

ECONOMIC GEOLOGY
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THE NATURE OF THE WITWATERSRAND
HINTERLAND : CONJECTURES ON THE
SOURCE-AREA PROBLEM

by

L.J. ROBB and M. MEYER

• INFORMATION CIRCULAR NO.178

UNIVERSITY OF THE WITWATERSRAND
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ABSTRACT

The Au- and U-bearing Witwatersrand Basin is generally regarded as being a palaeoplacer deposit, and this inevitably raises questions regarding the nature of the source area. A number of domal outcrops of the Archaean basement are exposed in the Witwatersrand hinterland, revealing the presence of a diverse suite of granitoids and a minor (< 10%) greenstone belt component. Samples from over 160 boreholes drilled adjacent to the basin have, in addition, revealed the nature of the sub-surface Archaean basement beneath the early Proterozoic sedimentary and volcanic cover. The granitic sub-surface basement is characterized by a pervasive, often intense, hydrothermal alteration which includes features such as greisenization, fluorite and carbonate veining, sericitization, chloritization, pyritization and hydraulic fracturing. These high-level, hydrothermally altered granites (HAGS) appear to have been preserved beneath the protective early Proterozoic cover and have largely been eroded from surface outcrops. The HAGS are significantly enriched in Au and U with respect, both to surface granitoids from the Witwatersrand hinterland, and the entire range of granites from the well-exposed Barberton Mountain Land.

The remarkable concentrations of Au and U unique to the upper portions of the Witwatersrand Basin indicate that a major, catastrophic change in the nature of the source region occurred immediately prior to deposition of the ore-bearing strata. A number of lines of evidence suggests that this change may be related to the emplacement of a suite of high level, fertile granitoids, the upper portions and roof zones of which are characterized by hydrothermal alteration and attendant mineralization easily accessible to erosion. The occurrence of the HAGS is considered to be widespread in the Witwatersrand hinterland and these rocks probably represent the principal source rock for the palaeoplacer deposits.

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I. INTRODUCTION

The largest accumulation of gold and uranium on Earth - the Witwatersrand Basin - has now been mined for one hundred years, producing approximately 38 500 metric tons of gold and 125 000 tons of U_3O_8 . With the widespread acceptance of the modified placer theory the question of the source of the detritus is omnipresent. In spite of the duration of mining activity and the wealth of information available ".... the nature of the hinterland to the Witwatersrand Basin and the sources of gold and uranium in it remain essentially speculative and debatable" (Pretorius, 1984).

Very little work has been addressed directly to the problem of where the Witwatersrand gold and uranium came from and, more specifically, what constituted the broad geological framework of the hinterland. Central to the problem is the question of whether a typical Archaean granite-greenstone terrane - such as that of the Barberton Mountain Land, for example - could represent an adequate source environment, or whether the hinterland must of necessity have comprised an exotic portion of the Earth's crust. Previous thoughts on the matter have referred to the Barberton granite-greenstone terrane as reflecting the nature of the Witwatersrand source area. Viljoen *et al.*, (1970) and Pretorius (1976), for example, put forward the "inverted stratigraphy" model whereby certain detrital components in the lower Witwatersrand successions were derived essentially from the upper volcano-sedimentary portions of a Barberton-type greenstone belt, whereas upper Witwatersrand detritus was shed from the lower mafic-to-ultramafic volcanic units. In addition, the granitic rocks adjacent to the greenstone belt were also considered to have contributed certain components into the basin.

The pre-existing models for the Witwatersrand provenance do not resolve the "source-area problem", for two reasons. First, a detailed examination of the hinterland *per se* as indicated by sedimentologically-derived directional indicators, has never been undertaken and the possibility of unknown components still exists. Second, in the consideration of a typical Archaean granite-greenstone terrane as the source region a serious mass balance problem exists (Reimer, 1984). There is clearly a need, therefore, to re-examine in detail the source area problem. The purpose of this paper is twofold; first, to present a summary of recently acquired data that sheds new light on the nature of the Witwatersrand hinterland, and, second, to provide a series of conjectural models that are intended as a framework within which ongoing research can be undertaken.

II. THE WITWATERSRAND BASIN

A. Lithologies and Depositional Environment

A great deal of information is already available on aspects related to the Witwatersrand Basin and much of this is summarized in numerous publications (Pretorius, 1976a, b; 1981; Tankard *et al.*, 1982). The basin is subdivided into a lower (West Rand Group) and upper (Central Rand Group) division (Figure 1). The lower division comprises essentially shales, sandstones (quartzites) and conglomerates in approximate proportions of 49% shale, 49% quartzite and 2% conglomerate. A minor volcanic component, the Crown lava, is essentially tholeiitic in composition and is on average 250m thick. The upper division is characterized by differing proportions of essentially similar lithologies, namely, approximately 5% shale, 85% quartzite and 10% conglomerate plus associated pyritic and pebbly quartzites.

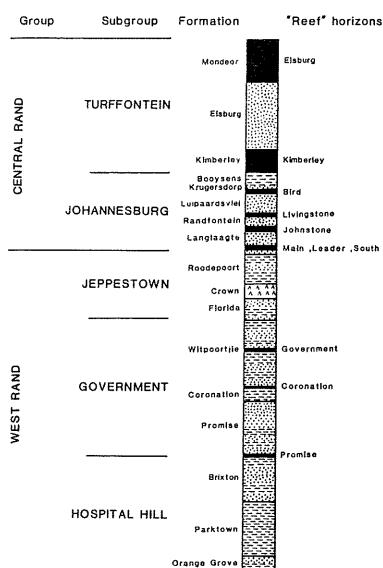


Figure 1 : Schematic stratigraphic column of the Witwatersrand Supergroup in the Central Rand area (after SACS, 1980)

Deposition of the West Rand Group is considered to have occurred during the interaction of marine shelf and tidal environments. During the early stages of deposition the basin formed in an epeiric sea that was essentially open-ended. Closure of the basin is thought to have occurred mid-way through the development of the lower division when a series of river-dominated fan deltas prograded onto a shallow shelf.

During the deposition of the Central Rand Group the Witwatersrand Basin shrank progressively as sediments prograded from the margins inwards, accumulating in shallow braided-stream environments. Alluvial fan-delta complexes mark the major entry points of fluvial systems into the basin. Palaeocurrent directions indicate that the hinterland was a broadly contiguous area to the north and west of the basin (Figure 2).

The nature of the various sedimentary units in the Witwatersrand Basin are known to reflect specific responses to tectonically induced uplift and erosion in the hinterland. The preponderance of argillaceous sediments in the upper portions of the West Rand Group indicates a gradual waning in the energy of the sedimentary process. The sudden influx of abundant arenites and conglomerates which mark the inception of Central Rand Group deposition is considered to indicate a rejuvenation in the energy of basin formation and probably reflects a major tectonic uplift in the source area. The age of the Witwatersrand Supergroup is bracketed by radiometric dating on basement granitoids and the overlying Ventersdorp Supergroup. Maximum constraints indicate that sediment deposition occurred between circa 2,8 and 2,3 Ga (Allsopp and Welke, 1986).

The economic ore-bearing horizons, or reefs, of the Witwatersrand Basin are almost exclusively contained within the Central Rand Group (Figure 1). The ore is represented essentially by free gold and uraninite/brannerite which is hosted in pyritic conglomerate horizons and sorted according to hydrodynamic principles.

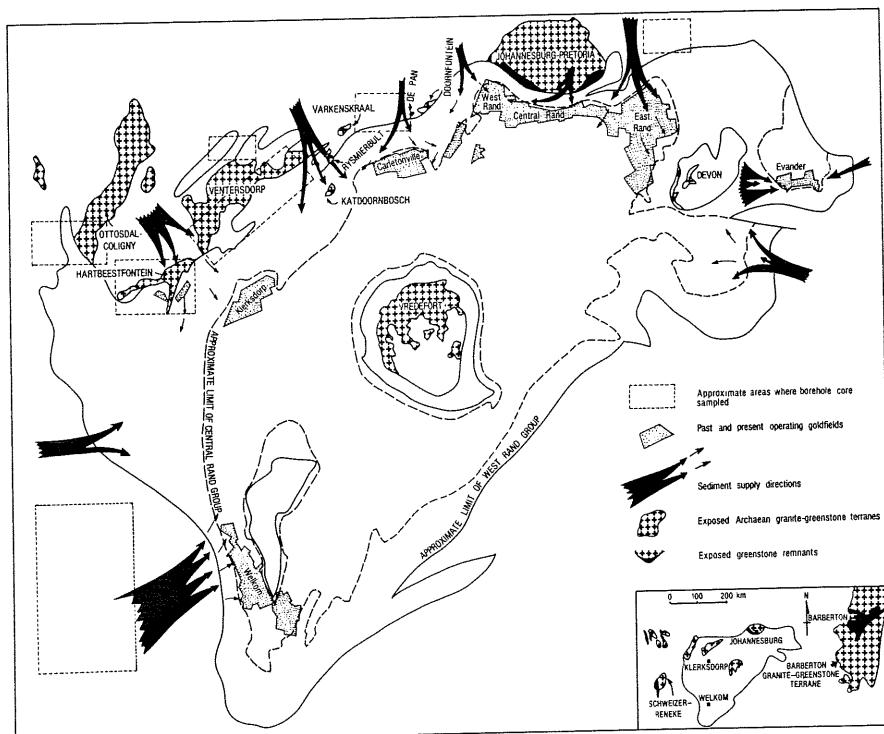


Figure 2 : Outline of the Witwatersrand Basin showing sediment supply directions and distribution of Archaean basement domes. Broad areas from which borehole cores of the Archaean sub-surface basement were obtained, are also shown.

