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THE GEOLOGY AND GEOCHEMISTRY OF THE ARCHAEAN GRANITES AND GNEISSES OF THE JOHANNESBURG-PRETORIA DOME

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ABSTRACT

The Johannesburg-Pretoria granite inlier, occupying an ovoid area of approximately 700 square kilometres constitutes one of a number of domical "windows" of ancient granite basement (± 3200 m.yrs. old) exposed on the Kaapvaal Craton in South Africa. Preliminary investigations involving the remapping of the area, have led to the establishment of a number of granite varieties each displaying distinctive field characteristics and possessing significantly variable geochemical, mineralogical, and textural properties. The oldest granites are represented by a variety of hornblende or biotite tonalitic gneisses. These grade into a complex array of migmatites and gneisses, the latter, in turn, passing transitionally into a suite of grey, homogeneous and porphyritic granodiorites. The youngest granitic rocks are represented by transgressive felsitic and porphyritic dykes.

A geochemical study, involving the collecting of over 500 granite samples, was undertaken over the dome. Thirty-three of these samples were chosen for chemical analysis and the results are presented and discussed. After additional selective screening, between 400 and 425 of the samples were partially analysed to determine their Na_2O, K_2O, Sr, and Rb contents. In addition, gamma ray spectrometry was employed to determine the gamma radiation emitted by each sample. Attempts have been made to establish the areal variability of this geochemical data using up to fifth order polynomial trend surfaces. The distribution patterns presented display a high degree of correspondence, not only between themselves but also with the geology of the granites and the available gravity interpretation of the area.

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THE GEOLOGY AND GEOCHEMISTRY OF THE ARCHAEAN GRANITES AND GNEISSES OF THE JOHANNESBURG-PRETORIA DOME

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THE GEOLOGY AND GEOCHEMISTRY OF THE ARCHAEAN GRANITES AND GNEISSES OF THE JOHANNESBURG-PRETORIA DOME

INTRODUCTION

The Johannesburg-Pretoria granite mass, occupying an ovoid area of approximately 700 square kilometres, constitutes one of a number of domical "windows" of ancient granite basement exposed on the Kaapvaal Craton in South Africa (see Figure 1). These domes form part of a fundamental basement framework upon which the stratigraphic successions, ranging in age from the earliest Precambrian, through to Phanerozoic times, were laid down. The distribution of the granite domes with respect to the important gold- and uranium-bearing strata of the Witwatersrand Sequence led to the formulation, by Brock and Pretorius (1964a), of what these authors referred to as "The Grid Pattern". It was demonstrated that the northeasterly trend of the Witwatersrand Basin is controlled largely by the trend of its two sides, but its long axis, significantly, passes through the centre of the Vredefort Dome. Three axial lines, roughly parallel were recognized, each joining positive areas caused by the updoming of granites. Between the three positive axial traces, illustrated in Figure 1, two synclinal axes are developed.

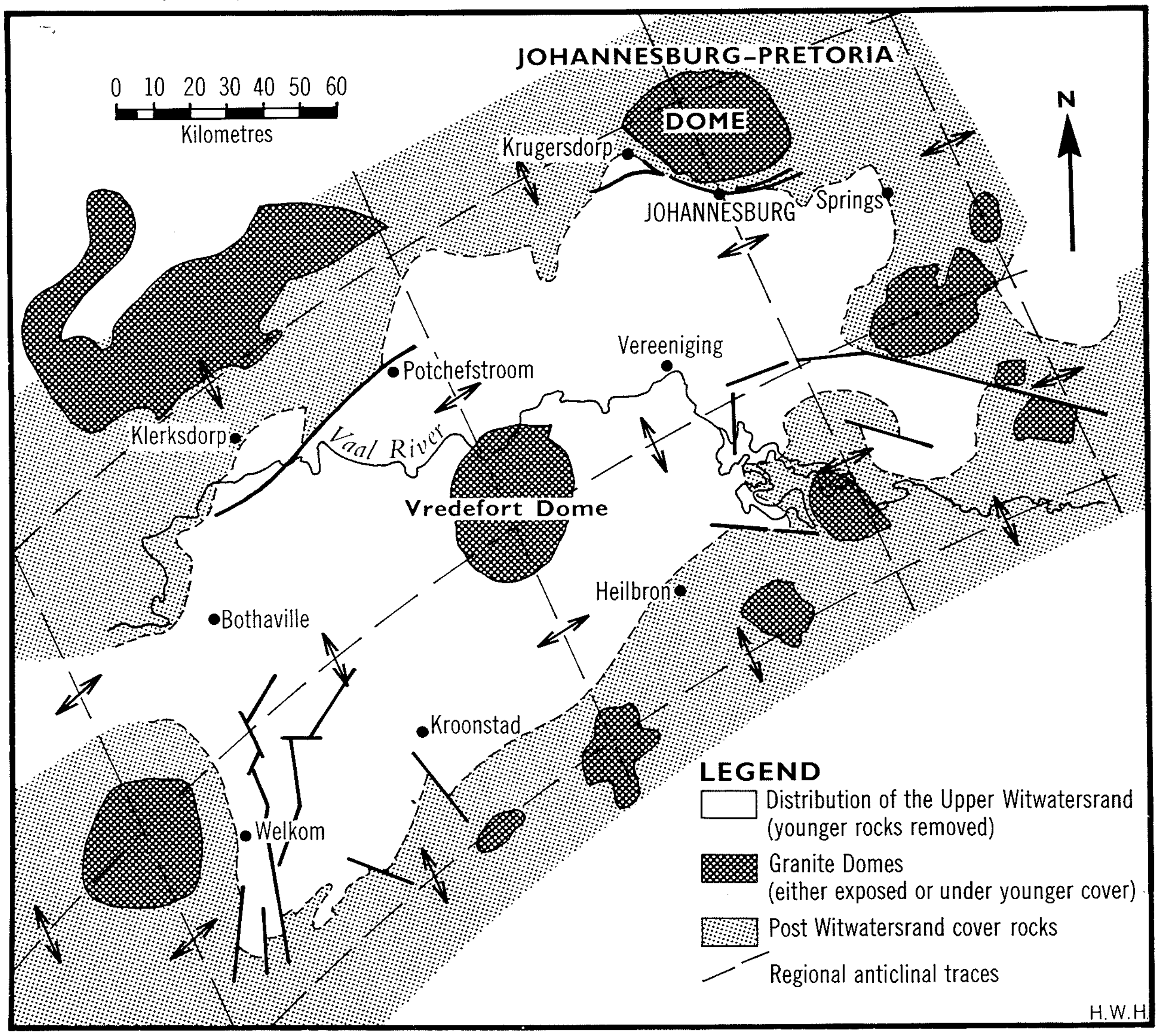


Figure 1. Distribution of Granite Domes on the Kaapvaal Craton (Modified after Brock and Pretorius, 1964.)

A set of cross-trends, aligned in a direction transverse to the dominant northeasterly trend, were also recognized by Brock and Pretorius (1964a). These are likewise marked by alignments of positive blocks and intervening depressions but the orientation of the axial traces are less positively defined. The writer, for example, favours a north-northeasterly trending axial direction in contrast to the northwesterly trend preferred by Brock and Pretorius (1964a).

However, despite varying interpretations that may be proposed with respect to the transverse axial trend directions it is important to realize that there exists a high degree of correlation between the centres of the most significant gold producing regions of the basin and the intersection of synclinal axes, while conversely, at the intersection of positive areas there are notable gaps in the occurrence of gold mineralization.

The development of "The Grid Pattern" in this, the most important gold producing region in the world is clearly the result of instability of the ancient basement complex. The granitic terrain together with its associated greenstone xenoliths experienced a long and involved evolutionary history with certain areas, in particular, having undergone constant changes resulting in the development of continuously active, positive regions - the domes.

The importance of the Johannesburg-Pretoria dome in the sedimentational and structural history of part of the Witwatersrand Basin has long been recognized, it being responsible also for the uptilting of the Witwatersrand Sequence, thereby exposing on surface, the auriferous conglomerate reef horizons that led ultimately to the development of the famous Witwatersrand Goldfield.

This paper forms part of the preliminary investigations hoped at establishing more about the ancient granite terrain in general as well as the processes and possible mechanisms responsible for updoming in selected areas.

PREVIOUS WORK

Although the Johannesburg-Pretoria granite mass has been studied by a number of researchers since the beginning of this century no comprehensive account of the geology and geochemistry of the area is available. The earliest investigations were carried out by Hall (1906), and Kynaston (1906, 1907, 1929) and led to the appearance, on two sheets, of a map published by the Geological Survey of South Africa showing the distribution of the "Old Granite" and its relationship to the surrounding younger formations. Only brief mention is made of the granite by these authors, both of whom recognized a dioritic marginal facies developed towards the west and southwest of the dome. Apart from a brief petrographical description of the granite in the vicinity of Craighall by Wagner (1907), and some chemical analyses by Wade (1909), and Horwood (1910), no further work was undertaken until 1932, when Willemse undertook a more detailed study of the petrography and tectonics of the granite mass as a whole. His account of the area first appeared as a Master's thesis at the University of Pretoria, but was subsequently published in 1933 by the Geological Society of South Africa, and has remained the only significant contribution dealing specifically with the granite dome. More recently aspects relating to the granitic rocks in the vicinity of the farm Zwartkop 525 JQ on the western and southwestern rim of the dome have been briefly dealt with by Hendriks (1961).

Geochronological investigations, involving the Rb-Sr age determinations of total rock and separated mineral fractions relating to the Old Granite exposed between Johannesburg and Pretoria, were carried out by Allsopp (1961). The total rock samples yielded concordant results and the age of emplacement of the granite was reported to be 3200 ± 65 m.yrs. Widely differing apparent ages were recorded for the separated mineral fractions and Allsopp concluded that diffusion of radiogenic strontium had taken place from mineral to mineral. He postulated a period of granite reheating occurring less than, though not greatly less than, 2120 m.yrs. ago.

Finally, Brook (1970) undertook a geomorphological study aimed at establishing the mode of origin and evolution of the inselberg landscape developed in the Witkoppen area, in the centre of the granite dome.

PART I

DESCRIPTIVE GEOLOGY OF THE AREA

A. THE SWAZILAND SEQUENCE

The oldest rocks in the area under discussion also constitute some of the most primitive assemblages developed anywhere on earth. Mainly present around the western, southwestern, and southeastern margins of the granite dome, but occurring also at numerous localities within the granites (see Figure 4), is a suite of mafic and ultramafic rocks analogous to the ancient formations developed towards the base of the Onverwacht Group in the Barberton Mountain Land and described by Anhaeusser (1969) and Viljoen and Viljoen (1969a).

As these early greenstone remnants are the subject of a separate study being carried out by the writer, only brief mention will be made of them in this presentation. Descriptive accounts of the pre-granitic rocks are, however, available in reports by Hall (1906), Kynaston (1907), and Mellor (1917, 1921). In addition, brief mention is made of these assemblages by Willemse (1933) and Hendriks (1961).

Willemse (1933) subdivided the pre-granitic rocks into two groups, the first of which he referred to as the basic schists and the second, which he called the acid-schists. He furthermore distinguished, on petrological grounds, three main rock varieties in the basic schist group. These he called the serpentinous variety, the amphibolite variety, and the hornblende variety.

The serpentinous varieties contain relic crystals of olivine, besides enstatite, monoclinic pyroxene, and a little felspar, and mainly represent the altered products of original dunitic or harzburgite primary rocks. In places, massive serpentinites may be found together with sheared, often talcy, serpentinous schists. The amphibolite variety consists essentially of slender hornblende needles, often bent, and found in a talcose-serpentinous matrix. The hornblende variety, for the most part, consists mainly of hornblende together with lesser amounts of microcline, plagioclase, orthoclase, and quartz. These minerals were considered to have been introduced into a rock originally of pyroxenitic composition.

The pre-granite acid-schists referred to by Willemse (1933) occur in only a limited area on the northwestern and northern margin of the dome. They are represented mainly by silvery-grey, quartz-sericite schists sometimes with tourmaline and/or magnetite crystals. While the writer is in general agreement with Willemse's subdivision of the basic schist group outlined above, he cannot support the inclusion of the acid-schist group into the category of pre-granitic assemblages. These rocks, only locally exposed around the northwestern rim of the dome, are considered to be essentially the products of intense structural alteration of a pre-Transvaal felsic volcanic horizon lying, where preserved in a few localities, conformably below the Black Reef quartzites.

The Swaziland Sequence rocks, occurring in isolated xenoliths and large continuous masses within, and peripheral to, the main granite body, are considered to represent the altered products of a primitive ultramafic and mafic magma. Although metamorphism and structural deformation have tended to destroy all the primary properties of these rocks there nevertheless remain a few localities where detailed study may reveal the original nature of the assemblages. Observations thus far suggest that most of the greenstone remnants constitute altered layered differentiated ultramafic assemblages that were probably formerly represented by an alternating succession of dunitic, harzburgitic, pyroxenitic and, to a lesser extent, gabbroic plutonic rocks. No evidence has yet been found, in the occurrences examined, to suggest the presence of rocks of extrusive volcanic origin such as is the case within the lower Ultramafic Unit of the Onverwacht Group in the Barberton greenstone belt.

The ancient remnants developed on the Johannesburg-Pretoria dome may well represent parts of the primitive crust or the lowermost formations of a former greenstone belt, or belts, now removed by erosion.

B. THE YOUNGER ROCKS MANTLING THE DOME

(a) Introduction

The rocks mantling the granite dome are depicted in Figure 4. Most of the successions, which will be discussed briefly in turn, previously either covered, or partially covered, the area now occupied by the granites and associated greenstone xenoliths. The stripping of the younger cover rocks was greatly assisted by the progressive upward movement of the granites throughout the geological history of the region.

(b) The Witwatersrand Sequence

Rimming the roughly elliptical inlier of the Johannesburg-Pretoria granite dome are rocks of widely differing ages, all of which dip at varying angles, and directions, away from the granite hub. Along the southwestern and southern margins of the dome are rocks of the Witwatersrand Sequence. The Sequence, described by Pretorius (1964), consists mainly of alternations of shales, quartzites, grits, and conglomerates. In the Lower Division are also found banded siliceous ironstones, a group of tillites, and a band of intercalated lava. One band of volcanic rock also occurs in the Upper Division. The formations, which have a maximum sediment age of 2720 ± 100 m.yrs. (Allsopp, 1964), lie unconformably on the granite and associated remnants of Swaziland Sequence rocks. On the Central Rand the Witwatersrand sediments strike approximately east-west and dip south at angles of between 10 and 45 degrees. Along the south-western rim, between Florida Hills and Krugersdorp, the strike varies between 106 and 133 degrees and average dips to the south of between 15 and 50 degrees were recorded by Roering (1968). The only other known development of Witwatersrand rocks in the area under discussion occurs on the farm Zwartkop 525 JQ on the western edge of the dome and is described by Hendriks (1961).

(c) The Ventersdorp Sequence

Rocks of the Ventersdorp succession are developed in four separate areas on the western, northern, eastern, and southeastern margins of the dome. West of the farm Zwartkop 525 JQ highly sheared felsic volcanics rest on granite and Witwatersrand strata. North of here, between Mooiplaats 524 JQ and Doornrandje 386 JR, the sheared quartz-sericite schists found in the area are considered by the writer to represent the altered remnants of a porphyritic felsic volcanic horizon lying conformably below the Black Reef quartzites. These acid schists, formerly regarded as belonging to the Swaziland Sequence by Hall (1906) and Willemse (1933), are the products of intense shearing and mylonitization along the northern rim of the granite dome. No intrusive granitic or pegmatitic veins were found in the schists, adding support to the contention that these rocks were deposited subsequent to the development of the granites.

In the east, near Tembisa, a localized occurrence of Ventersdorp volcanic breccia, set in a tuff matrix, occupies a position between the Black Reef quartzites and the old granites. These rocks are of intermediate composition. A further development of Ventersdorp strata occurs on the southern flank of the granite dome, in a downthrown fault block which has an apex near the Rietfontein Consolidated Mine, and which extends in a northeasterly direction towards Kempton Park. Here the successions, which overlap onto the granite and associated greenstone remnants, consist essentially of lavas of intermediate composition but also contain noteworthy intercalations of shales, tuffaceous sediments, and volcanic breccia.

(d) The Transvaal Sequence

Rocks of the Transvaal Sequence mantle practically the entire northern periphery of the Johannesburg-Pretoria dome. Resting unconformably on the granite and associated greenstone relics, and in places conformably on the Ventersdorp volcanic successions, the lowermost member, which in this area is represented by the Black Reef quartzite horizon, dips at shallow angles outwards from the centre of the dome. The Black Reef quartzite horizon in places forms a prominent topographical rim to the granite mass and is overlain by thin shale bands and a great thickness of dolomitic rocks.

The age of the rocks of the Transvaal Sequence has been firmly set between 1950 and 2300 million years, the lower limit being fixed by the age of intrusion of the Bushveld Igneous Complex (Nicolaysen, 1962) while the upper limit represents the age of the underlying Ventersdorp lavas which were extruded some 2,300 million years ago (van Niekerk and Burger, 1964).

(e) The Karroo Sequence

A limited development of Karroo sediments form a thin veneer across parts of the southeastern portion of the dome in the region north of Kempton Park. Rock outcrops are rarely encountered and the distribution of the younger cover sequence can only be inferred from the mapping of soil types. The reddish-coloured Karroo soils are generally found occupying the flatter, more elevated parts of the southeastern portion of the dome. Where erosion occurs, grey, decomposed, sandy granitic soils make an appearance. The exact extent of the Karroo cover over the eastern and northeastern parts of the dome is not clear. The possibility cannot be excluded, however, that some of the occurrences of deep reddish-coloured soils may represent the products of decomposition, either of greenstone xenoliths, Transvaal or pre-Transvaal successions, or even mafic dykes.

GRAVITY DISTRIBUTION OVER THE DOME

Two independent gravity surveys have been undertaken across the central regions of the Kaapvaal craton and both cover the region occupied by the Johannesburg-Pretoria dome. The first of these surveys was carried out by Mr. C.A. Cousins in 1948, while in later years Smit and others (1962) conducted a gravity survey of the entire country on behalf of the Geological Survey of South Africa. Both the surveys emphasized strikingly symmetrical gravity distribution patterns over the exposed as well as over the "blind" granite domes that occur on the craton. Over all these areas, except over the Vredefort Dome, low gravity values were recorded. Over the Johannesburg-Pretoria dome an anomalous asymmetrical pattern of low density material was measured. The results of the two surveys across the latter area are shown together in Figure 2.

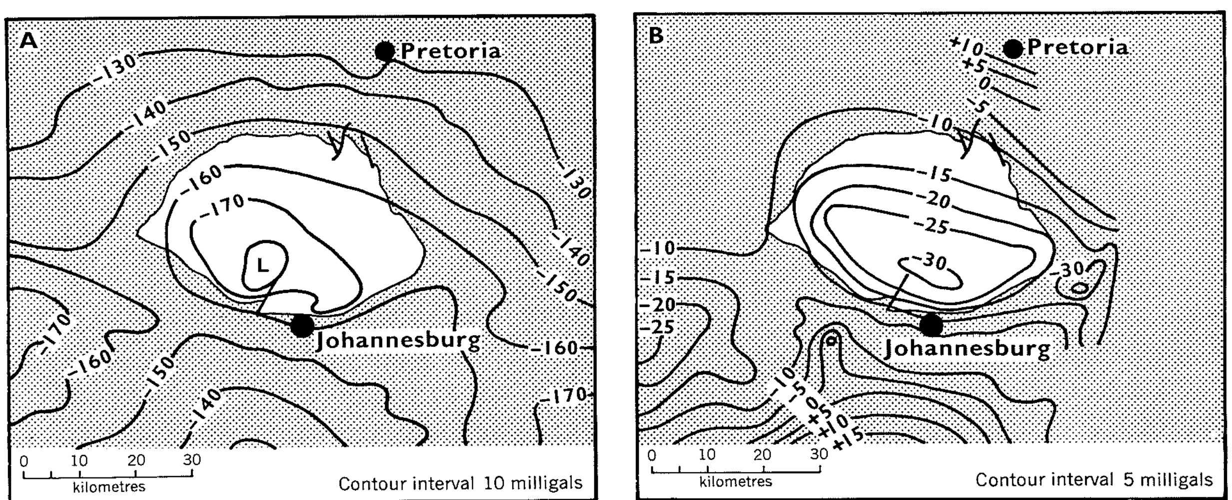


Figure 2. Bouguer Isogal maps showing an asymmetrical density distribution over the Johannesburg–Pretoria Granite Dome. A.Gravity map after Smit and others (1962). B.Gravity survey after C.A.Cousins (1948). Datum point between Heilbron and Kopjes in the O.F.S.

Two traverses were made by Cousins across the dome (personal communiction, 1971). The first of these followed the main road between Krugersdorp and Pretoria while the second traverse extended from Johannesburg to Pretoria along the old highway. A gravity low, occupying the area south of the dome centre, was defined, the long axis trend of which has an orientation of approximately 115 degrees. Virtually the identical asymmetrical pattern, depicting an area of low density material south of the dome centre, was recorded by Smit and his co-workers (1962). Although the contouring patterns of the gravity data differ somewhat visually, there is, nevertheless, a considerable degree of correspondence depicted by the two independent interpretations of the gravity distribution over the dome. The significance of the gravity pattern will become apparent later when the geological and geochemical areal variability of the granites is discussed.

THE GRANITIC ROCKS OF THE JOHANNESBURG-PRETORIA DOME

A. INTRODUCTION

Willemse (1933) described the geological features of the granitic rocks of the Johannesburg-Pretoria dome and concluded that, besides variations in colour and also the development of a gneissic facies towards the south and southwest, the composition of the granite, both mineralogically and chemically, appeared to be very constant throughout the area. However, during the course of sampling the granitic rocks, it became increasingly evident to the writer that a need existed for the compilation of a new geological map of the area.

As a result of the revised mapping several new granite types have been recognized. These include :

(i) Granite-gneisses consisting of hornblende or hornblende-biotite tonalites, leuco-biotite tonalites and/or biotite trondhjemites, occurring mainly along the southeastern, southern, and southwestern margins of the dome, in contact with rocks of the Swaziland Sequence. In addition, biotite tonalites and trondhjemites occur in the gneissic and migmatitic terrain, particularly in the northwestern quadrant of the granite inlier.

(ii) Homogeneous, medium-coarse grained, pinkish-grey granodiorites, which appear to grade into the various tonalitic gneisses and which, in places, abut against greenstone remnants particularly along the southern and southwestern margins of the dome.

(iii) Homogeneous, medium-textured, grey granodioritic-to-adamellitic granites occupying the south-central and southeastern portions of the dome. A prominently porphyritic variation of this granitic suite occupies a large part of the southwestern quadrant of the dome.

