16.90	16.94	16.14	15.77	16.27	15.76	15.92	15.92				
MnO	0.32	0.29	0.25	0.29	0.26	0.25	0.27	0.28	0.24	0.28	0.29	0.28	0.28	0.25	0.27	0.32	0.27	0.30	0.30	0.24	0.26	0.25	0.25	0.26	0.19	0.19				
MgO	7.86	7.97	8.01	7.94	8.73	7.79	7.82	7.88	8.13	7.45	8.66	8.24	8.16	6.14	7.37	7.29	7.16	7.13	6.36	10.75	11.95	11.60	11.64	12.08	11.97	11.97				
CaO	11.21	11.17	11.27	11.03	11.28	11.17	11.38	11.19	11.32	11.52	11.99	12.10	11.88	11.53	11.66	11.71	11.63	11.55	11.47	12.37	12.21	12.40	12.21	12.26	12.32	12.32				
Na2O	1.12	1.10	1.13	1.13	1.00	1.19	1.16	1.09	1.15	1.23	0.80	0.93	0.85	1.07	1.07	1.02	1.06	1.02	1.06	0.88	0.88	0.75	0.73	0.77	0.71	0.70				
Al[20]	0.20	0.20	0.17	0.21	0.15	0.24	0.17	0.18	0.20	0.24	0.15	0.15	0.17	0.07	0.07	0.07	0.07	0.07	0.07	0.23	0.30	0.19	0.22	0.19	0.16	0.17				
H2O*	2.03	2.03	2.02	2.02	2.03	2.02	2.03	2.02	2.02	2.00	2.00	2.03	1.98	2.02	2.03	2.02	2.01	2.00	2.00	2.05	2.03	2.06	2.04	2.05	2.07	2.04				
Total	101.33	101.27	101.10	101.12	100.97	101.35	101.12	100.72	101.41	100.96	100.21	101.93	99.52	101.27	101.66	101.59	100.84	100.72	100.36	101.14	100.36	101.02	100.05	100.60	101.08	100.12				

N = Number of spot analyses averaged for mean

B. B. D. D. 1000

BU - Below detection limit.

$\text{FeO}^*$  - Total iron analysed as  $\text{FeO}$ .

$\text{H}_2\text{O}^*$ - $\text{H}_2\text{O}$  calculated from

TABLE 3. (Continued).

Sample #	UP41				91PAR10				90PAR3				91YRE2				DB248				DB255					
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4		
N	3	2	2	3	46.91	46.94	46.50	47.33	46.70	48.40	48.65	47.46	45.46	45.32	46.88	49.18	45.71	46.46	47.99	51.42	53.44	52.42	53.83	55.20		
Si	0.46	0.43	0.40	0.42	0.46	0.43	0.31	0.29	0.43	0.31	0.29	0.40	0.36	0.52	0.33	0.23	0.42	0.30	0.26	0.16	0.01	0.01	0.01	0.01		
Ti	0.25	0.45	10.84	10.25	0.20	0.19	0.19	0.19	10.31	8.19	7.74	9.88	11.13	12.02	7.47	5.74	9.60	9.08	7.17	4.33	2.28	3.44	2.32	1.59		
Al <sup>vi</sup>	0.20	0.22	0.20	0.19	0.22	0.07	0.16	0.19	0.22	0.07	0.16	0.19	0.01	0.01	0.12	0.16	0.30	0.17	0.16	0.08	0.01	0.12	0.01	0.01		
Cr <sup>vi</sup>	16.18	15.82	16.67	15.76	15.31	15.39	15.55	14.93	18.72	18.54	17.06	18.15	19.73	19.28	18.91	18.01	13.35	13.84	12.59	12.17						
Fe <sup>vi</sup>	0.30	0.31	0.33	0.30	0.21	0.25	0.25	0.22	0.30	0.31	0.23	0.41	0.38	0.39	0.38	0.37	0.21	0.27	0.21	0.27	0.17	0.20				
MnO	11.34	11.50	10.73	11.55	12.33	13.46	13.81	12.58	9.71	9.26	11.54	11.52	9.41	9.87	10.81	12.50	15.04	14.42	15.88	16.51						
MgO	11.97	12.11	11.89	12.02	11.63	11.07	10.66	11.73	12.07	12.23	12.14	12.13	12.04	11.92	12.12	12.29	12.89	12.73	12.82	12.86						
CaO	0.80	0.71	0.82	0.79	0.84	0.67	0.62	0.80	0.94	0.92	0.53	0.43	0.72	0.66	0.54	0.28	0.23	0.24	0.23	0.24	0.17	0.13				
Na <sub>2</sub> O	0.18	0.15	0.17	0.16	0.15	0.10	0.09	0.13	0.17	0.21	0.11	0.03	0.11	0.08	0.07	0.01	0.08	0.10	0.08	0.10	0.06	0.06				
K <sub>2</sub> O	2.05	2.03	2.04	2.06	2.05	2.05	2.05	2.06	2.03	2.04	2.04	2.02	2.01	2.01	2.02	2.06	2.07	2.06	2.07	2.06	2.09	2.11				
H <sub>2</sub> O <sup>vi</sup>	100.64	99.67	100.59	100.85	100.18	99.96	99.87	100.38	100.90	101.38	100.45	100.00	100.43	100.22	100.43	101.51	99.61	99.65	99.35	100.85						
Total																										
Si	6.86	6.93	6.82	6.89	6.83	7.07	7.10	6.91	6.73	6.67	7.17	7.29	6.83	6.93	7.12	7.48	7.74	7.62	7.73	7.83						
Al <sup>vi</sup>	1.14	1.07	1.18	1.11	1.17	0.93	0.90	1.09	1.27	1.33	0.83	0.71	1.17	1.07	0.88	0.53	0.26	0.38	0.27	0.17						
Ti	0.05	0.05	0.04	0.05	0.05	0.04	0.03	0.04	0.04	0.06	0.04	0.03	0.05	0.05	0.03	0.03	0.02	0.00	0.00	0.00	0.00	0.00				
Cr	0.02	0.03	0.02	0.02	0.03	0.01	0.02	0.02	0.00	0.00	0.01	0.00	0.02	0.04	0.02	0.02	0.01	0.00	0.01	0.00	0.00	0.00				
Fe	1.98	1.95	2.04	1.92	1.87	1.88	1.90	1.82	2.32	2.28	2.09	2.25	2.47	2.40	2.35	2.19	1.62	1.68	1.51	1.44						
Mn	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.04	0.03	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.03	0.02	0.02	0.02				
Mg	2.47	2.53	2.35	2.51	2.69	2.93	3.01	2.73	2.14	2.03	2.52	2.55	2.10	2.19	2.39	2.71	3.25	3.12	3.40	3.49						
Ca	1.88	1.91	1.87	1.87	1.82	1.73	1.67	1.83	1.92	1.93	1.91	1.93	1.90	1.93	1.92	2.00	1.98	1.95								
Na	0.23	0.20	0.23	0.22	0.24	0.19	0.18	0.23	0.27	0.26	0.15	0.12	0.21	0.19	0.16	0.08	0.06	0.07	0.05	0.04	0.01	0.01	0.01			
K	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.04	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01		
Sum	15.32	15.31	15.32	15.30	15.35	15.31	15.28	15.32	15.42	15.39	15.23	15.24	15.37	15.34	15.30	15.18	15.09	15.11	15.10	15.05						
Mg <sup>#</sup>	56	56	53	57	59	61	61	60	48	47	55	53	46	48	50	55	67	65	68	69	71					

