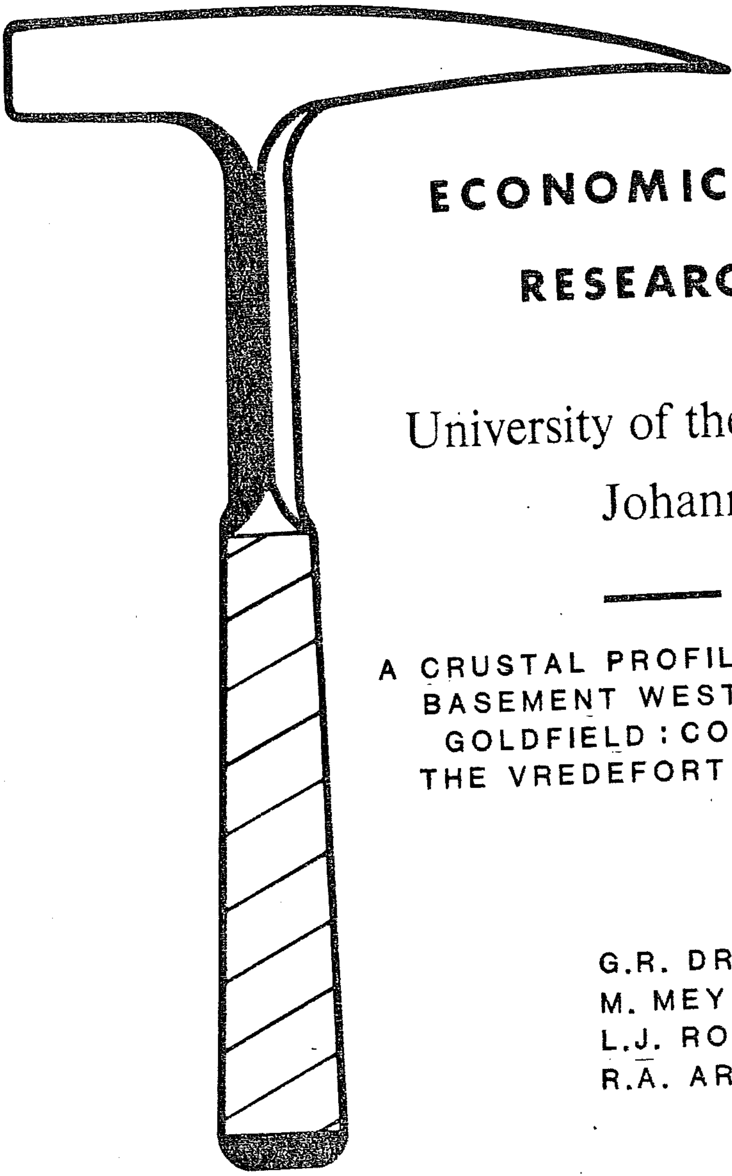

ECONOMIC GEOLOGY RESEARCH UNIT

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A CRUSTAL PROFILE IN THE ARCHAEAN BASEMENT WEST OF THE WELKOM GOLDFIELD : COMPARISONS WITH THE VREDEFORT CRUSTAL PROFILE

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by

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ABSTRACT

Recent geophysical modelling has revealed a shallow eastward-dipping magnetic anomaly - the Colesberg trend - oriented approximately north-south, some 100km west of the Welkom Goldfield. The geometry of this structure, together with the nature of several borehole intersections of the Archaean basement on both sides of the Colesberg trend, suggest that a crustal block in this region is tilted approximately 5° east to reveal a crustal profile sub-outcropping against overlying Phanerozoic strata. Rocks to the west of the Colesberg trend include complex, heterogeneous tonalitic-to-dioritic gneisses and migmatites with primitive Rb/Sr and K/Rb ratios and low radioelement abundances. Rocks east of the trend, including the Schweizer-Reneke dome, are generally massive granodiorites and adamellites with more evolved trace element characteristics.

The crustal profile revealed to the west of the Welkom Goldfield is significantly different, in terms of granite types and ages of crust-forming events, from the near-vertical crustal profile exhibited in the centre of the Vredefort structure. Conditions of metamorphism may be different, with the Welkom profile lacking any evidence of the dynamic metamorphism observed at Vredefort. Furthermore, tilting of the Vredefort crustal block is the obvious cause of overturning in adjacent early Proterozoic strata, whereas steeply dipping compressional structures in similar strata along the western margin of the Welkom Goldfield appear to be unrelated to the shallow crustal tilt evident west of this area. The nature of the rocks described here, and their differences to the Vredefort basement, indicates that composite crustal profiles may vary in character from one segment to another, even over relatively short distances.

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I. INTRODUCTION

A. The Vredefort crustal profile

Massive uplift has exposed a segment of the Archaean basement in the Vredefort structure, which occupies a central position within the Witwatersrand basin (Figure 1). The Vredefort structure comprises two crystalline slabs, now nearly vertical in attitude (Bisschoff, 1972; Slawson, 1976; Stepto, 1979 and Hart *et al.*, 1981a), referred to as the Outer Granite Gneiss (OGG) and the Inlandsee Leucogranofels (ILG). Separating these two slabs is a magnetically anomalous zone of highly brecciated, chemically distinct, rock which has been termed the Vredefort discontinuity (Hart and Andreoli, 1986). It is now recognized by most workers in the area that the exposed basement in the Vredefort structure reveals a 15km profile through the Archaean crust, increasing in depth towards the centre of the dome (Slawson, 1976; Hart *et al.*, 1981a,b; Hart and Andreoli, 1986).

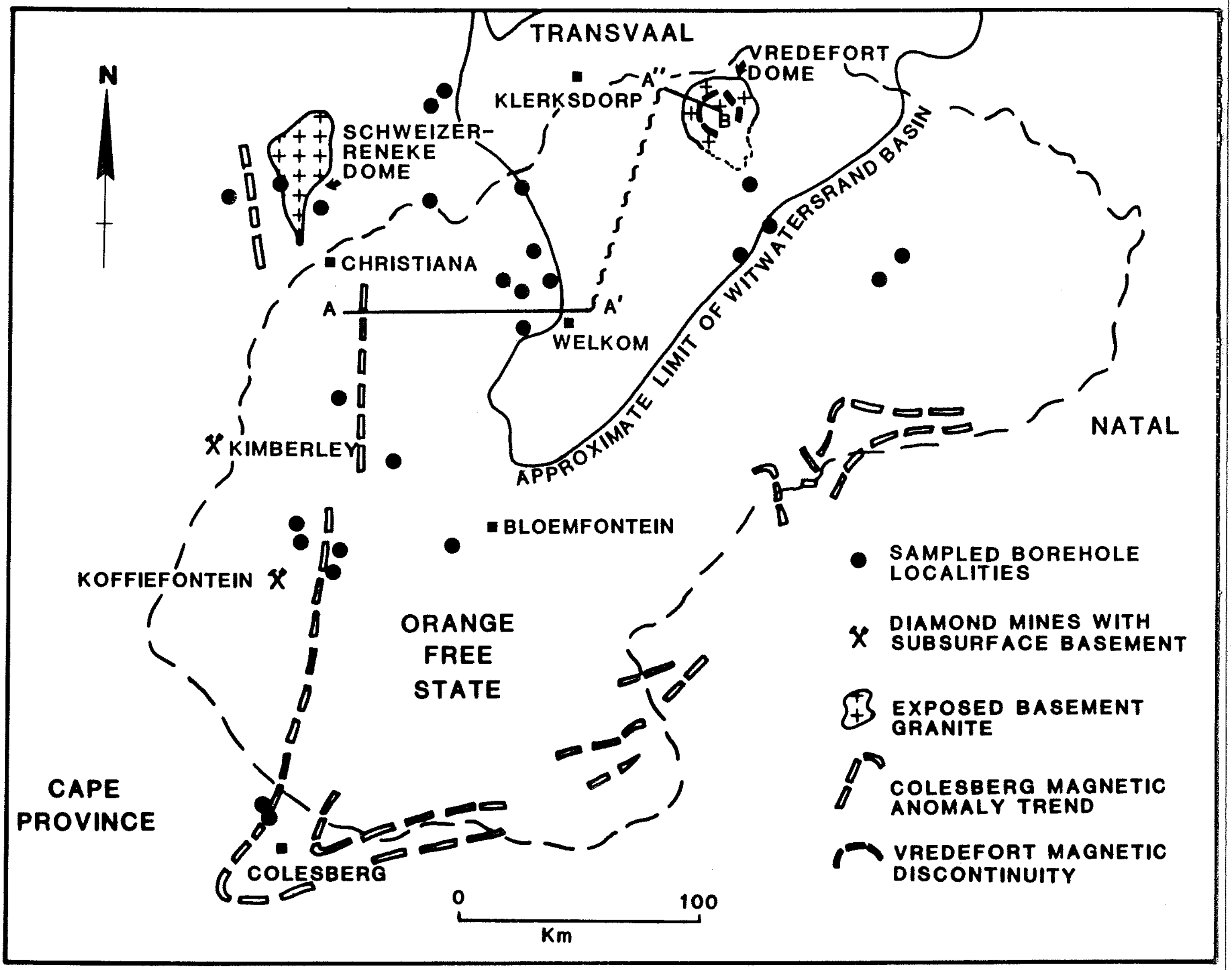

Figure 1: Locality map showing the positions of sampled boreholes, the Schweizer-Reneke dome and the positions of the Kimberley and Koffiefontein mines, in relation to the Colesberg Magnetic Anomaly trend. The interrupted profile A-A' - A"-B is that shown in Figure 8.