(iv) Transitional Zone granodioritic gneisses, migmatites, and porphyritic granites, including isolated "castle koppies" or granite tors, occupying a broadly arcuate region in the central and southwestern parts of the dome.

(v) Foliated banded-gneisses and migmatites containing mafic and ultramafic xenoliths, together with irregularly distributed, partially homogenized, and, in places, porphyritic granodioritic phases. These rocks occupy practically the entire northern half of the granite dome.

(vi) Transgressive felsitic dykes occurring predominantly in the western parts of the granite dome but not being entirely restricted to this area alone.

(vii) A variety of hybrid granitic rocks, diorites, coarse-grained porphyritic granite dykes, pinkish-red, medium-to-coarse grained, porphyritic granites and gneisses (possibly granites affected by their proximity to Pilanesberg dyke-intrusions) and sheared, sericitized and silicified granites. Rock-types falling into this last category are found scattered in various places across the dome.

The distribution of the abovementioned categories of granitic rocks are depicted in a map of the granite dome in Figure 4.

B. THE ANCIENT TONALITIC GNEISSES

Tonalitic gneisses similar in many respects to the varieties that have been recognized in Swaziland (Hunter, 1968) and in the areas surrounding the Barberton Mountain Land (Anhaeusser, 1966, 1969; Viljoen and Viljoen, 1969b and c) have been identified at several places within the Johannesburg-Pretoria granite dome where they are intrusive into rocks of the Swaziland Sequence.

As in the case of the classification of the granitic rocks of the Barberton region proposed by Viljoen and Viljoen (1969c) the term Ancient Tonalitic Gneisses is used in this paper in a broad sense to include a wide variety of biotite- and hornblende-bearing tonalitic granites and gneisses grading locally into dioritic, granodioritic, and quartz-dioritic gneisses and including a variety of metamorphic rocks derived principally from a mafic and/or ultramafic primary source.

The term "tonalite", employed by the abovementioned authors, has been adopted to describe granitic rocks which are characteristically rich in soda plagioclase and which contain only small amounts of potash felspar. The scheme follows a chemical classification proposed by Harpum (1963) for the granitic rocks of Tanganyika (Tanzania).

As these ancient granites almost invariably possess a well-developed gneissic fabric the term "tonalitic gneiss" has been employed to distinguish this distinctive granite variety from the many other granitic rock-types manifest in the Archaean terrains. A further characteristic feature of this type of granite is the general tendency for it to develop circular or elliptical, diapirically emplaced, plutons or domes that are usually responsible for the imposition of the structural style peculiar to the very early greenstone belts of the shield areas (Anhaeusser and others, 1969).

Although there is reason to suspect that the tonalitic gneisses, developed around the edges of the mafic and ultramafic greenstone remnants of the Johannesburg-Pretoria granite inlier, behaved in a manner similar to their counterparts in the Barberton region, and places elsewhere, there is insufficient evidence available to confirm this hypothesis. As will be pointed out later, considerable changes appear to have taken place within the granites over a period of time resulting in the masking or obliteration of many of the earliest events that occurred in the region.

On petrological and chemical grounds two main varieties of ancient tonalitic gneisses have been recognized :

(i) Mesocratic hornblende-biotite tonalitic gneisses and,

(ii) Leucocratic-biotite tonalitic gneisses and/or biotite trondhjemites.

These varieties appear, in places, to be gradational into one another with the mesocratic hornblende-tonalites representing the most basic members of a granitic series which ranges through a hornblende-biotite tonalitic variety to biotite trondhjemites and leuco-biotite tonalitic gneisses.

(a) <u>Mesocratic Hornblende-Biotite Variety</u>

(i) <u>Occurrence and Description</u>

Rocks falling into this category are found principally along the southwestern and southern margins of the dome, being particularly prevalent between Parkview and Linden (see Figure 4) and in the Struben's Valley area north of Florida Hills. In the field the rocks are generally strongly foliated and range in colour from very dark greenish-grey to grey, depending on the distance from greenstone remnants. The colour variations are an expression of the degree of contamination suffered by the granites at the time of their emplacement. Commonly encountered in these rocks are inclusions, mainly of amphibolite, which are usually aligned with their long dimensions parallel to the foliation planes in the gneisses. The foliation is also generally more prominently developed closer to the greenstone remnants and decreases in a direction away from the contacts, with the granites becoming almost homogeneous in places. In all but a few places where the tonalitic gneisses can be seen in contact with the mafic and ultramafic assemblages of the Swaziland Sequence the structural fabrics developed in the latter formations are conformable with any foliation that may be discernable in the invading granites.

In some places, as for example in the Struben's Valley area, there is a tendency for the tonalites to develop a prominent banding, which in turn becomes strongly folded in a manner similar to that shown in Plate 1A,B. Although outcrop limitations exist the writer gained the impression that the complexly folded tonalites, showing leucocratic and melanocratic banding, could well represent an embyonic stage in the development of a migmatitic gneiss. Only the absence of pegmatites and the lack of concomittant, metasomatically introduced, volatile constituents, as well as more complete segregation phenomena, prevent the rock from being called a true migmatite. The development of banding in these rocks is probably due to a process akin to metamorphic differentiation. Similar findings, whereby tonalitic gneisses appear to pass through several stages of segregation and plasticization to ultimately form migmatites, have been reported from the southern part of the Barberton region investigated by Viljoen and Viljoen (1969c).

Apart from the dark colour, the foliation, and the generally medium-coarse texture, the tonalitic gneisses are notably devoid of pegmatites and quartz veins. Mineralogically, the most distinctive minerals are those imparting to the rocks their generally dark colouration. These include hornblende, which is often totally altered to chlorite, and biotite. Frequently the pale-green, soda-rich plagioclase (albite-oligoclase) is completely saussuritized and/or sericitized and epidote and sericite become prominent secondary components of the rocks, occurring either in a disseminated form or filling veins and joint planes. Other mineral components of the rocks include microcline and quartz, together with accessory quantities of sphene, apatite, and magnetite.

(ii) Chemical Data

The mesocratic hornblende-biotite tonalites, as mentioned previously, are the most basic of the granitic rocks encountered anywhere on the Johannesburg-Pretoria dome. The distinctive chemical composition of these rocks is illustrated in Part 1 of Table I where three examples, typical of the hornblende and hornblende-biotite tonalitic gneisses encountered on the southern margin of the dome, are presented. Apart from the distinctive K_2O and Na_2O relationships which permit the rocks to be classified as tonalites, according to the scheme suggested by Harpum (1963), the most notable chemical features include a low silica content, and relatively high concentrations of iron, magnesium, calcium, and titanium. In general, the hornblende-biotite tonalites of the Johannesburg-Pretoria dome appear to be even more basic than their counterparts from the Barberton granitic terrain. For comparison the average composition of four hornblende tonalitic gneisses from the Kaap Valley Granite, which represents the most basic diapiric pluton in the Barberton region, is listed in Column B of Table I. Notable differences occur in the silica, iron, magnesium, calcium and sodium contents of the tonalitic gneisses from the two areas. A possible explanation for the variability may hinge around the nature and composition of the primitive mafic and ultramafic greenstone material assimilated by the invading granites. The Kaap Valley Granite, for example, probably assimilated material mainly forming part of the Theespruit and Komati Formations (Anhaeusser, 1969) whereas the ancient tonalitic gneisses of the Johannesburg-Pretoria dome may have invaded the equivalent of the lowermost, or Sandspruit Formation of the Barberton model. It is of interest to note that Viljoen and Viljoen (1969a) found the chemical variations between the Sandspruit and the later Komati Formations to be significantly different, particularly with respect to the higher Ca/Al ratio of the former rock assemblage. These chemical differences they maintained were probably indicative of an originally higher pyroxene (diopside) content of the earlier magma. In a similar way, the relatively high Ca/Al ratios of the tonalites from the Johannesburg-Pretoria dome may reflect the presence, originally, of Ca-rich mineral phases in the earliest greenstone material subsequently digested by the granites.

Apart from the major element characteristics of the hornblende-biotite tonalites the trace elements Sr and Rb also reflect features of interest. These elements are chemically incompatible accounting for the increase of the one at the expense of the other in most of the rocks analysed. In general, the tonalitic gneisses have extremely low Rb contents and very high Sr contents. These findings are in accord with those of Viljoen and Viljoen (1969b) for the Barberton tonalites. A direct comparison of the values listed in the rock analysis tables cannot be made, however, as different standards were employed in the separate studies. An anomalous reversal of the trend outlined above, is reflected in Part 1 of Table I by sample RP7 from Roosevelt Park, and is probably due to the influence of the intrusion of the Pilanesberg dyke referred to as the Robinson Dyke by Schreiner and van Niekerk (1958).

(b) Leuco-Biotite Tonalitic Gneisses and/or Biotite Trondhjemites

(i) Occurrence and Description

Rocks of this category are found in widely separated areas on the Johannesburg-Pretoria granite inlier but occur particularly along the southwestern and southeastern margins of the dome in the Struben's Valley and Linbro Park areas respectively. In addition, biotite tonalites and trondhjemites occur at numerous localities in the migmatite-gneiss terrain occupying the northern half of the dome, and occurring more particularly on the farms Zwartkop 525 JQ, Bultfontein 533 JQ, Rhenosterspruit 495 JQ, and Zandspruit 191 IQ, in the northwestern quadrant of the area.

In general, the rocks grouped into this category are leucocratic and contain more quartz while biotite is the principal ferromagnesian mineral. As with the tonalitic gneisses described in the previous section these rocks are also strongly foliated and frequently contain aligned mafic xenoliths, particularly in areas approaching greenstone contacts. An example of foliated gneiss of this type, containing inclusions orientated in the plane of the gneissic fabric, is shown in

TABLE 1

ANCIENT TONALITIC GNEISSES

Part 1 : Mesocratic Hornblende-Biotite Variety

(hornblende tonalites, hornblende-biotite tonalitic gneisses)

Sample Number	PV2	LN1	RP7	A	B
SiO_2	62.21	62.37	60.79	64.41	64.84
Al_2O_3	15.89	15.93	15.99	15.95	15.44
Fe_2O_3	1.45	1.42	1.54	1.46	1.80
FeO	3.38	3.42	3.59	3.81	2.44
MgO	3.43	3.56	3.52	2.45	2.60
CaO	5.64	5.58	5.27	5.36	4.25
Na_2O	3.87	3.79	4.23	3.39	4.93
K_2O	1.58	1.55	2.24	1.45	1.53
H_2O-	0.07	0.06	0.09	-	0.20
H_2O+	1.64	1.61	1.69	0.80	0.90
CO_2	0.17	0.11	0.09	-	-
TiO_2	0.52	0.53	0.58	0.62	0.49
P_2O_5	0.27	0.27	0.28	-	0.18
MnO	0.10	0.10	0.11	0.10	0.04
Rb ppm	142†	130†	319†		16*
Sr ppm	766†	925†	56†		481*
TOTAL	100.22	100.30	100.01		

PV2 : Parkview Golf Course, southern edge of dome

LN1 : Linden, southern edge of dome

RP7 : Roosevelt Park, southern edge of dome.

A : Hornblende-biotite tonalite : Average of 22 analyses (Nockolds, 1954)

B : Average of 4 hornblende tonalite gneiss samples from the Kaap Valley Granite near Barberton (Viljoen and Viljoen, 1969)

* : Rb and Sr values calibrated using International Rock Standard G-1 (Rb ppm 210; Sr ppm 250)

† : Rb and Sr values calibrated using International Rock Standard GSP-1 (Rb ppm 343; Sr ppm 247 - Flanagan, 1969)

Plate 1C. Apart from mineralogical and chemical differences, the leuco-tonalitic gneisses behave in an almost identical manner to the mesocratic hornblende-biotite tonalitic variety.

Mineralogically, as has already been mentioned, the rocks are rich in quartz and biotite. Plagioclase felspar (mainly of oligoclase-albite composition) generally shows varying degrees of alteration to sericite and/or epidote. Other minerals occurring in variable, but generally lesser amounts include muscovite, microcline, and chlorite, while sphene and apatite comprise accessory constituents. The biotite and, to a lesser extent, the muscovite and chlorite, possesses a subparallel alignment usually apparent in hand-specimens but particularly clearly evident in thin-sections. The strongest mineral orientation is generally found closest to the contacts of greenstone remnants and decreases in intensity away from these regions, becoming almost homogeneous in places. Where best-developed, as in the Struben's Valley area and at Linbro Park, the mineral orientation and foliation in the gneisses has an almost vertical disposition and possesses a preferred strike direction ranging between 120° and 145°. Notably absent, or only rarely developed in these rocks, are pegmatites and quartz veins.

On the northern side of the dome vestiges of similar intensely foliated leuco-biotite gneisses are to be found as relics within the otherwise reconstituted migmatitic terrain. Mineralogically these rocks are identical to those on the southwestern and southeastern margins of the dome but, as will be shown later, they differ notably in their geochemical properties. Occurring in an essentially migmatitic terrain these rocks have, in places, undergone metamorphic segregation into leucocratic and melanocratic bands and frequently intense folding has destroyed the original character of the rocks. Pegmatite veining is also prominent but the tonalitic gneisses appear to have withstood any widespread metasomatic transformation.

Although the foliation developed in many of the gneisses on the northern half of the dome is variable from one point to the next there is an overall east-southeasterly trend developed across the entire region (see Figure 4). This trend is frequently parallel or sub-parallel to the foliation visible in the gneisses developed on the southern half of the dome.

(ii) Chemical Data

Unlike the hornblende-biotite tonalites the leuco-biotite tonalites reflect slightly higher amounts of silica, alumina, and sodium, and lesser amounts of iron, magnesium, calcium, potassium, titanium, phosphorus, and manganese. Although roughly comparable, the alkali contents of the two classes of tonalitic gneisses given in Parts 1 and 2 of Table I are such that they can be shown to occupy two essentially separate fields when plotted on a standard alkali diagram as portrayed in Figure 3. Both classes of rock fall into Harpum's (1963) tonalite range but it can be seen that the leuco-biotite tonalitic gneisses have relatively greater quantities of Na_2O while still maintaining a somewhat comparable K_2O content. Many of the gneisses have chemical affinities with the trondhjemitic class of igneous rock first described from Norway. In Table I, Part 2, six analyses of leuco-biotite tonalitic gneisses and/or biotite trondhjemites from various parts of the dome are listed and compared with rocks of similar composition from Barberton, Swaziland, and elsewhere in the world. Samples SB1 and HD26 are not fully representative of this class but have been included as examples of tonalitic gneisses that have undergone 'granodioritization' but which have not altogether lost their field identity.

Additional geochemical information worthy of mention is that relating to the Rb and Sr trace quantities in these rocks. The Sr contents of the leuco-biotite tonalitic gneisses again by far exceeds the amount of Rb present in the rocks. On average there is also less Sr in these rocks than in the mesocratic hornblende-biotite tonalite varieties shown in Part 1 of Table I. Although once again not directly comparable, the relative amounts of Sr and Rb detected in the Johannesburg-Pretoria tonalitic gneisses are of the same order of concentration as in the leuco-biotite-quartz tonalitic gneisses from the southern regions of the Barberton Mountain Land (Viljoen and Viljoen, 1969b).

Of interest is the behaviour of the Sr and Rb in the two samples SB1 and HD26, mentioned above, both of which show major element deviations from their former tonalitic character. The Sr-Rb ratio of sample SB1 is comparable to those of the samples listed in the first four columns. Sample HD26, however, has suffered almost total transformation with both the major and minor or trace element concentrations being reorganized by metasomatic processes.

TABLE 1

ANCIENT TONALITIC GNEISSES

Part 2 : Leuco-biotite tonalitic gneisses and/or biotite trondhjemites

Sample Number	RK2	SK5	LP2	SB7	SB1	HD26	A	B	C	D	E
SiO_2	66.38	66.42	67.46	70.03	73.50	69.51	67.67	69.99	66.15	70.96	71.49
Al_2O_3	16.03	16.43	16.81	16.54	14.40	14.76	16.87	15.31	15.56	14.93	14.79
Fe_2O_3	1.17	0.98	0.52	0.49	0.26	1.08	2.22	1.02	1.36	0.79	0.76
FeO	2.30	2.27	2.23	1.44	1.04	1.65	2.18	2.23	3.42	1.04	1.41
MgO	1.89	1.73	1.17	0.43	0.21	0.83	1.09	0.88	1.94	0.78	0.92
CaO	4.30	4.33	3.30	2.55	1.72	2.69	4.42	2.93	4.65	2.32	3.25
Na_2O	4.54	4.61	5.01	6.00	4.60	4.23	4.18	4.79	3.90	5.38	4.82
K_2O	1.39	1.39	1.61	1.36	3.06	3.71	0.57	1.58	1.42	1.92	1.62
H_2O-	0.08	0.02	0.05	0.10	0.12	0.12	–	–	–	0.13	0.07
H_2O+	1.01	0.95	1.09	0.76	0.49	0.72	0.29	0.63	0.69	0.56	0.66
CO_2	0.08	0.06	0.03	0.12	0.16	0.04	–	–	–	–	–
TiO_2	0.40	0.41	0.38	0.29	0.19	0.38	0.28	0.42	0.62	0.18	0.31
P_2O_5	0.09	0.13	0.09	0.09	0.03	0.12	0.15	0.15	0.21	0.06	0.10
MnO	0.07	0.06	0.06	0.06	0.04	0.07	0.06	0.05	0.08	0.05	0.02
Rb ppm	157†	76†	118†	97†	116†	317†	–	–	–	52*	
Sr ppm	570†	619†	582†	860†	541†	376†	–	–	–	498*	
TOTAL	99.73	99.79	99.81	100.26	99.82	99.91	–	–	–	–	–

RK 2 : Rembrandt Park, southeastern edge of dome

SK 5 : Zwartkop 525 JQ, western edge of dome

LP 2 : Bultfontein 533 JQ, northwestern segment of dome

SB 7 : Rhenosterspruit 495 JQ, northwestern segment of dome

SB 1 : Rhenosterspruit 495 JQ, northwestern segment of dome

HD26 : Zandspruit 191 IQ, North Riding area.

A : Basic Trondhjemite : Malletuen, Norway (Davis, 1963).

B : Biotite (muscovite) Tonalite : Average of 20 analyses (Nockolds, 1954).

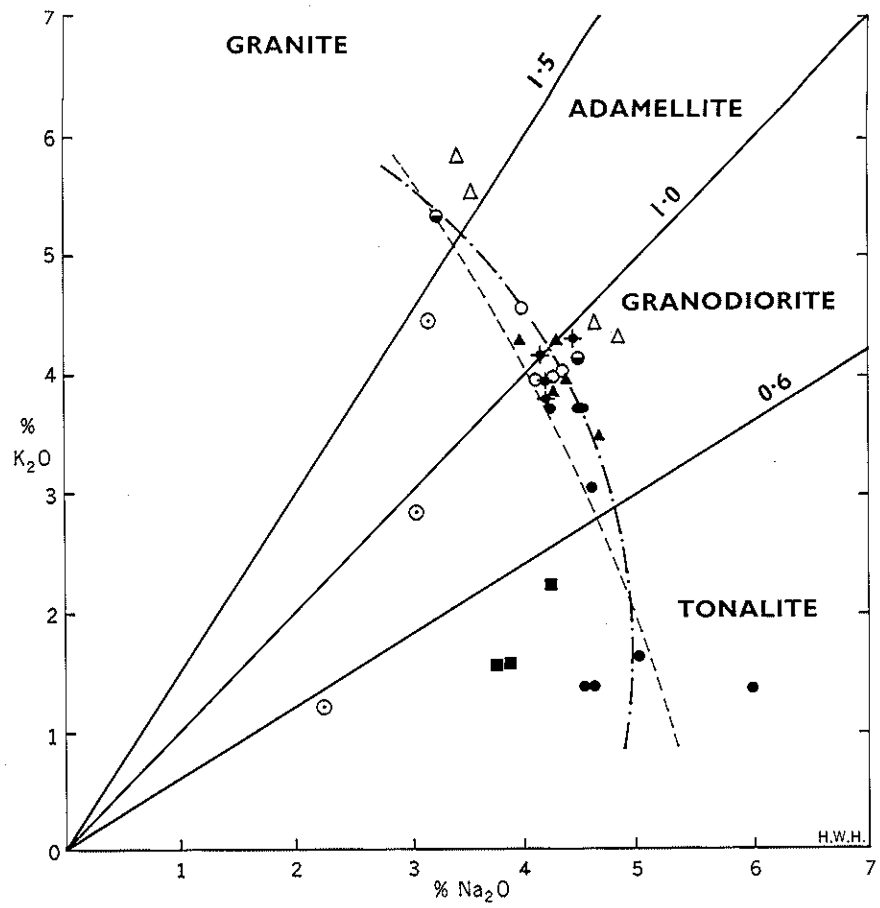
C : Average Tonalite : Average of 58 analyses (Nockolds, 1954).

D : Average of 3 leuco biotite-quartz tonalitic gneisses. Southern edge of Barberton Mountain Land (Viljoen and Viljoen, 1969).

E : Average of 5 tonalitic gneisses of the "Ancient Gneiss Complex" in Swaziland (Hunter, 1968).

† : Rb and Sr values calibrated using GSP-1 Rock Standard (Flanagan, 1969).

* : Rb and Sr values calibrated using G-1 Rock Standard.



- Porphyritic granite dyke
- Felsite dykes
- Reddish, porphyritic granites
- Homogeneous, medium–coarse, pinkish–grey granodiorites
- Homogeneous, medium–textured, grey granodiorite suite
- "Castle koppie" granodiorites
- Diorites and hybrid granites
- Leuco-biotite tonalites, biotite trondhjemites, and granodiorites
- Hornblende-biotite tonalites
- Line of best fit of present data
- Line of best fit of granites surrounding the Barberton Mountain Land (Viljoen and Viljoen, 1969)

Figure 3.
K_2O-Na_2O Relationships of selected Granite Types from the Johannesburg–Pretoria Dome.

C. HOMOGENEOUS, MEDIUM-COARSE, PINKISH-GREY GRANODIORITES

(i) Occurrence and Description

A limited development of granitic rocks falling into this category occur along the southern and southwestern edge of the dome and appear to be gradational into the tonalitic gneisses described previously. The most characteristic features of this granite are its medium-coarse, pinkish-grey colouration, coupled with a relatively homogeneous texture. Not everywhere does this description hold true, as the granitic rocks are in some cases very pale grey or white in colour. It is not unusual to find variably sized mafic inclusions scattered about the granite, the latter seemingly in a disorientated state. Outcrops are, however, seldom sufficiently continuous to allow more detailed observations to be made.