TABLE 4. Composition of plagioclases in Dominion Group metavolcanics from the Vredefort area

Sample #	90PAR3				90VRE2		DB248	
	Plag.#	1	2	3	4	1	2	1
N.	1	1	1	1	2	2	2	2
SiO <sub>2</sub>	46.50	47.41	46.99	47.33	46.90	46.55	67.64	68.30
Al <sub>2</sub> O <sub>3</sub>	34.25	33.87	34.23	33.54	33.62	33.71	20.60	20.07
FeO*	0.01	0.01	0.01	0.01	0.08	0.01	0.10	0.18
MgO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CaO	18.02	17.43	17.75	17.36	17.63	17.53	1.67	1.09
Na <sub>2</sub> O	0.90	1.28	1.04	1.24	1.26	1.25	10.42	11.14
K <sub>2</sub> O	0.01	0.01	0.01	0.01	0.01	0.01	0.50	0.09
Total	99.70	100.02	100.04	99.50	99.51	99.07	100.94	100.88

Atomic Proportions on the Basis of 8 Oxygens.

Si	2.14	2.17	2.15	2.18	2.16	2.16	2.94	2.97
Al	1.86	1.83	1.85	1.82	1.83	1.84	1.06	1.03
Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.89	0.86	0.87	0.86	0.87	0.87	0.08	0.05
Na	0.08	0.11	0.09	0.11	0.11	0.11	0.88	0.94
K	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00
Sum	4.97	4.97	4.96	4.97	4.97	4.98	4.99	5.00

An	92	88	91	89	89	89	8	5
Ab	8	12	9	11	11	11	89	94
Or	0	0	0	0	0	0	3	1

N-Number of spot analyses averaged for mean

FeO\*- Total iron analysed as FeO

and high K<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, and incompatible trace element contents, but low Ni and Cr. In addition to Ti/V, low Ti/V and high Ti/V groups are mainly distinguished by higher and lower Ti/Zr respectively. Stratigraphically, in the Klerksdorp area, the mafic lava types are interbedded along with the felsic volcanics in semi-consistent units of low Ti/V (groups I and II) and high Ti/V (groups III and IV) lavas in each sampled borehole. There is a general tendency for low Ti/V units to occur near the top of the boreholes above the high Ti/V units (see Marsh *et al.*, 1989, fig. 2).

Compared to the average "primitive low Ti/V type" (group I), which they resemble most closely, Vredefort-area amphibolites are depleted in Na<sub>2</sub>O and K<sub>2</sub>O, and enriched in

TABLE 5. Compositions of oxides in Dominion Group metavolcanics from the Vredefort Area

Sample #	90VRE1				90VRE3				90PAR6		
	1	2	3	4	1	2	3	4	1*	2	3
Oxide #	1	1	2	1	1	2	1	1	1	3	2
N.	1	1	2	1	1	2	1	1	1	3	2
SiO <sub>2</sub>	0.14	0.08	0.26	BD	BD	BD	1.38	BD	30.34	BD	BD
TiO <sub>2</sub>	52.16	55.67	52.34	52.05	51.73	52.28	50.08	51.29	39.43	52.73	54.36
Al <sub>2</sub> O <sub>3</sub>	BD	0.07	BD	BD	BD	BD	0.89	BD	0.93	BD	BD
FeO*	44.54	33.41	45.99	45.48	45.15	44.95	44.44	44.46	0.74	44.34	41.73
MnO	2.04	1.63	1.31	1.39	1.21	1.31	1.31	1.25	BD	1.62	1.87
MgO	BD	BD	BD	BD	BD	0.08	BD	0.15	BD	0.12	0.06
CaO	0.16	7.94	0.03	0.06	0.18	0.10	0.31	0.11	28.82	0.17	0.24
Total	99.04	98.80	99.93	98.98	98.27	98.72	98.41	97.26	100.26	98.98	98.26
<u>Atomic Proportions on the Basis of 6 Oxygens:</u>											
Si	0.01	0.00	0.01	0.00	0.00	0.00	0.07	0.00	1.19	0.00	0.00
Ti	2.00	2.06	1.99	2.00	2.00	2.01	1.91	2.00	1.16	1.99	2.07
Al	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.04	0.00	0.00
Fe	1.90	1.38	1.95	1.95	1.94	1.92	1.89	1.93	0.02	1.86	1.77
Mn	0.09	0.07	0.06	0.06	0.05	0.06	0.06	0.06	0.00	0.07	0.08
Mg	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00
Ca	0.01	0.42	0.00	0.00	0.01	0.01	0.02	0.01	1.21	0.01	0.01
Sum	4.00	3.93	4.01	4.01	4.01	4.00	4.00	4.00	3.63	3.93	3.94

N - Number of spot analyses averaged for mean

BD - Below detection limit

FeO\* - Total iron analysed as FeO.

90PAR6-1\* = sphene

CaO and Al<sub>2</sub>O<sub>3</sub> (Table 1B; Figures 2-4). Like the average group I composition from the data of Marsh *et al.* (1989, Table 1B), the Klerksdorp borehole samples analysed in our laboratory have higher alkalies and lower CaO content than the Vredefort-area samples (Table 1A), so this difference is not due to interlaboratory bias.