The OGG represents the upper portion of the Vredefort crustal profile and exhibits consistent whole rock isochron ages of circa 3050my (Hart *et al.*, 1981b). These rocks, which exhibit amphibolite facies metamorphism, are granodioritic in composition and often display gneissic and/or schlieric textures. Major mineral constituents include quartz, pink orthoclase, plagioclase and variable biotite (3-30%), with accessory amounts of sphene, apatite and zircon. The lower crustal rocks - the ILG - exhibit high metamorphic grades and Rb-Sr and Th-Pb ages of circa 3500Ma (Hart *et al.*, 1981b). The ILG has also been affected by an episode of strong uranium depletion which has reset certain isotope systems at circa 2800Ma ago. The ILG comprises a variety of rock types including mafic granulites and strongly foliated leucocratic granofelsic rocks. The latter consist essentially of recrystallized quartz and partially recrystallized feldspar, with accessory amounts of brown biotite, microcline, orthopyroxene, zircon and monazite (Hart *et al.*, 1981a).

The Vredefort discontinuity forms an abrupt contact between the OGG and ILG and is characterized by a zone of pseudotachylite and brecciated dolerite (Hart and Andreoli, 1986; Hart *et al.*, 1987, Reimold *et al.*, 1985). The rocks associated with the discontinuity, especially in the ILG, have a grey, greenish-brown colour and a waxy lustre that is typical of charnockites (Hart and Andreoli, 1986). The rocks are further characterized by variable proportions of biotite, hornblende, clinopyroxene and occasional orthopyroxene, and are enriched in magnetite, apatite, zircon and monazite. Fe and Cu sulphides have also been identified in these rocks (Hart and Andreoli, 1986). A horseshoe-shaped negative magnetic anomaly, convex to the northwest, lies within the Vredefort structure (Corner *et al.*, 1986) and is approximately coincident with the areal extent of the magnetite-rich, charnockitic rocks of the Vredefort discontinuity (Hart and Andreoli, 1986).

B. Present study area

Along the southwestern extremity of the Witwatersrand Basin 30 boreholes intersecting Archaean basement granites have recently been examined in an attempt to determine the nature of the Witwatersrand Basin hinterland (Figure 1). In the same region Corner *et al.*, (1986) have identified a major positive magnetic anomaly trend (the Colesberg trend) which follows the shape of the present perimeter of the Witwatersrand Basin (Figure 1). It has been suggested that the anomaly may reflect a magnetite-rich layer within the crust, exposed by eastward tilt of approximately 4-8°, which is similar, albeit shallower dipping, to the mid-crustal discontinuity described within the Vredefort structure (Corner *et al.*, 1986; Corner and Wilsher, 1987; Hart and Andreoli, 1987). In the light of these suggestions, the available borehole core, as well as surface and subsurface outcrops sampled on both sides of the Colesberg trend, have been examined with a view to establishing whether any significant differences occur in the nature of the basement on either side of the anomaly and if so, whether these differences are comparable to those described for the Vredefort basement profile. If the Vredefort analogy is applicable, the basement to the west of the magnetic anomaly should represent a lower crustal segment, similar to the ILG, whereas to the east, upper crustal material, similar to that of the OGG, should occur.

II GRANITES TO THE WEST OF THE COLESBERG TREND

A. Kimberley/Koffiefontein subsurface outcrop

Underground mine visits to the De Beers Diamond Mines in Kimberley and Koffiefontein (Figure 1) enabled examination and sampling of the subsurface Archaean basement. A heterogeneous migmatitic-to-gneissic phase (Figure 2a), not unlike that of portions of the Ancient Gneiss Complex in Swaziland, occurs in both the Kimberley and Koffiefontein areas. At least two phases of pegmatite veining are apparent, an older, more albite-rich pegmatite phase and a younger cross-cutting alkali feldspar-rich pegmatite phase (Figure 2a). The younger pegmatite exhibits varying degrees of hematitization.

The migmatite is markedly stromatic (layered) in appearance and is characterized by a well-developed mineral foliation (Figure 2b) and compositional banding. Compositional units range from a leucosome-rich banded gneiss, to a strongly foliated dioritic palaeosome. The medium-to coarse grained leucosome-rich banded gneiss comprises layers of consertal-textured, remobilized quartz, plagioclase and minor microcline, separated by laths and stringers of biotite (altering to chlorite) and hornblende. Accessory phases include zircon and apatite. The dioritic gneiss is generally finer-grained, having stringers of secondary quartz and plagioclase occurring within a hornblende-biotite-garnet-quartz host (Figure 2c). Minor amounts of secondary muscovite occur, associated with the quartz stringers, while little or no chloritization of biotite was observed. Zircon, apatite and sphene occur as accessory minerals, together with varying amounts of disseminated, euhedral pyrite and magnetite.

At Koffiefontein a massive, coarse-grained granite intrudes the older gneiss-migmatite basement, and numerous xenoliths of the latter occur within the younger granite. This granite is quite unlike the migmatitic phase, comprising essentially quartz, plagioclase and microcline in approximately equal proportions with accessory zircon and apatite. The rock contains only minor biotite and no hornblende. Secondary muscovite occurs throughout, replacing the feldspars.

B. Borehole core to the west of the Colesberg Trend

The basement sampled in most of the boreholes drilled west of the Colesberg trend is similar to that exposed in the Kimberley-Koffiefontein mines discussed above. These rocks are also characterized by a strong gneissic fabric, which in places becomes highly schistose. Cross-cutting this fabric are numerous pegmatitic and aplitic veins, chlorite-quartz-carbonate veins, quartz-pyrite-pyrrhotite veins and highly chloritized/pyritized slickenside surfaces. Pervasive muscovitization, albitization and carbonate metasomatism are also prevalent.

These rocks vary in modal composition from tonalitic to granodioritic, but are predominantly tonalitic in character, comprising essentially recrystallized quartz and partially recrystallized plagioclase, with accessory amounts of zircon, apatite, garnet, sphene and monazite, and varying amounts of magnetite, pyrite, chalcopyrite and pyrrhotite. The gneissic fabric observed in borehole core is manifest as an alignment of hornblende and biotite grains and grain clusters. In places, the fabric assumes that of an augen gneiss, where the finer-grained tonalite and mafic minerals are arranged about porphyroblastic, secondary quartz blebs.

Figure 2a: *Strongly foliated dioritic gneiss cut by later pegmatite veins, exposed at the De Beers diamond mine, Kimberley, west of the Colesberg trend.*

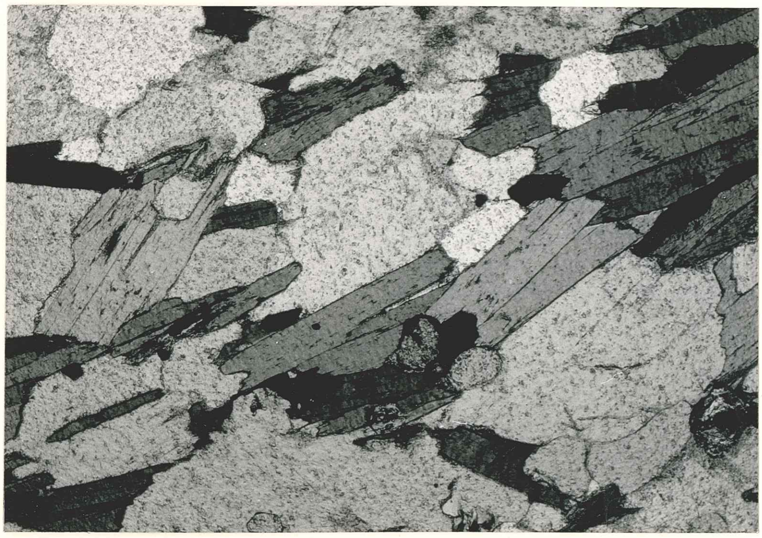

Figure 2b: *Well-developed mineral foliation in a banded gneiss from the Archaean basement west of the Colesberg trend.*

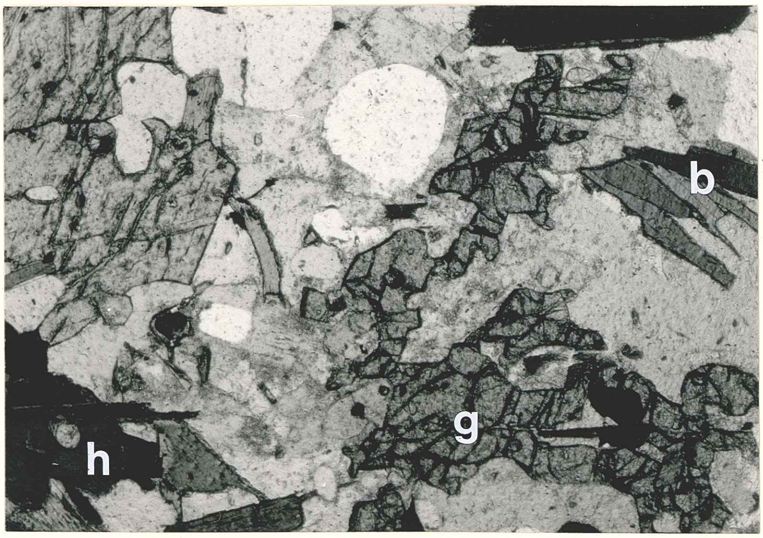

Figure 2c: *Microphotograph showing co-existing hornblende (h), biotite (b), and garnet (g) in a tonalite gneiss west of the Colesberg trend.*

Magnetite generally occurs associated with the hornblende-chlorite-leucoxene assemblages, while pyrite, chalcopyrite and pyrrhotite occurs disseminated throughout the host as euhedral crystals, and in veins and breccia zones.

C. Borehole core situated on the Colesberg Trend

Two boreholes were drilled directly into the Colesberg magnetic anomaly trend (Figure 1), and these revealed a rock-type that is not unlike the gneisses and migmatites which occur west of the magnetic anomaly. However, these rocks exhibit varying degrees of megacrystic development, and are further characterized by occasional brecciated portions, hematitization, as well as abnormally high (up to 5%) contents of magnetite. No pseudotachylite was observed in these core.