B. The Nature of Detrital Components

Most of the economically viable minerals (gold, uraninite, platinoids) as well as a host of other heavy minerals (pyrite, zircon, chromite, rutile, cobaltite, arsenopyrite etc.) in the reef horizons, are of detrital origin (Liebenberg, 1955; Ramdohr, 1955). Examination of the nature and distribution of these components has a direct bearing on the source area from which they were derived and in the sections that follow those characteristics pertinent to the nature of the Witwatersrand hinterland are discussed.

(i) Pyrite

A considerable amount of petrographic and geochemical work has been carried out on detrital pyrite in the Witwatersrand Basin in order to assess the nature of its origin (Hallbauer, 1981; Hallbauer and Kable, 1982; Hallbauer and von Gehlen, 1983; Hirdes, 1979; Saager, 1981; Saager and Köppel, 1976; Utter, 1978). A recent study (Meyer *et al.*, 1985) has compared the Co, Ni and Au contents of detrital pyrites from a variety of reef horizons in the Witwatersrand Basin with hypogene pyrites derived from a number of different rock types in the adjacent Archaean granite-greenstone basement (Figure 3). The Witwatersrand detrital pyrites are characterized by Co/Ni ratios averaging approximately one. Pyrites with similar Co/Ni ratios and Co and Ni abundances were found to occur in gold deposits from the Murchison and Pietersburg greenstone belts, as well as from a variety of granites in the southwestern Transvaal. By comparison, pyrites from gold mines in the Barberton greenstone belt are depleted in cobalt, and typically have Co/Ni ratios that are an order of magnitude lower than those previously described. Meyer *et al.*, (1985) concluded that the detrital pyrites in the Witwatersrand Basin were probably polygenetic in origin, having been derived from granitic rocks as well as volcano-sedimentary greenstone accumulations within which gold deposits of the Murchison-Pietersburg type are hosted. It would appear that, contrary to previous models (Viljoen *et al.*, 1970; Pretorius, 1976), Barberton-type gold deposits did not contribute pyrite to the Witwatersrand detritus.

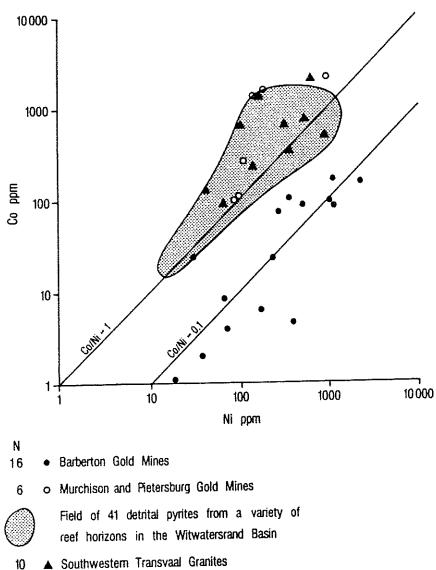


Figure 3 : Co versus Ni plot of pyrites from conglomerates of the Central Rand Group, as well as from a number of different rock types in the Archaean basement of the Kaapvaal Craton.

(ii) Chromite

Chromite is almost invariably hosted in mafic or ultramafic igneous rocks and the presence of detrital grains in the Witwatersrand reef horizons indicates that such rocks must have formed a component of the source area. Attempts have been made to compare the chemistry of detrital chromites with grains derived from greenstone belt lithologies adjacent to the Witwatersrand Basin (Eales and Reynolds, 1983; Meyer, 1983; Stupp, 1984; Utter, 1978). This data is compiled in Figure 4 and shows that the distribution of Cr in chromites from the Barberton greenstone belt is markedly bimodal, with the low-Cr peak reflecting mafic host rocks and the high-Cr peak ultramafic host rocks. Detrital chromites from the West Rand Group exhibit a similar bimodal distribution pattern whereas those from the Central Rand Group are positively skewed unimodal. Chromites in the lower Witwatersrand succession appear, therefore, to have been derived from a range of volcanic rock types, as reflected in the Barberton greenstone belt. The source area for upper Witwatersrand sediments, however, seems to have been somewhat different, with chromites apparently derived from a dominantly ultramafic host rock.

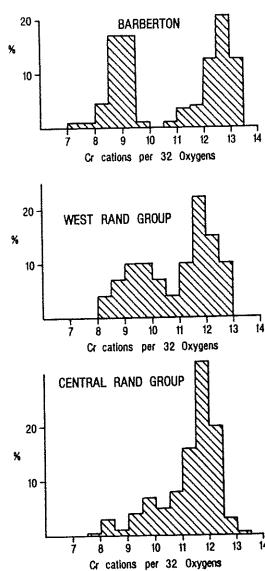


Figure 4 : Percentage histograms of chromium contents in chromites from the Barberton greenstone belt and the West Rand and Central Rand Groups. Data is derived from Utter, 1978; Eales and Reynolds, 1983; Meyer, 1983; and Stupp, 1984.

(iii) Gold

Geochemical and morphological studies of gold particles have suggested that transport distances were minimal (Hallbauer and Utter, 1977) and that gold fineness and mercury contents may be indicative of specific source regions (Hallbauer, 1982; Hallbauer and Utter, 1977). Erasmus *et al.*, (1982) and von Gehlen (1983) have demonstrated that Witwatersrand gold particles typically have mercury contents of between 1 and 5%. It is also pointed out that mercury contents of gold particles from Murchison gold mines are similar to that of the Witwatersrand gold, but that mercury in gold from Barberton gold mines never exceeds about 0.2%. This would appear to support the suggestion made above regarding the source of pyrites in the Witwatersrand reefs. It should be pointed out, however, that this data is contentious and some workers regard both gold fineness and mercury contents as being the result of metamorphic redistribution (Oberthür and Saager, 1984). It is not yet clear, therefore, whether the characteristics of gold grains can be used to identify the nature of the source area.

(iv) Uraninite

Detrital uraninite grains in the Witwatersrand reef horizons are generally characterized by high thorium contents of up to 10% (Feather, 1981; Grandstaff, 1974; Oberthür, 1983). This fact points to an enhanced stability of uraninite, arguing in favour of its detrital origin. In addition, it has been suggested that the high thorium contents point to a granitic source for the uraninite, rather than a pegmatitic source (Ramdohr, 1979).

(v) Other Detrital Components

Many workers have studied other detrital components in the Witwatersrand reef horizons and these include zircon, Co-Fe arsenosulphides, carbon nodules, diamonds etc. Zircon grains from the Vaal and Kimberley reefs have been analyzed for their trace element content (Watterson *et al.*, 1983). These data indicate a limited variability of trace element distribution by comparison with the reported ranges in the literature. However, statistically significant differences do exist in zircons from the two reef horizons indicating that although derived from the same broad rock type (i.e. granites *sensu lato*), different types of granite (*sensu stricto*) existed in the source area. Co-Fe arsenosulphides are known to occur as detrital components in the Witwatersrand reefs (Oberthür and Saager, 1984). Minerals such as arsenopyrite and cobaltite may be found in a variety of rock types ranging from acidic to mafic in composition, and also form components of ore occurrences such as gold-quartz lodes and massive sulphides. Rounded carbon nodules ("fly-speck" carbon) have also been regarded as having a detrital origin in the Witwatersrand reefs (Saager *et al.*, 1982). The origin of these nodules is not yet understood although similar grains have been detected in hydrothermally altered granites in the Witwatersrand hinterland (Hallbauer, 1984; see later). Probably the most exotic of all the detrital components in the reef horizons are greenish diamonds, many of which weigh between one and two carats (Feather and Koen, 1976). This implies that even kimberlitic rock-types occurred in the source area. Regarded collectively these studies concur in establishing the varied and complex nature of the Witwatersrand hinterland.