Pegmatitic veins, although not very prominent, are nevertheless encountered in these granites. Their intensity of development is variable but the behaviour pattern is more in keeping with that recorded in the areas occupied by the tonalitic gneisses rather than with the granites further to the north. In some localities, particularly in the southwestern region, on the farms Rietvallei 180 IQ and Wilgespruit 190 IQ, rocks of this type appear to occupy a position immediately in contact with serpentinites and talcose schists belonging to greenstone remnants. In this area there do not appear to be any intervening tonalitic gneisses as is generally the case in the Struben's Valley area and in the region between Parkview and Craighall Park (see Figure 4). Mineralogically the granites contain large crystals of microcline, quartz, and plagioclase. Sericite is abundant while biotite, epidote, and sphene, are relatively rare constituents of the rocks. The medium-coarse texture of these granites has been a contributory factor to the alteration or decomposition processes of the rocks and, particularly in the region north of Struben's Valley, building sand has been quarried from a number of localities. Because of this alteration tendency the writer often experienced difficulty in obtaining suitably fresh material for geochemical study purposes.

(ii) Chemical Data

Four samples typical of this granite-type have been analysed and the results are presented in Table 2. Although the specimens were collected from widely separated areas they nevertheless demonstrate a very consistent chemical composition. As can be seen from a plot of the alkali oxides K_2O and Na_2O, in Figure 3, there is a clustering of points in the upper regions of the granodiorite field while one sample falls into the adamellite field.

Subtle major element variations exist between this class of granitic rocks and the neighbouring class of homogeneous-to-porphyritic granodioritic rocks described in the following section and for which chemical analyses are provided in Table 3. The main variations appear to involve the total iron, magnesium, calcium, and titanium contents of the two varieties, with these elements being slightly more abundant in the pinkish-grey granodiorite suite margining the tonalitic gneisses. Insufficient analyses are presently available, however, to conclusively distinguish the quantitative geochemical variations that may exist between these granites. Added support to the contention that differences exist in the chemistry of the two varieties may emerge from a more rigorous study of the trace element abundances in the granites. From the variations in the Sr and Rb concentrations alone, it is apparent that differences do clearly exist. In Table 2 it can be seen that except in the case of sample WP1, roughly equal quantities of Rb and Sr occur in the pinkish-grey granodiorites, whereas in Table 3 the general tendency of the typical grey, homogeneous, as well as porphyritic granites (represented by samples BR14, RK7, and FD2), is for them to contain greater quantities of Rb, thereby lowering considerably the Sr/Rb ratios of the latter granite variety.

D. THE GREY GRANODIORITE SUITE

Essentially two varieties of granite comprise the rock-types broadly classified into the grey granodiorite suite. These are : (a) homogeneous, medium-textured granodioritic-to-adamellitic granites and, (b) porphyritic granodiorites.

(i) Occurrence and Description

Both varieties of rocks belonging to the grey granodiorite suite occur mainly on the southern half of the Johannesburg-Pretoria dome where they occupy the greater part of the region between the zone of transitional gneisses, migmatites, and homogeneous granitic rocks (see Figure 4) and the ancient tonalitic gneisses and medium-coarse pinkish-grey granodiorites already discussed. Although for purposes of simplification, emphasis is given to the two categories or sub-divisions mentioned above, it should be pointed out that additional variations do exist from place to place but their limited areal extent hardly justifies inclusion on any but the most detailed of maps.

The homogeneous, medium-textured, granodiorites occupy most of the south-central and eastern regions of the dome, embracing the area from Ferndale and North Riding in the west, through Bryanston, Rivonia, and Morningside in the centre, to Modderfontein 35 IR in the east. The southern limits of this granite variety extend to Rosebank, Bramley, and Orange Grove.

The essentially porphyritic granodiorites occur mainly west of Ferndale and extend from Boschkop 199 IQ through Honeydew, and westwards towards Muldersdrift. Porphyritic granitic phases are not, however, restricted to this area alone but may be found developed to a lesser extent in places within the homogeneous granodiorites. This is the case, for example, in the Oaklands-Orange Grove area where coarse porphyritic granites are developed over a relatively large area. Homogeneous and/or porphyritic granite phases are also developed within the area of Transitional Zone gneisses and migmatites which occupy the central areas of the granite dome (see Figure 4), as well as in places north of here, and more specifically in the northeastern quadrant of the granite inlier.

Ghost remnants or nebulites of banded gneiss and migmatite, as well as isolated mafic xenoliths, occur throughout the areas occupied by the grey granodiorite suite. These xenoliths

TABLE 2

Homogeneous, medium-coarse, pinkish-grey granodiorites grading into tonalites

Sample Number	MD21	MD4	WP1	VP2
SiO_2	71.17	72.26	74.16	73.44
Al_2O_3	14.58	14.42	13.77	13.91
Fe_2O_3	0.91	0.49	0.47	0.30
FeO	1.30	1.11	0.72	1.29
MgO	0.58	0.33	0.19	0.38
CaO	1.77	1.62	1.08	1.43
Na_2O	4.26	4.34	4.00	4.12
K_2O	3.97	4.02	4.58	3.97
H_2O-	0.11	0.01	0.03	0.09
H_2O+	0.72	0.80	0.65	0.64
CO_2	0.06	0.15	0.26	0.10
TiO_2	0.31	0.23	0.16	0.27
P_2O_5	0.11	0.06	0.03	0.09
MnO	0.06	0.04	0.05	0.05
Rb ppm	247†	292†	336†	196†
Sr ppm	240†	283†	150†	210†
TOTAL	99.91	99.88	100.15	100.08

MD21 : Muldersdrift area; southwestern part of dome

MD 4 : Rietvallei 180 IQ, south of Muldersdrift

WP 1 : Windsor Park, Randburg - one mile north of Northcliff

VP 2 : Victory Park between Linden and Craighall Park.

† : Rb-Sr values calibrated using GSP-1 Rock Standard (Rb ppm 343; Sr ppm 247 - Flanagan, 1969).

appear to be relics of what was probably a much more extensive gneissic and migmatitic terrain which subsequently underwent transformation to a more homogeneous physical state. This transformation from the one state to another appears to have taken place mainly by a process of metamorphism which, together with the metasomatic introduction of certain of the more mobile elements such as potash and rubidium, caused the original parent rock, or paleosome, to be converted to the newly formed rock portion referred to by Mehnert (1968) as the neosome.

In places where the porphyritic granodiorites are most prominently developed the metamorphism was probably most intense and resulted in crystalloblastic mineral growth. A progressive coarsening of the grain-size took place and whatever preferred mineral orientation there may originally have been was totally destroyed. The metasomatic transformation in the area covered by the grey granodiorite suite appears to have been more effective than elsewhere across the dome. Despite the apparent homogeneity that exists in this region, clues to the history of the past are, nevertheless, available in the form of the nebulitic and rheomorphosed relics, as well as mafic resister xenoliths similar to the one illustrated in Plate 2B.

Occasionally, extremely large felspar porphyroblasts, or megablasts, are developed in the granodiorites. These may be due to a number of factors, including the presence of intrusive pegmatite veins, or structural disturbances that have created local heat-energy sources as, for example, along fracture and shear planes or where folding has been intense. A further common contributor to the formation of large often zoned megablasts, similar to those shown in Plate 2C , has been the emplacement, into the granites, of mafic dykes. A number of dyke varieties exist (see later) but it appears that those related to the Pilanesberg period of dyke emplacement (Gelletich, 1937; Schreiner and van Niekerk, 1958) have been mainly responsible for the exceptionally large felspar megablasts developed in places across the dome. Frequently the idiomorphic felspar porphyroblasts, found in close proximity to mafic dykes, have a strongly preferred long-axis orientation which is generally aligned parallel to the strike of the dyke itself (see Plate 2D).

Mineralogically, the granites of the grey granodiorite suite consists of quartz, plagioclase (albite-oligoclase) orthoclase, and microcline. Lesser amounts of biotite, muscovite, epidote, and sphene are also present while sericitization and saussuritization of the felspar is common.

(ii) Chemical Data

Analyses of a variety of granites forming part of the grey granodiorite suite are listed in Table 3, while a standard plot of the alkali percentages present in these rocks is provided in Figure 3 where a range in composition from granodioritic to adamellitic is evident. A comparison, in Table 3, of these analyses with those of an average adamellite and an average granodiorite, based on the findings of Nockolds (1954), shows several points of difference particularly with regard to the respective quantities of silica, total iron, magnesium, calcium, and phosphorus. A greater degree of correspondence is available, however, when comparing the Johannesburg-Pretoria grey granodiorite suite with the similarly aged Homogeneous Hood Granites found in Swaziland and in the area to the south of the Barberton Mountain Land (Hunter, 1968; Viljoen and Viljoen, 1969b).

Samples BR14 and RK7 may be regarded as representative of the medium-grained, grey, homogeneous granodiorites occupying the greater portion of the south central region of the dome, while sample FD2 is typical of the porphyritic granodiorites developed to the west of Ferndale. Very little difference is apparent between the two varieties yet a subtle distinction can be made by comparing the relative amounts of calcium, sodium, and potassium present in the rocks. Although this distinction may be somewhat dubious from the data presented in Table 3 the conclusions to be drawn from the trend surface analysis, shown later, do provide additional supporting evidence.

Sample NT1C from an area north of Honeydew provides an example of a medium-coarse textured homogeneous granodiorite with a major element chemistry comparable to the earlier examples discussed. The main variation in this instance is provided by trace element geochemistry which demonstrates a very much higher Sr-Rb ratio than was the case for the other samples. Another variation is provided by sample BL2A from the area north of Craighall, and which consists of a dark-coloured, porphyritic granodiorite. This medium-fine grained rock probably represents the granitized product of a former mafic remnant or a melanocratic part of a migmatite or gneiss (melanosome of Mehnert, 1968). The lower silica content and the higher concentrations of iron, magnesium, calcium, titanium, phosphorus, and strontium, lend support to this possible explanation. Other examples could doubtless be found within the limits of the grey granodiorite suite but these would not deviate too greatly from those already discussed.

<u>TABLE 3</u>

<u>Homogeneous, medium-textured, grey, granodioritic-to-adamellitic suite and porphyritic granodiorite suite</u>

Sample Number	BR14	RK7	FD2	NT1C	BL2A	A	B	C
SiO_2	74.03	74.81	74.03	72.38	68.23	72.38	69.15	66.88
Al_2O_3	14.41	13.81	14.17	14.38	14.41	13.95	14.63	15.66
Fe_2O_3	0.25	0.04	0.51	0.51	1.42	0.85	1.22	1.33
FeO	0.86	0.81	0.71	1.11	2.60	1.40	2.27	2.59
MgO	0.27	0.07	0.30	0.30	1.02	0.51	0.99	1.57
CaO	1.34	1.04	1.14	1.65	2.49	1.33	2.45	3.56
Na_2O	4.68	4.29	3.98	4.39	4.23	3.76	3.35	3.84
K_2O	3.50	4.30	4.30	3.97	3.86	4.67	4.58	3.07
H_2O-	0.10	0.02	0.07	0.01	0.03	0.08	-	-
H_2O+	0.41	0.58	0.66	0.77	0.72	0.68	0.54	0.65
CO_2	0.07	0.08	0.05	0.11	0.07	-	-	-
TiO_2	0.16	0.12	0.18	0.24	0.81	0.26	0.56	0.57
P_2O_5	0.05	0.02	0.05	0.07	0.30	0.23	0.20	0.21
MnO	0.06	0.04	0.05	0.04	0.07	0.09	0.06	0.07
Rb ppm	320†	415†	425†	328†	214†	189*	-	-
Sr ppm	179†	106†	163†	302†	382†	134*	-	-
TOTAL	100.19	100.03	100.20	99.93	100.26			

BR14 : Medium-grained grey granodiorite, Bryanston area. Centre of dome

RK 7 : Grey granodiorite, Lombardy 36 IR, southeastern part of dome

FD 2 : Grey porphyritic granodiorite, Boschkop 199 IQ, west of Ferndale

NT1C : Medium-coarse, grey, leuco-granodiorite, Zandspruit 191 IQ, north of Honeydew

B12A : Medium-fine grained, dark-coloured, porphyritic granodiorite, Blairgowrie, between Craighall Park and Ferndale.

A : Homogeneous Hood Granite - Average of 8 analyses of granites from Swaziland (Hunter, 1968) and from Lochiel, south of the Barberton Mountain Land (Viljoen and Viljoen, 1969).

B : Average Adamellite : Average of 121 analyses (Nockolds, 1954).

C : Average Granodiorite : Average of 137 analyses (Nockolds, 1954).

† : Rb-Sr calibrated using GSP-1 Rock Standard (values after Flanagan, 1969).

* : Rb-Sr calibrated using G-1 Rock Standard.

Mention was made earlier of the not infrequent development of strongly porphyritic granites in close proximity to mafic dykes of Pilanesberg age. In the field these coarsely crystalline rocks, which also contain large felspar idioblasts or megacrysts, are characterized further by a deep reddish colouration. Two new analyses, and one previously given by Willemse (1933), are shown in Table 5. Sample FN2 from the Fontainebleau area is located near the Robinson Dyke described and dated by Schreiner and van Niekerk (1958). The high K_2O and Rb concentrations are noteworthy, and are probably representative of metasomatic enhancement of these elements either by the dyke or by the processes responsible for the development of the porphyritic granites in this area and to the northwest.

The reddish colouration of these rocks is, as Willemse (1933) suggested, due to the staining of the felspars by oxides of iron. Chemical analyses provided in Table 5 demonstrate, however, that no significant variations occur in the total iron contents of these granites so that the amount of this material introduced into these rocks must have been slight. The reddish-coloured, often porphyritic granites, at first gave the impression that they represented an entirely separate granite event. This possibility was, however, dispelled after finding highly contorted and banded migmatites similarly stained in areas adjacent to Pilanesberg dykes found transgressing the migmatite-gneiss terrain.

E. TRANSITIONAL ZONE GRANODIORITES, GNEISSES, MIGMATITES AND PORPHYRITIC GRANITES

(i) Occurrence and Description

Granitic rocks of divergent types are manifest in a zone which is transitional between essentially homogeneous and/or porphyritic granodiorites and a region underlain predominantly by gneisses and migmatites. The limits of the so-called Transitional Zone are of a purely arbitrary nature although the writer, in defining this region on a map (see Figure 4), has made use of the restricted presence of a number of "castle koppies", or granite tors, the development of which may be linked genetically to the behaviour of the various granites in their vicinity.

As the remarks already made about the homogeneous and porphyritic grey granodiorites also apply to this area, only a few brief notes need be added with respect to their development in the Transitional Zone. Likewise, any remarks made about the migmatites and gneisses occupying the northern half of the granite dome, will have general applicability to this region now under discussion.

The castle koppies or granite tors have, as mentioned previously, been largely responsible for defining the limits of the zone which occupies a broadly arcuate region in the central and southwestern parts of the dome, and extending from Buccleuch and Halfway House in the east, through to Witkoppen 194 IQ in the centre, and Honeydew in the southwest. The conspicuous, spheroidally weathered, boulder strewn, hills present a unique variation to the otherwise relatively featureless, gently convex, erosion surfaces covering by far the greater part of the surface area of the Johannesburg-Pretoria granite dome (see Plate 2A).

The individual tors, or tor fields, are widely separated from one another by granite country not unlike that found elsewhere on the dome, but, geologically, a variety of granitic rock-types make up the intervening areas. Discontinuous exposure and the restricted areal distribution of the phases encountered in the region makes unrealistic any attempts at plotting these variations on any but the most detailed maps.

Being essentially a transitional zone between relatively homogeneous granites on the one side and inhomogeneous gneisses and migmatites on the other, gradational interfingering of the two types form by far the majority of the exposures. Strongly foliated banded gneisses are in evidence in places, the average trends of which are comparable to those found in the gneissic terrain to the north as well as in the ancient tonalitic gneisses along the dome's southern margin. Despite the banded nature of many of the gneisses and migmatites in several places, there is frequently evidence to suggest that the paleosome has undergone varying degrees of rheomorphism, resulting in the development of nebulites which in turn represent a stage in the evolutionary trend towards partial or total homogenization. In certain select outcrops the full range of conditions and products can be observed. The homogeneous granites represent the penultimate stage of development while the porphyritic granites terminate the cycle.

(ii) The Castle Koppies or Granite Tors

Although no detailed study of the granite tors was undertaken by the writer there are several points of interest worthy of mention in their connection. Considerable variability was encountered in the textural characteristics of the granites making up the individual tors. This variability ranged from fine-grained homogeneous material with or without phenocrysts, to medium, medium-coarse, and coarse granites, as well as banded and foliated gneisses and migmatites. Mafic xenoliths, both granitized and in a relatively well-preserved condition are also encountered where exposure permits observation. Numerous attempts at quarrying the tors have been made but seldom were the ventures successful. The variability in the texture, colour, and nebulitic inclusions probably contributed to the lack of demand for the granite as a building stone.

A recent study of the Witkoppen tor occurrences by Brook (1970) led him to conclude that the compositional (mineralogical) variation in the granites of ten widely spaced sites in the largest group of tors in the area was of sufficient magnitude to suggest that the tors owed their resistance to other than compositional characteristics.

The number of samples taken at each site by Brook varied between 1-5, and in total 24 samples were examined. The quartz content was found to vary from 15-29 per cent of the rock, while felspar ranged from 54-76 per cent and biotite and sphene ranged between 6-20 per cent. Brook (1970) furthermore concluded that the Witkoppen tors do not consist of granite different in lithology from that forming the surrounding country. However, his mineralogical investigations showed that the spatial variation of quartz, felspar, and biotite and sphene contents did indicate that the granites of the tor field are slightly richer in felspar and biotite and sphene than the granites of peripheral areas, which have a higher quartz content. Brook (1970) maintained that, because of an apparent lack of correlation between rock composition (mineralogical) and topography, the Withoppen tors could not be explained in terms of a difference in rock composition. Instead he proposed that the tors were formed by strong jointing, coupled with differential deep weathering beneath the Post African I surface of King (1967). Post African II incision, he contended, exhumed these features which are now being destroyed under subaerial conditions.

While the arguments presented by Brook (1970) may well be partly valid it is the writer's contention that the explanations offered do not adequately explain the lack of similar features elsewhere on the dome. The reasons for their being located in the central part of the granite inlier are, it is maintained, connected with geological as well as geochemical variations occurring within this so-called transitional zone. The evidence, provided by Brook (1970) demonstrating that the tor field granites are richer in felspar, biotite, and sphene, than the surrounding granites, has not been given the attention that it deserves. The felspar content of the tors is particularly significant as it was found that it ranged between 54-76 per cent of the total rock with the potash-rich variety, microcline, accounting for between 42-53 per cent, and the rest consisting of plagioclase felspar.

The K-rich felspar in the Transitional Zone is considered by the writer to have been introduced by metasomatic replacement of pre-existing, more sodic gneisses and migmatites. Locally, as for example where individual tors are now situated, a process of at least partial mobilization, or rheomorphism, probably took place and resulted in the development of a semi-plastic mobilizate. Ill-defined chemical and textural differences were generated and the homogenization process, although incomplete, nevertheless produced material having a tendency to joint in a manner suitable for the production of sub-angular joint blocks and weathered core stones. These core stones ultimately gave rise to the precariously perched boulders so typical of the castle koppies or granite tors found in the area.

(iii) Chemical Data

Four new chemical analyses of rocks situated in the Transitional Zone are presented in Table 4. Included also is an analysis, quoted by Willemse (1933), of a granite from the Halfway House area. The four new analyses are all derived from quarries situated in granite tors in the Witkoppen and Honeydew areas (see Figure 4 for sample localities). The exact locality of the Halfway House sample is, however, not known.

Based on a plot of the alkali contents of the granites (see Figure 3) the castle koppie samples cluster into the granodiorite field as defined by Harpum (1963). Relatively little difference exists between the granodiorites of the castle koppies and those of the grey granodiorite suite presented in Table 3. The examples provided, however, demonstrate the chemical variations that can be expected from one tor locality to another. Major element fluctuations of

TABLE 4

Transitional Zone granodioritic gneisses, migmatites, and porphyritic granites - "Castle Koppie" development

Sample Number	WK4	LF7	HD34	HD31	A	B
SiO_2	68.49	74.33	71.81	73.28	73.92	72.21
Al_2O_3	14.29	13.95	14.32	14.23	14.07	14.39
Fe_2O_3	1.42	0.21	0.85	0.45	0.52	0.66
FeO	2.54	0.91	1.38	1.14	0.89	1.33
MgO	0.93	0.09	0.51	0.29	0.38	0.60
CaO	2.34	1.09	1.84	1.46	1.22	1.58
Na_2O	4.20	4.41	4.24	4.16	3.83	4.37
K_2O	3.98	4.35	3.82	4.18	4.35	3.57
H_2O-	0.09	0.03	0.14	0.02	0.01	0.16
H_2O+	0.65	0.59	0.61	0.56	0.44	0.58
CO_2	0.05	0.05	0.07	0.03	-	0.43
TiO_2	0.78	0.13	0.34	0.24	0.21	0.25
P_2O_5	0.28	0.02	0.12	0.04	0.09	0.10
MnO	0.06	0.05	0.06	0.05	0.04	0.03
Rb ppm	181†	434†	305†	349†	-	105*
Sr ppm	335†	168†	374†	219†	-	278*
TOTAL	100.10	100.21	100.11	100.13	99.97	

WK 4 : Fine-grained biotite-rich granodiorite "Castle Koppie", Witkoppen 194 IQ, centre of dome

LF 7 : "Castle Koppie", Wilgespruit 190 IQ, southwestern part of dome

HD34 : North of Honeydew, southwestern part of dome

HD31 : "Castle Koppie", north of Honeydew, southwestern part of dome.

A : Halfway House Granite - eastern edge of dome. Exact locality unknown. (Willemse, 1933).

B : Average of three analyses of Nelspruit Migmatite, north of the Barberton Mountain Land (Viljoen and Viljoen, 1969).

† : Rb and Sr values calibrated using GSP-1 Rock Standard (Rb ppm 343; Sr 247 - Flanagan, 1969).

* : Rb and Sr values calibrated using G-1 Rock Standard.

significance occur in the silica, total iron, magnesium, calcium, and titanium concentrations of the various granodiorites, while the trace elements Sr and Rb also show marked variations.

As mentioned in a previous section, the granitic rocks of the Transitional Zone are considered to represent an intervening metasomatic stage developed between the basic gneisses and migmatites of the northern half of the dome and the grey granodiorite suite on the southern side. The chemistry of the resulting granitic assemblages in this zone can be closely compared with that of the granodioritic gneisses and migmatites that are developed on the northern flank of the Barberton Mountain Land. The average of three Nelspruit migmatites is given in Column B of Table 4. With the possible exception of the Rb-Sr values very little major element variation of much significance is apparent.