These compositional differences are most likely the result of different metamorphic histories resulting in different mineralogy and possibly different fluid/rock ratios during alteration. Greenschist facies metamorphism in the Klerksdorp area at lower temperature and higher fluid/rock ratio led to depletion in Ca and enrichment in Na ( $\pm$  K) accompanied by an increase in H<sub>2</sub>O ( $\pm$  CO<sub>2</sub>) in the Dominion mafic lavas. Na went into abundant albite, whereas Ca is a main component only in minor phases: actinolite, clinozoisite and calcite. In the amphibolite-facies mineral assemblage, however, Ca is stable in both abundant hornblende and calcic plagioclase but there are no abundant Na-bearing minerals. Thus Na is mobile leading to very low Na in some Vredefort-area Dominion samples (e.g. 90PAR5, Table 1B). K is very low in the amphibolites but highly variable with some high values in the greenschist-facies rocks (Figure 4).

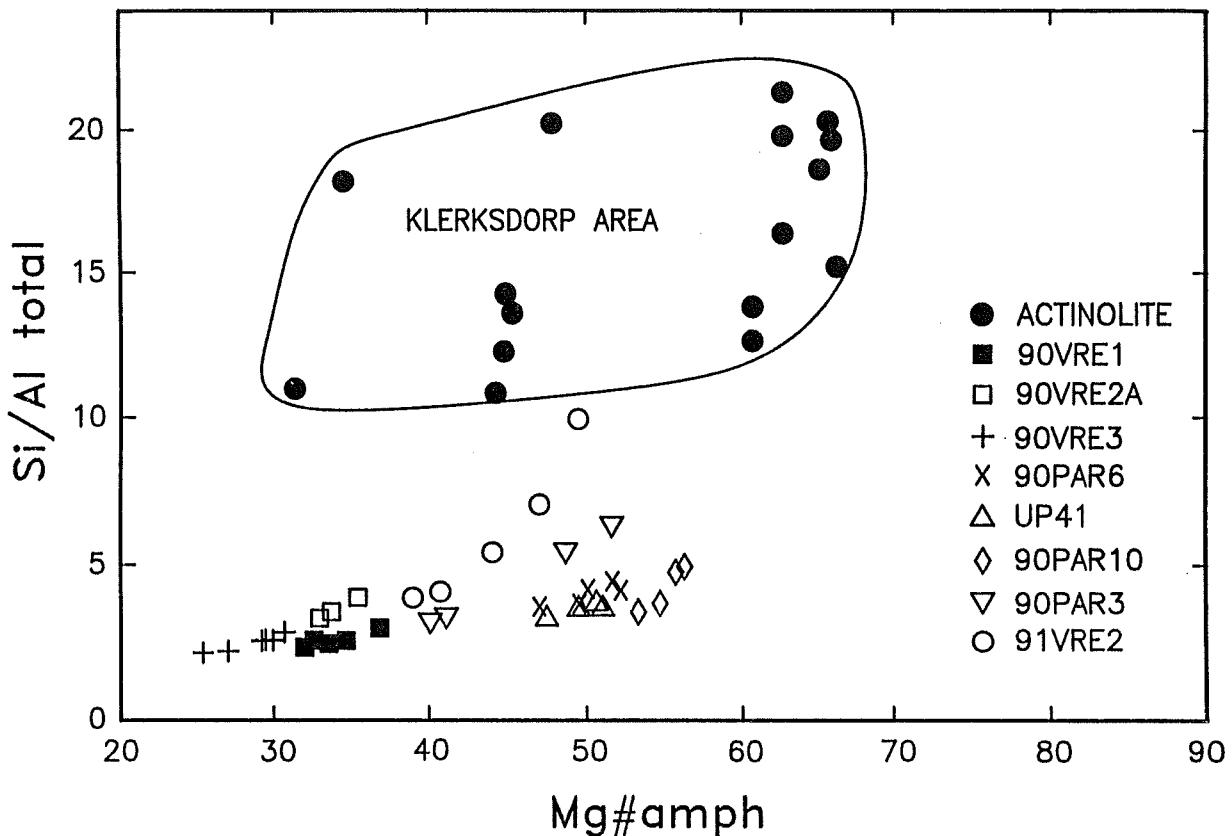


Figure 10: Amphibole  $\text{Si}/\text{Al}^{\text{total}}(\text{Al}^{\text{IV}} + \text{VI})$  cations versus amphibole  $\text{Mg}\#$  ( $\text{Mg}^{2+}/\text{Mg}^{2+} + \text{Fe}^{2+}$ ). Actinolites from Klerksdorp area samples compared to hornblendes from Vredefort area.

### Petrogenesis

Petrogenetic modelling of the Dominion Group mafic lavas is hampered by the lack of primary phases in the recrystallized metavolcanics and the scatter of compositions on major element and trace element variation diagrams. This allows few constraints to be placed on magmatic evolutionary models and preferred scenarios rest strongly on assumptions of source composition, melting process and intensive parameters of fractionation.

Original work by M. Bowen (1984) assumed that all Klerksdorp-area Dominion mafic lavas represented a single liquid line of descent in spite of their scatter on variation diagrams. Bowen (1984) used graphical analysis of silica variation diagrams and systematics of immobile incompatible trace elements (Nb, Ti, Y, Zr) to model crystal fractionation as a two-step process: initial fractionation was dominated by hornblende leading to an increase in  $\text{Al}_2\text{O}_3$ , accompanied by decreasing  $\text{CaO}$  and  $\text{MgO}$ , with increasing  $\text{SiO}_2$ ; the second stage was extensive fractionation of plagioclase and orthopyroxene to account for decreasing  $\text{Al}_2\text{O}_3$  from the intermediate to most siliceous differentiates. However, more rigorous modelling of the same data by Marsh *et al.* (1989) showed that hornblende fractionation could not account for trace element variation within group I samples.