C. Relative Abundances of Au and U in Reef Horizons

It is well known that the various reef horizons in the Witwatersrand Basin are characterized by a positive correlation between Au and U, although considerable variation exists in the relative abundances of the two elements. The Kimberley Reef in the Evander goldfield, for example, exploits only gold, whereas the Beisa Reef (a correlative of the Main Reef) in the Welkom goldfield is essentially mined for uranium. Many reefs, however, are intermediate in character and mine gold with uranium as a by-product.

It is also now well established that hydrodynamic sorting is responsible for a measure of sedimentary control in the deposition of gold and uraninite, and there is a tendency for Au/U ratios to decrease down the palaeoslope (Buck and Minter, 1985; Smith and Minter, 1980). This means that curvilinear regression curves will result when gold and uranium distribution data are plotted on arithmetic coordinates. However, when this data is plotted on logarithmic coordinates (Smith and Minter, 1980) linear regression curves, with the form $\lg Au = m \lg U + c$ result. Consequently, when Au and U data for a number of different reef horizons are plotted on logarithmic coordinates, the family of curves that result will be characterized by differing slopes and intersections, providing a means for meaningful statistical comparison. Considered in isolation, the slope and intercept of any one reef horizon will undoubtedly reflect Au and U distribution as a function both of sedimentological sorting and source control. If any two reef horizons are compared in which sedimentological parameters are similar (c.f. Smith and Minter, 1980) than observed differences can probably be attributed almost entirely to the nature of the source.

In Figure 5 the regression curves for Au and U data for 11 different reef horizons are plotted on logarithmic coordinates. It is apparent that the various reef horizons are characterized by differing slopes of their regression curves as well as differing intercepts on the Au and U coordinates. However, the majority of the reefs have curves with slopes of approximately one, indicating that the incremental ratios (i.e. the incremental increase in gold divided by the corresponding increment in uranium, for any particular reef) are approximately constant. This implies that variations in the distribution of Au and U in any particular source rock were coupled or, simply, that the gold/uranium ratios were constant. Reef horizons with similar slopes but differing intercepts on, for example, the Au axis, imply differences in the abundance of Au in the source rocks but any enrichment in the one element must again be matched by a proportionate increase in the other. The source rocks for these reefs must have had the potential to concentrate both gold and uranium.

By contrast, a few reefs (e.g. Ellsburg No. 5 Reef, Promise Reefs, Basal Reef) have slopes which differ significantly from one on logarithmic coordinates (Figure 5). In these reefs, the incremental ratios are not constant and this implies that the source rock can exhibit a marked enrichment of Au without a concomitant increase in U, or vice versa. These source rocks therefore, have the potential to concentrate only one of the two elements. Examples of such rocks might be the Au-quartz lodes in a greenstone belt environment, or uranium-bearing leucogranites.

Comparative interpretation of Au-U distribution in Witwatersrand reef horizons provides useful information concerning the nature of the hinterland. It would appear from the above data compilation (Figure 5) that most of the reefs were derived from source rocks in which both gold and uranium were capable of being enriched. Certain reefs, however, are characterized by derivation from a source in which either gold or uranium is preferentially concentrated.

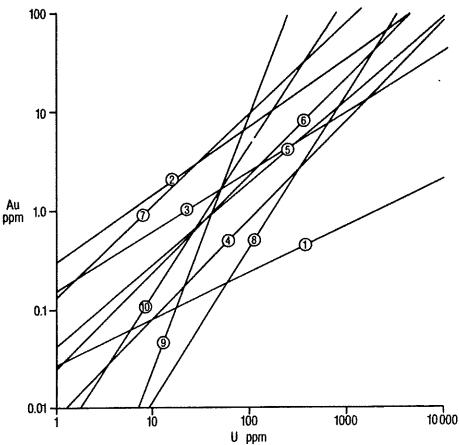


Figure 5 : Log-log plot of Au versus U for reef horizons from the Dominion and Witwatersrand Basins. The curves represented are :-

1. Promise Reefs; 52 samples; Meyer (1983)
2. Basal Reef; 54 samples; Smit (1984)
3. Dominion Reefs; 19 samples; Hiemstra (1968)
4. White Reef; 147 samples; Steyn (1975)
5. Vaal Reef; 88 samples; von Rahden and Urli (1969)
6. Leader Reef; 106 samples; Smith and Minter (1980)
7. Ventersdorp Contact Reef; 56 samples; von Rahden and Urli (1969)
8. Carbon Leader; 23 samples; Zumberge et al., (1978)
9. Elsburg No. 5 Reef; 106 samples; Smith and Minter (1980)
10. Kimberley Reef; 59 samples; Rasmussen et al., (1973)

(NOTE : Curves are extrapolated to intersect x and y coordinates and do not reflect the ranges of Au and U values in the reefs)

III. THE NATURE OF THE ARCHAEN GRANITE-GREENSTONE BASEMENT IN THE WITWATERSRAND HINTERLAND

In Figure 2 the hinterland of the Witwatersrand Basin is broadly defined, in terms of palaeocurrent directional indicators, as being a contiguous region essentially to the north, northwest and west of the presently defined limits of the basin. In this region a number of surface exposures of Archaean granites and greenstones are preserved. These occurrences are loosely referred to as "domes" as they represent uplifted segments of the Archaean crust which have been repeatedly mobilized even in post-Transvaal Supergroup times.

In addition to surface exposures, a large number of bore-hole intersections of the sub-surface basement in the Witwatersrand hinterland (Table I) have also been examined, these providing valuable additional information to the sparse surface outcrops. Examination of both surface and sub-surface geology indicates that greenstones apparently represent a minor component (overall, less than 10%) in the Witwatersrand hinterland. Finally, a third component which has been recognized in the areas studied is a regionally extensive palaeoregolithic which possibly represents a zone of weathering preserved beneath overlying Proterozoic cover.

A. Greenstones

In the Witwatersrand hinterland the occurrence of greenstone belts is restricted to the southern half of the Johannesburg-Pretoria dome, and to the Schweizer-Reneke dome and areas to its north. In the region between Johannesburg and Schweizer-Reneke (Figure 2) no remnants of greenstones have been detected, either on surface or in numerous borehole intersections.

Greenstones in the southwestern quadrant of the Johannesburg-Pretoria dome are fairly well preserved and have been mapped in detail (Anhaeusser, 1977; 1978). The Roodekrans ultramafic complex northwest of Krugersdorp comprises a sequence of layered, eruptive, ultramafic flow units and high-Mg komatiitic basalts. The Muldersdrif ultramafic complex north of Krugersdorp is a differentiated intrusive complex consisting of repetitive cycles of serpentinized dunite, harzburgite, pyroxenite and gabbro, within which chrysotile asbestos mineralization occurs. This package of mafic-ultramafic volcanic and intrusive rocks is very similar to the assemblages characterizing the lower portions of the circa 3,5 Ga Onverwacht Group in the Barberton greenstone belt.

Further to the west, the Amalia greenstone belt bisects the Schweizer-Reneke dome and occurs as a linear, north-south striking belt which is correlated lithostratigraphically with the Kraaipan Group (SACS, 1980). Lithologies include metavolcanic rocks and metasedimentary units of both chemical and clastic derivation. Banded ferruginous cherts are abundant and are known to host minor gold mineralization (Snowdon and Watchorn, 1984).

B. Granites

(i) Surface Exposures

The largest and best exposed of the granite *sensu lato* domes in the Witwatersrand hinterland is the Johannesburg-Pretoria dome which forms a major elliptical hub of elevated basement outcrop to the north of the Central Rand goldfield (Figure 2). This area has been mapped in detail (Anhaeusser, 1973) and found to contain a wide variety of granite types as well as the sporadic greenstone remnants described above. Granitic rock types include mesocratic hornblende-biotite tonalite gneisses, biotite trondhjemite gneisses, homogeneous pink and grey granodiorites, adamellites and porphyritic granites as well as a complexly deformed migmatite and gneiss terrane in the northern half of the dome. Fine grained felsic dykes, which may be genetically related to the Archaean granites of the dome (Anhaeusser, 1973) also occur. A Harpum diagram of K_2O v Na_2O (Figure 6) illustrates the wide ranging composition of the granites in the Johannesburg-Pretoria dome. U-Pb zircon age determinations for tonalitic gneisses in the southern portion of the dome have yielded an age of 3170 ± 34 Ma (Anhaeusser and Burger, 1982) whilst granodiorites from the central portions of the dome have yielded Rb-Sr whole rock ages of 3132 ± 64 Ma (Allsopp, 1961).