F. THE MIGMATITE AND GNEISS TERRAIN

(i) Occurrence and Description

Migmatites and gneisses occupy practically the entire northern half of the Johannesburg-Pretoria granite dome. Exposure is somewhat variable across the region, being very good in the northwestern quadrant of the inlier where numerous rivers dissect the granites, and relatively poor in the north-central, and northeastern segments of the map area. The best outcrops are generally to be found along the main river courses as well as in some of the tributary streams. A feature elsewhere, of the gneissic and migmatite terrain is the smooth, gently rolling, nature of the land surface which is generally devoid of rock outcrops. Where outcrops do occur they are frequently difficult to sample as the gneissic granites tend to decompose more readily than any of the granitic rocks found elsewhere. Figure 5, which is a map showing the distribution of sample localities across the granite inlier, illustrates the fact that there were less sampling opportunities in this area than on the southern half of the dome. Nevertheless, sufficient exposure is available to demonstrate the variations that occur from place to place within the migmatite-gneiss terrain.

Numerous small inclusions are commonly encountered in the migmatites. These are generally comprised of black hornblende amphibolites with ultramafic inclusions being less common. The xenoliths are invariably irregularly shaped and are generally invaded by pegmatitic veinlets in a manner similar to the example shown in Plate 1E. Larger greenstone remnants are also found irregularly distributed across the area. Many of these are, however, not of sufficient extent to be included on the map of the region. Large remnants of amphibolite and serpentinite as well as a variety of hybrid rocks occur in the area northeast of Muldersdrift in the western half of the dome. Numerous scattered xenoliths can be found on the farms Zandspruit 191 IQ and Rietvallei 538 JQ, to the north of Honeydew and North Riding, while further occurrences of this type can be found in the Halfway House area. On the northwestern rim of the dome gneisses and migmatites interfinger with greenstone remnants on the farms Zwartkop 525 JQ, Tweefontein 523 JQ, Mooiplaats 524 JQ, and Rietfontein 532 JQ. It is suspected that many more mafic and ultramafic xenoliths are developed in the area than are readily apparent but, because of poor exposure, their presence can only be surmized from such evidence as the dark colouration of soils and the nature of the vegetation cover.

The gneisses developed across the region are usually either strongly foliated or consist of alternating leucocratic and melanocratic bands. In many places a complex variety of migmatites are encountered, many of which are intricately folded, as in the example shown in Plate 1D. Although the foliation trends vary from place to place an average trend, striking at approximately 120-130 degrees, emerges from a systematic regional study of the gneisses. The attitude of the foliation is generally steeply dipping or vertical. In places, particularly around the north-eastern margins of the dome, very flat dipping foliation planes were encountered. On the farm Brakfontein 399 JR almost horizontally banded gneisses are gently folded about vertical axial planes and the plunges of the wave-like folds are at shallow angles to the southeast.

Apart from the gneisses and migmatites that occupy most of the region, a number of granitic variations exist in localized areas. Nebulitic, homogeneous, and porphyritic phases are not uncommon. In addition, numerous pegmatites may be found intruding the gneisses and migmatites, often causing locallized segregation of the paleosome into melanocratic and leucocratic bands. The pegmatitic veins generally consist of quartz and felspar with lesser amounts of muscovite developed in places. Graphic quartz-felspar intergrowths are also common.

The mineralogy of the gneisses and migmatites is extremely variable. The strongly foliated tonalites or trondhjemites contain large amounts of biotite, quartz, and soda-plagioclase, the latter generally partially altered to sericite and epidote. Lesser amounts of K-felspar, muscovite, sphene, apatite, and occasionally hornblende and chlorite, are also present together with some blue opalescent quartz. The more homogeneous, nebulitic phases have lesser quantities of biotite and more quartz and felspar (oligoclase-albite, orthoclase, microcline, perthite). Some of the felspar idioblasts occurring in the homogeneous and porphyritic phases show well-developed zoning.

The evidence presented in the field clearly illustrates that the migmatite-gneiss terrain underwent a long and complex history involving several stages of evolution. Although further detailed investigations are called for the writer suggests the following sequence of events apply to the region : From the evidence supplied by the presence of all the basic inclusions and greenstone remnants, it is contended that rocks of mafic and/or ultramafic composition initially occupied the greater part of the region now exposed as the Johannesburg-Pretoria granite inlier. This in fact implies that the writer considers the early crustal material to have been of this composition, if not entirely, then at least in part. The first events to disturb these primitive successions resulted from the widespread influx, into the upper levels of the crust, of a relatively basic granitic medium which soaked into the environment stoping and assimilating much of the earlier material. This event although of a widespread nature was, however, insufficiently intense to totally destroy the pre-existing environment and numerous greenstone remnants remained intact or partially altered. Where the granitization process was more complete small basic resisters, in the form of amphibolite or serpentinite xenoliths, remain as a legacy of the past.

Within the granitized regions a continuous process of transformation took place possibly because the early event had provided avenues for the relatively unimpeded passage of further felsic constituents. The more completely granitized regions presumably possessed higher heat flow properties, a factor that was to aid further the influx of more volatile granitic ichors in a continuous sequence of events.

The first-formed granitic rocks in the area were the tonalitic gneisses, described in an earlier section. These, coupled with their contained mafic xenoliths, were then caught up in the ensuing process of migmatite formation which resulted from potash metasomatism, selective anatexis, palingenesis, and rheomorphism. Partial mobilization of the granites, coupled with the generation of locally variable stress fields, produced flowage folding of extraordinary complexity. The continuing process created segregated patches, lenses, and veins and differential metamorphism either created or destroyed the melano- and leuco-cratic banding in the rocks. Nebulitic development ensued and the process passed to completion with the development locally, of homogeneous and porphyritic granite phases. These processes were more successfully accomplished in the Transitional Zone and in the area occupied by the Grey Granodiorite Suite discussed earlier.

(ii) Chemical Data

The migmatite-gneiss terrain contains a complex array of granite types similar in many respects to the varieties already discussed in earlier sections. As a consequence no further chemical considerations will be given here to the rocks of the area. The regional geochemical variability of Na_2O, K_2O, Sr, and Rb is, however, discussed later in connection with the trend surface analysis studies of the data derived from over 400 samples collected across the granite dome.

G. FELSITIC DYKES

(i) Occurrence and Description

Fine-grained felsitic rocks are prominently developed in the western half of the granite dome but are not entirely restricted to this area. First described by Kynaston (1907), these acid dykes have prompted discussion from numerous subsequent investigators of the region including Wagner (1907), Mellor (1917), and Hendriks (1961), but the most comprehensive account of these rocks is that provided by Willemse (1933).

The quartz-felsites are recognized in the field by their generally pale-pinkish colour, their exceptionally fine-grained texture, and the intense nature of the jointing manifest in these rocks.

Willemse (1933) provided evidence to suggest that the felsites were intruded into the granites, a fact supported by the writer. Mineralogically these rocks possess a micropegmatitic-

TABLE 5

Porphyritic Granites - pinkish-red, medium-coarse, granites (possibly affected by proximity to Pilanesberg dykes)

Sample Number	FN2	LF1	A
SiO_2	74.63	72.70	73.96
Al_2O_3	13.45	14.24	13.05
Fe_2O_3	0.12	0.58	0.77
FeO	0.95	1.06	0.88
MgO	0.54	0.21	0.45
CaO	0.59	1.27	1.06
Na_2O	3.24	4.48	4.58
K_2O	5.35	4.15	4.40
H_2O-	0.17	0.04	0.05
H_2O+	0.69	0.74	0.46
CO_2	0.09	0.06	0.01
TiO_2	0.16	0.24	0.16
P_2O_5	0.04	0.06	tr
MnO	0.03	0.05	0.05
Rb ppm	419†	-	
Sr ppm	201†	-	
TOTAL	100.05	99.88	99.88

FN 2 : Pinkish-red medium-coarse grained granite, Fontainebleau area, southern edge of dome

LF 1 : Pinkish-red granite-gneiss, Wilgespruit 190 IQ, southwestern part of dome

A : Red Granite. Rietfontein 2 IR, north of Rivonia - centre of dome (Willemse, 1933).

† : Rb-Sr values calibrated using GSP-1 Rock Standard (Flanagan, 1969).

texture consisting of a fine-grained mosaic of quartz and felspar, the latter generally altered to sericite. In places felspar phenocrysts give the rock a porphyritic texture.

The best developed felsite dykes occur in the region extending northeast from Muldersdrift to the farm Bultfontein 533 JQ. Outcrops of this rock-type in the area are generally poor except in the river cuttings near Muldersdrift. Here the intrusive nature of the felsites into the granite can be seen together with some exceptional jointing. Mafic dykes also transgress the felsites at this locality. Two other examples of felsitic dyke rocks were encountered on the southern and southeastern margins of the granite dome, the latter striking approximately east-west and intruded into ancient tonalitic gneisses. The first of these occurs south of Emmarentia Dam near Roosevelt Park, while the second dyke was found on the farm Lombardy 35 IR.

(ii) Chemical Data

Four new chemical analyses of felsite dykes found in the area are presented in Table 6. Three of the samples are from pale-pinkish grey coloured dykes occurring in the Muldersdrift area. Two of these (MD16B and MD22) are intruded into grey, somewhat porphyritic granodiorites, while sample SK13 invades an area underlain by gneisses and migmatites. The remaining sample EM1 is intruded into hornblende-biotite tonalites.

While the chemistry of each of these examples is closely comparable, the influence of the host rocks on the composition of the felsites from the different localities is nevertheless apparent. Sample EM1, from the dyke intruded into basic tonalitic gneisses, reflects higher total iron, magnesium, sodium, and titanium, and lower potash and silica contents than the remaining felsite varieties. A relatively high calcium content is also evident. The felsite dyke SK13, which cuts through the migmatite-gneiss terrain, shows the influence of having been intruded into the leuco-biotite tonalites as is indicated by the relatively high calcium and sodium, and low potash contents of the rocks. The dykes closest to Muldersdrift on the other hand, having intruded somewhat porphyritic granodiorites, reflect a high potash-soda ratio.

Willemse (1933) concluded that the quartz-felsite dyke occurrences in the Johannesburg-Pretoria granite dome were probably coincident with Ventersdorp extrusions. While possessing no evidence to the contrary the writer would, however, like to suggest a possible alternative explanation. The felsitic dykes may not necessarily constitute an entirely separate event post-dating the granites of the area. They may rather represent the rapidly chilled, filter-pressed products of remobilized phases of the pre-existing granitic rocks of the area. A similar explanation was extended by Scholtz (1946) for the quartz-felsite dykes transgressing the younger Precambrian granite plutons of the southwestern Cape Province, South Africa, an average analysis of which is given in Column A of Table 6. Thus, despite their intrusive relationships these felsitic rocks need not necessarily be totally unrelated to the granites enveloping them.

H. OTHER GRANITIC AND RELATED ROCKS

Mention has been made previously of hybrid granitic rocks occurring in areas where greenstone remnants have undergone metasomatic changes as a result of granitization processes. These rocks take on an extremely variable character depending upon the nature and the degree of assimilation of the xenolithic rocks affected by the invading granites as well as on the chemical and textural properties of the invaded assemblages. Because of the wide variety of hybrid granite types that exist in the area no attempt at classification has been made. A few examples illustrating the chemical peculiarities of some of these rocks are, however, presented in Table 7. Sample SK3 represents a fine-grained, foliated diorite, found on the western margin of the granite dome on the farm Zwartkop 525 JQ. This rock passes gradationally into an amphibolite forming part of the Swaziland Sequence in the area. Sample HD29, on the other hand, occurs on the farm Zandspruit 191 IQ in the area north of Honeydew, and represents the hybridized product of assimilation of a small greenstone xenolith entirely surrounded by porphyritic and altered tonalitic gneisses.

Several peculiar granitic dykes intrude the dome. One distinctive variety (HD24B) comprises a microgranite dyke containing large and small, irregular inclusions of considerable compositional and textural diversity. Three such occurrences were noted, two on the farm Zandspruit 191 IQ, and the other near Muldersdrift.

A granite dyke containing large felspar porphyroblasts, or megacrysts, invades the essentially porphyritic grey granodioritic assemblage on the farm Nooitgedacht 534 JQ between

TABLE 6

Felsitic Dykes

Sample Number	EM1	MD16B	MD22	SK13	A
SiO_2	73.19	75.96	75.87	76.08	79.65
Al_2O_3	13.95	13.48	13.56	13.30	12.03
Fe_2O_3	0.49	0.16	0.14	0.08	0.52
FeO	1.84	0.29	0.26	0.42	0.79
MgO	0.18	0.09	0.12	0.08	0.33
CaO	0.34	0.23	0.07	0.58	0.87
Na_2O	4.85	3.52	3.43	4.62	1.88
K_2O	4.35	5.53	5.86	4.44	2.64
H_2O-	0.15	0.02	0.06	0.20	0.23
H_2O+	0.35	0.55	0.52	0.22	0.75
CO_2	0.12	0.08	0.02	0.03	-
TiO_2	0.12	0.03	0.03	0.03	0.09
P_2O_5	0.01	0.01	0.01	0.01	0.08
MnO	0.04	0.03	0.03	0.03	0.06
TOTAL	99.98	99.98	99.98	100.12	99.68

EM 1 : Felsite dyke. Emmarentia (between Roosevelt Park and Parkview)

MD16B)
MD22) : Felsite dyke. Muldersdrift, southwestern edge of dome

SK13 : Felsite dyke east of Zwartkop 525 JQ (western portion of dome)

A : Average of 3 quartz-felsite dykes from the younger Pre-Cambrian Granite Plutons of the Cape Province (Scholtz, 1946).

TABLE 7

Diorite, hybrid granite, microgranite dyke, porphyritic granite dyke and sheared and altered granites

Sample Number	SK3	HD29	HD24B	LP8	LR2	A
SiO_2	54.93	59.43	67.46	71.13	72.60	78.61
Al_2O_3	12.59	17.67	13.67	14.60	13.88	7.76
Fe_2O_3	1.54	0.95	1.23	1.03	0.87	4.51
FeO	5.87	1.65	3.28	1.43	1.42	1.69
MgO	9.76	3.41	2.10	0.52	1.57	0.90
CaO	8.91	3.92	4.54	1.81	0.06	2.60
Na_2O	2.24	3.17	3.05	4.50	0.09	2.10
K_2O	1.20	4.49	2.85	3.72	7.50	1.74
H_2O-	0.01	0.16	0.02	0.06	0.03	-
H_2O+	2.00	1.66	1.12	0.77	1.39	-
CO_2	0.04	2.91	0.13	0.05	0.05	-
TiO_2	0.47	0.32	0.27	0.32	0.20	-
P_2O_5	0.10	0.13	0.05	0.10	0.07	tr
MnO	0.17	0.08	0.09	0.05	0.05	-
Rb ppm	56†	260†	-	244†	414†	-
Sr ppm	237†	154†	-	312†	28†	-
TOTAL	99.83	99.95	99.86	100.09	99.78	99.91

SK 3 : Fine-grained foliated diorite, Zwartkop 525 JQ, western edge of dome

HD29 : Hybrid granite resulting from assimilation of greenstone xenolith. Zandspruit 191 IQ, north of Honeydew

HD24B : Microgranite dyke with inclusions, Zandspruit 191 IQ, one mile north of North Riding

LP 8 : Porphyritic granite dyke. Nooitgedacht 534 JQ, 3.5 miles northwest of Honeydew

LR 2 : Sheared and sericitized granite below Orange Grove Quartzites, Linksfield Ridge

A : Orange Grove Granite quoted by Horwood (1910), and Wade (1909). Exact locality unknown.

† : Rb-Sr values calibrated using GSP-1 Rock Standard (Flanagan, 1969).

Honeydew and Muldersdrift. An analysis of this dyke (sample LP8), which weathers to form large isolated rounded boulders, is given in Table 7.

Apart from the variations described above, attention is also drawn to the presence of highly sheared granites generally located in close proximity to major faults or crush-zones that occur commonly on the dome. In addition, sheared and sericitized granites are frequently developed at the contacts of the younger cover rocks rimming the area. A fairly typical example of the geochemical changes that take place in sheared and altered granites of this type is provided in Table 7 by sample LR2, from the Linksfield Ridge on the southeastern margin of the granite dome. Prior to shearing this granite, which underlies the Orange Grove Quartzites of the Witwatersrand Sequence, was probably a mesocratic tonalitic gneiss. As a result of silicification and sericitization both the silica and potash concentrations in rocks that have suffered this form of deformation increase considerably at the expense of most other elements, particularly sodium and calcium. The Rb concentration is also enhanced at the expense of Sr.

MAFIC DYKES

Hypabyssal mafic dykes are prolifically developed in all the areas underlain by granitic rocks. The dykes vary considerably in orientation, age, and in chemical and mineralogical composition. No detailed study of these rocks was attempted and only the most obviously exposed dykes were included on the geological map of the region (Figure 4). A great many more exist but are decomposed and do not outcrop, their presence being noted mainly by soil colour changes.

Four main dyke varieties were encountered :

(a) Ancient, partly or totally granitized dykes;

(b) Diabase dykes;

(c) Porphyritic diabase dykes;

(d) Composite dykes.

(a) Ancient Granitized Dykes

Very ancient dykes are found in isolated localities particularly in the migmatite-gneiss terrain, but not entirely restricted to this area alone. Good examples are rare, the best exposure of one of this type being found in the Halfway House quarry on the farm Waterval 5 IR. These dykes were intruded into the area at least prior to the onset of the major granitization event that was responsible for the destruction and homogenization of the early gneisses and migmatites. In the quarry mentioned above, the dyke comprises large irregular blocks of partially or completely granitized amphibolite, the latter cut by anastomizing veins and stringers of pegmatite and leuco-granite. The transformed dyke produces a zone with a migmatitic appearance and is surrounded by nebulitic and homogeneous granitic phases typical of the varieties found in the Transitional Zone.

(b) Diabase Dykes

Dark, fine-to-medium textured, diabasic dykes are the most commonly encountered variety found in the granites. They frequently produce low, narrow, tree and bush-clad ridges which can be traced for long distances throughout the area. The precise age of these dykes is uncertain but many of them penetrate the Transvaal Sequence quartzites and dolomites on the northern rim of the dome and probably represent a phase of activity associated with the emplacement of the Bushveld Igneous Complex dated at 1950 m.yrs. by Nicolaysen (1962).

(c) Porphyritic Diabase Dykes

A few diabase dykes, intruded mainly into the northwestern quadrant of the Johannesburg-Pretoria dome, are conspicuously porphyritic, containing large, sometimes zoned, felspar phenocrysts up to 5 cms across. In most cases the felspars are strongly saussuritized and form nodular lumps on the weathered outcropping surfaces. The porphyritic and the non-porphyritic diabase dykes are probably of a similar age - the main difference between them being due to their variable cooling histories at the time of emplacement.

(d) Composite Dykes

A number of composite dykes, consisting of mixed mafic and felsic components, transgress the area, penetrating rocks of all ages except the Karroo sediments. A number of these dykes can be traced for considerable distances not only in the granite terrain but also southwards into the Witwatersrand Sequence where they are intersected in many of the gold mines along the Central Rand. Two such dykes viz., the Gemspost Dyke and the Robinson Dyke, have been dated by Schreiner and van Niekerk (1958) and van Niekerk (1962). The former was found to be 1330 ± 80 m.yrs. old and the latter 1290 ± 180 m.yrs. old. Both dykes form part of the so-called Pilanesberg dyke-system described by several investigators (Krahmann, 1936; Gelletich, 1937; and Gough, 1956).

Apart from possessing peculiar palaeomagnetic properties (Gough, 1956) these dykes are usually responsible for the reddish-pink discolouration, as well as the development of large felspar megacrysts or porphyroblasts, in the granites through which they intrude. In addition, the dykes are usually of a composite nature consisting of dark, mafic, doleritic or diabasic material, together with a more felsic portion of fine-grained reddish-grey syenite. In the western half of the dome the Pilanesberg dykes strike preferentially in a north-northwest direction while in the centre of the dome, near the Leeukop Farm Colony, these dykes have a west-northwesterly preferred orientation.

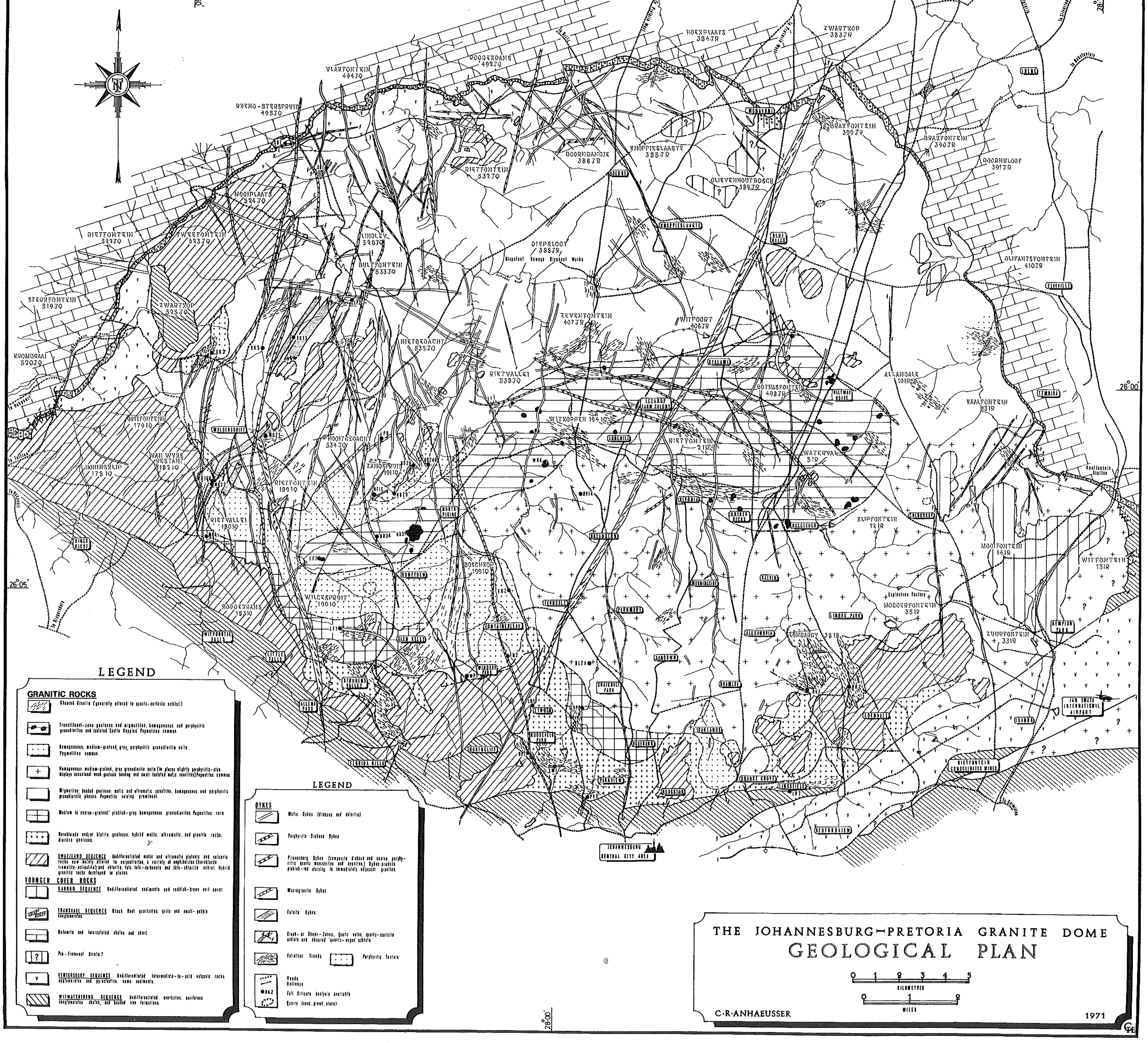
THE SHEAR OR CRUSH ZONES

Willemse (1933) considered that many of the quartz veins and highly schistose granites represent crush-zones in the granite dome. As can be seen from the geological map of the area (Figure 4) a considerable number of very prominent crush-zones or faults transgress the region, being best developed on the western half of the dome. The most extensive dislocation or crush-zone splits the dome into two, roughly equal, segments and extends in a northeasterly direction from Northcliff in the south through Ferndale, Bryanston, and Kyalami, to the farm Brakfontein 399 JR in the north. The fault zone, like many others in the granites is marked by a prominent quartz ridge. Vertical, as well as right lateral wrench movements along this fault plane have been primarily responsible for the northward displacement of the Witwatersrand quartzites in the Northcliff area, but the affects of this fault on the regional geochemistry are also apparent from the trend surface analysis presented later. Strongly sheared granites generally flank the quartz-vein prominences. In the Glen Kelly area the granites are totally altered to quartz-augen schists consisting of quartz and sericite and shredded by stringers and veins of quartz. The strong northeasterly trend in these sheared granites does not extend into the Swaziland Sequence rocks to the south, the latter possessing a prominent northwesterly trend. No adequate explanation for this phenomenon can yet be offered. The prominent primary shear-zones are often accompanied by second-order splays and a consistent geometrical relationship between the various fracture zones is apparent. Several stages of dislocation are evident with some of the main quartz-filled shear zones being themselves offset by right-lateral faulting.