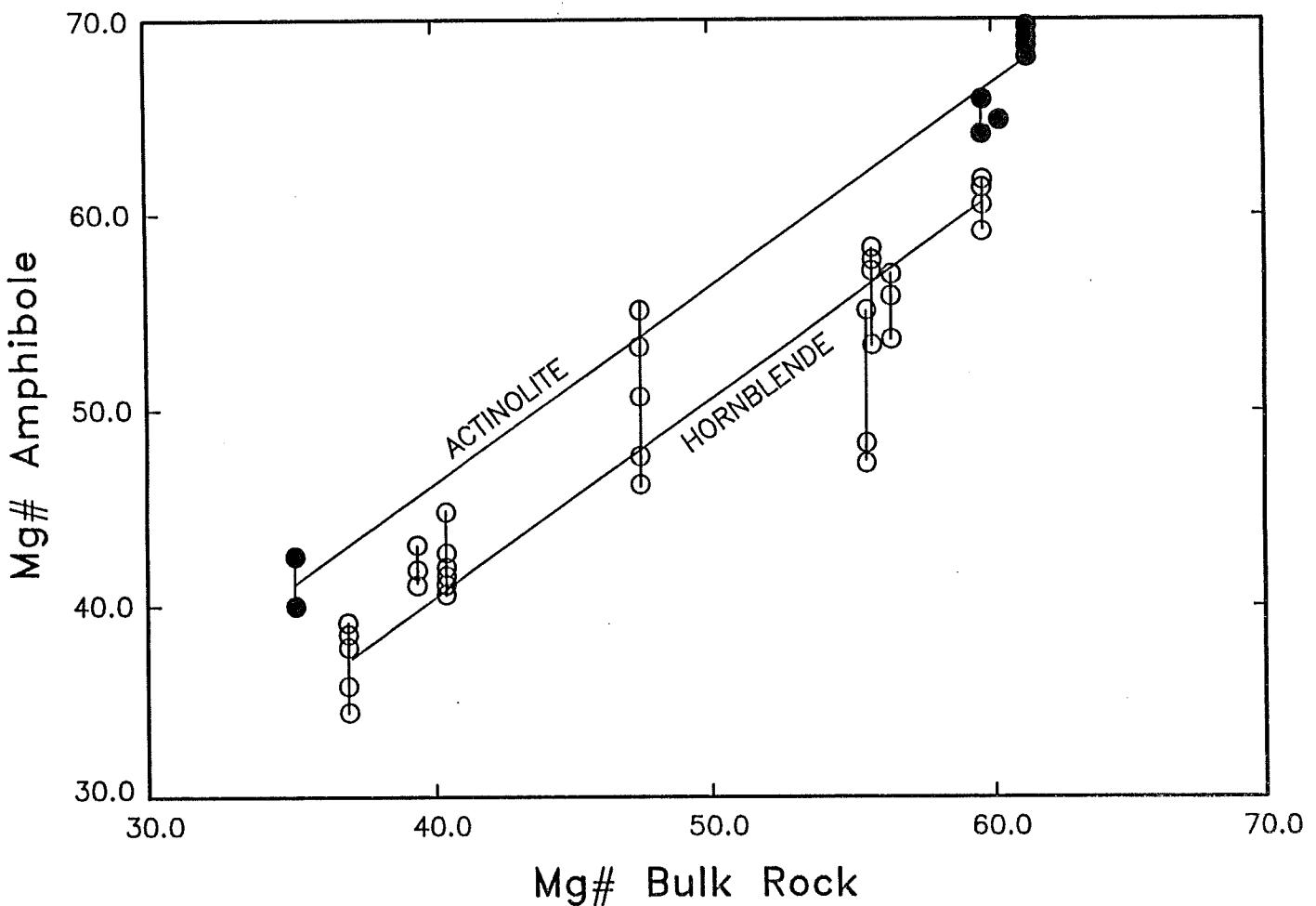


Figure 11: Amphibole Mg# versus bulk-rock Mg# (all Fe as FeO) as in Table 1B). Symbols as in Figure 10. Actinolites from Klerksdorp area (solid dots) compared to hornblendes from Vredefort area (open dots).

Marsh *et al.* (1989) suggested that group I basalts evolved from primary mantle-derived liquids by fractionation of small amounts of olivine ( $\pm$  Cr-spinel). The range in composition of group I basalts was explained by variable degrees of melting of a heterogenous mantle source to produce a range of primary magmas. The more evolved groups II-IV mafic lava types probably developed by fractional crystallization involving olivine, pyroxene and plagioclase with minor FeTi oxide in the later stages according to these authors. This assumed fractionation sequence is typical of that thought to occur in shallow-level tholeiitic magma chambers. The difference between the low and high Ti/V suites was tentatively attributed to differing partition coefficients for Ti and V and/or differing  $fO_2$  conditions during fractionation (Marsh *et al.*, 1989).

In this paper quantitative models for the origin of Vredefort-area Dominion mafic lavas are explored. Since Dominion Group lavas overlie continental crust in the form of granitoid basement, it can be assumed that they traversed this crust if they originated by partial melting in the upper mantle or sub-continental lithosphere. Thus, partial melting and fractionation may have occurred at relatively high pressures (at the base of the crust) and