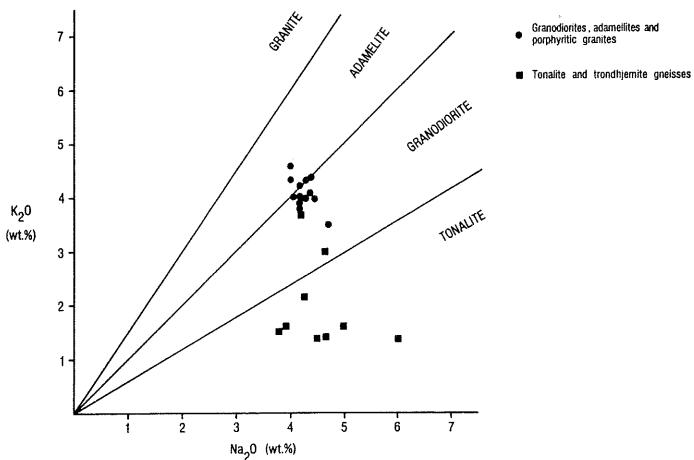


Figure 6 : K_2O versus Na_2O plot showing the composition of granitoids from the Johannesburg-Pretoria dome. Data from Anhaeusser, 1973

Most of the remaining granite domes in the Witwatersrand hinterland are very poorly exposed and cannot be mapped in the same detail as the Johannesburg-Pretoria dome. However, field studies have brought to light a considerable amount of information that was hitherto unknown. The Devon dome (Figure 2) crops out between the East Rand and Evander goldfields and comprises mainly granodiorites as well as a minor component of strongly foliated migmatitic gneiss. The main granodioritic phase varies from medium-grained to porphyritic in texture and in places a bimodal occurrence of finer-grained granodiorite intrusive into coarser-grained granodiorite is observed.

West of Randfontein a number of small granite outliers crop out along the axis of the West Rand anticline. The Doornfontein dome (Figure 2) is underlain by a coarse-grained, homogeneous, porphyritic granite (*sensu stricto*) which is cut by abundant pegmatites and quartz veins. A few kilometres further west the De Pan outlier (Figure 2) reveals an extensive outcrop of granite which is bisected by a major mafic intrusion, the Oberholzer dyke. East of the dyke the granite is similar to that in the Doornfontein dome, whereas to the west a complex array of foliated, often migmatitic, tonalitic gneisses occur (Robb, 1986). The contrasting compositions of the Doornfontein and De Pan granites are illustrated in the Harpum diagram of Figure 7.

The Ventersdorp dome represents a major zone of basement uplift (Figure 2), but is very poorly exposed. Sporadic fresh outcrops in the centre of the dome reveal an homogeneous, massive, medium-to coarse-grained granodiorite. Very coarse grained pegmatites occur sporadically throughout the granite. At the extreme southern tip of the dome an outcrop of highly altered epidote-K-feldspar-hematite rock occurs, which probably represents a form of intense hydrothermal alteration. The Hartbeestfontein dome occurs to the southwest of the Ventersdorp dome (Figure 2) and comprises mainly medium-to-coarse-grained granodiorite-adamellite (Figure 7) which in places contains a moderately well-developed foliation. Pegmatite dykes are abundant and the eastern margin of the dome is tectonically disturbed and characterized by the presence of fault breccias.

The Ottosdal-Coligny dome also represents a major zone of basement uplift and, like its Ventersdorp counterpart, is also very poorly exposed. Sporadic outcrops in the southern portion of the dome reveal a grey, medium-grained, massive adamellite which is compositionally not unlike the Hartbeestfontein granite (Figure 7). By contrast, the northern portion of the dome is underlain by an unusual, reddish, coarse-grained, massive, adamellite. Although similar in terms of major element composition to the granitoids in the southern portion of the dome (Figure 7), the reddish adamellite is quite different both in appearance and trace and rare-earth element abundances (Meyer and Robb, unpub. data).

The Schweizer-Reneke granite dome in the far western Transvaal (Figure 2) consists of granites which, although exhibiting textural variations on a regional scale, are compositionally fairly uniform and straddle the adamellite-granite (*sensu stricto*) field in Figure 7. This granite has been dated, yielding a Rb-Sr whole rock age of 2640 ± 55 Ma (Allsopp, 1964; recalculated). The northern portion of the dome is characterized by a coarse-grained, massive granite in which plagioclase is saussuritized and K-feldspar stained pink. The remainder

of the dome contains medium-grained, weakly foliated granites as well as massive, coarse-grained phases. Many of the samples contain abundant muscovite, and chlorite and a few are characterized by the presence of fluorite. This assemblage indicates a degree of hydrothermal alteration in the Schweizer-Reneke granitoids. Furthermore, these rocks contain an exotic suite of accessory minerals which includes allanite, monazite-like phases and thorite.

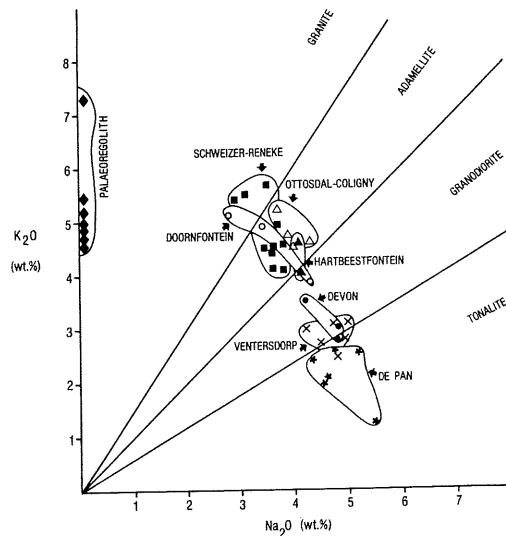


Figure 7 : K_2O versus Na_2O plot showing the composition of granitoids from various surface outcrops in the hinterland of the Witwatersrand Basin. Also shown are compositions of the palaeoregolith exposed at surface unconformities.

(ii) Borehole Intersections of the Archaean Basement

A total of 162 boreholes have been sampled in order to study the nature of the sub-surface Archaean basement in the Witwatersrand hinterland. The broad geographic distribution of the boreholes sampled is illustrated in Figure 2 and a summary of their distribution in terms of overlying sequences is presented in Table I.

TABLE I
SUMMARY OF BOREHOLE INFORMATION

AREA	No. of Boreholes	Overlying Sequences
West Rand Anticline	20	Transvaal - 10 Venterdorp - 9 Dominion - 1
Venterdorp Dome Environs	16	Transvaal - 1 Dominion - 11 Venterdorp - 4
Hartbeesfontein Dome Environs	42	Venterdorp - 2 Dominion - 40
Ottosdal-Coligny Dome Environs	14	Venterdorp - 3 Dominion - 11
Schweizer-Reneke Dome Environs	7	Venterdorp - 7
Area west of Welkom Goldfield	12	Dominion - 1 Witwatersrand - 2 Venterdorp - 3 Karoo - 6
Environs of East Rand and Evander Goldfields	51	Transvaal - 7 Karoo - 44

In the same way that the granitoids exposed at surface exhibit a wide range in composition and texture, so the sub-surface granite samples intersected in borehole core revealed a diversity of types. In addition, however, a major proportion of the granite cores examined are characterized by an overprint of hydrothermal (*sensu lato*) alteration, a feature which was only occasionally detected in the surface expression (e.g. the southern tip of the Ventersdorp dome and portions of the Schweizer-Reneke dome). Possible reasons for the differences between surface and sub-surface granites are discussed in a later section.

The most common characteristics of the granite cores is the presence of carbonate + chlorite or sericite + carbonate + chlorite alteration and/or replacement. Macroscopic features evident include discrete quartz + calcite veins often filling fractures (Figure 8a), zoned veins comprising chlorite + carbonate + sericite + quartz + pyrite (Figure 8c), and fluorite veins accompanied by secondary pyritization (Figure 8b). Cored samples often show a tectonic overprint which in some cases is clearly the result of autobrecciation or hydraulic fracturing (Figures 8d and 10d). Some samples exhibit a moderate to intense, pervasive argillic alteration (Figure 8c). Sericitization of felspars and propylitization of mafic minerals is a feature common to most of the hydrothermally altered granites observed.