The degree and intensity of deformation and shearing is particularly evident around the margins of the dome and may be due to the interaction of the updoming granite on the younger cover rocks. The intense shearing on the northern rim has affected not only the granites but also some pre-Transvaal acid volcanic rocks, resulting in the development of quartz-sericite schists in many areas. The deformation responsible for the more prolific shearing and faulting on the western half of the dome may also be related to the events responsible for the development of the West Rand Syncline and discussed by Roering (1968).

The age of the faulting and shearing on the dome is clearly later than the age of the youngest cover rocks in the area (excluding the Karroo sediments). Many of the shear-zones and quartz-filled veins are cut by the diabase dyke swarm as well as by the younger composite Pilanesberg dykes. It thus appears that the latest faulting and shearing of significance took place after the deposition of the lower formations of the Transvaal Sequence, yet prior to the intrusion of the majority of the mafic dykes. This event would then have occurred roughly 2,100 m.yrs. ago, or at approximately the same time as the period of granite reheating postulated by Allsopp (1961).

FIGURE 4


THE JOHANNESBURG–PRETORIA GRANITE DOME
GEOLOGICAL PLAN
KILOMETRES
MILES
C.R. ANHAEUSSER
1971
LEGEND
GRANITIC ROCKS
YOUNGER COVER ROCKS
LEGEND
DYKES
JOHANNESBURG CENTRAL CITY AREA
JAN SMUTS INTERNATIONAL AIRPORT
26°00′
26°05′
27°50′
28°00′
28°15′
VLAKFONTEIN 494 J Q
RHENO-STERSPRUIT 495 J Q
DOORNKRAAL 520 J Q
STERKFONTEIN 519 J Q
RIETFONTEIN 532 J Q
TWEEFONTEIN 533 J Q
ZWARTKOP 525 J Q
NOOITGEDACHT 534 J Q
RIETVALLEI 538 J Q
WITKOPPEN 194 I Q
RIETFONTEIN 2 I R
WATERVAL 5 I R
KLIPFONTEIN 12 I R
MODDERFONTEIN 35 I R
WITFONTEIN 15 I R
ZUURFONTEIN 33 I R
KAALFONTEIN 13 I R
OLIFANTSFONTEIN 410 J R
DOORNKLOOF 391 J R
ZWARTKOP 383 J R
HONINGKLIP 178 I Q
WILGESPRUIT 190 I Q
ROODEKRANS 183 I Q

PART II

REGIONAL GEOCHEMICAL STUDY OF THE GRANITES

A. INTRODUCTION

Apart from the 33 select granite samples for which full chemical analyses were made available in an earlier section a more comprehensive regional geochemical study was initiated, use being made of many samples collected across the entire dome area. Although it is the intention to ultimately examine in greater detail the geochemical variations of a wide variety of elements contained in the granitic rocks of the Johannesburg-Pretoria dome it was decided for the purpose of this presentation to limit the initial investigation to the determination of four selected chemical parameters. Thus the alkali metals sodium, potassium, rubidium, and strontium were chosen first, principally because of their general usefulness and applicability to the study of granitic rocks.

Na_2O and K_2O, the oxides of the alkali metals Na and K, are relatively abundant in granitic rocks whereas Rb and Sr are present in markedly lesser quantities measurable only in trace or minor amounts. The behaviour of the oxides Na_2O and K_2O have proved to be most useful in the classification of ancient granitic rocks (Harpum, 1963; Hunter, 1968; Anhaeusser, 1969; Viljoen and Viljoen, 1969b) while the elements Rb and Sr were found to provide useful additional as well as supplementary information relating to the Archaean granites surrounding the Barberton Mountain Land (Viljoen and Viljoen, 1969b).

The alkali metals, furthermore, provide important information relating to the petrogenesis of granitic rocks as they are prominent components of the most important rock-forming minerals, being contained as they are largely in the felspar and mica group of minerals. With the exception of Na and Sr, which show a steady decrease, the concentration of all the alkali metals increases with fractionation (Heier and Adams, 1964). In the majority of cases of fractionation no pronounced geochemical coherence can be expected between Na and K, and K increases relatively more than Na resulting in a steady increase in the K/Na ratio.

B. SAMPLE PREPARATION AND ANALYTICAL TECHNIQUE

Microscopic investigations revealed that few of the granitic samples collected were in a completely unaltered state. Even specimens obtained from the deepest of quarries showed varying degrees of sericitization and/or saussuritization. Only the best-preserved, least-altered, and most representative rock material was used for analysis. Samples, free of any weathered surfaces and generally ranging between 2 and 4 kilograms in weight, were collected at each of over 500 localities. Initial crushing was carried out in a jaw crusher and was followed by the fine grinding, to -325 mesh, of each sample in two stages using a Siebtechniek pulverizing apparatus with a widia steel (W-Co steel) vessel and ring.

Representative fractions of each sample were pressed into aluminium-backed, 40 mm diameter, pellets for use in X-ray fluorescence equipment. Apart from the determinations of the Na_2O values, which were carried out by X-ray fluorescence analysis under the auspices of the National Institute for Metallurgy, Johannesburg (N.I.M.), the K_2O, Sr, and Rb data was acquired by the writer in the Department of Geology, University of the Witwatersrand, with the assistance of Mr. I. Wright of the Johannesburg Consolidated Investment Company Mineral Processing Research Laboratory.

For the determination of K_2O, Sr, and Rb use was made of a Phillips PW 1540 X-ray fluorescence vacuum spectrograph. In addition to the local standard granite NIM-G, the following international rock standards were used in the calibration of the working curve used by the writer in the determination of the K_2O data : the United States Geological Survey standards W-1, GSP-1, AGV-1 and BCR-1; the French standards GA, GH, GR, and BR; the Canadian standard SY-1; and the Tanzanian standard T-1. No mass absorption corrections were made. An excellent straight line working curve could be constructed for the international rock standards, the values of which compared very favourably with the published data listed by Flanagan (1969) and Roubault and others (1966). In addition the 33 analysed granites, listed earlier in Tables 1 to 7, were used as check samples and provided supplementary analysis control.

Rb and Sr determinations were carried out using a LiF 110 crystal and a Mo tube operating at 50 kV and 20 mA. Three background readings were taken at 35°2θ, 37°2θ and 40°2θ respectively. Sr and Rb Kα peaks were measured at 36.00°2θ and 38.14°2θ respectively. Peak positions were counted for 100 seconds while 50 second background readings were taken. Pulse height discrimination was used and the mass absorption coefficients were determined by employing the Reynold's Method, using the Mo Compton Peak. Calculations to determine the amounts of Sr and Rb in each sample were undertaken using the formula :

$$\begin{array}{c}\text{Conc. Unknown}\\ \text{(in ppm)}\end{array} = \frac{(P - BG)x}{(P - BG)_S} \times \frac{x^t}{S^t} \times \begin{array}{c}\text{Conc. Standard}\\ \text{(in ppm)}\end{array}$$

where P = count on peak

BG = calculated counts at background

x = unknown sample

S = standard sample, and

t = time for fixed count.

Note : $\frac{x^t}{S^t}$ = mass absorption coefficient correction factor

The United States Geological Survey standard granodiorite (GSP-1) was used as a reference. The values employed were 343 ppm Rb and 247 ppm Sr (after Flanagan, 1969).

C. GAMMA RADIATION ANALYSIS

In an attempt to assess the areal variability of the gamma radiation of the granites of the Johannesburg-Pretoria dome, portions of the samples used in the geochemical study were subjected to scintillation spectrometry. In order to standardize the amount of each sample used in the experiment, 120 grams of granite, pulverized to -120 mesh, were weighed out into flat plastic containers having a diameter equal to the scintillation crystal used in the analysis. The apparatus employed enabled the gamma rays emitted by the granite samples to be detected by causing them to interact with a material responding to the interaction by scintillation - that is, by emitting photons of visible light whose intensity is directly proportional to the energy of the absorbed gamma ray. The scintillating material used in the apparatus, made available to the writer by the Nuclear Physics Research Unit at the University of the Witwatersrand, Johannesburg, was a single 76 x 76 mm thallium-activated, sodium iodide crystal with a resolution of 9 per cent for the Co^{60} 1.33 Mev peak.

The crystal was optically coupled to a photomultiplier tube, which detected the light emissions and converted them to electronic pulses which were then, in turn, counted for a given counting period. The results obtained represent a record of the comparative - not absolute - gamma ray energy emitted by the radioactive nuclei in each sample. It was established that to statistically justify a confidence level of approximately 5 per cent variation in the count recorded by each sample it was necessary to fix the counting time at 10 minutes per determination. Despite careful lead screening and shielding during the counting procedure this rather lengthy approach was found to be unavoidable in order to discriminate between the actual sample radiation and the background natural and cosmic radiation.

In order to gain an indication of the type of radiation being measured in the granites a few samples were tested using a 45 cc Ge (Li) semiconductor detector, with a resolution of 2.5 Kev for the Co^{60} 1.33 Mev peak, coupled to an Intertechnique 4000 channel analyser. The results demonstrated that, in some samples, K^{40} was responsible for most of the gamma radiation emitted, while in others Bi^{214} and Pb^{214}, the decay products of radium, were also contributors to the total radiation measured.

It is important to note that only fresh samples were used in the radiation analysis. This procedure has the advantage over any field scintillometer study which unavoidably records radiation emitted from both fresh and weathered rock at any one sample locality. Where weathered material is present (and this usually is the case except possibly in quarries and trenches) equilibrium is upset because uranium leaches preferentially to K and Th. The radiation data acquired from fresh samples eliminates, therefore, any equilibrium uncertainties that may apply to the region being investigated.

D. METHODS OF STUDY

Apart from careful observation and detailed geological mapping other attempts at assessing the quantitative areal variability of granitic rocks have been made using modal and chemical properties obtained from samples regarded as representative of the granites that were being studied. Varying success has been obtained by several investigators in estimating the areal and/or linear modal and chemical variability possessed by specimens collected from a granitic complex (Saha, 1954, 1968; Taubeneck, 1957; Whitten, 1957; Dawson, 1958; Mehnert, 1960), but it was Whitten (1959, 1960, 1961a, 1961b and 1962) who demonstrated that trend surface analysis provides probably the most valuable means of expressing quantitative data in an objective manner.

With the view in mind of trying to establish the areal chemical variability of the granitic rocks of the Johannesburg-Pretoria dome the writer embarked upon a rigorous sampling programme in an attempt to obtain quantitative geochemical data. As has been pointed out by Krumbein (1960) and Whitten (1961a) the collection and analysis of a few typical specimens do not usually permit generalizations to be made about the composition of the whole mass represented. All too frequently, these authors maintain, the assumption is made that isolated "typical specimens" typify the whole complex. This approach they add, has relatively little value until it is viewed in relation to the target population of specimens which comprise the whole rock-mass under study.

Whitten (1961a) has pointed out the difficulties that exist when trying to establish a suitable method of sampling a large area, as typicality and inhomogeneity depend to a great extent on the scale factor. Because of the vagaries of natural outcrop, sample collection, even in well-exposed terrains, can seldom be obtained on a grid superimposed over a map of the area. For this reason, therefore, the writer attempted to sample only where suitable exposure was made available. Within the built-up city limits sample opportunities were often made available in trenches and excavations or where road and other municipal services frequently exposed suitable material for study purposes. Exposure elsewhere on the granite dome was found to be generally good as numerous rivers dissect the region providing areas of fresh outcrop. In addition, the region is well-traversed by a closely spaced road network providing access to innumerable small-holdings and agricultural plots. A number of quarries supplying building stone, sand, and gravel are also located in the granites and provide useful additional sampling sites.

Initially, over 500 samples were collected across the area embraced by the granite dome. Subsequent sample screening reduced the number used in this study to between 400 and 425, representing approximately one sample per 1.5 square kilometres of terrain occupied by granitic rocks in the dome area. Figure 5 provides a measure of the density and distribution of the sample control points used in the trend surface analysis of the geochemical data presented in Figures 6-12. In general, good coverage is provided across most of the dome although sampling is less dense in the north-central area as well as in the extreme eastern portion of the region. Poor exposure in parts of the gneiss and migmatite terrain, coupled with the tendency for rocks in this area to be more decomposed than elsewhere, provided sampling problems on the northern half of the dome. The presence of the thin veneer of Karroo sediments coupled also with poor exposure and frequently decomposed surface granitic material also made sampling problematical in the eastern part of the dome.

E. THE TREND SURFACE ANALYSIS

In studying the areal variability of the geochemical data derived from the granite samples collected over the Johannesburg-Pretoria dome use was made of an IBM360/50 computer installed at the University of the Witwatersrand, Johannesburg. The FORTRAN computer programme utilized in the analysis was developed at the Economic Geology Research Unit by Mr. T. C. McGiddy and is a multiple regression technique based on the method of least squares.

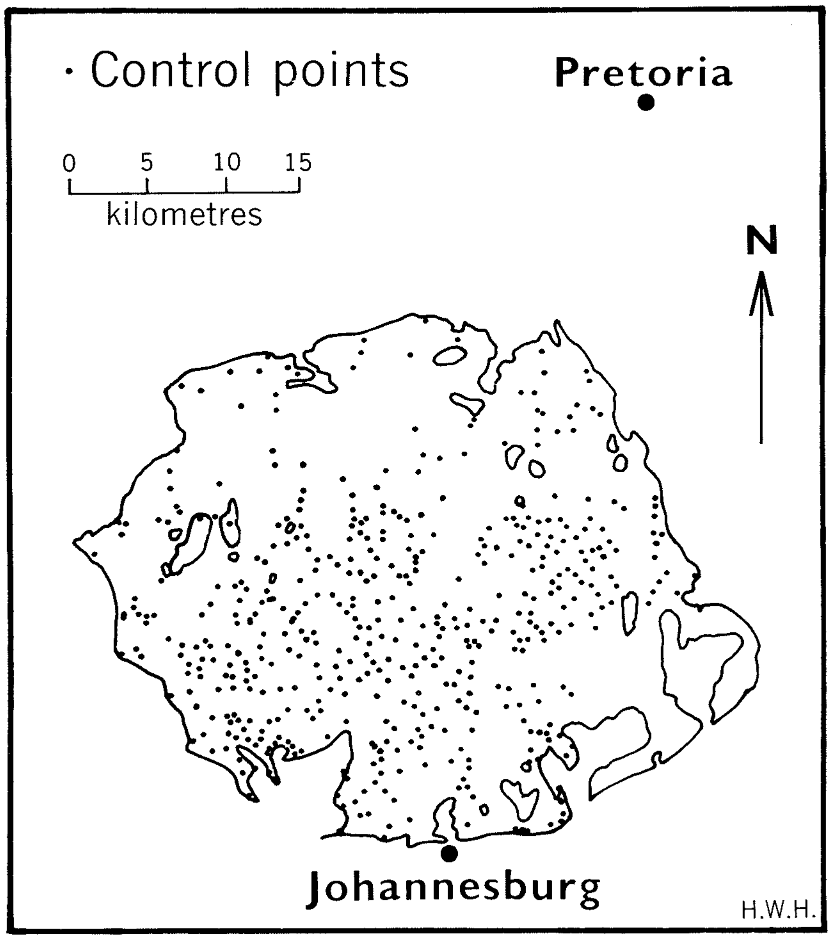


Figure 5. Distribution of samples collected on the Johannesburg–Pretoria Granite Dome.

The polynomials fitted were the linear, quadratic, cubic, quartic, and quintic surfaces, containing one dependent variable (e.g. gamma radiation, Na_2O, Sr/Rb, etc.) and two independent variables (i.e. geographic coordinates of the sample localities). In this paper only the trend surfaces of each dependent variable are presented and discussed. In addition, the percentage fit of the data has been included as a gauge of the confidence that may be attributed to each of the computed surfaces. It should be added that the trend surface programme developed by McGiddy also provided the associated confidence levels, computed by the analysis of variance, and furthermore generated the residuals, or deviations, from the various trend components. However, this information and its significance still remains to be assessed.

The results of the trend surface analysis study are summarized graphically in the accompanying Figures 6-12. For each dependent variable one of the five computed surfaces has been omitted from the data sets on the basis that the surface rejected does not provide a significant or discriminatory percentage fit when viewed in relation to the remaining surfaces.

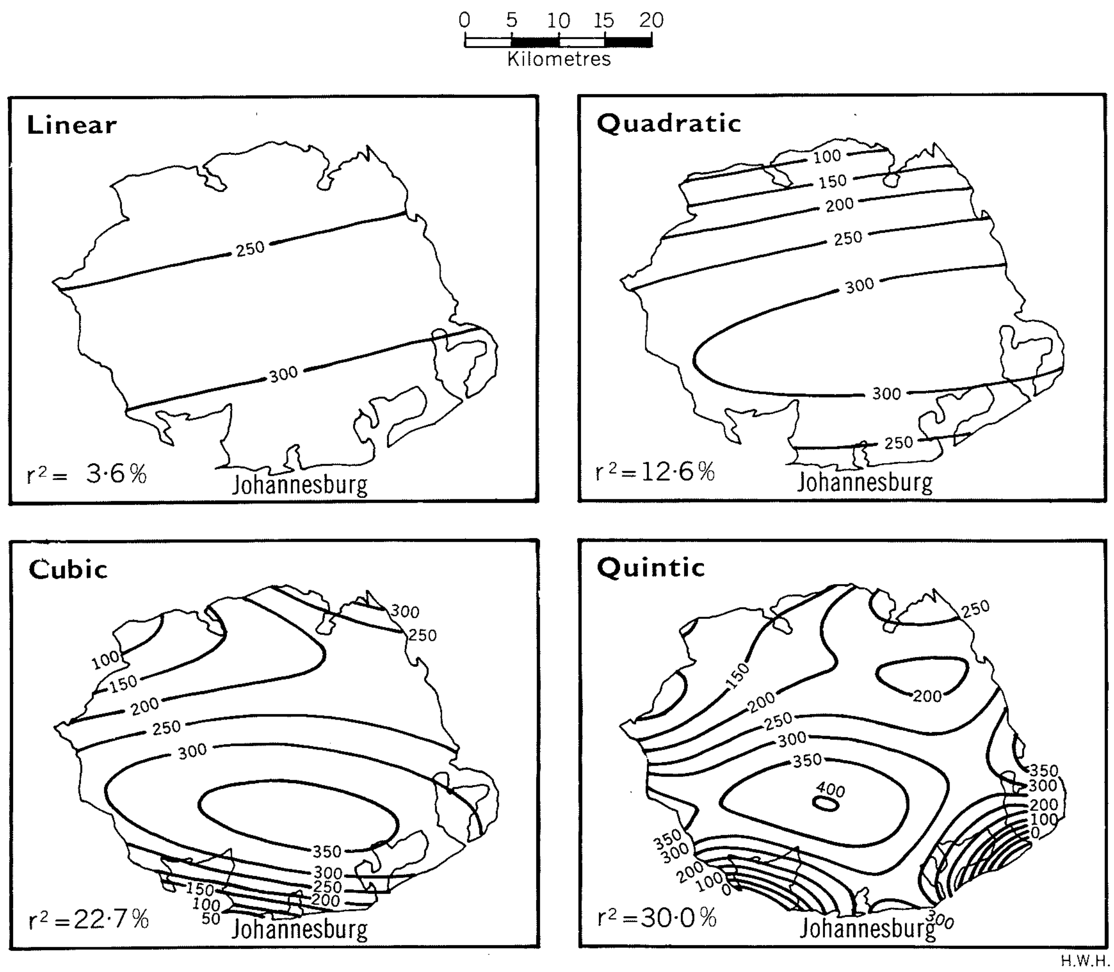
Parslow (1971) concluded that the precision of the multiple regression curve fitting routine falls off rapidly when simple mathematical functions (e.g. cubic polynomials) are applied to large geographic areas. This, he added, could be minimized by increased sampling and the use of higher order polynomials. He warned, however, that surfaces markedly higher than cubic are prone to 'rippling' and suggested that wherever possible, curve fittings should be restricted to linear, quadratic or cubic. The results of the present study demonstrate that the best precision for all data sets was derived from the quartic as well as quintic surfaces so that it would appear, judging from Parslow's (1971) findings, that the sampling of the granites on the dome has been sufficiently adequate to overcome any limitations that may have resulted from less intensive control.