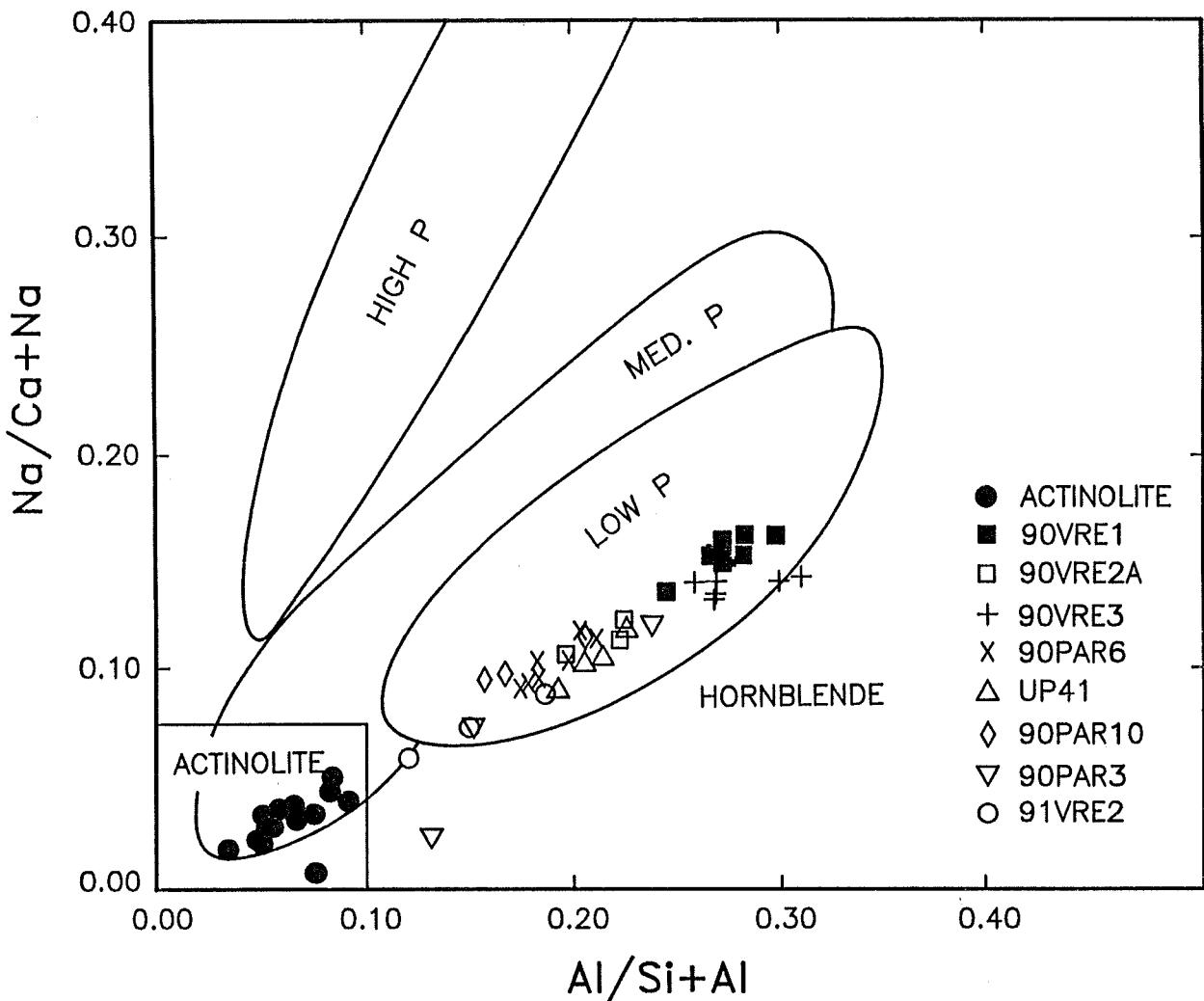


Figure 12:  $Na/Ca+Na$  cations in amphibole versus  $Al/(Si+Al)$  cations. Actinolites from Klerksdorp area samples compared to hornblendes from Vredefort area. Low P. Med. P and High P fields for low pressure, medium pressure and high pressure facies series in mafic schists from Laird and Albee (1981).

crustal (or lithospheric) contamination could have occurred during magma ascent. The tholeiitic fractionation trends defined by evolved Dominion lavas, and the rare occurrence of plagioclase-phyric flows (M. Bowen, 1984), suggest plagioclase-dominated fractionation (i.e. low pressure) in shallow-level magma chambers at least in the later stages. On the other hand, compositional variation among the more primitive lavas, especially a decoupling of major element and incompatible trace element behaviour, implies complex processes in their origin. This could have been variable degrees of partial melting, source heterogeneity, magma mixing or contamination, or a combination of these processes.

Crystal fractionation models, which are only a few of several models permitted by the data, are presented in Table 6 for some representative Vredefort-area Dominion samples. In the first model (Table 6, no. I), the most primitive basalt (91PAR10,  $Mg\# = 60$ ), is the

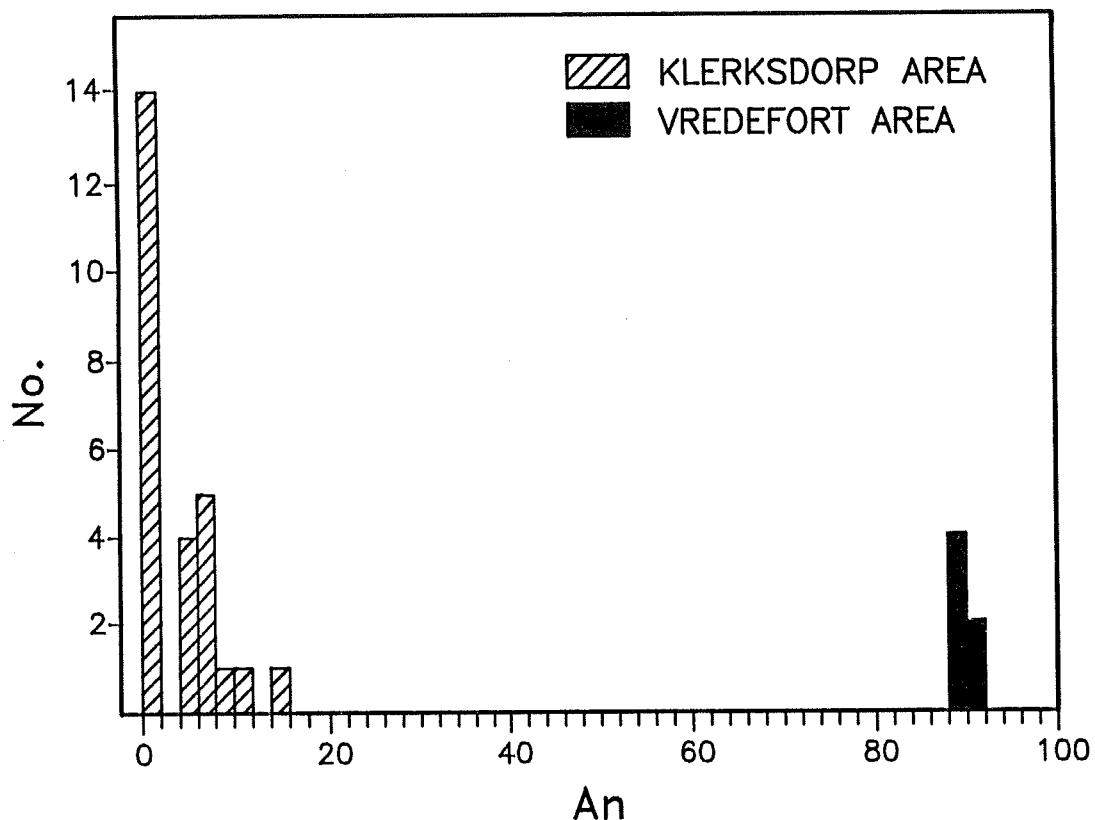


Figure 13: Histogram showing plagioclase composition in terms of mole percent anorthite component for Vredefort area amphibolites and Klerksdorp area greenschist-facies metavolcanics.