In thin section two broad types of hydrothermal alteration are evident. Pervasive alteration and replacement of minerals is commonplace, and sericite + carbonate replacement of plagioclase felspar (Figure 9a) as well as alteration of pre-existing biotite to an assemblage comprising chlorite + minor epidote + rutile-leucoxene (Figure 9c), have been observed. A further style of alteration is evident as a pervasive chloritization of granite along grain boundaries (Figure 9b). Hydrothermal vein-type alteration is also a very common feature and veins exhibit a diverse and varied paragenesis from one sample to the other. Veinlets and fracture-fill include carbonate-chlorite (Figure 10a), quartz-pyrite, quartz-carbonate, quartz-carbonate-chlorite, quartz-carbonate - hematite-pyrite, and fluorite-quartz-chlorite-pyrite-chalcopyrite (Figure 10b). Many samples exhibit an incipient form of greisenization which includes muscovitization, chloritization and albitization of K-felspars (Figure 10c). In thin section micro-brecciation is commonly observed, with breccias cemented by fluorite (Figure 10d), sericite, chlorite and carbonate minerals.

Accessory minerals in the hydrothermally altered granites include zircon, monazite, epidote, sphene, fluorite and leucoxene. Opaque phases observed are pyrite, chalcopyrite, molybdenite, arsenopyrite, uraninite, magnetite, hematite and rounded carbon modules (Figure 9d). In addition small particles of gold have been extracted by acid treatment from hydrothermally altered granites in the Witwatersrand hinterland (Hallbauer, 1982).

In summary, the hydrothermally-altered granites (HAGS) are clearly characterized by a diversity of alteration styles which are also variable from one area to the next. The above observations are only of a preliminary nature and a more detailed study of the alteration assemblages and their distribution is currently underway.

C. Palaeoregoliths

The Archaean basement domes described above are overlain by strata of widely differing ages and examples of unconformities between the underlying granitoids and the basal Dominion Group arenites, the Orange Grove quartzites, various lithostratigraphic horizons of the Ventersdorp Supergroup and the Black Reef quartzite are preserved. A particularly interesting feature of these unconformities is the presence of a regionally pervasive quartz-sericite rock preserved on the basement immediately beneath the unconformity. Rocks of this nature have been described as representing palaeosols or palaeoregolith protected from erosion by the capping of an overlying rock sequence (Gay and Grandstaff, 1980; Kimberley *et al.*, 1984; Retallack *et al.*, 1984). Alternatively these rocks may reflect zones of alteration caused by enhanced fluid flow along the channel-way formed at the unconformity. In all likelihood it is probable that these contact zones represent both the sites of early-Proterozoic weathering and erosion, as well as a superimposed effect caused by enhanced fluid flow. The western margin of the Devon dome and the southern flank of the Johannesburg-Pretoria dome are both overlain by the Orange Grove quartzite, beneath which a quartz-sericite regolith is preserved at a number of localities. The Varkenskraal and Rysmierbult domes along the West Rand anticline (Figure 2) do not contain exposures of the basement granite, but along their margins numerous exposures of quartz-sericite regolith are preserved beneath the Black Reef quartzite. Finally, along the southern margins of the Hartbeestfontein dome, a quartz-sericite palaeoregolith is preserved beneath the basal conglomerate of the Dominion Group arenites. Samples of the quartz-sericite rock from a number of these localities all exhibit marked leaching of Na, Ca and, to a lesser extent, Mg, with slight enrichment of K, factors which accord with the expected behaviour of these elements in the surficial weathering environment (Holland, 1984). If the quartz-sericite rock is indeed a palaeoregolith or palaeosol, or even a modified equivalent thereof, this unit would undoubtedly constitute a regionally pervasive component of the Witwatersrand hinterland which has hitherto never been considered.

The palaeoregolith has also been observed in a number of the borehole cores examined. In the cores it is evident that the palaeoregolith is generally 3-10m thick and commonly characterized by a stratification, with a bleached upper zone comprising quartz + sericite + leucoxene, and a darker, lower zone consisting of quartz + sericite + chlorite + leucoxene ± sulphides. This zonation possibly reflects the presence of a water-table in the original weathering zone (Fryer, 1977). It is interesting to note that fission track micro-mapping has shown that the leucoxene in the palaeoregolith is generally enriched in uranium and it has been suggested that this phase may represent the detrital precursor to much of the brannerite found in the Witwatersrand reef horizons (Robb and Meyer, 1985).

D. Geochemistry

(i) Major Elements

The pervasive, and often intense, hydrothermal alteration which characterizes the granitoids sampled in borehole core renders the plotting of geochemical data on standard diagrams, in which fields of igneous rocks are defined, invalid. The Harpum-type diagrams, for example, (Figures 6 and 7) in which the compositions of relatively fresh surface granitoids were defined, cannot be used to establish the nature of HAGS in which open-system alteration may have occurred. Particularly noticeable in the borehole granitoid samples is the abundance of hydrated rock compositions clearly reflecting the presence of an hydrothermal alteration overprint.

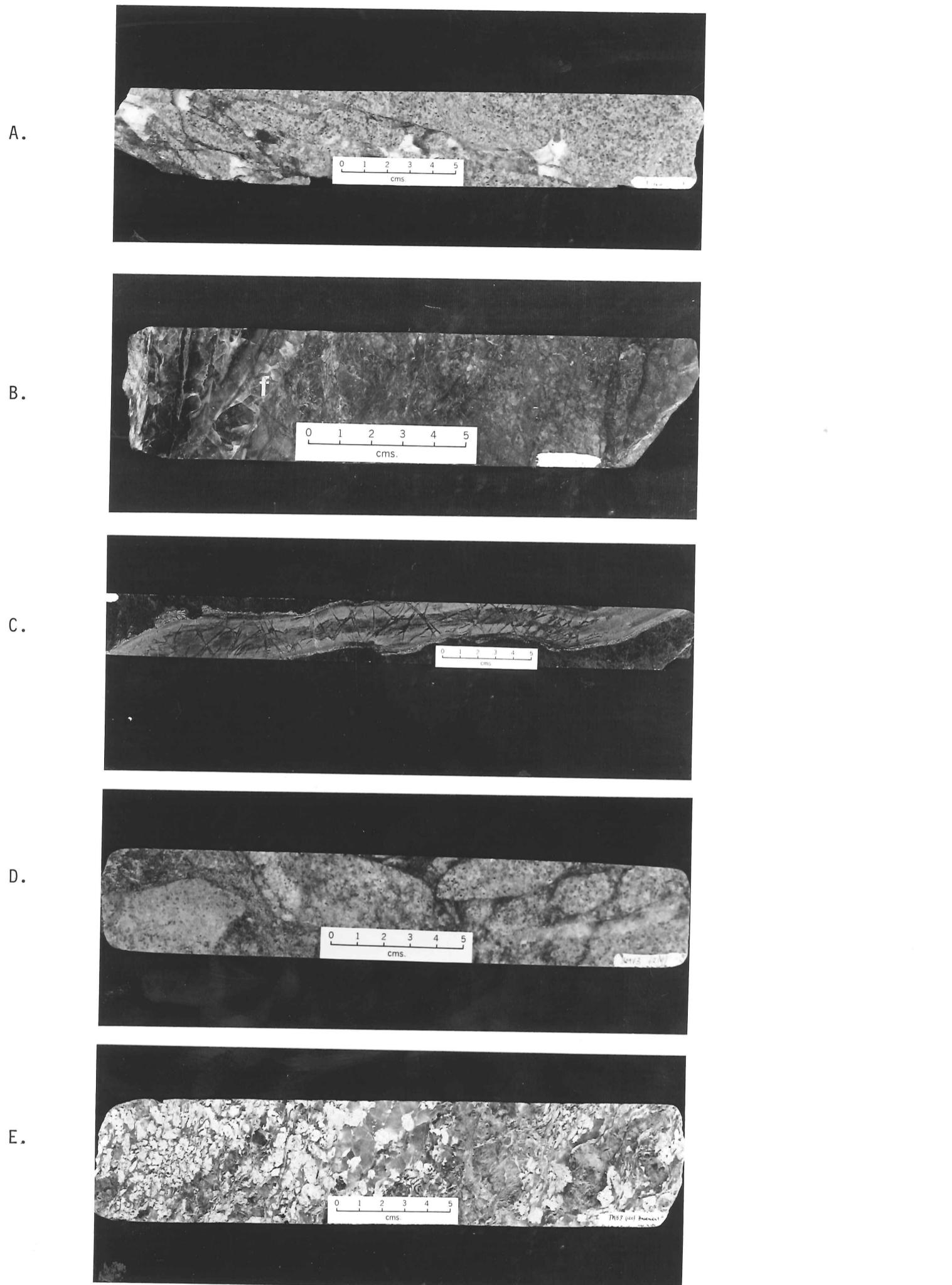


Figure 8 : Polished slabs of borehole core from the Witwatersrand hinterland :-

- A. Quartz + calcite veins forming fracture-fill in sericitized granite.
- B. Fluorite veins (f) in intensely sericitized granite also containing a dense filligree of pyrite veinlets.
- C. Zoned hydrothermal vein comprising very fine grained chlorite + sericite + carbonate mineral and dense network of quartz + pyrite dessication cracks. Vein contains 64ppb Au.
- D. Granitic "breccia" probably formed by hydraulic fracturing; rounded to angular fragments of propylitized granite set in a fine grained matrix of calcite + chlorite + rock flour.
- E. Intense argillic alteration of felspars in a coarse-grained soda-rich granite. Small black blebs are rounded carbon nodules (see Figure 9d for microphotograph).