Little need exists for any detailed discussion of the trend surface maps, as each is essentially self explanatory. Attempts at assessing the trend surface analysis data should be done in conjunction with the geological map of the region (Figure 4), bearing in mind also the remarks made about the various granite types outlined in an earlier section of this presentation. In order, however, to emphasize certain factors made evident by the computed contour surfaces of the radiation and geochemical data, each diagram will be dealt with briefly in turn.

(a) Gamma Radiation Surfaces (Figure 6)

Figure 6 **Johannesburg – Pretoria Dome**
COMPARATIVE TREND SURFACES OF TOTAL GAMMA RADIATION

N



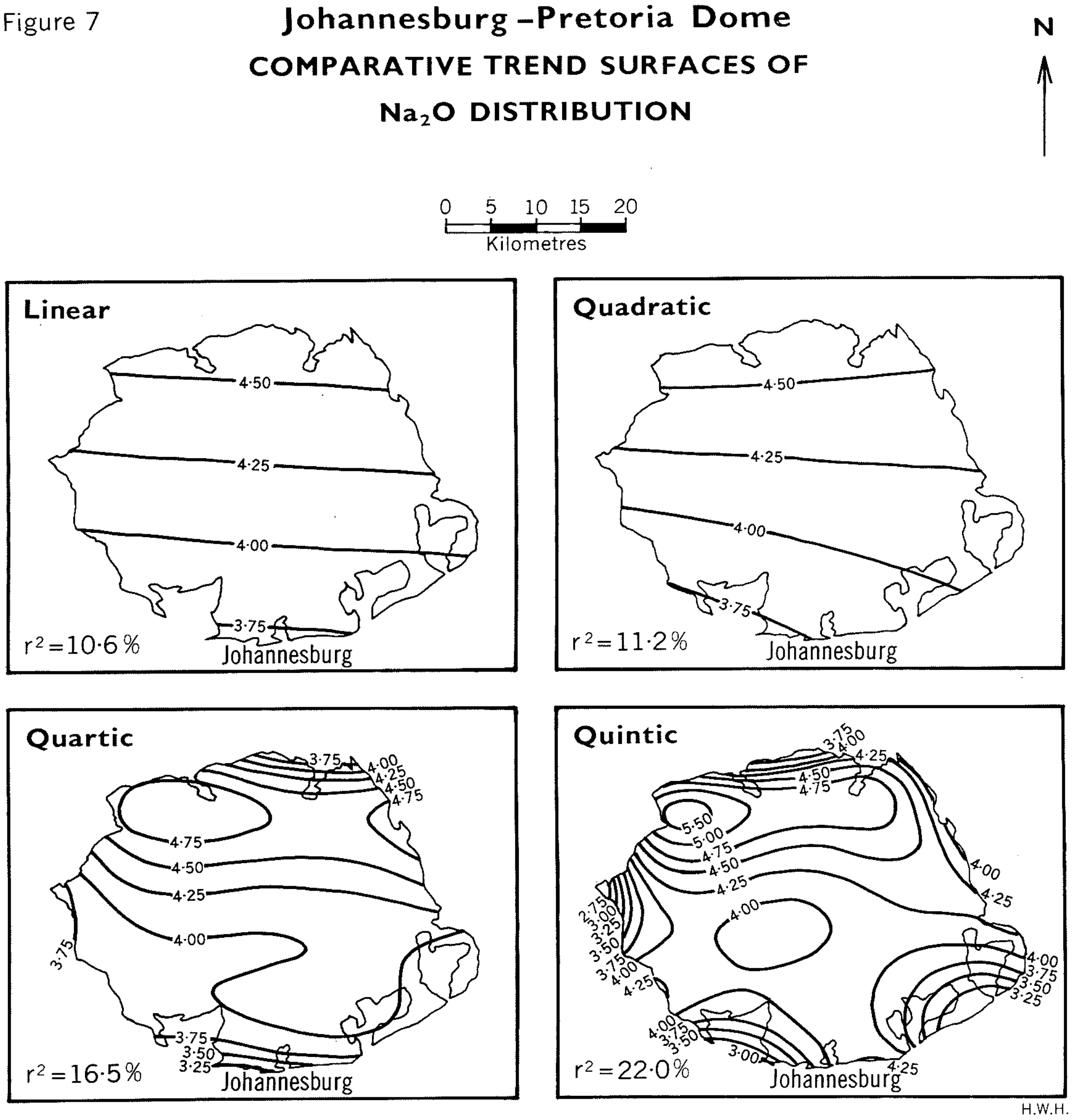
Percentage fit (r^2)
Number of control points 425
Contour interval 50 counts per minute

Limited information is available from the 1st and 2nd degree surfaces of the radiation data. Considerably greater significance can, however, be ascribed to the 3rd and 5th degree surfaces, both of which show a build up of gamma radiation activity in the southern half of the dome with a local high developed over the region that corresponds in the field with the homogeneous and porphyritic granites of the grey granodiorite suite. A similar relationship was established by Aucott (1968) who found the highest gamma activity to be associated with the porphyritic phases of the Galway Granite in Ireland. There is also very good agreement between the area of highest gamma activity and the position of the asymmetrical low gravity distribution patterns depicted by the Bouguer isogal maps of the region shown in Figure 2. This correspondence is marked, furthermore, by the almost coincidental trend of contours on the southern side of the dome. This direction which ranges between 90-120 degrees is broadly parallel to the regional foliation trends in the migmatite-gneiss terrain on the northern side of the dome as well as in the foliated tonalitic gneisses and greenstones margining the dome's southern rim.

The pattern, depicted by the higher order radiation surfaces, finds additional or complimentary support in all the other trend surface analysis maps presented in Figures 7-12.

(b) Na_2O Surfaces. (Figure 7)

Figure 7 **Johannesburg – Pretoria Dome**
COMPARATIVE TREND SURFACES OF Na_2O DISTRIBUTION



Percentage fit (r^2)
Number of control points 400
Contour interval 0·25%

The broad or regional variations of the Na_2O distribution in the granites of the Johannesburg-Pretoria dome are made evident in the 1st and 2nd degree surfaces presented in Figure 7. This trend corresponds, once again, to a direction varying between approximately east-west, and east-southeast. The 4th and 5th degree surfaces, however, provide refinements to the data and clearly localize regions of greater and lesser sodium contents. These areas correspond very well with the known geology of the granites. Probably the best representation is provided by the quartic surface which shows an area of relatively high sodium distribution occupying the migmatite-gneiss terrain on the northern half of the dome while, in addition, the surface provides some discrimination between the homogeneous grey granodiorites in the southeast and their porphyritic counterparts in the southwestern quadrant of the inlier.

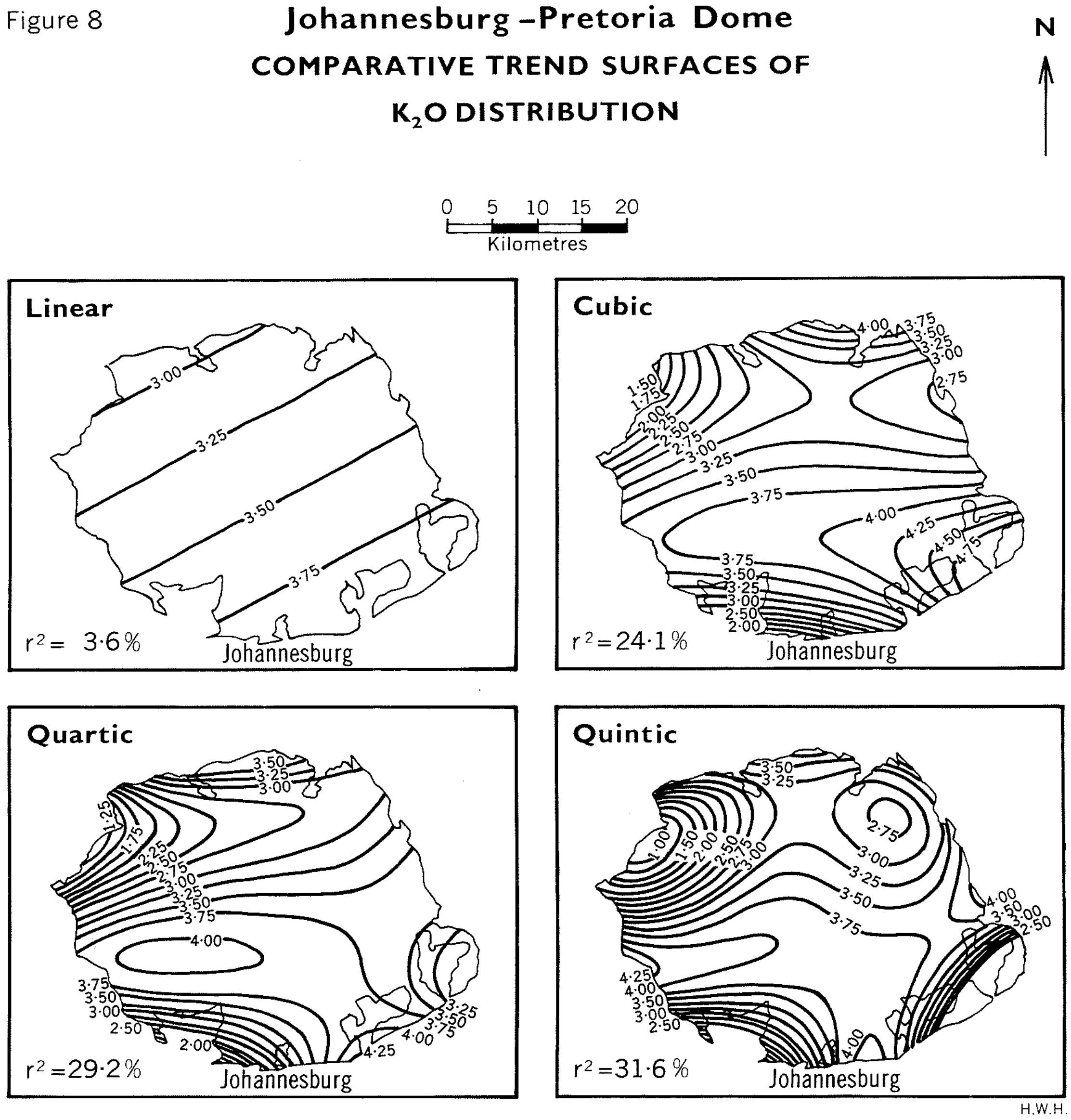
The regions of low sodium content in the diagrams presented in Figure 7 also correspond very favourably with the areas of high K_2O content shown in the trend surfaces in Figure 8. A further high order of correspondence is achieved by the quintic surfaces of the Na_2O and Sr data. Areas of high sodium content coincide with areas where strontium is relatively abundant in the granites.

(c) K_2O Surfaces (Figure 8)

Figure 8 **Johannesburg – Pretoria Dome**

COMPARATIVE TREND SURFACES OF

K_2O DISTRIBUTION



Percentage fit (r^2)
Number of control points 400
Contour interval 0·25%

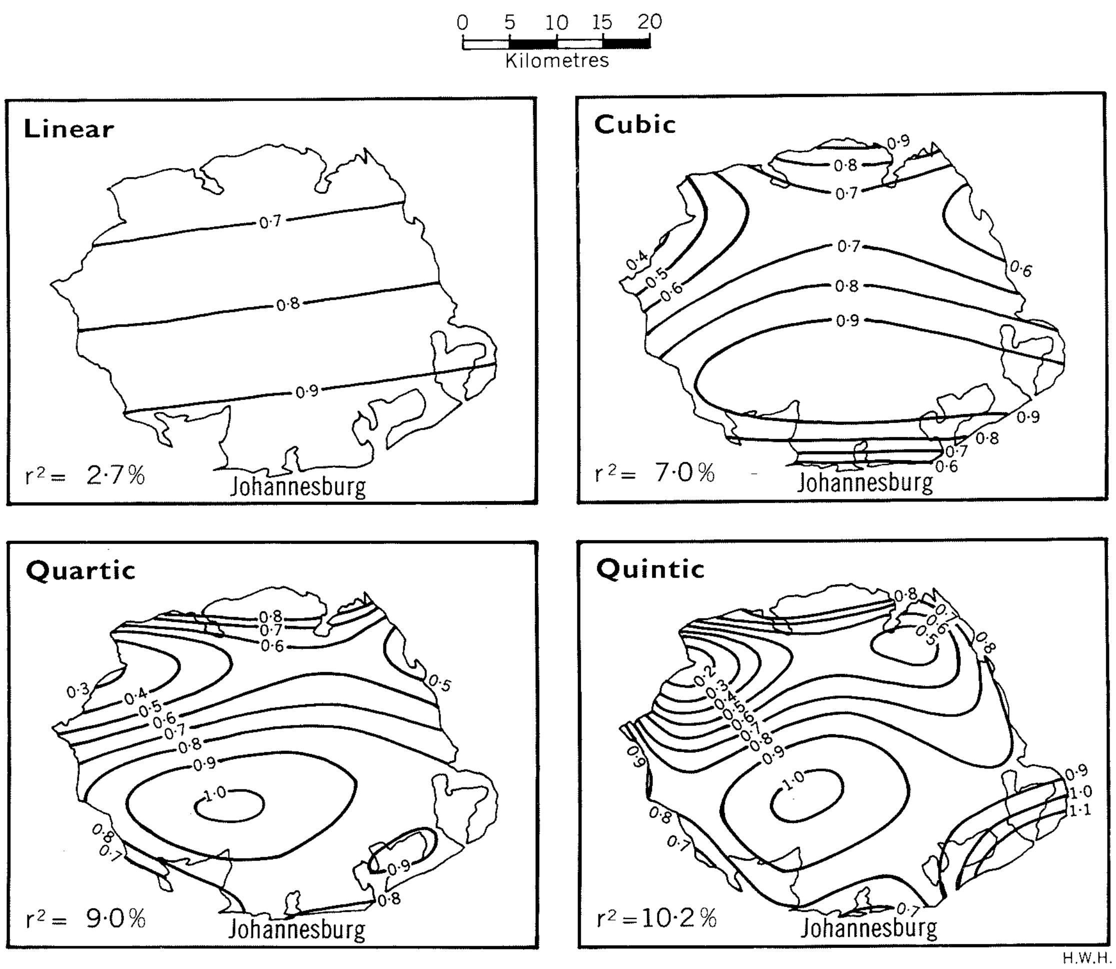
The distribution of K_2O across the granite inlier is demonstrated in Figure 8. The overall trend is the reverse of the situation portrayed by the areal distribution of Na_2O in Figure 7, with the greatest concentration of K_2O occurring in the south-central area of the dome. This distribution is best reflected in the 3rd, 4th, and 5th degree surfaces. In addition, it is evident that there is a decrease in the abundance of K_2O in both directions away from areas underlain by the granitic rocks of the grey granodiorite suite. In the south and southeast, the ancient tonalitic gneisses contain low K_2O percentages and are responsible for the overall decrease in these regions, while in the north, relatively low K_2O values reflect conditions in the migmatite-gneiss terrain. The quartic and quintic trend surfaces are, once again, the most informative computed surfaces and tie in very favourably with the geological as well as with the gravity interpretations of the region. Additional good correlation is provided by a comparison of the Rb and potash distribution patterns. There clearly exists a close geochemical coherence between these two elements.

(d) K/Na Surfaces (Figure 9)

Figure 9 **Johannesburg – Pretoria Dome**

COMPARATIVE TREND SURFACES OF POTASH-SODA RATIOS

N



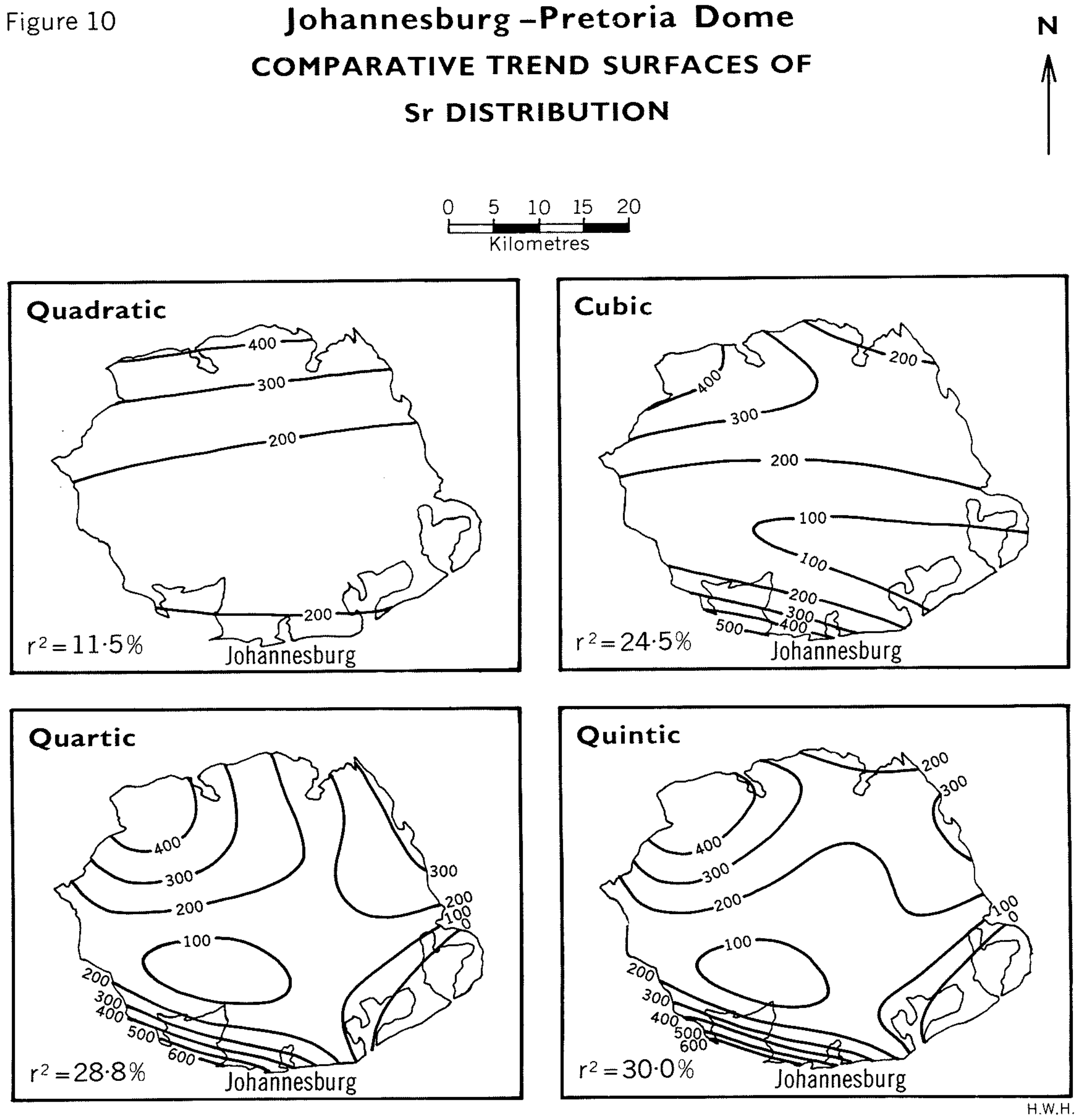
Percentage fit (r^2)
Number of control points 400
Contour interval 0·1

The K-Na ratio trend surface maps merely provide additional support for the conclusions already drawn with respect to the areal distribution of these elements in the area under discussion. The highest ratios occur over the areas of homogeneous granite development and decrease concentrically about this region. The excellent correspondence, in each case, between the contoured "high spots" of the gamma radiation data, as well as the K_2O, Rb, and K/Na data, with that of the gravity distribution pattern is of great significance. A genetic link undoubtedly exists between these and many other parameters. It is contended that the palingenetic processes responsible for the development of the homogeneous and porphyritic grey granodiorites were largely responsible for the doming phenomena. The areal distribution of the geochemical data, coupled with the geological characteristics of the various granite-types encountered in the area leave, furthermore, very little doubt as to the causes of the development of an asymmetrical density distribution pattern over the dome.

(e) Sr Surfaces (Figure 10)

Figure 10

Johannesburg – Pretoria Dome
COMPARATIVE TREND SURFACES OF Sr DISTRIBUTION



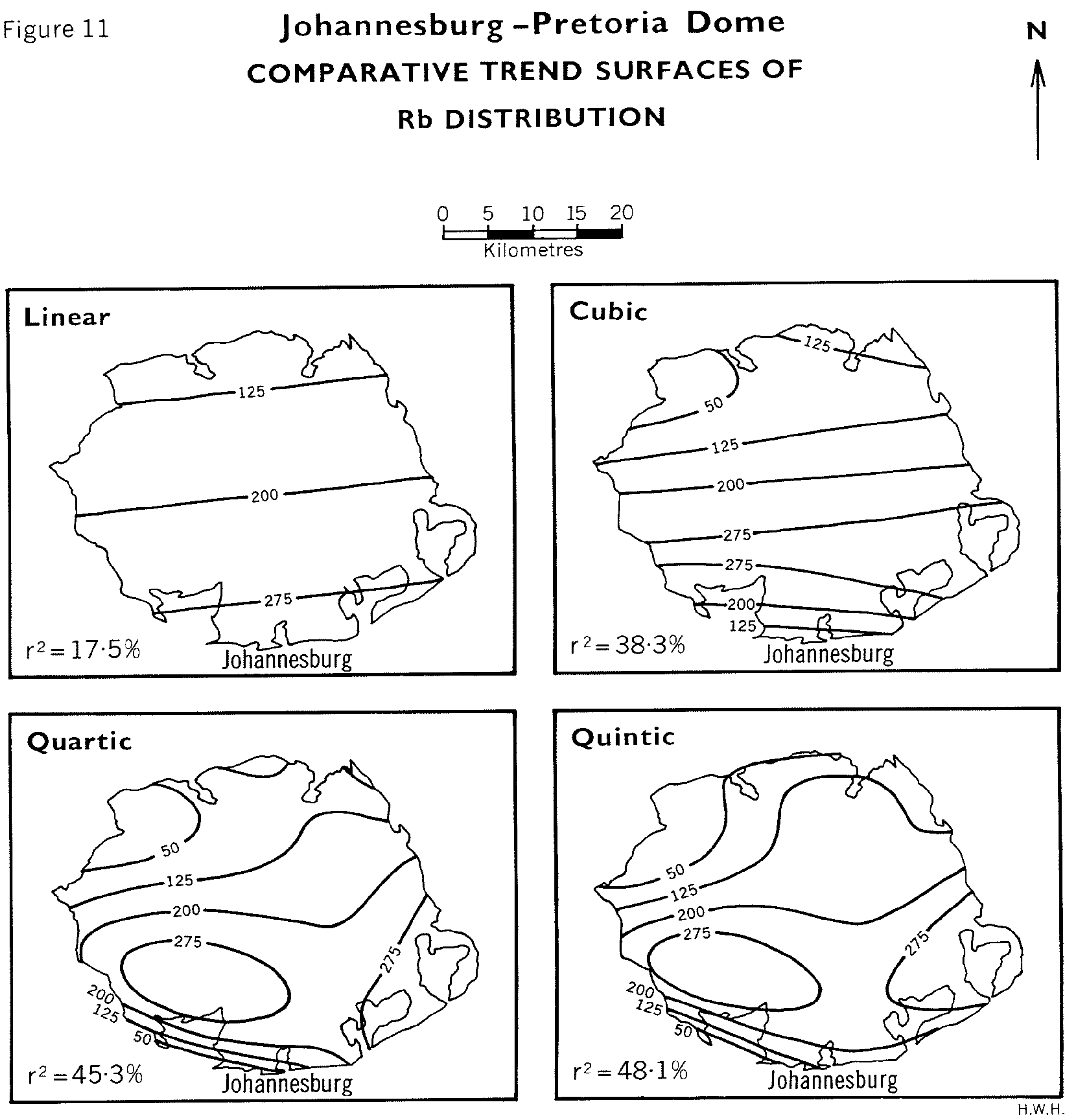
Percentage fit (r^2)
Number of control points 400
Contour interval 100 p.p.m.