assumed parent liquid and an evolved andesite (90VRE1, Mg#=41) is the final derivative. Least-squares calculations show that 33% fractionation of olivine + clinopyroxene + plagioclase in the proportions 40:30:30 is sufficient to account for the major element variation. However, the least-squares fit of this solution is poor (sum  $R^2 = 1.21$ ). The observed increase in Si, Ti and P, and decrease in Mg is well accounted for by this model; however, observed increases in Al and Fe are more than predicted. The alkalis and trace elements do fit this model. Alkalies may have been redistributed by alteration but the trace element discrepancies indicate that this model is inadequate. Very large decreases in Ni and Cr contents and the increase in Sr are much greater than predicted; for the incompatible elements, Zr increase is accommodated by the model, but Ce, Yb and especially the observed increase in  $\text{Ce}_N/\text{Yb}_N$  are not predicted. Thus the simplest model, involving closed-system equilibrium fractionation of tholeiitic mineral phases, which gives the best fit to the major element spread of the data, is inadequate to explain the wide range of trace element concentrations and ratios. More complex models of open-system fractionation, different degrees of partial melting, contamination or mixing are thus required. The entire range of compositions was probably generated in a multi-step process as explored below.

A more realistic model, suggested by the apparent inflection in  $\text{Al}_2\text{O}_3$  variation (Figure 4), also noted by M. Bowen (1984), is a two-step process involving a change in fractionating crystal assemblage, using sample 90PAR3 as an intermediate composition (Table

6, Nos. II and III). The suggestion of M. Bowen (1984) of early fractionation of hornblende is illustrated for a different primitive parent magma (UP41, Mg#=57) in Table 6 (no. II). The increase in Al is accounted for by this model, but the predicted increase in Si and decrease in Ti are not observed, and trace elements again do not fit the model.

Alternatively, if early magmatic evolution proceeded along a path defined by UP41 as the parent and 90PAR3 as the intermediate derivative, the negligible change in Si with substantial decrease in Mg may be accounted for by 8% orthopyroxene fractionation (Table 6, no. III). This model accounts for the major element variation but again the trace elements do not fit, especially a predicted increase in Ni and Cr. The second step in this model derives andesite 90VRE1 from the intermediate parent 90PAR3 by 54% crystallization of olivine + clinopyroxene + plagioclase in the proportions 11:47:42.

Even with these more complex models, closed-system equilibrium crystal fractionation alone cannot account for the observed variation in compatible elements or incompatible trace element ratios. Large decreases in Ni and Cr might be explained by higher partition coefficients in olivine and pyroxene and removal of Cr-spinel. However, the observed range of LREE/HREE is not easily explained by any fractionation process. In Figure 9, two modelled trends show the change in  $Ce_N/Yb_N$  and Ce for processes of equilibrium fractional crystallization (FC) and batch partial melting (PM). The fractional crystallization model was calculated using the average group I primitive mafic lava composition from the Klerksdorp area as an assumed parent magma and fractionating a changing mineral assemblage initially dominated by olivine, then clinopyroxene and finally plagioclase. The resulting flat trend on Figure 9 shows that fractional crystallization cannot duplicate the observed increase in  $Ce_N/Yb_N$  from the most primitive to the most evolved mafic lavas. The partial melting model was calculated assuming modal melting of a typical garnet lherzolite assemblage such as that observed in xenoliths in kimberlites from the Kaapvaal Craton and presumed to represent the composition of the sub-continental lithosphere (at least in the Mesozoic). The assumed source composition is a garnet peridotite xenolith from the Roberts Victor Mine with an appropriate LREE:HREE ratio to produce compositions similar to the Dominion Group samples on melting. [Many other lherzolite xenoliths in Kaapvaal kimberlites have much higher LREE/HREE and would not be suitable source material (e.g. see BVSP, 1981, chap. 1.2.11; and Philpotts *et al.*, 1972)]. The partial melting model trend shows a dramatic increase in  $Ce_N/Yb_N$  with decreasing degrees of melting due to the presence of 6% garnet in the source which has a high partition coefficient for the HREEs (Table 7).

This simple modelling based on REE compositions suggests that the most primitive Dominion lavas were generated by minor (10-20%) fractionation from a peridotitic upper mantle source (similar to A in Figure 9) or formed by moderate degrees (20-30%) of melting of a more LREE-enriched source. The REE data for the Klerksdorp area lavas, combined with the new data for Vredefort area samples, suggests that compositional variation within the low Ti/V groups (I and II) is dominated by partial melting processes whereas that for the high Ti/V groups (III and IV) can be accounted for by fractional crystallization of a LREE-enriched source. A similar effect of LREE-enrichment can be achieved by contamination or assimilation and fractional crystallization processes as shown qualitatively by the vector in Figure 9 pointing to the range of compositions for granitoid crustal rocks of the Vredefort Dome basement (Hart *et al.*, 1990).

TABLE 6. Fractional crystallization model for the petrogenesis of Vredefort-area Dominion Group lavas