The gneisses in the vicinity of the Colesberg trend comprise recrystallized quartz, plagioclase, biotite and hornblende, with minor microcline and clinopyroxene, and accessory zircon, apatite and sphene. Magnetite, pyrite and hematite occur as individual, euhedral crystals disseminated throughout the rock, along intergranular boundaries, and in stringers and veins. Intense hematitization, sericitization and albitization of plagioclase grains and phenocrysts is evident, particularly adjacent to veins and fractures. Biotite exhibits a high degree of alteration to chlorite (plus epidote, carbonate and leucoxene) whereas hornblende is comparatively little altered. The breccia zones are characterized by intense hematitization and carbonate development. Breccia fragments exhibit partial resorption and the matrix comprises predominantly chlorite, epidote and carbonate, with lesser amounts of quartz. Accessory magnetite, pyrite, apophyllite and zircon are also observed within the breccia zones.

III GRANITES TO THE EAST OF THE COLESBERG TREND

The majority of the boreholes sampled occur to the east of the magnetic anomaly, and these generally exhibit massive homogeneous, occasional porphyritic textures (Figure 2d), and are granitic to granodioritic in composition. Although the samples lack any penetrative fabric, the elongation of quartz crystals and occasional alignment of phenocrysts and biotite/chlorite assemblages, does impart a weak fabric to some of the samples. Exceptions to these characteristics are observed in two boreholes situated very close to the magnetic anomaly which are, in many ways, not unlike the boreholes occurring west of the Colesberg trend. Another exception is the borehole situated immediately to the southwest of Bloemfontein (Figure 1), where the basement is granophyric in character, and thought to represent a suite of sub-volcanic felsic rocks preserved in a local graben (T.R. Marshall, pers. comm.).

The more massive, homogeneous, granitic to granodioritic rock types comprise essentially quartz, plagioclase and microcline. The dominant platy mineral is biotite, which displays varying degrees of propylitic alteration to an assemblage of chlorite (plus epidote, quartz, magnetite and leucoxene). Minor secondary muscovite occurs within many of the samples. Zircon, apatite, uraninite, kerogen nodules (usually associated with the propylitic alteration assemblage), a monazite-like phase and allanite occur in accessory amounts. Molybdenite was observed in one borehole, while pyrite and chalcopyrite occur disseminated throughout the remainder of the samples in varying amounts. Megacrysts of both microcline and albite are observed poikilitically enclosing quartz, biotite, accessory

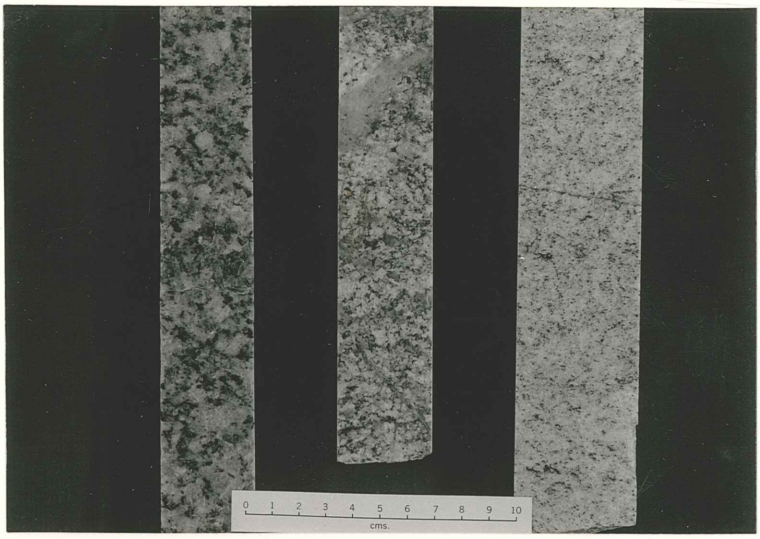

Figure 2d: *Typical, massive granitic textures in three borehole cores intersecting the Archaean basement east of the Colesberg trend.*

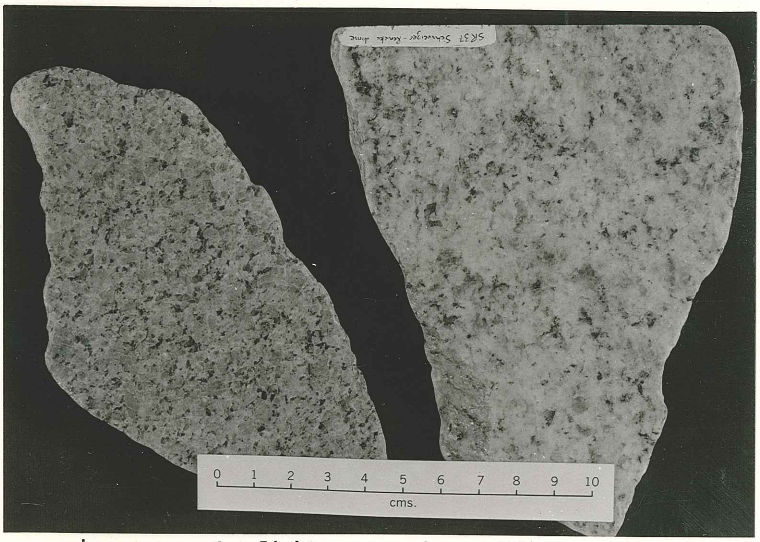

Figure 2e: *Typical textures of adamellite samples from the Schweizer-Reneke dome. Sample on left is from the north-easterly-sector, that on the right from the southwesterly sector.*

phases and albite or microcline respectively. Conspicuous veining and occasional micro-brecciation is observed in certain of the boreholes and quartz-hematite-goethite and quartz-carbonate-fluorite parageneses occur. Micrographic and myrmekitic microtextures often occur adjacent to, and within, the veins and breccia zones.

IV. SURFACE OUTCROPS FROM THE SCHWEIZER-RENEKE DOME

The Schweizer-Reneke dome (Figure 1) can be sub-divided into northeasterly and southwesterly sectors. The essentially porphyritic, granitic to granodioritic rocks from the northeastern portion of the dome (Figure 2e) have undergone hydrothermal alteration and are characterized by a distinctive green and red colouration. In contrast, the adamellitic rocks from the southwestern region are comparatively unaltered. Separating these two sectors is a well-developed shear zone that is sub-parallel, but probably off-set, with respect to the Colesberg trend. The shear zone manifests itself as a positive feature comprising essentially quartz-mylonite. Some of the outcrops observed over the Schweizer-Reneke dome exhibit a weakly developed penetrative fabric which appears to be related to, and becomes better developed towards, the shear zone.

In thin section, the Schweizer-Reneke dome comprises a medium- to coarse-grained, occasionally porphyritic, consertal-textured rock. Major mineral constituents are quartz (exhibiting recrystallization along grain boundaries), plagioclase and microcline. Biotite altering to chlorite occurs as a minor constituent. Secondary muscovite also occurs replacing the feldspars. Megacrysts of microcline poikilitically enclose quartz, as well as sericitized plagioclase, and orthoclase. In places, the megacrysts exhibit coronas of micro-crystalline quartz. Accessory minerals include magnetite, hematite, fluorite, zircon and apatite. A highly metamict phase - possibly monazite - was also observed in some samples. Pervasive sericitization, chloritization, hematitization and minor carbonate replacement of plagioclase are the dominant alteration styles.

The position of the Schweizer-Reneke dome in relation to the Colesberg trend is unclear as the magnetic anomaly weakens in intensity (either due to bifurcation or tectonic disruption) some 30km south of the granite outcrop. Borehole core to the west of the dome (Figure 1) exhibit characteristics very similar to the gneissic-to-migmatitic basement rocks west of the Colesberg trend. Borehole core to the southeast of the dome, as well as the granites on the dome itself, are, however, more akin to granites encountered in areas east of the Colesberg trend.

V. GEOCHEMISTRY

The compositions of all granite samples studied are shown on K_2O versus Na_2O and Streckeisen plots in Figure 3. It is apparent that granitoids from west of the Colesberg trend are generally more sodic than those from east of the anomaly. Although the compositional range is large, rocks from west of the trend are typically tonalitic to granodioritic and have an average K_2O content of 2.22 and an Na_2O content of 4.45, with mean K_2O/Na_2O = 0.43. By contrast, rocks to the east of the trend are typically granodioritic to adamellitic with average K_2O and Na_2O contents of 3.55 and 4.24 respectively, and mean K_2O/Na_2O = 0.90.