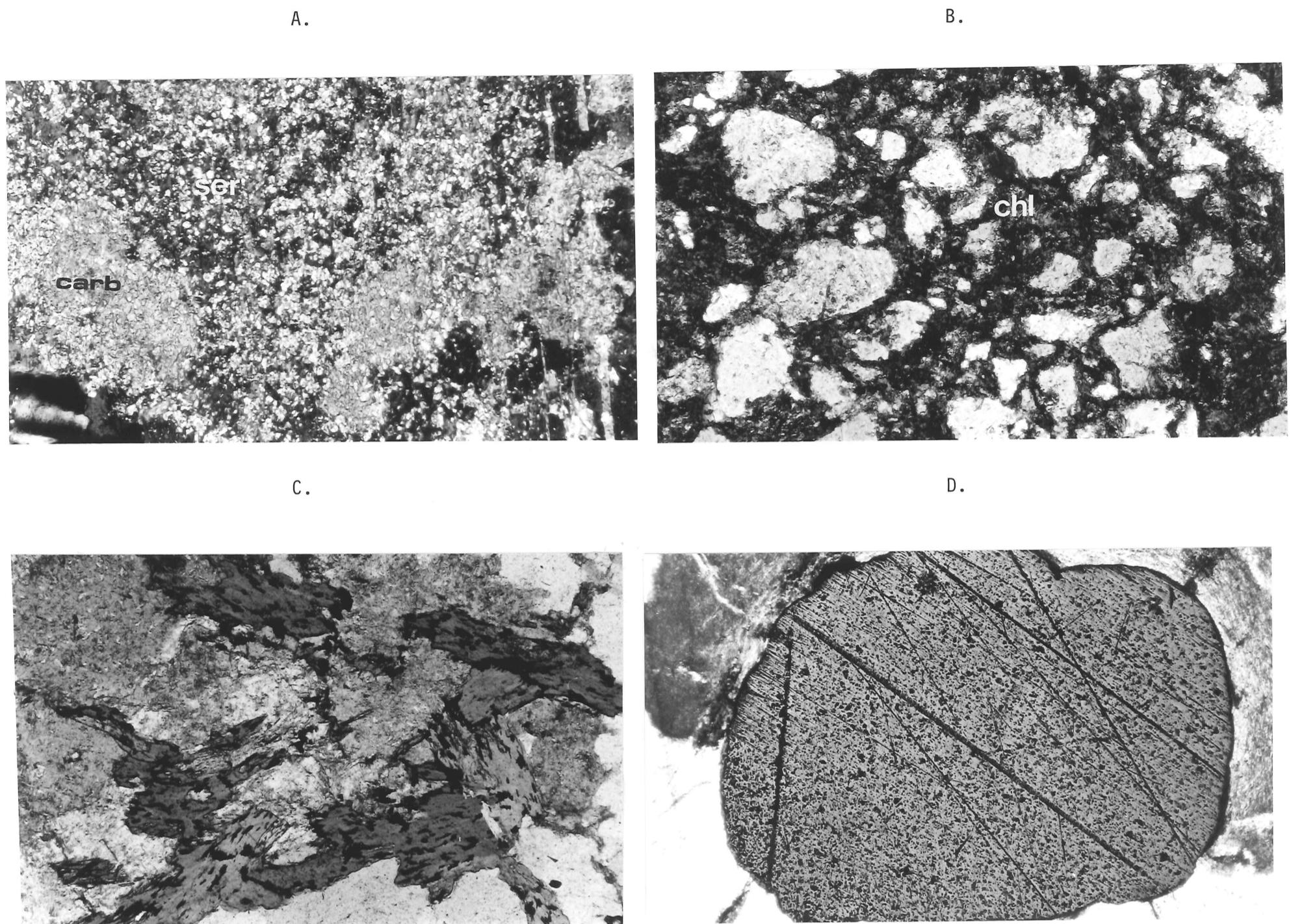


Figure 9 : Microphotographs of hydrothermal alteration in granites from the Witwatersrand hinterland (length of field of view is 2mm) :-

- A. Pervasive sericite (ser) and later carbonate (carb) alteration/replacement of plagioclase felspar (Note:- length of field of view here is 1mm).
- B. Intense chloritization (chl) of granitoid occurring principally along grain boundaries.
- C. Pervasive alteration of pre-existing biotite to greenish, Fe-rich chlorite, minor epidote and semi-opaque blebs of Ti-rich material (rutile/leucoxene).
- D. Rounded carbon nodule (also containing 900ppb Au and 6000ppm U) in coarse grained granite affected by intense argillic alteration.

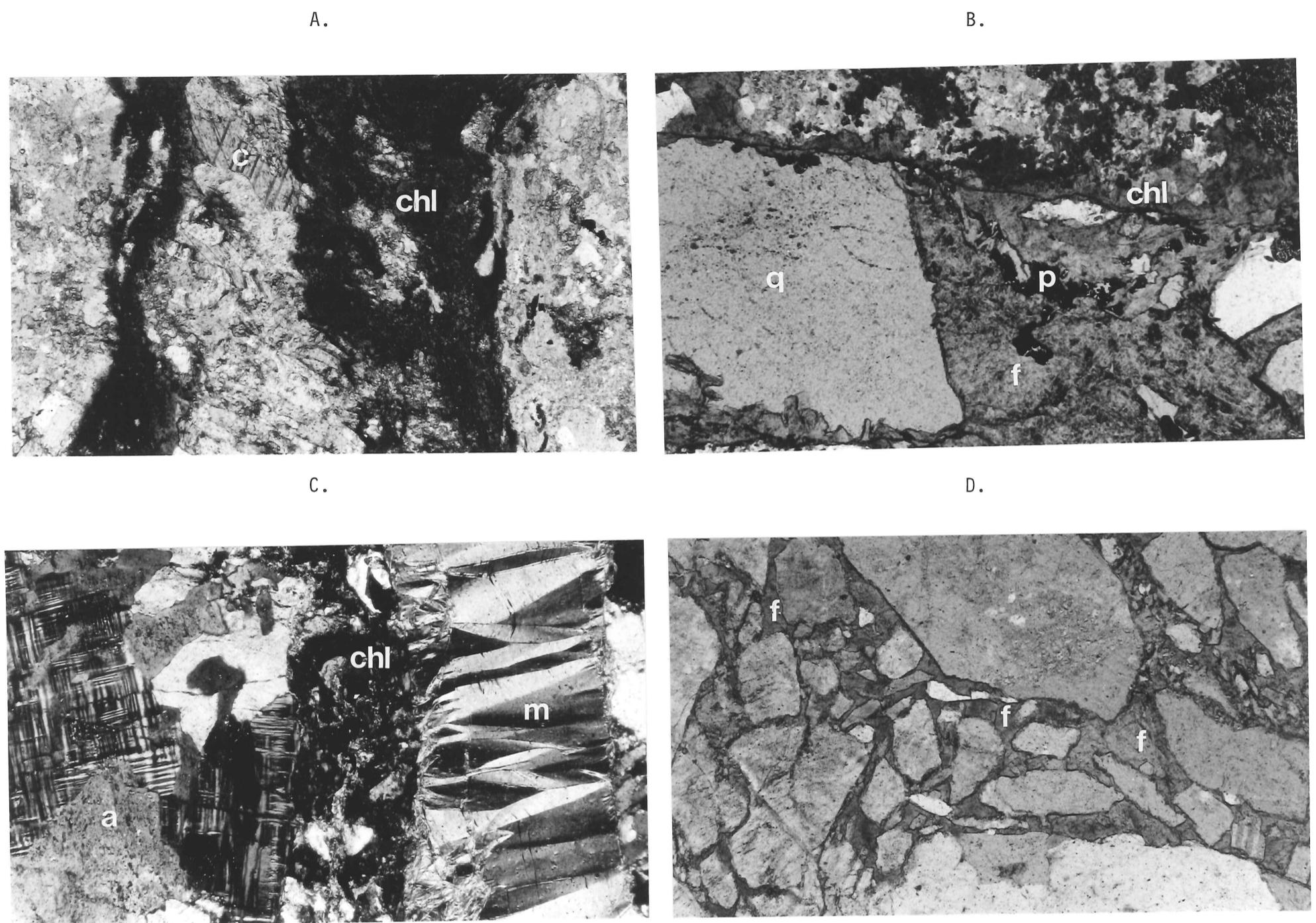


Figure 10 : Microphotographs of hydrothermal alteration in granites from the Witwatersrand hinterland (length of field of view is 2mm) :-

- A. Zoned veinlet of calcite (c) and chlorite (chl) in granite.
- B. Zoned veinlet comprising fluorite (f) - quartz (q) - chlorite (chl) - pyrite (p) - chalcopyrite in granite.
- C. Greisen-type alteration in potassic granite, with intense muscovitization (m), chloritization (chl), and albitization (a) of pre-existing microcline.
- D. Micro-brecciated texture in granite, with matrix comprising purple fluorite (f).