Equilibrium Fractional Crystallization  $C_f = C_o/(F+D(1-F))$

I. PARENT 91PAR10			DERIVATIVE 90VRE1			II. PARENT UP41			DERIVATIVE 90PAR3					
Co(obs)	Cl(obs)	Cl(cal)	Diff.	MINERALS		Co(obs)	Cl(obs)	Cl(cal)	Diff.	MINERALS				
SiO <sub>2</sub>	55.7	58.5	59.0	-0.5	Olivine	-13%	Fo82		54.0	54.8	55.8	-1.0	Hbld.	-16%
TiO <sub>2</sub>	0.80	1.09	1.02	0.07	Cpx	-10%	Mg80		0.71	0.76	0.51	0.25	F =	0.84
Al <sub>2</sub> O <sub>3</sub>	13.5	15.2	14.6	0.6	Plag	-10%	An85		14.2	15.5	15.4	0.1		
FeO*	9.15	9.62	9.20	0.42	Tot. xtais =		-33%		10.7	8.61	8.67	-0.06		
MgO	8.54	4.10	4.20	-0.1	F =	0.67			7.83	6.73	6.99	-0.26		
CaO	9.79	9.64	9.54	0.10					11.1	12.1	11.2	0.9		
Na <sub>2</sub> O	1.93	1.36	2.27	-0.91					1.09	0.90	1.05	-0.15		
K <sub>2</sub> O	0.26	0.09	0.35	-0.26					0.10	0.25	0.00	0.25		
P <sub>2</sub> O <sub>5</sub>	0.18	0.25	0.24	0.01					0.14	0.15	0.16	-0.01		
Sum of squares of residuals = 1.21														
Ni	279	41	236	-195					306	293	334	-41		
Cr	784	11	779	-768					851	821	745	76		
Sr	434	827	587	240					552	623	646	-23		
Zr	111	163	165	-2					95	100	109	-9		
Ce	30.6	51.1	45.3	5.8					26.4	23.1	30.8	-7.7		
Yb	1.43	1.64	2.07	-0.43					1.25	1.29	1.42	-0.13		
CeN/YbN	5.9	8.7	6.1	2.6					5.9	5.0	6.0	-1.0		
Sum of squares of residuals = 1.32														
III. PARENT UP41			DERIVATIVE 90PAR3			IV. PARENT 90PAR3			DERIVATIVE 90VRE1					
Co(obs)	Cl(obs)	Cl(cal)	Diff.	MINERALS		Co(obs)	Cl(obs)	Cl(cal)	Diff.	MINERALS				
SiO <sub>2</sub>	54.0	54.8	54.7	0.1	Opx	-8%	54.8	58.5	57.7	0.8	Olivine	-6%	Fo77	
TiO <sub>2</sub>	0.71	0.76	0.76	0	F =	0.92	0.76	1.09	1.04	0.05	Cpx	-25%	Mg77	
Al <sub>2</sub> O <sub>3</sub>	14.2	15.5	15.4	0.1			15.5	15.2	15.8	-0.6	Plag	-23%	An85	
FeO*	10.7	8.61	9.12	-0.51			8.61	9.62	10.0	-0.38	Tot. xtais =		-54%	
MgO	7.83	6.73	6.45	0.28			6.73	4.10	4.03	0.07	F =	0.46		
CaO	11.1	12.1	12.0	0.1			12.1	9.64	9.90	-0.26				
Na <sub>2</sub> O	1.09	0.90	1.19	-0.29			0.90	1.36	0.66	0.7				
K <sub>2</sub> O	0.10	0.25	0.11	0.14			0.25	0.09	0.38	-0.29				
P <sub>2</sub> O <sub>5</sub>	0.14	0.15	0.15	0			0.15	0.25	0.23	0.02				
Sum of squares of residuals = 0.49														
Ni	306	293	323	-30			293	41	280	-239				
Cr	851	821	911	-90			821	11	448	-437				
Sr	552	623	599	24			623	827	839	-12				
Zr	95	100	103	-3			100	163	206	-43				
Ce	26.4	23.1	28.6	-5.5			23.1	51.1	27.1	24				
Yb	1.25	1.29	1.35	-0.06			1.29	1.64	1.48	0.16				
CeN/YbN	5.9	5.0	5.9	-0.9			5.0	8.7	5.1	3.6				
Sum of squares of residuals = 1.00														

TABLE 7. Partition Coefficients (D=conc. in mineral/conc. in liquid) used in Fractional Crystallization and Partial Melting model calculations in Table 6 and Figure 9

I. Fractional Crystallization

	Doliv(1)	Dcpx(1)	Dopx(1)	Dplag(1)	Damph(1)
Ni	10	2	4	0.01	3
Cr	0.2	10	2	0.01	12
Sr	0.001	0.01	0.01	2.2	0.5
	Doliv(2)	Dcpx(3)	Dopx(3)	Dplag(3)	Damph(4)
Zr	0.025	0.1623	0.0465	0.0126	1.339
Ce	0.0046	0.0838	0.0277	0.2214	0.574
Yb	0.0468	0.6335	0.2540	0.0410	1.488

II. Partial Melting

	Doliv(5)	Dcpx(5)	Dopx(5)	Dgarn(5)
Ce	0.0005	0.0334	0.0109	0.0051
Yb	0.0091	0.4266	0.1195	5.235

Sources:

- (1) - Olivine, clinopyroxene, orthopyroxene, plagioclase and amphibole/liquid partition coefficients for basaltic rocks from Cox *et al.* (1979, table 14.1)
- (2) - Olivine phenocryst/groundmass partition coefficient for olivine tholeiite from Hawaii (Fujimaki *et al.*, 1984, table 2, #5)
- (3) - Clinopyroxene, orthopyroxene, and plagioclase phenocryst/groundmass partition coefficients for calc-alkaline andesite from Japan (Fujimaki *et al.*, 1984, table 2, #8)
- (4) - Hornblende phenocryst/groundmass partition coefficient for calc-alkaline andesite from Japan (Fujimaki *et al.*, 1984, table 3, #9)
- (5) - Olivine, clinopyroxene, orthopyroxene and garnet/matrix partition coefficients for megacrysts in kimberlite from Bentfontein kimberlite pipe, South Africa (Fujimaki *et al.*, 1984, table 1, #1)

Nd isotopic composition, LREE enrichment and high SiO<sub>2</sub> content of Dominion mafic lavas are suggestive of crustal contamination or assimilation and fractional crystallization. However, Marsh *et al.* (1989) were unable to successfully model this process using known Archaean crustal compositions; they noted that Fe and Ti contents were too high in the evolved Dominion lavas, and they concluded that the isotopic character and incompatible trace element enrichment were inherited from the mantle source. However, since the isotopic data of Marsh *et al.* (1989) include only one high Ti/V mafic lava sample, and REE data are also heavily biased toward primitive samples, the possibility of assimilation and fractional crystallization processes affecting the more evolved lavas is still a moot question.

## Metamorphic Petrology

While it has long been recognized that the petrography of the mafic lavas of the Dominion Group in the Klerksdorp and Vredefort areas indicated higher metamorphic grade in the latter area, no attempt has previously been made to quantify or explain this observation. Recent studies of the metamorphic petrology of the Vredefort Dome have concentrated on the granitic and granulitic rocks composing the core of the structure

(Schreyer, 1983; Hart *et al.*, 1991). These showed that metamorphic grade increases dramatically from the collar and Outer Granite Gneiss at amphibolite-facies grade to the core Inlandsee Leucogranofels where high-grade granulite facies rocks occur. This has been explained as an upturned crustal cross-section revealing upper to lower crustal lithologies. On the other hand, Bisschoff (1982) noted the higher grade of "hornblende hornfels facies" rocks in the collar of the Dome and attributed them to contact metamorphism with heat from "concealed intrusions" (probably alkaline granite bodies) in the collar. However, there is no systematic change in the mineral phase assemblage nor in amphibole or plagioclase compositions at constant bulk-rock composition in the entire sampled exposure of Dominion amphibolites around the Vredefort collar. This constancy implies homogeneous metamorphic conditions for the northern and western collar exposures and argues against the suggested contact metamorphism related to alkaline granitoid intrusive bodies in the north (Bisschoff, 1982). Rather, metamorphism appears to be of regionally higher grade in the Vredefort collar rocks compared to the peripheral parts of the Witwatersrand Basin sampled in the goldfields. The widespread occurrence of higher metamorphic grade conditions around the collar suggests that this is a regional phenomenon due to deeper burial of basal strata near the centre of the Witwatersrand Basin and/or to the additional heat supplied by the abundant mafic intrusives in the collar section (Figure 1).