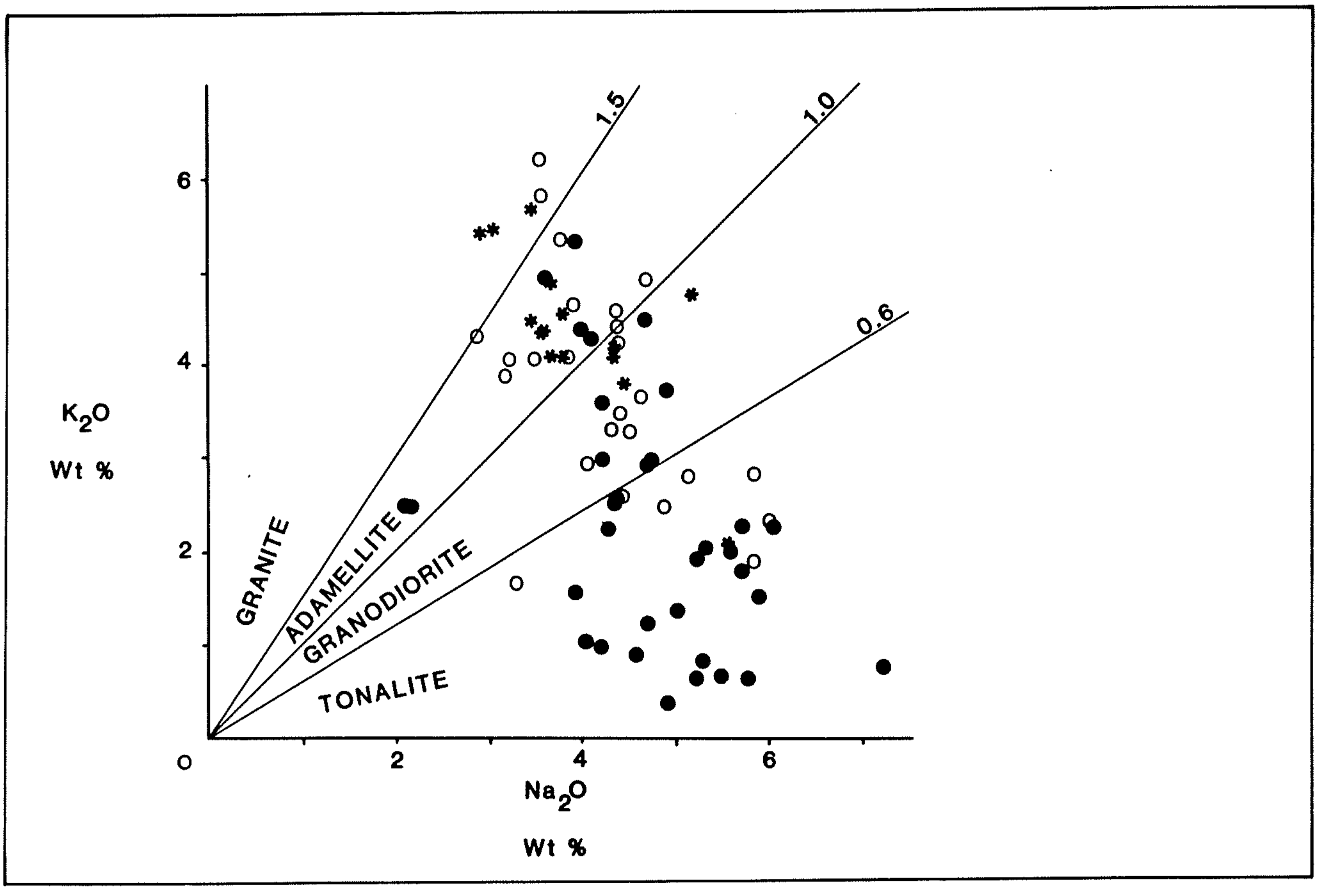

Figure 3a: *Plot of K_2O versus Na_2O showing the composition of granites in the study area. Open circles represent granites east of the Colesberg trend; closed circles represent granites west of the Colesberg trend; asterisks represent granites from the the Schweizer-Reneke dome.*

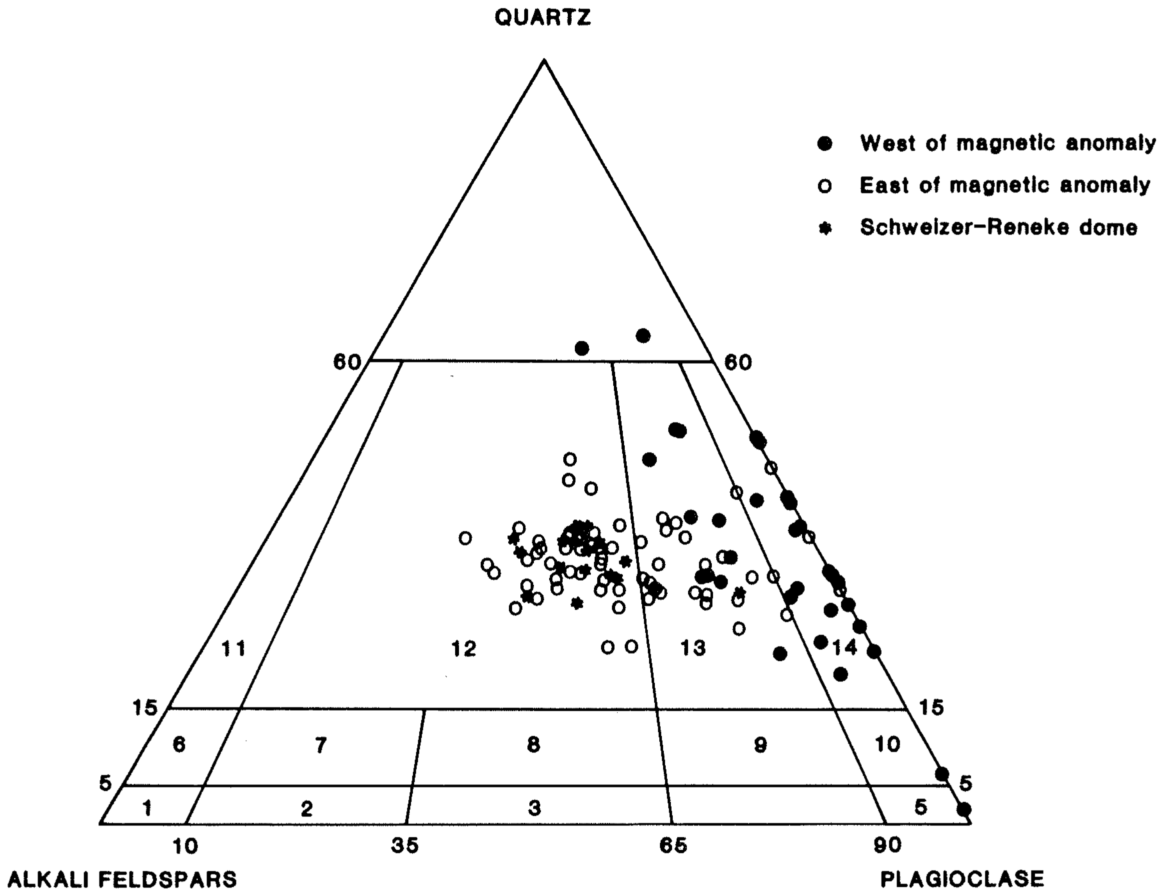

Figure 3b: *Streckeisen plot showing the composition of granites in the study area. Symbols as in Figure 3a; 1 = alkali syenite, 2 = syenite, 3 = monzonite, 4 = monzodiorite/monzogabbro, 5 = diorite/gabbro, 6 = quartz alkali-granite, 7 = quartz syenite, 8 = quartz monzonite, 9 = quartz monzodiorite, 10 = quartz diorite/quartz gabbro, 11 = alkali-granite, 12 = granite, 13 = monzotonalite/granodiorite, 14 = tonalite.*

Significant differences between granitoids west of the Colesberg trend and those east of it are also noted in the plot of Sr versus Rb (Figure 4). The tonalitic migmatites and gneisses of the western zone exhibit a significant range in Sr content (100-1000 ppm) and comparatively low Rb contents, compared to the granitoids east of the trend which have lower Sr contents and Rb contents which range from 100-400 ppm. Although considerable overlap occurs, samples from the Schweizer-Reneke dome have higher Rb contents than the granitoids from the western zone and higher Sr contents than samples from the eastern sector (Figure 4). It is interesting to note that granites from west of the anomaly have similar Rb-Sr characteristics to the tonalite and trondhjemite gneisses from the Barberton region. The granitoids from east of the anomaly, with more evolved Rb/Sr ratios, have similar characteristics to many of the late granite plutons in the Barberton area and Swaziland (Robb, 1981).

Averaged, chondrite normalized, REE ratios are plotted in Figure 5 and also reveal a significant difference between Schweizer-Reneke and the remainder of the samples. The Schweizer-Reneke adamellites have the lowest REE abundances with a CE_N/Yb_N ratio of 22 and no Eu anomaly. Rocks west of the Colesberg trend exhibit a similar pattern, but are enriched in total REE. Granitoids east of the anomaly exhibit a flatter REE trend (CE_N/Yb_N = 6) and a negative Eu anomaly.

The REE data are also compared to the data envelopes for the OGG and ILG in the Vredefort dome (Figure 5). Vredefort granitoids have markedly lower REE contents than the averages for granitoids from both the east and