In Figure 11 total volatiles expressed as loss on ignition are plotted against $\text{Fe}_2\text{O}_3 + \text{MgO}$ for both surface and borehole granitoid samples. The relatively unaltered surface granitoids exhibit a well-defined positive correlation between loss on ignition and $\text{Fe}_2\text{O}_3 + \text{MgO}$ suggesting that the volatile phase occurs mainly as water bound in hydrous mafic phases such as biotite and hornblende. Maximum loss on ignition in these rocks is approximately 1.9 weight per cent, this occurring in tonalite gneisses of the Johannesburg-Pretoria dome, the latter containing up to 15% modal biotite and hornblende. The trend defined by the surface granitoids, therefore, illustrates the expected loss on ignition in a granitoid rock where the volatiles are contained mainly within hydrous mafic minerals.

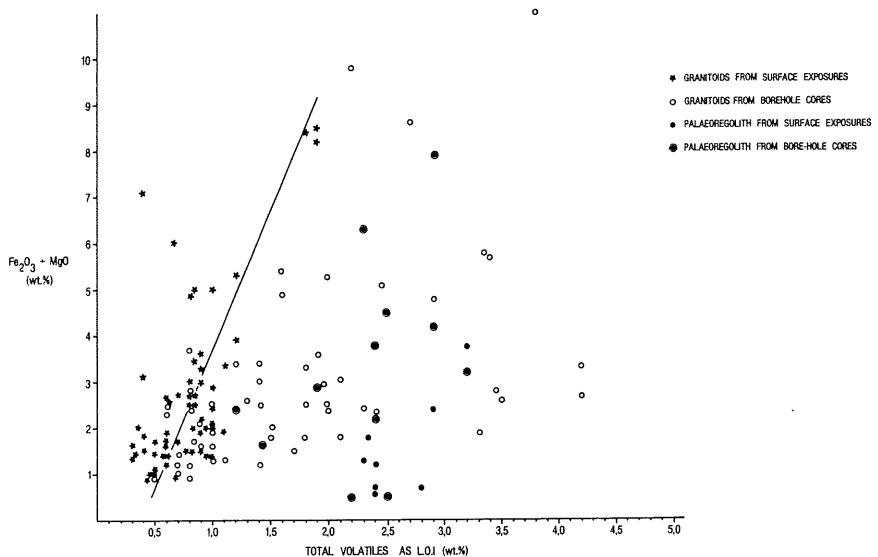


Figure 11 : Plot of $\text{Fe}_2\text{O}_3 + \text{MgO}$ versus total volatile content as loss on ignition for granitoids and the palaeoregolith from the Witwatersrand hinterland.

By contrast, granitoid samples from the borehole core show no relationship to the well-defined trend for surface granitoids and a large proportion of samples have losses on ignition considerably in excess of those expected if water were the dominant volatile phase, and bound mainly in hydrous mafic minerals. Clearly the HAGS contain other volatiles, of which CO_2 is almost certainly an abundant component, in addition to less abundant phases such as S, F and B. In addition water in the HAGS is probably also associated with mineral assemblages not reflected in the $\text{Fe}_2\text{O}_3 + \text{MgO}$ factor, namely sericite. The diagram clearly illustrates that many of the samples obtained from borehole cores are characterized by an hydrothermal alteration which is reflected in terms of an enhanced content of volatile components.

Also plotted on Figure 11 are the losses on ignition for palaeoregolith samples both at the surface and in borehole core. These rocks are also characterized by high volatile contents with variable $\text{Fe}_2\text{O}_3 + \text{MgO}$ abundances indicating the presence of either a sericite + quartz, or sericite + quartz + chlorite assemblage. The palaeoregolith does not generally contain evidence of CO_3 alteration and, consequently, CO_2 is unlikely to be a major volatile component. Rather, water is probably the main volatile phase bound in both sericite and chlorite.

The chemical characteristics of the HAGS are also compared to the unaltered surface granitoids in a multi-cationic La Roche-type F1-F2 diagram (Figure 12). This diagram is designed to plot the compositions of major silicate mineral phases at widely disparate points in the coordinate system so that the effects of superimposed, open system alteration are maximized. As a reference the diagram shows a calc-alkaline trend defined by average compositions of tonalite, granodiorite, adamellite and granite (*sensu stricto*). The surface granitoids plot in a fairly restricted field which do not coincide, for the most part, with the average igneous rock compositions. This is because the surface granitoids tend to be slightly enriched in silica and depleted in mafic minerals.

By contrast, the HAGS from the borehole cores occupy a broad field which is unrelated to any specific compositional trend. Nothing specific can be said about this observation except that the rock compositions are considerably more diverse than those exhibited by the relatively unaltered surface granitoids. This diversity is clearly unrelated to primary compositions and more likely reflects the varied styles of hydrothermal alteration described above.

An interesting feature of the F1-F2 diagram is the well-defined trend exhibited by the palaeoregolith samples (Figure 12). These samples occupy a discrete trend which rigorously defines a tie-line joining microcline and quartz to muscovite compositions. If the palaeoregolith samples do indeed reflect early weathering processes, then the observed trend probably represents the progressive alteration of granite to regolith. This accords with petrographic observations of the palaeoregolith which reveal the presence of a range of textures from incipient regolith in which feldspar relics are still preserved, to possible "palaeosol" in which original rock texture is totally destroyed and an assemblage of quartz + sericite + chlorite is evident.

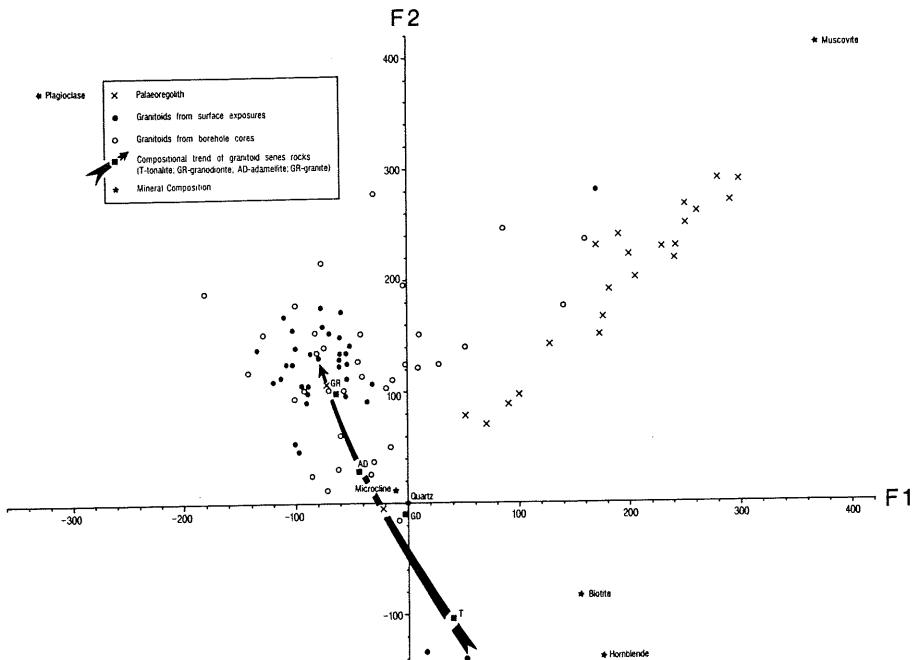


Figure 12 : Multi-cationic La Roche-type diagram plotting factor F1 $[(Al-K)-(Fe-Mg)-2Na]$ versus factor F2 $[(Al-K)-(Fe-Mg)-4Ca;$ in millications per 100g] for granitoids and palaeoregolith from the Witwatersrand hinterland.