It was demonstrated earlier (see Table 1, Parts 1 and 2) that the granitic rocks belonging to the ancient tonalitic gneiss assemblage are particularly enriched in Sr. Thus the patterns of Sr distribution depicted in the quartic and quintic trend surfaces in Figure 10 have a ready explanation. The lowest intensities of this element are to be found directly superimposed over the reconstituted or homogenized grey granodioritic rocks of the dome, while the highest concentrations occupy the peripheral granite areas.

Unlike rubidium and potash, or strontium and sodium, Sr and Rb are chemically incompatible, and display no coherence. This accounts for the fact that when the Rb content of a rock increases there is a marked decrease in the Sr content. This relationship was demonstrated by the geochemical data obtained for the ancient granitic assemblages surrounding the Barberton Mountain Land by Viljoen and Viljoen (1969b). Likewise in the present study, a comparison of the Sr and Rb trend surface maps, shows beyond doubt, the validity of this lack of coherence in the granitic assemblages of the Johannesburg-Pretoria dome.

(f) Rb Surfaces (Figure 11)

Figure 11



Percentage fit (r^2)
Number of control points 400
Contour interval 75 p.p.m.

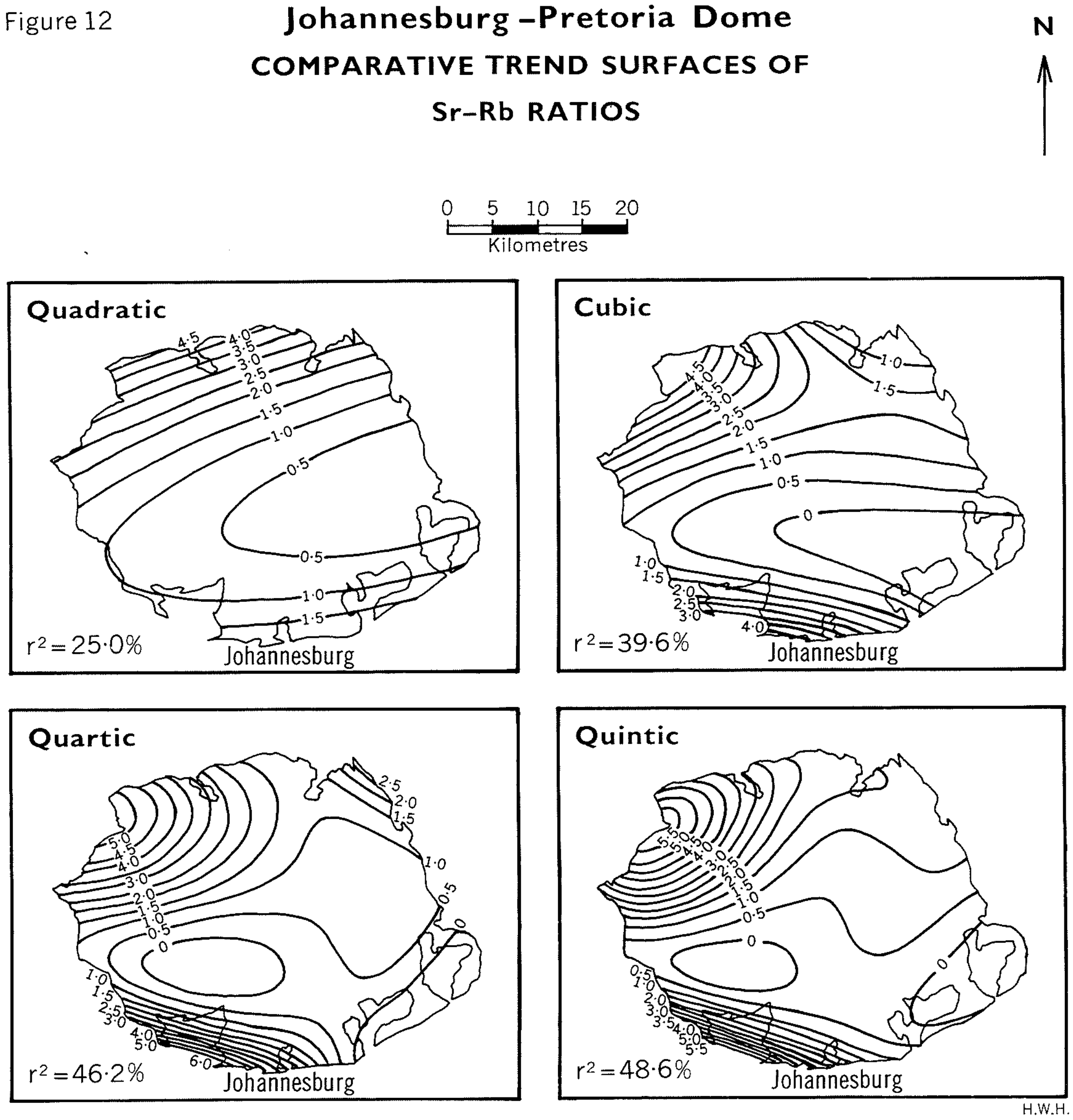
Little need be said about the Rb patterns displayed in Figure 11 as they portray, with only minor variations, the features previously discussed. Geochemically there is a well-established coherence of Rb with K a factor of importance which allows the two elements to be employed as a useful guide to the petrogenetic and fractionation histories of granitic rocks. Although no K/Rb trend surfaces have yet been computed an unmistakeable trend of decreasing K/Rb ratios would certainly emerge. This would reflect a fractionation trend from the tonalitic gneisses, through to the grey granodiorite suite involving an introduction of Rb. Such a relationship was established for the Barberton granites by Viljoen and Viljoen (1969b) who were able to demonstrate a similar fractionation trend from the oldest, most basic granites to the younger more acidic varieties.

(g) Sr/Rb Surfaces (Figure 12)

Figure 12 **Johannesburg – Pretoria Dome**

COMPARATIVE TREND SURFACES OF

Sr–Rb RATIOS



Percentage fit (r^2)
Number of control points 400
Contour interval 0·5

The trend surfaces computed for the Sr/Rb ratios again provide, particularly with respect to the higher order surfaces, useful corroborative evidence reflecting the geochemical characteristics of the granites of the dome.

Finally, an additional feature of interest is displayed by the higher order trend surfaces, not only of the Sr/Rb data but also of all the other variables displayed in Figures 6-11. The quintic surface in Figure 12 shows, for example, a sharp swing of the contours about a position which would coincide approximately with the major fault or crush zone which divides the Johannesburg-Pretoria granite dome into roughly two equal halves. The right lateral displacement along this fault is reflected in the change of direction of the contours about the line of the fault zone. In Figure 8, as well as in most of the remaining diagrams the fault zone appears to coincide either, with a break in the contours or, with their termination or closure.

DISCUSSION AND CONCLUSIONS

The preliminary investigations, involving the geological mapping and initiation of a geochemical study programme, demonstrate conclusively the varied and complex nature of the granitic rocks comprising the Johannesburg-Pretoria dome. As investigations are continuing it is not the intention at this stage to become involved in any discussion on the origin of the granites or in the various processes responsible for their development. The results made available by this study show, beyond doubt, that the granites have been influenced by a progressive series of events, each in turn being responsible for profound geochemical changes from place to place across the dome. This is borne out by the high degree of correspondence or agreement that exists between the geology of the granites and the areal variability patterns of the geochemical data depicted by the trend surface analysis study.

The sequence of events so far established for the granitic rocks of the dome area may be summarized in the following scheme :

---

* *

4. Continued, yet selective, processes of rheomorphism, anatexis, granitization, and metasomatism, causing partial or complete obliteration of earlier granitic events and giving rise to the essentially homogeneous and porphyritic grey granodiorites (Youngest Event).

* *

3. Progressive stages of alteration due to metamorphic, metasomatic, and palingenetic processes, giving rise to migmatites and gneisses.

* *

2. Intrusion of early granitic material probably represented by rocks of the Ancient Tonalitic Gneiss assemblage. These granites were responsible for the complete or partial assimilation of the pre-existing crustal rocks.

* *

1. Swaziland Sequence (Oldest Event) - primitive mafic and ultramafic assemblages probably representing part of the ancient crust.

The writer makes the assumption that the earliest crustal material developed over most of the region was initially of mafic and ultramafic composition. This contention appears to be supported by the presence, in all the varieties of granitic rocks in the area, of large and small remnants or xenoliths of Swaziland Sequence amphibolite or serpentinite. This early crustal material was then intruded by granitic rocks now represented by the ancient tonalitic gneisses. In the Barberton area these early tonalites were intruded into the lower formations of the Onverwacht Group as diapiric plutons (Viljoen and Viljoen, 1969b). This style of granite emplacement probably occurred in the area discussed in this paper but limitations, brought about by incomplete exposure, do not permit verification of this possibility, although many of the characteristic features associated with the diapiric plutons in the Barberton area are displayed in isolated outcrops on the southwestern, southern, and southeastern margins of the dome.

The granites in their evolutionary development appear to have behaved in a manner somewhat similar to the mantled gneiss domes described by Eskola (1948). However, the Johannesburg-Pretoria dome does not seem to have experienced the full range of conditions necessary for it to be considered a mantled gneiss dome in the strictest sense. The stages of its development are believed to have been as follows : It is envisaged that the early granitic event described above was responsible for widespread granitization, assimilation, and digestion of the primitive basement material. The granitization process was, however, incomplete and numerous, irregularly sized, resister relics remained, either intact, or in various stages of metamorphism.

The next event of significance was the initiation of the processes responsible for the rheomorphism and homogenization of the earlier granitic assemblages. As a result of the influx of the granitophile elements, particularly K, Si, Al, and a number of rare elements such as Rb, and probably Hf, La, U, and Th, the granites began to rise, and embryonic doming commenced. These preliminary events probably triggered the erosion of the granite-greenstone terrain and contributed to the initial stages of sedimentation of the Witwatersrand Basin.

Successive stages of sedimentation and volcanism continued over widespread regions, resulting in the development of the Witwatersrand, Ventersdorp, and Transvaal Sequences. During the evolution of these assemblages the granitic basement material also underwent changes with the domical areas, in particular, acting as positive, continuously rising masses. This upward movement caused the younger cover rocks to tilt in all directions away from the rising dome. It is at this stage of the dome's development that there appears to be a departure from Eskola's (1948) model of a mantled gneiss dome. Although erosion has today stripped most of the cover rocks from the dome area there is no evidence to suggest that a late magmatic granite may have intruded the overlying younger formations. This is further supported by the absence of intrusive granites in the areas occupied by the other domes on the Kaapvaal craton as well as by the apparent lack of metamorphism in the younger cover rocks directly above or adjacent to these domes. However, the events that occurred in the Johannesburg-Pretoria granite dome, while possibly not sufficiently intense enough to generate a magmatic intrusive granite, may have stopped just short of this stage by producing only the homogenized, porphyritic granodioritic assemblages.

A further deviation from Eskola's (1948) mantled gneiss dome lies in the apparent lack of conformity of the foliation of the Johannesburg-Pretoria granites with the overlying cover rock disposition. Homogenization of pre-existing granitic phases could be held responsible for the obliteration of any fabric that may have been present in the granites but there is evidence, particularly in the migmatite-gneiss terrain, demonstrating that a widespread east-southeasterly trend predominates across most of the dome area.

The revised geological interpretation of the granites of the Johannesburg-Pretoria dome may call for a similar revision of the geochronological aspects relating to the ages of the granites of the area. As far as can be established by the writer the samples employed in the dating of the granites by Allsopp (1961) were not fully representative of the granite varieties exposed on the dome as they derive essentially from the areas underlain by homogenized and porphyritic granodiorites. If, as Allsopp (1961) maintains, the total rock age of 3200 ± 65 m. yrs. is the true age of emplacement of the granites dated (which in effect are the homogenized granites only) then the ancient tonalitic gneisses and migmatites must be still older. The questions that are now raised concern the significance of the dates thus far recorded in the area. Does the 3,200 m.yr. old event in fact reflect the time of homogenization? If it does, to what should the 2120 m.yr. old event be ascribed? Presumably most of the remobilization and homogenization occurred before the deposition of the Witwatersrand Sequence as little or no metamorphic effects are apparent in these rocks. As the doming was a continuous process, seemingly caused by reheating and geochemical changes in the granites, the later age may reflect the time of an updoming surge in post-Transvaal times. The 2120 m.yr. age might also reflect the time of intrusion of the diabase dyke swarm found in the area. It is hoped that these, and a host of other problems, will be resolved as the investigations are persued.

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* *

KEY TO PLATES

PLATE 1

A. Isoclinally folded hornblende-biotite leuco-tonalitic gneisses showing the development of dark and light coloured bands. Locality - Struben's Valley, southwestern quadrant of the Johannesburg-Pretoria Dome.

B. Folded hornblende-biotite leuco-tonalitic gneiss from same locality as A above.

C. Elongated mafic xenoliths aligned parallel to, and within, the foliation planes of a leuco-biotite tonalite gneiss. Locality - close to the contact of a Swaziland Sequence remnant on the farm Lombardy 35 IR, southeastern quadrant of the dome.

D. Folded banded gneiss or migmatite typical of the type encountered in places in the migmatite/gneiss terrain occupying the northern half of the Johannesburg-Pretoria Dome.

E. Folded gneissic and migmatitic leuco-biotite tonalites, or biotite trondhjemites, containing irregularly shaped amphibolite xenoliths and cut by late pegmatite veins and stringers. Locality - Zwartkop 525 JQ, northwestern quadrant of the dome.

F. Strongly foliated gneiss exposed in the Crocodile River on the farm Tweefontein 523 JQ, northwestern quadrant of the dome.

PLATE 2

A. Large sub-angular granite boulders forming a typical granite tor (castle koppie) in the area occupied by the Transitional Zone granites. Locality - Lonehill, on the farm Witkoppen 194 IQ, centre of dome.

B. Coarse-grained, homogeneous, porphyritic grey granodiorite containing an isolated mafic inclusion. Some felspar porphyroblasts are evident in the amphibolite xenolith. Locality - southwestern quadrant of the dome.

C. Prominently developed felspar porphyroblasts in homogeneous, porphyritic granodiorites located in the southwestern quadrant of the dome. Extra large, often strongly aligned, felspar porphyroblasts are commonly encountered close to mafic dyke intrusives.

D. Large, well-aligned felspar porphyroblasts in granite-gneisses occurring adjacent to a Pilanesberg-type dyke on the farm Zevenfontein 407 JR, centre of dome.

E. Pegmatite vein cutting porphyritic grey granodiorite near Honeydew, southwestern quadrant of dome. Coarse, well-formed, microcline crystals occur on the margins of the vein which has a fine-grained centre.

F. Large, idiomorphic felspar crystals showing twinning and graphic quartz intergrowth textures in a pegmatite intruding grey granodiorites north of Parkmore, south-central portion of the dome.

* *

PLATE 1

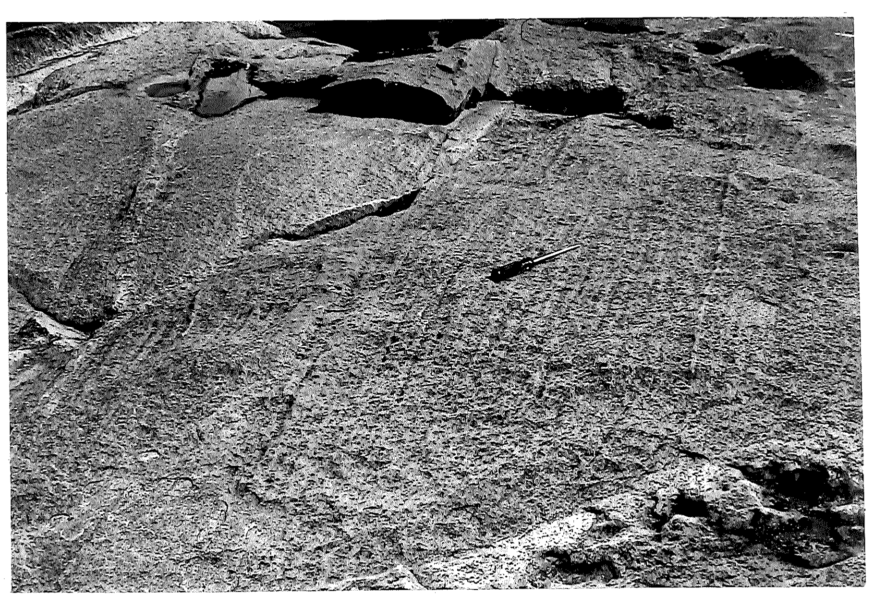
A

B

C

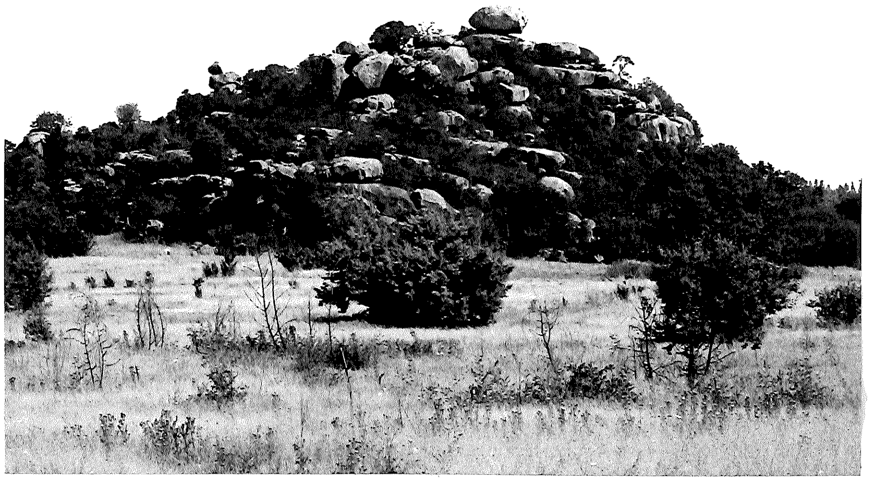
D

E



F

PLATE 2



A

B

C

D

E

F

APPENDIX

Table of Chemical Data

Sample Number Δ	Gamma Radiation *	Na_2O †	K_2O †	Sr ϕ	Rb ϕ
AD01	3603	4.77	3.04	265	259
AD02	2040	4.98	3.31	335	245
AD03	2447	5.13	3.38	333	180
AD04	1782	4.82	3.38	580	255
AD05	2528	4.55	3.95	389	281
AD06	2453	4.44	4.08	233	300
AD07	2460	4.54	3.72	503	303
AD08	2077	4.42	3.90	458	201
AD09	2312	4.49	3.49	415	220
AD10	1895	4.62	2.64	460	193
AL01	4791	4.14	4.35	150	383
AL02	3841	4.08	4.88	179	362
AL03	2875	3.76	4.17	72	304
AL04	2087	3.76	4.35	79	289
AL06	1416	5.44	–	–	–
AL07	667	4.64	1.44	486	144
AL09	2608	3.89	4.75	190	340
BC01	3784	4.11	4.92	98	499
BC02	4986	4.24	4.81	94	500
BC03	7488	3.82	5.33	126	371
BC04	6825	3.89	4.92	117	326
BC05	2034	4.83	2.51	552	182
BC06	2334	4.37	3.90	369	217
BC07	3820	3.89	4.98	157	354
BC08	3789	4.12	4.92	127	338
BF01	3279	0.39	–	147	266
BF02	2264	4.16	1.95	494	163
BF03	1329	4.64	3.61	371	119
BH01	2144	4.73	3.43	311	206
BH02	3010	4.07	4.58	268	244
BH03	1584	4.74	3.50	–	–
BH04	1091	5.91	1.14	374	138
BL01	1858	4.54	4.08	182	386
BL02	2343	4.41	3.85	382	214
BL03	3769	4.29	4.30	364	301
BL04	3425	4.45	4.46	107	445
BL05	5217	4.50	4.70	83	424
BL06	4743	5.32	2.63	236	287
BQ01	4535	4.28	4.12	185	312
BQ02	4681	3.85	5.21	186	255
BQ03	2454	4.18	4.70	167	254
BQ04	1509	5.07	2.29	323	147

Sample Number Δ	Gamma Radiation *	Na_2O †	K_2O †	Sr ϕ	Rb ϕ
BR01	12015	4.54	4.54	51	409
BR02	4484	4.76	3.66	102	268
BR03	3637	4.39	4.58	113	407
BR04	3493	4.32	4.58	162	347
BR05	3605	4.21	4.81	125	422
BR06	3621	4.50	4.40	103	274
BR07	3545	4.26	4.88	75	425
BR08	2903	4.36	4.70	137	319
BR09	2725	4.23	4.81	121	327
BR10	4257	4.22	4.75	126	441
BR11	2595	4.64	4.07	162	270
BR12	1783	3.84	3.54	502	163
BR13	3783	4.10	5.04	122	373
BR14	3866	4.76	3.50	179	320
BR15	2431	4.35	4.23	269	181
BR16	2992	4.43	3.84	120	310
BR18	2312	4.16	4.64	223	270
BR19	2309	4.32	4.23	421	282
BR20	2872	4.15	4.40	374	285
BR21	2905	4.19	4.53	334	253
BR22	3272	4.32	4.17	239	308
BR23	4260	3.28	6.01	274	519
BR24	2577	4.53	4.17	140	322
BR25	2421	4.98	3.31	237	302
BR26	2676	4.41	–	–	–
BR27	5596	4.13	4.81	166	343
CH01	3954	6.40	1.66	87	208
CH02	4410	3.93	5.10	102	569
CK01	3108	4.36	3.95	100	351
CK02	2459	4.10	4.64	–	–
CK03	2701	4.20	4.58	258	282
CK04	2340	4.20	4.70	221	412
CK05	1869	4.58	3.96	167	405
CK06	8706	5.94	1.95	284	356
CK07	1716	4.48	3.54	278	268
CK08	1578	4.71	3.72	206	313
CK09	2329	4.30	3.54	368	162
CK10	3183	4.44	4.30	304	393
CK11	3317	4.04	4.92	132	369
CR01	924	6.04	1.90	778	133
CR02	1991	4.85	4.30	295	129
CR03	987	6.09	1.45	536	68
CR04	1456	5.56	2.24	305	103

FOOTNOTE : Δ Sample numbers plotted on Sample Locality Map.