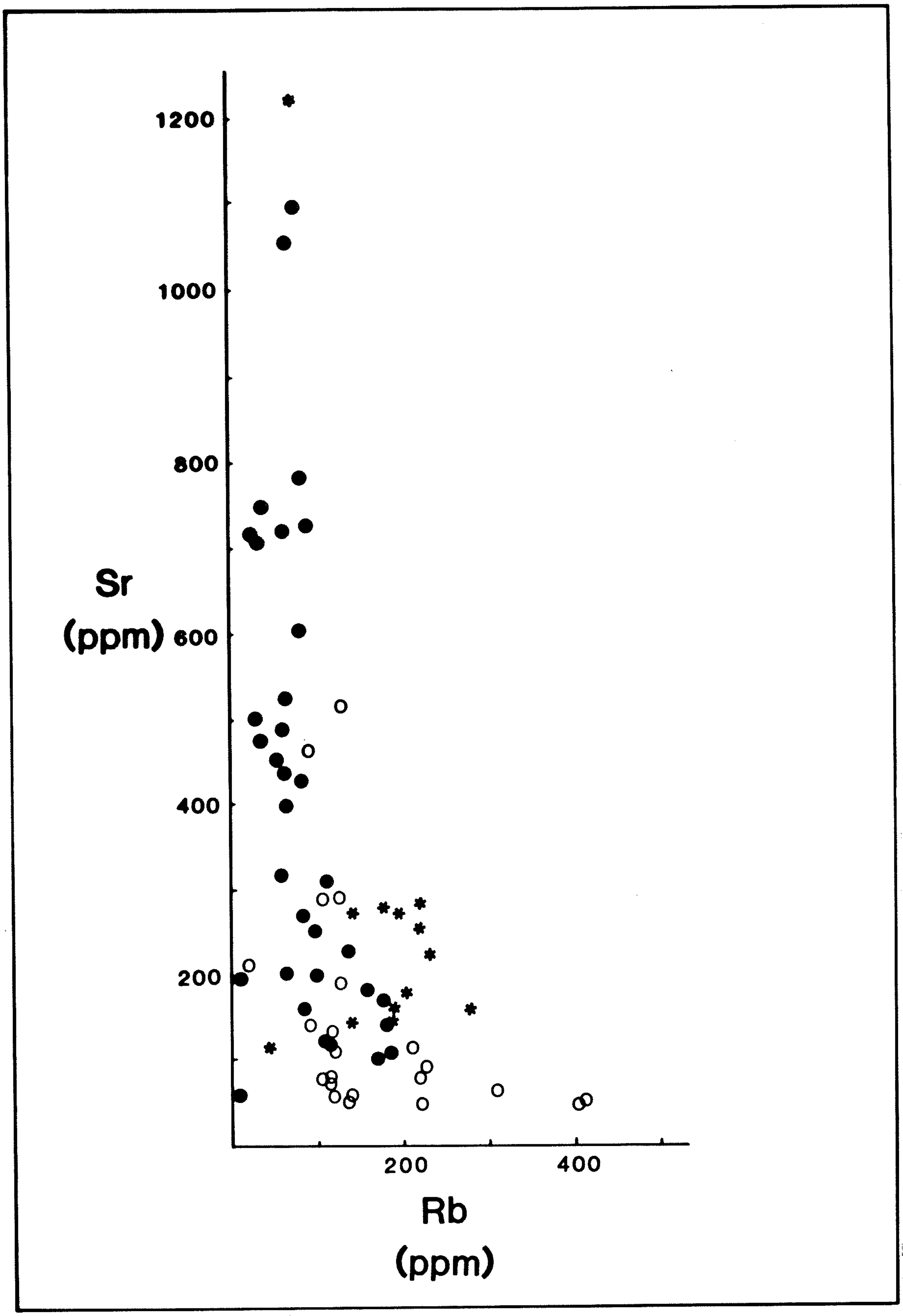

Figure 4: *Plot of Rb versus Sr for granites from the study area. Symbols as in Figure 3.*

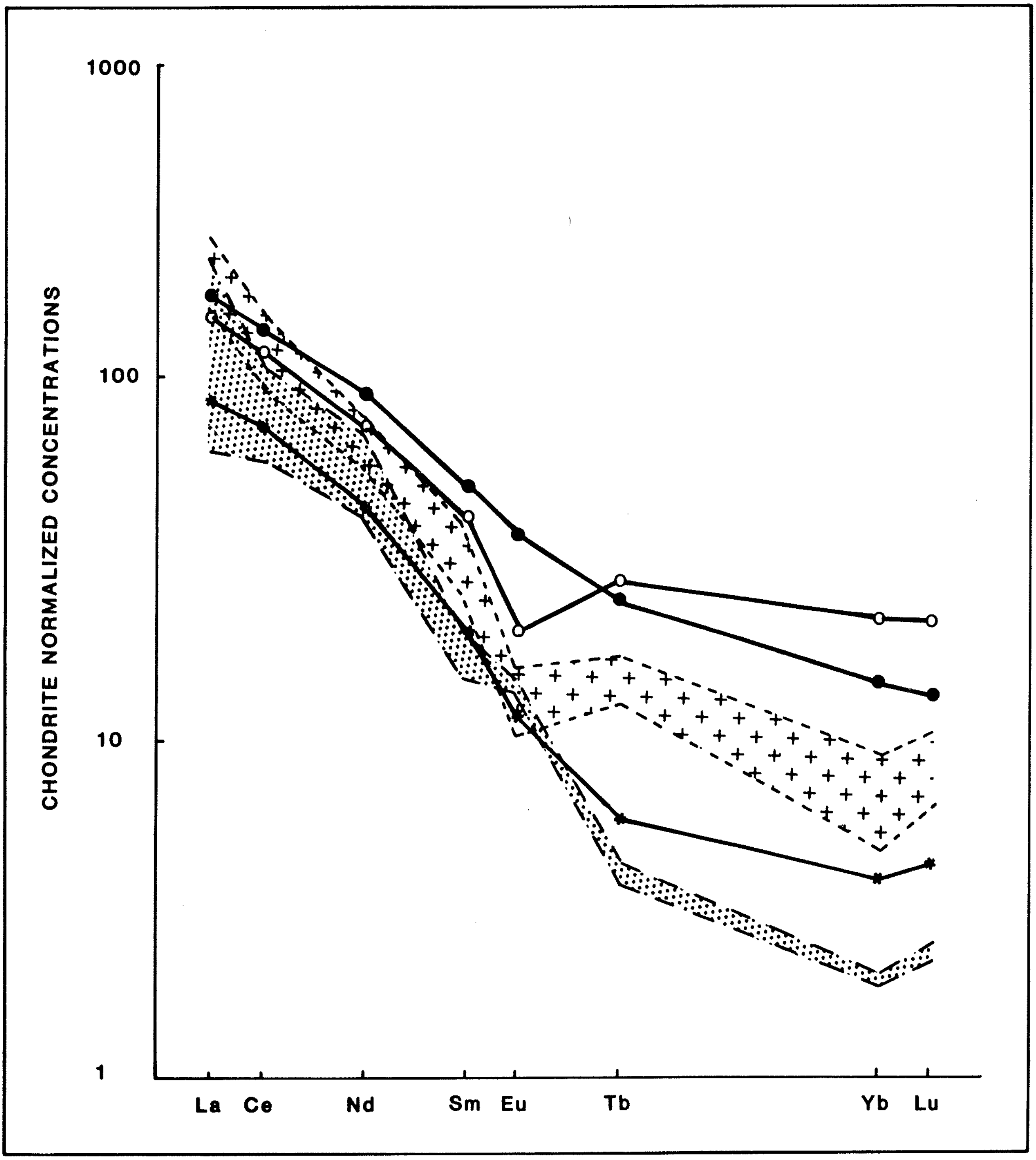

Figure 5: *Averaged chondrite-normalized rare earth element traces for granites from the study area. Symbols as in Figure 3. Also shown are envelopes of data for the OGG (crosses) and ILG (dots) from the Vredefort dome.*

west side of the Colesberg trend. Granites from the Schweizer-Reneke dome, with a more fractionated REE pattern, more closely resemble the pattern for the ILG although the HREE are more depleted in the latter. The REE pattern for the OGG is similar - in terms of LREE abundances and a slight negative Eu anomaly - to the granites from east of the Colesberg trend although the HREE in the Vredefort rocks are more depleted.

Migmatitic rocks from the Broodkop area south of the Vredefort dome (Colliston *et al.*, 1987) have different REE patterns (i.e. high HREE abundances) to OGG and ILG, but are comparable to certain of the samples from east of the Colesberg trend.

Radioelement abundances are illustrated in the plot of U versus U/Th in Figure 6. The gneissic-to-migmatitic rocks west of the Colesberg trend have very low U contents ($\bar{X}$ = 0,9ppm) and a fairly restricted range (0,2 - 2ppm) compared to the higher abundances ($\bar{X}$ = 4,6ppm) and broader range (3 - 11ppm) in the granites east of the trend. U/Th ratios are, however, similar in granitoids from both sides of the magnetic anomaly and range between 0,1 - 0,6. The Schweizer-Reneke adamellites exhibit moderate U abundances, but samples from the altered northeasterly sector are characterized by very low U/Th ratios ($\cong$ 0,1). The latter have probably been affected by uranium depletion associated with hydrothermal alteration.

These radioelement data are also compared to the U and Th data of Hart *et al.*, (1981) for the Vredefort basement granitoids. Most Vredefort samples, especially from the northeastern and northwestern sectors of the dome are characterized by very low U abundances ($\cong$ 1ppm) and very low U/Th ratios ($\cong$ 0,1). These characteristics have been attributed to major radioelement (particularly uranium) depletion during a period of high grade metamorphism at circa 2800Ma ago (Hart *et al.*, 1981a, b). Certain of the Vredefort granitoids, particularly those from the southwestern sector, as well as the Broodkop migmatite, do, however, contain much higher radioelement abundances, with values of up to 27 and 36ppm U, and 67 and 46ppm Th, respectively, having been detected (Hart *et al.*, 1981a; Colliston *et al.*, 1987).

Averaged trace element profiles normalized against abundances in the primitive mantle also reveal significant differences between the granitoids on either side of the Colesberg trend. The tonalitic gneisses and migmatites west of the anomaly are depleted in Rb, Th, U, K, Ba, Ta, Zr, Hf and Y, but enriched in the LREE and Sr, relative to the granitoids east of the Colesberg trend (Figure 7a). With the exception of U, adamellites from the Schweizer-Reneke dome (Figure 7b) show similar LIL element abundances to the granitoids east of the Colesberg trend, but all other elements shown in Figure 7b, with the exception of Sr, are depleted with respect to the latter.

VI. METAMORPHISM

Granitoids east of the Colesberg trend show little or no evidence of a regional metamorphic overprint and alteration is manifest mainly as deuteric and vein-related hydrothermal processes (Drennan, in prep.). In contrast, the gneissic-to-migmatitic basement rocks west of the Colesberg trend are characterized by a penetrative mineral fabric and compositional banding, as well as mineral assemblages diagnostic of high metamorphic grades. In certain samples from borehole core in the Colesberg region and southwest of the Schweizer-Reneke dome, clinopyroxene-hornblende-biotite assemblages coexist, whereas gneisses from the Kimberley area reveal an association of garnet-biotite-hornblende.