Although conventional wisdom previously assumed that the overlying arenaceous strata of the Witwatersrand Supergroup were essentially unmetamorphosed (Minter, 1979), recent studies, concentrating on pelitic units, have shown widespread greenschist facies metamorphic conditions of  $350 \pm 50^\circ\text{C}$  temperature and 1-3 kb pressure (Phillips, 1987; Wallmach and Meyer, 1990; Phillips and Law, 1992) and ubiquitous alteration (Phillips, 1988; Sutton *et al.*, 1990) in parts of the sequence sampled at numerous gold mines around the periphery of the basin. Locally occurring kyanite-bearing assemblages (Schreyer and Bisschoff, 1982) and assumptions based on the thickness of overlying strata indicate relatively high pressure metamorphic conditions, 2.5 to 4.5 kb, at least locally (Wallmach and Meyer, 1990). Witwatersrand sediments in the collar of the Vredefort Dome are acknowledged to be metamorphosed to higher grade than those on the basin margins; temperature and pressure conditions increase from about  $400^\circ\text{C}$  at 2 kb in the collar to over  $700^\circ\text{C}$  at 5 kb for the core granulites (Bisschoff, 1982; Schreyer and Abraham, 1978) suggesting a high geothermal gradient of about  $50^\circ\text{C}/\text{km}$  (Phillips, 1987).

### **P-T Conditions and the Greenschist-Amphibolite Transition**

The change of metabasite mineral assemblage from chlorite+albite+quartz±actinolite±clinozoisite in the greenschist-facies Dominion mafic lavas of the Klerksdorp area to hornblende+quartz+Ca-plagioclase in the Vredefort area represents a change in P-T conditions of metamorphism, whether due to local (intrusive) or regional heat sources. Experimental work has constrained the temperature of this change, based on the disappearance of chlorite, at  $550^\circ\text{C}$  at 2 kb to  $575^\circ\text{C}$  at 5 kb at  $\text{fO}_2$  of QFM (Liou *et al.*, 1974). The same experimental work and observation of natural assemblages (e.g. Cooper and Lovering, 1970; Laird, 1980; Laird and Albee, 1981) shows that a change in amphibole and plagioclase composition occurs in about the same temperature interval; amphibole composition, in changing from actinolite to hornblende, increases in Al, Ti, Na and K, and

decreases in Si, and plagioclase increases in Ca and Al ( $\text{Al}^{\text{total}}$  and  $\text{Al}^{\text{IV}}$ ), with corresponding decreases in Na and Si.

Spear (1980, 1981b) examined the systematics of exchange reactions between plagioclase and amphibole in the greenschist-amphibolite facies transition. He showed that the transition can be approximated by the reaction: albite + tremolite (actinolite) = edenite (hornblende) + 4 quartz. The transition involves dehydration and results in an increase in the modal abundance of quartz as hornblende + quartz are formed at the expense of plagioclase at higher temperatures.

An upper temperature limit for the Vredefort Dominion Group amphibolite assemblage can be estimated from experiments on the breakdown of hornblende where the first appearance of clinopyroxene is at about 780°C ( $P=1-2$  kb,  $f\text{O}_2=\text{QFM}$ : Spear, 1981a).

If a steep geothermal gradient of  $\geq 50^\circ\text{C}/\text{km}$  is characteristic of the Witwatersrand Basin as a whole, as suggested by Phillips (1987), then the approximately 200°C higher minimum metamorphic temperature of the Vredefort area amphibolites suggests burial under at least 4 km more overburden in the centre of the basin (and corresponding pressure about 1 kb higher) than in the peripheral goldfields of the Klerksdorp area. Alternatively, high heat flow may have been supplied by more abundant mafic intrusives in this area as suggested by Phillips and Law (1992). These intrusives occur within and below the Dominion Group in the Outer Granite Gneiss as well as in the overlying West Rand Group in the collar (see Figure 1). Although these many bodies vary in composition, mineralogy, and probably in age, evidence presented by Bisschoff (1972) suggests that they were emplaced before the upturning of the collar strata during the Vredefort structural event (e.g.  $> 2.0$  Ga, Hart *et al.*, 1991). Therefore they were emplaced in an already deeply buried crustal location and the combined heat of a high geothermal gradient and igneous intrusion can readily account for the higher metamorphic grade.

In summary, the metamorphic assemblage of the Vredefort-area Dominion amphibolites indicate metamorphic conditions of 550°C to about 800°C at pressures of 2 to 4 kb if  $f\text{O}_2$  is approximately QFM. The assemblage does not provide independent constraint on the pressure of metamorphism which is assumed from the occurrence of kyanite in the Witwatersrand Supergroup and assumptions as to the thickness of overlying strata (6-7 km of Witwatersrand Supergroup + 4-7 km of Ventersdorp Supergroup) implying depths of burial (10-14 km total).

## CONCLUSIONS

Petrography and geochemistry of samples from the amygdaloidal amphibolite unit forming the basal stratum of the supracrustal sequence in the collar of the Vredefort Dome confirm correlation with the Rhenosterhoek Formation mafic lavas of the Dominion Group in the Klerksdorp area. The metavolcanics are primitive basalts showing limited evidence of fractionation but a wide range of incompatible element contents and ratios. A petrogenetic model involving variable degrees of melting of subcontinental lithosphere similar in composition to some garnet lherzolite xenoliths in Kaapvaal Craton kimberlites best fits the

trace element data. Differences in alkali and calcium contents and mineralogy between the Klerksdorp-area and Vredefort-area metavolcanics can be explained by higher temperature metamorphism in the latter area consistent with a high geothermal gradient in the Witwatersrand Basin, but possibly augmented by a regional-scale contact metamorphism caused by abundant mafic intrusions in the lower Witwatersrand strata emplaced during the early Proterozoic.

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