* Number of counts. Fixed counting time of 10 minutes per sample.

† Values in weight per cent.

ϕ Values in ppm.

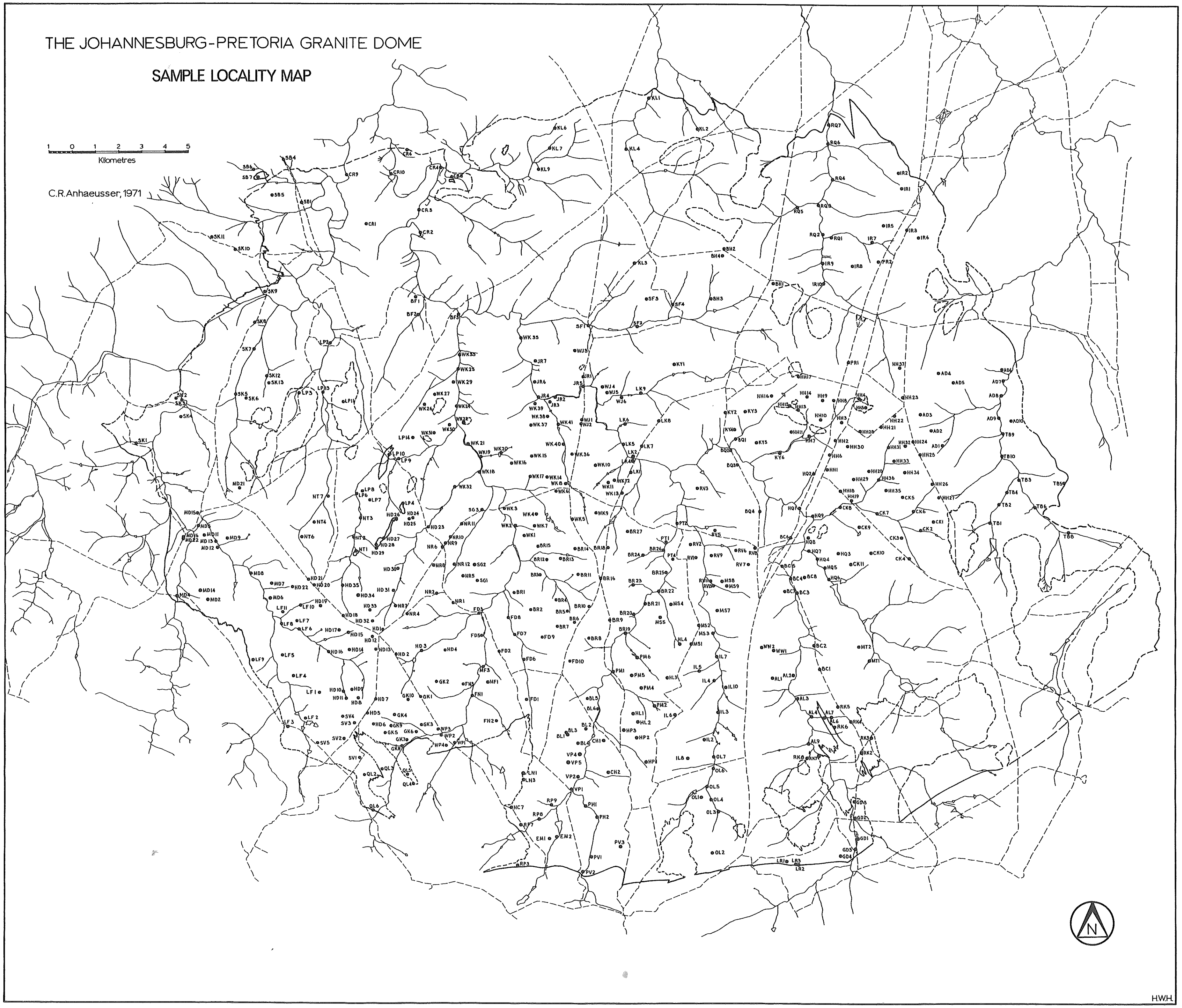
Sample Number Δ	Gamma Radiation *	Na_2O †	K_2O †	Sr ϕ	Rb ϕ
CR06	1789	4.13	4.29	474	134
CR08	2093	4.69	2.52	1021	168
CR09	688	5.49	2.35	554	87
CR10	1731	4.36	4.07	416	134
EM01	1766	4.94	4.21	–	–
EM02	1002	3.70	1.83	781	188
FD01	2933	4.22	4.46	158	400
FD02	3823	4.18	4.35	163	425
FD03	2679	4.36	4.40	229	353
FD05	3657	4.73	3.90	243	411
FD06	3220	5.00	4.81	104	651
FD07	4081	4.40	4.58	121	419
FD08	2765	4.83	3.72	252	395
FD09	6529	5.72	2.74	28	262
FN01	2855	4.37	3.90	245	388
FN02	2868	3.71	5.35	201	419
FN03	2622	4.28	4.12	246	394
GD01	2129	3.90	4.23	163	299
GD02	2476	4.16	3.84	213	225
GD03	2183	4.11	3.72	145	235
GD04	2962	0.10	5.97	21	520
GD05	1925	4.20	5.80	43	261
GK01	2964	4.49	4.17	248	363
GK02	2627	0.12	5.10	–	–
GK03	3491	0.12	3.90	24	423
GK04	2880	0.11	4.88	32	433
GK05	2663	0.06	3.95	11	500
GK06	2690	0.12	5.33	24	489
GK07	2987	0.13	4.81	141	478
GK08	698	3.74	1.27	513	71
GK09	2731	4.00	–	–	–
GK10	3005	0.10	4.91	32	474
HD01	3950	4.18	4.30	243	577
HD02	3084	4.34	4.07	207	514
HD03	3236	4.33	4.01	216	427
HD04	3387	4.21	–	–	–
HD05	3243	4.52	3.78	194	251
HD06	2955	3.42	5.04	70	390
HD07	3217	4.44	4.54	213	351
HD08	4316	4.20	–	–	–
HD09	3519	0.11	5.15	42	675
HD10	2908	4.58	4.24	182	329
HD11	2894	4.56	–	–	–
HD12	2783	4.18	4.70	182	433
HD13	2934	4.13	–	–	–
HD14	2434	4.14	4.24	248	430
HD15	3244	4.40	4.40	186	385
HD16	2822	4.75	3.95	250	250
HD17	3125	5.15	4.12	105	527
HD18	2977	4.28	4.35	311	623
HD19	3390	4.26	4.40	231	390
HD20	3609	–	–	–	–
HD21	3215	4.21	4.54	264	348
HD22	2571	4.42	4.17	221	349
HD23	3563	4.82	4.12	73	360
HD24	3432	4.09	4.47	261	266
HD25	3870	4.23	–	–	–
HD26	3120	4.23	3.75	376	317
HD27	3446	4.77	3.72	213	300
HD28	2463	4.29	3.78	335	376
HD29	3028	3.11	4.65	114	381
HD30	3284	4.14	4.45	211	384
HD31	3102	4.23	4.14	219	349
HD32	2753	4.35	3.90	256	387
HD33	2902	4.30	4.40	238	350
HD34	3808	4.35	3.81	308	442
HD35	2696	4.29	4.23	228	298
HH01	1743	4.72	3.72	247	314
HH02	2094	4.54	3.54	478	238
HH03	2675	4.00	5.67	249	323
HH04	2635	5.43	2.52	283	330
HH05	758	2.39	2.00	299	143
HH06	1938	5.19	1.94	761	300
HH07	2041	5.35	2.06	173	187
HH08	3139	4.44	–	–	–
HH09	2017	6.03	1.15	252	180
HH10	2027	5.46	1.38	446	197
HH11	1419	6.07	1.21	245	166
HH13	2032	5.27	2.52	186	217
HH14	1797	3.85	5.61	169	248
HH15	2122	4.63	4.01	280	220
HH16	3128	4.33	4.54	191	315
HH17	3751	3.94	5.40	146	321
HH18	2230	4.48	4.17	363	288
HH19	3115	4.22	4.40	222	280
HH20	2715	4.54	3.95	234	364
HH21	1952	5.57	1.72	302	251
HH22	2810	4.34	4.01	340	272
HH23	1608	5.38	2.52	263	208
HH24	3783	4.62	3.50	248	323
HH25	2737	4.00	4.35	230	168
HH26	3391	3.99	4.40	220	361
HH27	3371	4.69	3.31	375	300
HH28	3403	4.41	4.18	336	186
HH29	3564	3.88	4.98	154	260
HH30	2891	4.43	4.35	162	264
HH31	3627	4.75	–	–	–
HH32	2698	4.33	4.40	391	228
HH33	2238	4.63	3.38	396	313
HH34	2484	4.36	3.71	374	305
HH35	4559	4.07	4.64	199	344
HH36	2234	4.23	4.70	234	336
HH37	1496	5.53	1.71	890	200
HL01	3803	4.40	4.45	163	412
HL02	3405	4.43	4.12	243	431
HL03	5725	4.40	3.61	309	288
HP01	6602	4.24	4.91	50	477
HP02	3558	4.00	4.70	170	366
HP03	3080	4.10	4.24	284	436
HQ01	3263	–	–	–	–
HQ02	2864	4.25	4.00	262	298
HQ03	3676	4.41	4.12	433	313
HQ04	2177	4.36	3.43	528	291
HQ05	2607	4.44	3.61	536	191
HQ06	3236	3.86	5.04	142	358
HQ07	1826	5.03	3.15	350	215
HQ08	2466	4.30	4.40	306	270
HQ09	3764	3.91	4.75	188	292

Sample Number Δ	Gamma Radiation *	Na_2O †	K_2O †	Sr ϕ	Rb ϕ
IL02	5207	4.11	4.75	97	402
IL03	3149	4.56	4.07	72	279
IL04	3530	3.97	4.12	164	395
IL05	3378	4.64	4.07	138	304
IL06	2424	4.58	4.07	127	381
IL07	3432	4.13	4.70	286	310
IL08	2631	4.29	3.61	275	262
IL10	3467	3.85	5.10	99	374
IR01	3026	4.40	4.07	250	226
IR02	2188	4.80	3.66	250	207
IR03	1749	5.99	1.38	327	134
IR05	2303	4.28	4.91	376	219
IR06	1550	4.79	3.43	297	212
IR07	1499	4.88	3.72	313	192
IR08	1741	4.53	3.61	406	195
IR09	4139	4.03	4.81	202	205
IR10	1378	5.20	1.49	259	174
JR01	821	4.79	2.00	602	225
JR02	1266	5.28	1.78	400	187
JR03	1883	4.62	–	–	–
JR04	1957	4.70	2.69	322	171
JR05	1768	4.44	3.90	294	238
JR06	694	4.92	1.60	548	168
KL01	1462	5.20	2.63	287	130
KL02	1253	5.17	3.10	270	151
KL03	1577	4.26	4.17	286	214
KL04	1611	4.96	3.31	374	153
KL06	2351	1.79	6.82	146	258
KL07	1924	4.94	3.10	545	116
KL09	2293	4.24	4.40	356	179
KY01	904	6.14	–	–	–
KY02	3740	4.39	4.30	171	317
KY03	2709	3.75	5.21	150	447
KY04	1506	5.37	2.46	197	184
KY05	1907	4.55	4.07	368	227
KY06	2094	6.09	1.33	199	146
LF01	5128	4.52	4.19	–	–
LF02	3698	3.91	4.58	122	393
LF03	3526	4.32	4.92	136	441
LF04	2383	0.12	5.50	14	609
LF05	3663	3.94	4.40	263	336
LF06	2820	4.21	3.72	282	243
LF07	4231	4.50	4.40	168	434
LF08	2990	4.34	3.95	294	300
LF09	3159	3.22	–	–	–
LF10	3251	4.08	4.53	209	462
LF11	3710	4.19	4.24	243	374
LK01	3410	3.41	5.57	137	370
LK02	3099	4.03	4.64	171	288
LK04	2945	–	–	–	–
LK05	2963	4.27	4.12	230	225
LK06	3657	4.36	3.84	332	270
LK07	2930	4.32	4.30	272	264
LK08	3461	4.18	4.45	252	220
LK09	2949	4.78	3.84	182	196
LN01	1169	3.85	1.58	925	130
LN03	795	4.08	1.03	63	88
LP02	679	5.17	1.56	582	118
LP03	566	5.08	1.45	766	141
LP04	2849	4.25	3.90	347	294
LP06	2783	3.57	5.56	226	340
LP07	2271	4.62	3.31	365	299
LP08	2644	4.63	3.61	312	244
LP09	2104	4.49	3.31	205	218
LP11	480	2.03	0.86	310	81
LP13	1689	5.27	0.87	523	56
LP14	2509	4.33	4.24	258	285
LR01	2969	0.09	6.13	16	521
LR02	4083	0.07	7.43	28	414
LR03	3835	0.08	7.10	28	446
MD02	4998	4.71	3.78	232	340
MD04	2566	4.44	4.07	283	292
MD05	2227	4.65	–	–	–
MD06	3769	4.25	3.78	249	213
MD07	3413	4.16	4.18	240	323
MD08	2513	4.41	3.66	194	266
MD09	2904	4.36	–	–	–
MD12	4158	4.82	–	–	–
MD13	2524	4.21	4.24	194	336
MD14	5354	4.45	3.95	251	331
MD16	3434	4.32	4.30	233	334
MD17	1326	2.50	1.38	293	85
MD21	2593	4.38	4.07	240	247
MD22	–	3.61	–	–	–
MF01	2997	4.18	–	–	–
MF03	2733	4.11	–	–	–
MS01	3000	4.53	4.12	148	322
MS02	2779	4.13	4.12	356	272
MS03	4501	4.12	4.88	409	416
MS04	2726	4.43	4.40	327	263
MS05	4301	3.89	4.99	212	271
MS07	4056	4.92	2.80	265	174
MS08	3548	3.66	5.40	–	–
MS09	2349	4.43	4.17	305	303
MT01	1499	4.50	3.79	149	310
MT02	1914	4.77	3.15	195	372
NC04	959	2.95	0.98	326	50
NC07	615	0.45	2.97	867	549
NR01	2176	4.83	3.25	280	332
NR02	2670	4.51	4.08	220	367
NR04	3278	4.32	4.12	251	393
NR05	4459	4.56	4.70	257	409
NR06	4682	4.29	4.88	78	477
NR07	3577	4.10	4.53	244	374
NR08	2917	3.33	5.56	58	556
NR09	2699	3.90	–	–	–
NR10	2976	4.51	4.46	196	426
NR11	4903	4.49	4.31	157	380
NR12	4187	4.46	–	–	–
NT01	2994	4.49	3.97	302	328
NT02	2812	4.18	4.35	307	338
NT03	3471	4.69	3.25	357	321
NT04	2302	3.99	5.04	186	358

Sample Number Δ	Gamma Radiation *	Na_2O †	K_2O †	Sr φ	Rb φ
NT06	2993	4.50	3.84	378	268
NT07	2249	4.41	3.95	285	256
OL01	2291	4.04	3.84	406	415
OL02	1760	4.23	–	284	168
OL03	3575	3.65	4.88	114	564
OL04	2420	4.25	3.72	272	294
OL05	2626	4.20	3.54	286	312
OL06	2947	4.33	3.95	397	330
OL07	3346	3.92	4.88	128	418
PH01	2021	4.20	4.23	294	248
PH02	2214	4.46	4.53	125	271
PM01	2027	4.20	3.54	391	178
PM02	5930	4.80	3.72	25	355
PM04	1298	5.52	–	–	–
PM05	4069	4.30	4.58	248	310
PM06	5937	4.28	5.04	223	367
PR01	2952	4.49	3.95	236	273
PR02	4191	3.78	5.34	171	304
PT01	2831	4.36	4.53	174	288
PT02	2630	4.67	3.66	367	250
PT04	5016	3.73	5.27	257	339
PV01	1067	3.87	1.90	780	92
PV02	1339	3.92	1.62	766	142
PV03	1038	3.41	2.29	872	85
QL01	239	0.58	–	38	13
QL02	1406	4.27	2.25	726	102
QL03	231	0.09	–	41	7
QL04	351	3.83	–	765	18
QL05	1693	4.26	2.52	519	128
QL06	1851	4.06	2.29	737	101
RK02	755	4.65	1.34	570	157
RK03	828	4.06	1.14	479	183
RK04	2797	4.28	3.78	296	357
RK05	2768	4.51	4.17	107	394
RK06	3600	4.20	4.47	125	400
RK07	3160	4.41	4.35	106	415
RK08	2070	4.15	4.30	93	438
RP03	1126	4.16	1.83	700	261
RP07	1086	4.14	2.19	56	319
RP08	906	3.79	1.32	136	109
RP09	1159	3.69	1.66	154	117
RQ01	2781	4.66	2.46	221	244
RQ02	1178	5.28	2.69	326	158
RQ03	1013	5.30	2.74	422	162
RQ04	2452	4.71	2.64	663	268
RQ05	1682	5.70	2.06	399	191
RQ06	5537	3.80	4.40	296	124
RQ07	1714	4.57	3.04	351	123
RV01	2785	3.82	4.64	256	299
RV02	2055	4.12	3.90	362	238
RV03	2174	4.79	–	470	366
RV05	3737	1.51	6.25	741	262
RV06	2407	4.13	3.25	629	292
RV07	3425	3.83	4.99	235	335
RV08	2595	4.30	3.90	351	247

Sample Number Δ	Gamma Radiation *	Na_2O †	K_2O †	Sr φ	Rb φ
RV09	4131	3.82	4.75	216	253
RV11	5151	4.08	4.45	140	381
RV13	6000	–	–	–	–
SB01	979	4.70	3.10	541	116
SB04	1551	3.50	4.64	166	187
SB05	2578	3.17	–	–	–
SB07	1142	6.11	1.35	860	97
SF01	810	5.77	2.52	427	123
SF02	1434	5.56	2.80	474	146
SF03	3895	3.34	–	–	–
SF04	1691	5.62	2.18	293	212
SG01	8713	4.08	4.01	119	375
SG02	3961	4.41	4.40	100	361
SG03	12064	3.91	4.35	170	295
SK01	3000	3.72	4.98	170	322
SK02	230	2.85	0.58	261	35
SK03	209	2.23	1.18	237	56
SK04	2567	1.37	–	–	–
SK05	546	4.86	1.36	619	76
SK06	2664	4.48	–	–	–
SK07	821	6.25	0.97	623	79
SK08	1349	5.52	2.87	334	142
SK09	799	5.69	1.27	551	109
SK10	3245	0.17	–	198	333
SK11	1066	4.86	1.95	373	96
SK12	722	5.36	0.92	440	84
SK13	3687	4.77	–	–	–
SV01	1599	3.81	2.13	18	95
SV02	1073	4.14	2.29	713	128
SV03	2879	4.15	4.64	141	432
SV04	2676	4.31	4.45	152	349
SV05	2672	4.26	2.18	773	104
TB01	5125	4.62	4.40	108	384
TB02	4847	5.07	3.49	151	469
TB03	3572	4.44	4.18	216	–
TB04	2126	4.44	4.40	237	319
TB05	2943	4.02	5.03	241	360
TB06	4352	4.03	5.10	112	482
TB08	2720	4.44	4.53	159	569
TB09	2705	4.46	3.66	446	329
TB10	2172	4.41	3.43	460	248
VP01	2290	4.34	3.84	230	250
VP02	2349	4.17	3.99	210	196
VP04	3545	4.19	4.75	162	415
VP05	756	4.19	1.33	778	117
WJ01	1521	4.33	4.12	367	226
WJ02	3056	4.35	–	–	–
WJ03	2474	1.14	–	130	376
WJ04	2639	4.20	4.24	340	244
WJ05	2171	4.37	3.49	715	232
WJ06	2162	4.54	3.84	287	276
WK01	3101	3.98	4.58	168	241
WK03	5241	3.63	5.35	225	340
WK04	1690	4.11	4.05	335	181
WK05	2639	4.29	4.58	137	332
WK06	1837	3.92	3.43	277	183

Sample Number Δ	Gamma Radiation *	Na_2O †	K_2O †	Sr φ	Rb φ	Sample Number Δ	Gamma Radiation *	Na_2O †	K_2O †	Sr φ	Rb φ
WK07	2892	4.26	4.08	277	199	WK29	1848	3.69	–	–	–
WK08	3173	4.03	4.70	181	239	WK30	2906	3.82	4.82	118	269
WK09	1965	3.63	4.45	392	194	WK31	5132	3.97	5.04	210	321
WK10	2904	4.81	3.43	330	374	WK32	3092	4.07	4.64	166	317
WK11	3634	3.45	5.51	204	460	WK33	771	6.42	1.72	687	132
WK12	4861	3.96	4.75	174	319	WK35	1758	5.69	1.33	535	197
WK13	3681	3.75	5.10	24	327	WK36	3181	3.59	5.56	136	372
WK14	3902	4.02	4.93	184	277	WK37	3969	3.02	–	–	–
WK15	2192	4.46	4.35	235	203	WK38	781	6.36	–	–	–
WK16	3902	4.27	4.40	216	308	WK39	805	5.31	–	–	–
WK17	2807	4.08	4.75	240	394	WK40	4259	4.42	4.40	211	189
WK18	4699	3.71	4.92	144	314	WK41	1877	4.29	4.01	424	198
WK19	4534	3.98	2.97	205	270	WP01	2918	4.13	4.75	150	336
WK20	2275	4.87	4.58	279	291	WP02	3599	4.30	4.40	206	407
WK21	2123	4.86	3.90	183	152	WP03	3213	2.38	–	369	680
WK22	3221	0.08	5.61	16	402	WP04	4385	3.30	4.58	58	385
WK24	2323	4.55	3.95	151	139	WW01	2945	4.36	4.30	120	409
WK25	1459	4.72	4.70	149	165	WW02	2535	4.53	–	–	–
WK27	3628	0.29	–	93	384						


THE JOHANNESBURG-PRETORIA GRANITE DOME
SAMPLE LOCALITY MAP
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Kilometres
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