A detailed study of the metamorphic pressure-temperature conditions pertaining to the gneiss-migmatite basement west of the Colesberg trend is beyond the scope of the present study. However, in an attempt to obtain preliminary geothermometric and geobarometric data on these rocks certain

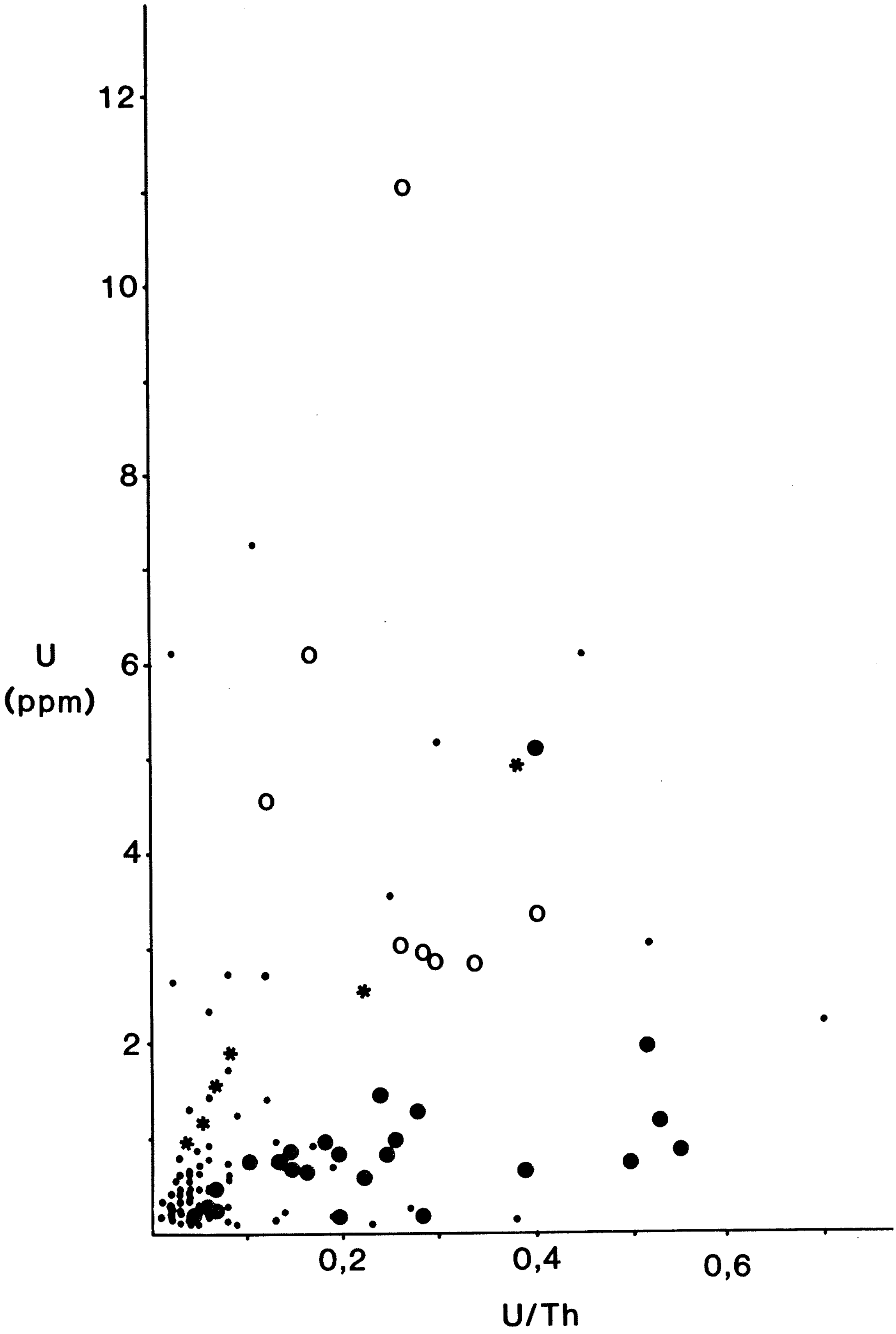

Figure 6: *Plot of U versus U/Th for granites from the study area. In addition, data from the basement granites of the Vredefort structure (small dots) are also shown for comparison (after Hart et al., 1981a). Symbols as in Figure 3.*

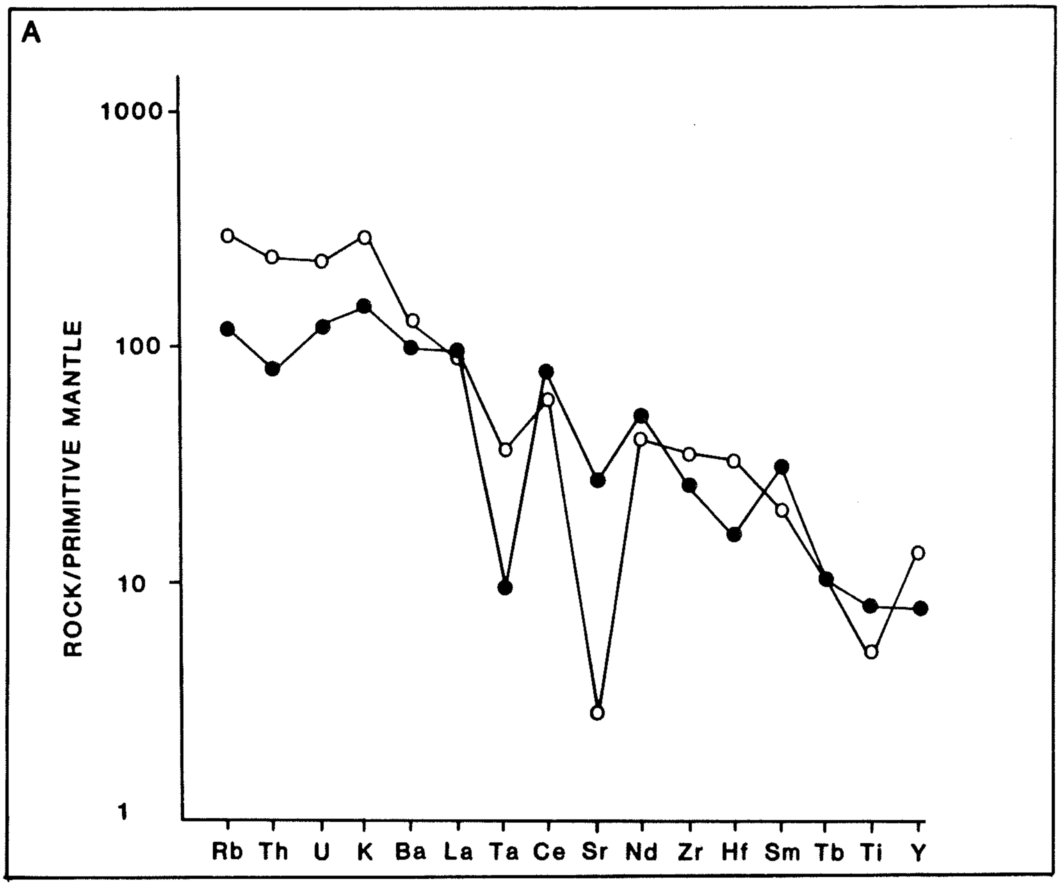

Figure 7a: *Averaged trace element profiles normalized against abundances in the "primitive mantle" (values from Taylor and McLennan, 1985) for granites from west and east of the Colesberg trend. Trace elements along the abscissa are ordered according to generally decreasing bulk incompatibility with respect to the mantle.*

critical mineral phases have been analyzed (Table 1). These data include coexisting garnet-biotite-hornblende from gneisses in the Kimberley area, and clinopyroxene from similar rocks in the Colesberg region. Geothermometric conditions can be obtained from the relationship between temperature and Fe-Mg partitioning in coexisting garnet and biotite, established empirically by Thompson (1976) and Ferry and Spear (1978). This relationship, namely:-

$\ln K = -2109/T(°K) + 0{,}782$ (after Ferry and Spear, 1978)
or $\ln K = -2730/T(°K) + 1{,}557$ (after Thompson, 1976)
where K = Mg/Fe(garnet)/Mg/Fe (biotite)

yields equilibration temperatures of 577°C and 566°C respectively, for the data provided in Table 1.

Geobarometric conditions can be estimated using an empirically-derived relationship between pressure and the tetrahedral:octohedral siting of Al in tschermakite, determined initially by Hammerstrom and Zen (1986), and confirmed over a wide range of pressures by Hollister et al. (1987). This geobarometer pertains to calc-alkaline rock compositions (diorite-tonalite-granodiorite) at pressures > 2kb in which a mineral assemblage of quartz-plagioclase (oligoclase) - orthoclase-biotite-magnetite-sphene occurs in association with hornblendes and would appear, therefore, to be

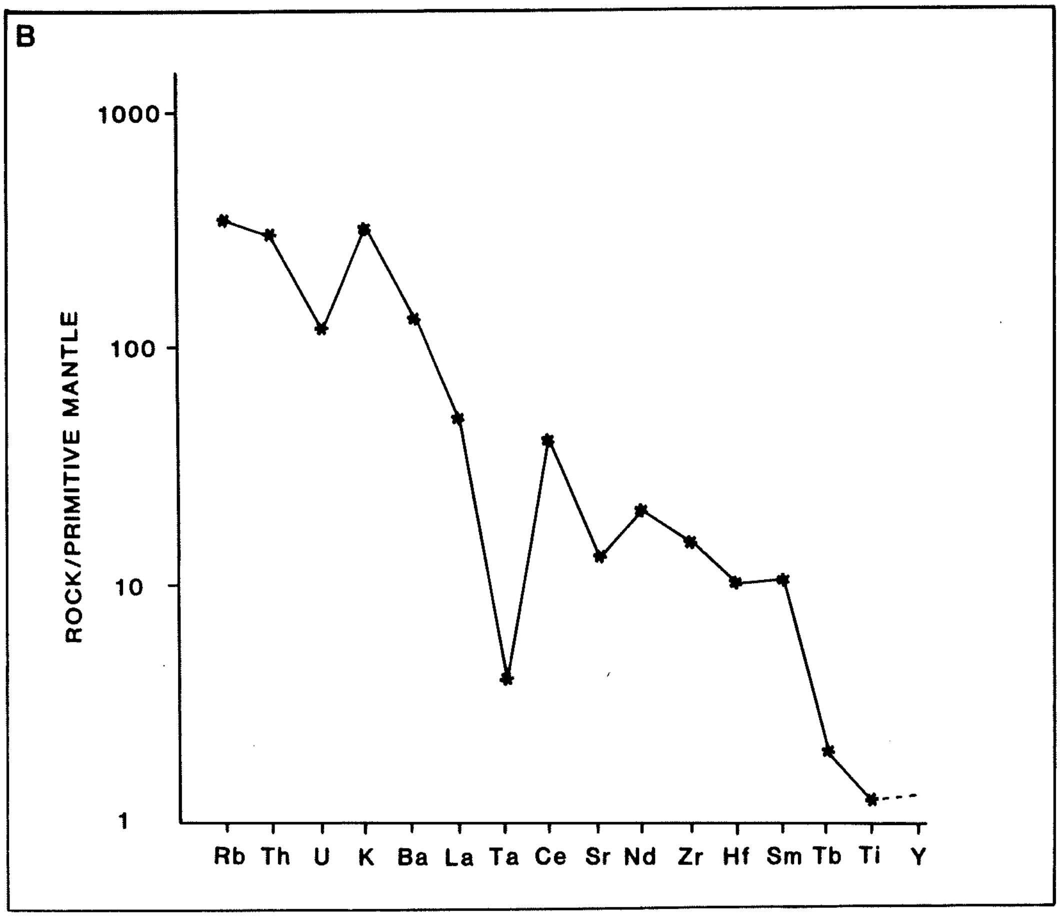

Figure 7b: *Averaged trace element profiles normalized against abundances in the "primitive mantle" (values from Taylor and McLennan, 1985) for samples from the Schweizer-Reneke dome.*

relatively well suited to the rocks in question. This relationship, namely:-

$P(kb) = 3,92 + (5,03 \times Al_T)$ (after Hammerstrom and Zen, 1986)
and $P(kb) = 4,76 + (5,64 \times Al_T)$ (after Hollister et al., 1987)
where Al_T = number of cations of Al per formula unit based on 23 oxygens

yields pressure estimates of 9 and 9,7kb respectively, for the data presented in Table 1. Assuming an average crustal density of $2,8g.cm^{-3}$, these values equate to depths in the crust of 25-27km.

These empirically derived estimates are clearly preliminary and need confirmation through more detailed study. The pressure and temperature estimates are, however, independently derived and suggest a geothermal gradient for the region of approximately $21\text{-}23°C.km^{-1}$. This range is entirely compatible with geothermal gradients within typical crustal rocks, and also accords with actual heat flow determinations around the edges of the Witwatersrand Basin which suggest geothermal gradients of $16\text{-}23°C.km^{-1}$ (Jones and Bottomley, 1986).

VII. STRUCTURE

A simplified section through the crustal profile envisaged in the area to the west of the Welkom Goldfield is presented in Figure 8 where it is also compared to the Vredefort crustal profile. The Archaean basement rocks of the Vredefort dome are surrounded to the north and west by a collar of steeply-dipping to overturned Proterozoic strata of the Dominion

TABLE 1. **MINERAL ANALYSES FROM TONALITE-DIORITE GNEISSES AND MIGMATITES TO THE WEST OF THE COLESBERG TREND**

	1	2	3	4
Wt.%	HORNBLENDE(n=1)	BIOTITE (n=2)	GARNET (n=5)	CLINOPYROXENE (n=3)
SiO_2	40,31	36,20	38,29	53,99
TiO_2	0,69	2,42	0,04	0,16
Al_2O_3	14,17	16,27	21,72	1,78
FeO	22,00	23,14	25,94	10,15
MnO	0,36	0,16	3,92	0,68
MgO	6,33	9,03	1,85	12,66
CaO	11,21	0,07	8,84	21,62
Na_2O	1,53	0,14	0,03	0,88
K_2O	1,14	9,15	0,01	0,05
P_2O_5	0,02	0,03	-	-
H_2O	1,75	3,64	-	-
F	0,39	0,57	-	-
Cl	0,05	0,04	-	-
TOTALS	99,95	100,86	100,64	101.97
CATIONS/ FORM UNIT	23(+1 OH,F)	22(+2 OH,F)	24	6
Si	6,212	5,535	6,021	1,649
Ti	0,080	0,278	0,005	0,004
Al	2,574	2,930	4,026	0,077
Fe	2,836	2,960	3,413	0,311
Mn	0,047	0,021	0,522	0,021
Mg	1,454	2,058	0,435	0,693
Ca	1,851	0,012	1,491	0,851
Na	0,458	0,042	0,008	0,062
K	0,224	1,785	0,003	0,003
P	0,002	0,004	-	-
TOTALS	15,738	15,625	15,924	3,671

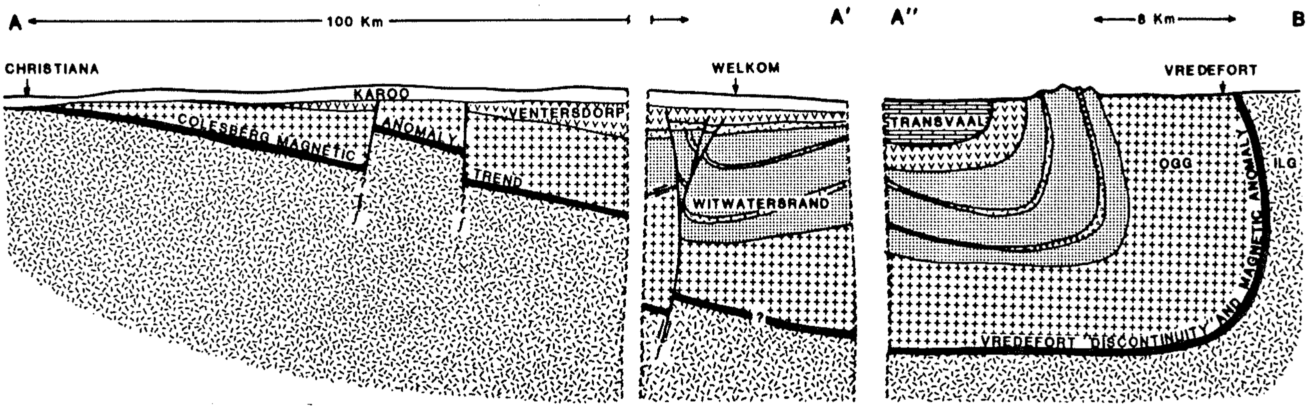

Figure 8: Schematic west-east section (not drawn to scale) of the crustal profile to the west of the Welkom Goldfield, and a comparison to a northwest-southeast section of the Vredefort structure. Structural details from Corner and Wilshire, 1987; Winter, 1986; Callow and Myers, 1986; Stepto, 1987; Profile trace is shown in Figure 1.

Group, the Witwatersrand and Ventersdorp Supergroups and the Transvaal Sequence. Dip angles of up to 70-80° inwards towards the core of the structure have been recorded, a feature which lends credence to the now well-known crust-on-edge hypothesis (Slawson, 1976; Hart *et al.*, 1981a, 1981b). Recent work in which the discontinuity between OGG and ILG is equated with the prominent annular aeromagnetic anomaly over the dome has led to the suggestion that the latter is also steeply-dipping to overturned and reflects the geometry of the collar strata. However, the mechanism by which the major overturning event occurred and the driving force behind this event is still a subject of intense debate and at least three hypotheses currently co-exist, namely (i) internally derived volatile degassing (Nicolaysen, 1987) (ii) externally derived bolide impact (Dietz 1961; French and Nielsen, 1987) and (iii) thrust faulting (Colliston *et al.*, 1987; Hart *et al.*, 1987; du Toit, 1958). Irrespective of the structural mechanism it is apparent that exposure of the mid-crustal discontinuity and aeromagnetic anomaly at Vredefort is a direct consequence of overturning or rapid uplift at circa 2000Ma.

The crustal profile described in this paper is, likewise, characterized by steeply-dipping to overturned Proterozoic strata of the Witwatersrand Supergroup at its eastern extremity (Figure 8). These structures are recorded over a strike length of at least 60km along the western edge of the Welkom Goldfield, from the Loraine Mine in the north (Winter, 1986) to the Beisa Mine in the south (Tweedie, 1986). The overturning in this region is related to compressional block faulting and thrusting that was syn-depositional, but pre-dated the final pulse of Witwatersrand sedimentation and Ventersdorp volcanism (Callow and Myers, 1986; Winter, 1986). Consequently, overturning of the Witwatersrand strata in the Welkom crustal profile pre-dated, by at least 700Ma, the overturning of similar rocks along the margins of the Vredefort structure.

VIII. ISOTOPIC CHARACTERISTICS

Very little detailed isotopic work has been carried out on the basement granitoids described from the Welkom crustal profile and only two sets of ages are available. The Schweizer-Reneke dome has yielded consistent whole rock Rb-Sr and Pb-Pb ages of 2767 ± 120Ma and 2780 ± 70Ma respectively (Barton *et al.*, 1986). These ages are similar to ages obtained from granitoid plutons elsewhere along the margins of the Witwatersrand Basin, and are considered to reflect a major crust-forming event at circa 2,8Ga ago (Barton *et al.*, 1986).

A suite of samples representing the gneissic-to-migmatitic basement west of the Colesberg trend has been collected from the Kimberley diamond mines for comprehensive geochronological and isotopic studies. Results thus far obtained are limited to U-Pb ion microprobe analyses on zircon, from the basement exposed in the Bultfontein Mine. The zircons analyzed are structurally complex, with well-defined cores rimmed by younger zircon growth. The older cores define a mean $^{207}Pb/^{206}Pb$ age of circa 3250Ma, with no indication of any older ages in the population analyzed. Analyses of the younger zircon rims lie along a chord on the U-Pb Concordia diagram indicating variable recent Pb-loss and a mean $^{207}Pb/^{206}Pb$ age of circa 2940Ma.

IX. COMPARISON WITH THE VREDEFORT CRUSTAL PROFILE

The recognition of a shallow easterly-dipping magnetic anomaly (the Colesberg trend) and its interpretation as an exposed mid-crustal feature similar to that observed within the Vredefort structure (Corner *et al.*, 1986) finds support from the examination of the surface and sub-surface Archaean basement west and southwest of the Welkom Goldfield. It is clear that differences exist in the nature of granitic rocks on either side of the Colesberg trend and these are compatible with differences that might be expected in material representing "lower" and "upper" crustal levels. The salient characteristics of the granitoid basement on either side of the Colesberg trend are summarized in Table 2, where attention is also drawn to the differences that exist between the present profile and that observed at Vredefort.

A. Rock Types

It is apparent from the descriptions above, and from Table 2, that major differences exist in the nature of the granitoid basement on either side of both the Colesberg trend, and the Vredefort discontinuity. At Vredefort, however, the OGG comprises a homogeneous suite of massive-to-gneissic granodiorites (sensu lato) within which schlieric remnants of mafic and ultramafic rocks occur. The ILG, by contrast, is dominated by a leucocratic, strongly foliated, granofelsic quartzo-feldspathic gneiss which is intruded by a younger, massive biotite granite in the central portion of the structure (Stepto, 1987). The leucogranofels is interlayered with numerous metabasic and metasedimentary remnants which locally reflect mineral assemblages indicative of a high grade (granulite facies) metamorphism (Schreyer, 1983; Stepto, 1987). Clearly, neither the ILG nor the OGG assemblages can be directly equated with the rocks observed from either west or east of the Colesberg trend.

B. Geochemistry

Despite the obvious differences that exist in the rock types from Vredefort and the present study, a number of chemical similarities are evident. Slawson (1976) first documented the progressive systematic decrease in Rb/Sr and increase in K/Rb ratios from the margin to centre of the Vredefort structure. Hart *et al.*, (1981a) presented detailed radioelement concentration profiles showing that U and Th abundances

TABLE 2. SUMMARY OF PRINCIPAL CHARACTERISTICS OF THE GRANITOID BASEMENT FROM THE WELKOM AND VREDEFORT CRUSTAL PROFILES

LOCALITY	CLASSIFICATION	K_2O/Na_2O	Rb/Sr	K/Rb	Th/U	AGE	CHARACTERISTICS	REFERENCES
East of Colesberg Magnetic Anomaly Trend	Granodiorite-Adamellite	0,90	1,35	318	3,7	2767 120Ma[1] (Rb-Sr) 2700 70Ma[1] (Pb-Pb)	- Medium to coarse grained, massive, homogeneous, often porphyritic. - Major constituents = quartz, plagioclase, microcline, with varying amounts of biotite. - Little or no evidence of regional metamorphic overprint	1. Barton et al, 1986.
West of Colesberg Magnetic Anomaly Trend	Tonalite/ diorite-migmatite-gneiss	0,43	0,42	412	4,2	3250Ma (zircon U-Pb)	- Medium to coarse grained, heterogeneous, gneissic to migmatitic. - Major constituents = quartz plagioclase, with 10-40% biotite and hornblende. Garnet and clinopyroxene also present - High metamorphic grades (T=570°C, P= 9-10Kb).	
OGG	Granodioritic gneiss	-	1,10[4]	251[4]	13,5[2]	3000 30Ma[3] (Rb-Sr) 3060 50Ma (Th-Pb)	- Coarse grained, schlieric to gneissic, exhibiting no systematic penetrative fabric - Major constituents = quartz, plagioclase, orthoclase, with 3-30% biotite - Amphibolite facies metamorphism.	2. Hart et al., 1981a. 3. Hart et al., 1981b. 4. Slawson, 1976.
ILG	Leucocratic granofels interlayered with mafic granulites	-	0,18[4]	440[4]	16,9[2]	2830 30Ma[3] (Rb-Sr) 3500Ma[3] (Th-Pb; Rb-Sr)	- Highly recrystallized, exhibiting strong penetrative fabric. - Major constituents = quartz, feldspar, with marked lack of mafic minerals. - Granulite facies metamorphism (T=700°C-900°C, P= circa 5kb)[5]	5. Schreyer, 1983

decrease in abundance in the same direction. These characteristics are consistent with the notion that the Vredefort structure has revealed a vertically differentiated crustal slab with the rocks at deeper levels being less evolved, or depleted, with respect to those at shallower levels (Heier, 1964). The Welkom crustal profile likewise exhibits similar characteristics with the gneissic-to-migmatitic basement west of the Colesberg trend being less differentiated, in terms of Rb/Sr, K/Rb and radioelement abundances (Table 2), than the granites to the east of the trend.

The differences in REE data between samples east and west of the Colesberg trend are similar to the differences between the OGG and ILG respectively. Samples west of the trend are more fractionated and exhibit no Eu anomaly, similar to observations made for the ILG, whereas samples east of the trend have a flatter trend and a negative Eu anomaly, similar to the OGG.

Chemical differences between the two areas are highlighted, however, by the pronounced uranium depletion (and very low U/Th ratios) evident in most of the Vredefort granitoids. Although radioelement abundances in rocks west of the Colesberg trend are low (Figure 6) there is little or no evidence that these rocks have been subjected to the severe uranium loss that characterizes the Vredefort basement.

C. Metamorphism

The existence of high-grade mineral assemblages in rocks of the central portion of the Vredefort dome (Stepto, 1979; Schreyer, 1983) have provided important support for the "crust-on-edge" hypothesis. Pressure and temperature conditions have been quantified with the recognition, at intermediate positions of the profile, but within the ILG, of a mineral reaction involving:-

garnet(1) + quartz → orthopyroxene + cordierite + garnet(2)

which suggests P-T conditions of approximately 700°C and 5kb (Schreyer, 1983). Closer to the core of the structure, the dehydration of hornblende to symplectic intergrowths of orthopyroxene, clinopyroxene, plagioclase and magnetite suggest temperatures in the range 875-900°C. Geobarometric conditions in this area are inferred, from the composition of Fe-rich pyroxenes (orthoeulite), to be low (3-4kb) and probably reflect a reaction related to post-metamorphic uplift (Schreyer, 1983).

These studies all point to the existence of a locally attained metamorphic event of unusually high temperature which coincided with a high-strain event that may be related to overturning and uplift. However, recent studies (R. Hart, pers. comm.) have been unable to relate the high metamorphic grades in the core of the structure to the overturning of collar rocks, and the earlier suggestions in this regard are, therefore, equivocal. Irrespective of the timing, it is nevertheless apparent that at some stage during the development of the ILG, the local geotherm was high (possibly $50°C.km^{-1}$). This scenario is quite different to that envisaged for the Welkom crustal profile where the attainment of high metamorphic grade with depth in the crust appears to be the result of a normal geothermal gradient. Furthermore, there is little or no evidence of the high-strain deformation that characterizes much of the basement at Vredefort.

D. Structure

As mentioned previously the massive overturning of early Proterozoic strata along the northern and western collar of the Vredefort dome is related to pronounced tilting of the adjacent basement granites (Bisschoff, 1971; Slawson, 1976). Consequently, the exposure of the near-vertical Vredefort discontinuity some 8km beneath the sediment-basement unconformity, is clearly related to the same event that was responsible for overturning of the collar rocks. By contrast, the Colesberg magnetic anomaly trend, which suboutcrops some 100km west of the Welkom Goldfield (Figure 1) appears to be unrelated, either spatially or chronologically, to the overturning of sediments in the Goldfield. This is because the geometric relationship between basement and overturned strata is quite different in the two areas, as illustrated in the simplified profiles presented in Figure 8.

E. Isotopic Characteristics

Basement rocks in the Vredefort structure exhibit distinctive isotopic characteristics. The OGG yields whole rock isochrons of circa 3050Ma in three decay systems, namely Rb-Sr, U-Pb and Th-Pb (Hart *et al.*, 1981b). By contrast, the ILG could be as old as circa 3500Ma old, with the leucogranofels having been reset approximately 2800Ma ago by an event that has been linked to granulite metamorphism in the lower crust (Welke and Nicolaysen, 1981; Hart *et al.*, 1981b). Recent dating has also revealed ages of 3330 $\pm$ 131Ma for the OGG and 2978Ma for the Broodkop migmatites SE of the Vredefort dome (Colliston *et al.*, 1987).

The gneissic-to-migmatitic basement west of the Colesberg trend is circa 3250Ma old and is, therefore, quite different to the ILG. Similarly, no 2800 Ma age is indicated by the data available for the basement west of the Colesberg trend, but rather a slightly older event (metamorphic?) is indicated by the growth of zircon rims at circa 2940Ma. These rocks have not, however, been dated by any of the whole rock techniques which have been extensively used in studies of the Vredefort structure, and further work with the Rb-Sr method may reveal the resetting event at circa 2800Ma indicated by the Vredefort data. Further dissimilarities in the age structure of the Vredefort and Welkom crustal segments are evident in the 2800Ma (Barton *et al.*, 1986) Schweizer-Reneke granite, an age which is quite distinct from the OGG.

X. CONCLUSIONS

It is apparent from both geophysical and geological evidence that basement tilting has revealed a shallow eastward dipping crustal profile beneath Phanerozoic cover sequences in the area west and southwest of the Welkom Goldfield. Although certain broad similarities exist, it is clear that the nature of the profile is quite different, with respect to degree of tilt, timing and relationship to Witwatersrand strata, to the Vredefort structure. It is also apparent that the crustal profile west of Welkom is compiled differently to that evident in the Vredefort structure, both from the point of view of granite types and the timing of crust-forming events. In spite of this, it appears that a vertical chemical differentiation of the crust nevertheless exists, and is clearly detected, in both the Welkom and Vredefort profiles. Consequently, vertical differentiation is a feature of crustal profiles even though the nature of the lower crust and upper crust may vary from one place to another.

The magnetic anomalies revealed in suboutcrop along the Colesberg trend, and as outcrop at the Vredefort discontinuity appear to be a regional feature at least in the southern Kaapvaal Craton. Although the origin of this magnetic zone is uncertain, it can probably be equated to the seismically-defined mid-crustal discontinuity which has been observed elsewhere in the world (Hart and Andreoli, 1986).

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