(ii) Au, U and Th Contents

Compilation of the means and ranges of Au, U and Th contents in the Archaean granitoid crust of the eastern and western Transvaal are presented in Figure 13. Data for the eastern Transvaal are derived from a collection of 190 samples (Meyer and Saager, 1985; Meyer *et al.*, 1985) representing the full range of granitoids in the Barberton region, and classified into three genetic groups termed magnetic cycles (Anhaeusser and Robb, 1981). Data for the Western Transvaal represent recently acquired samples collected in the hinterland of the Witwatersrand Basin, and described above.

Au contents of granitoids from the Barberton region and from surface samples in the western Transvaal exhibit low mean values (circa 1ppb) and restricted ranges. By contrast, HAGS sampled in borehole core in the Witwatersrand hinterland exhibit significantly higher mean values ($\bar{x} = 109$ ppb and $G = 6$ ppb) with a much broader range. The maximum Au content obtained in the HAGS was 5,9ppm. Palaeoregolith show similar mean values and ranges, with a maximum Au content of 5,4ppm being obtained in one sample (Figure 13ii).

Granites from the eastern Transvaal basement become progressively enriched in uranium from the first magmatic cycle through to the third magmatic cycle (Meyer *et al.*, 1985). Surface samples from the western Transvaal granitic basement show the closest resemblance, in terms of means and ranges, to granitoids of the third magmatic cycle at Barberton. The HAGS show a slight enrichment in their mean U contents with respect both to unaltered surface granitoids and to the palaeoregoliths. The latter, however, exhibit similar ranges in their U contents to the HAGS (Figure 13iii).

Thorium contents also show a systematic increase from the first to the third magmatic cycles in the Barberton region. Granitoids, and the palaeoregoliths, from the western Transvaal all exhibit similar Th ranges and mean values, and these are essentially indistinguishable from granitoids of the second and third magmatic cycles in the eastern Transvaal (Figure 13 iii).

Differences in the Au and U contents of the HAGS, and of surface granitoids from the Witwatersrand hinterland and the Barberton region, are emphasized in the Au-U scattergram in Figure 14. Most surface granitoids exhibit a restricted range of Au contents in the range 1-3ppb, with U contents being more variable and falling in the general range 1-10ppm. Similar average values are also evident for the Barberton granitoids. By marked contrast, the HAGS exhibit a much broader range in Au and U contents, with maximum values of 5,9ppm Au and 34ppm U being obtained in the present data set. The hatched area in Figure 14 represents the range of Au and U contents in typical Archaean granitoids; the upper limit of 2,5ppb Au is derived from statistical evaluation of available data in the Barberton region (Saager and Meyer, 1984) whereas the maximum value of 6ppm U is a figure above which most granites are regarded as being enriched (cf. Meyer *et al.*, 1985). It is clear that most of the HAGS (> 75%) fall outside this field and must be regarded as being enriched either in gold or uranium, or both.

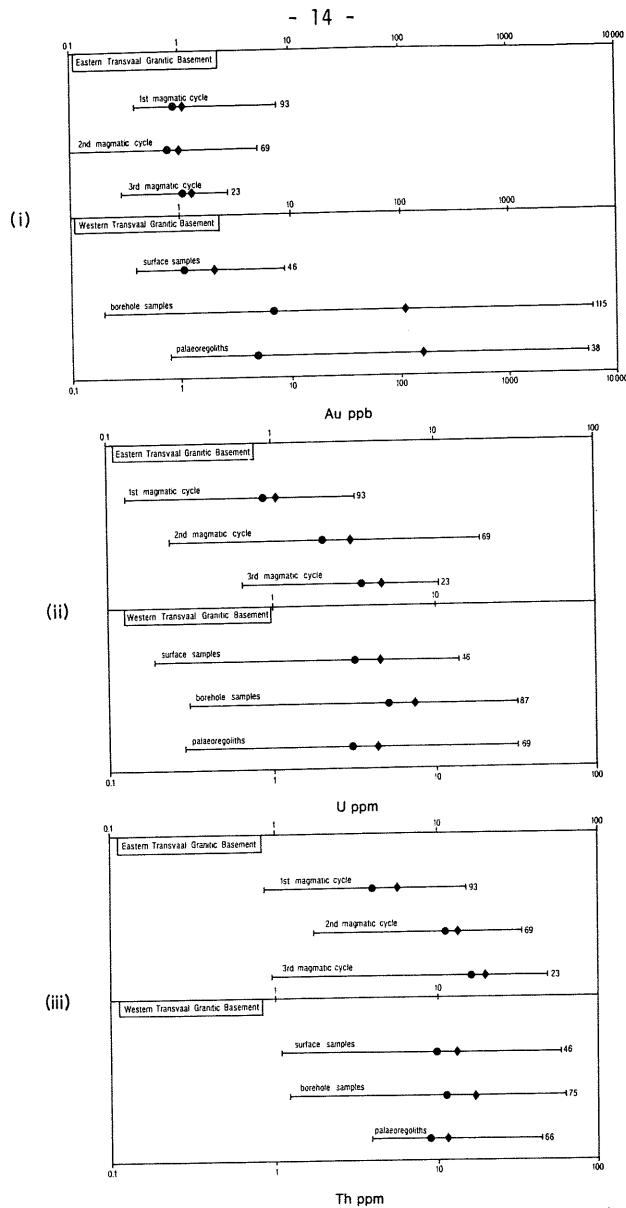


Figure 13 : Bar diagrams showing ranges, arithmetic means (diamond) and geometric means (dot) for Au(i), U(ii) and Th(iii) contents of granitoids from the eastern Transvaal basement and granitoids and palaeoregoliths from the hinterland of the Witwatersrand Basin.

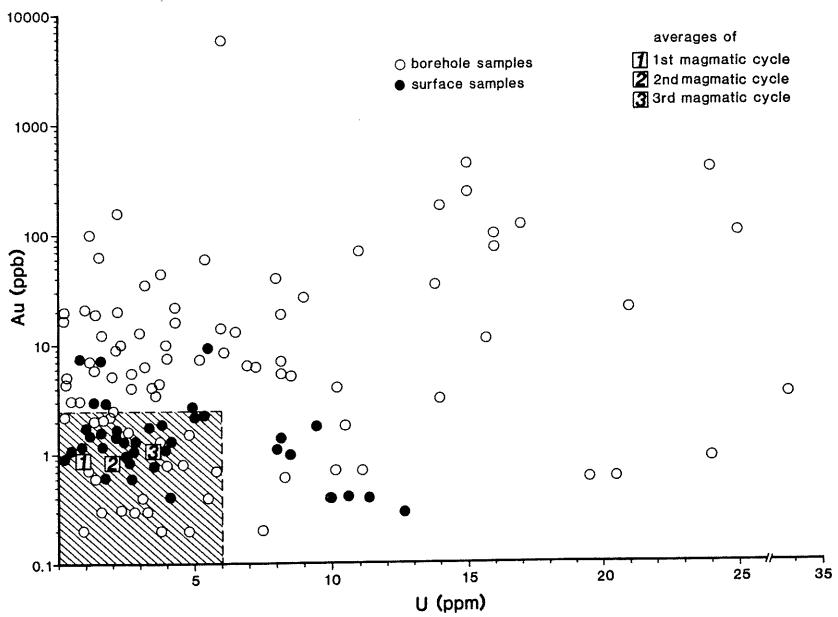


Figure 14 : Plot of Au versus U for granitoid samples from surface outcrops (dots) and from sub-surface borehole core (open circles) in the hinterland of the Witwatersrand Basin. Points 1, 2 and 3 represent averages of first, second and third magmatic cycle rocks from the Barberton Mountain Land. Samples plotting outside the hatched area are considered to be enriched in either gold or uranium, or both (see text for further explanation).

IV CONJECTURES ON THE SOURCE-AREA PROBLEM

As mentioned previously the major enigma to understanding the Witwatersrand palaeo-placer mineralization revolves around the source of the Au and U. The previous two sections have emphasized various factors pertaining to the depository itself and the nature of its hinterland, both of which are regarded as being relevant to the source-area problem. In the following section a series of models is constructed, in which an attempt is made to test the feasibility of the hinterland described above as a source area for the palaeoplacer deposits.

A. Mass Balance Considerations

In any consideration of the mass balance relationship between source area and placer-type mineralization, an obvious pre-requisite is an estimate of the dimensions and content of the depository. The Witwatersrand Basin is approximately 350 km long and 150 km wide (Figure 15). The maximum cumulative depth of the entire succession is slightly over 10 km (Tankard *et al.*, 1982). An estimate of the volume of the entire basin can, therefore, be calculated assuming an inverted prismatic shape for the depository (Figure 15). Using this assumption, a figure of 262 500 km³ is obtained as the volume of the entire basin. The volume of the upper Witwatersrand succession can be calculated by assuming that its shape represents a smaller inverted prism within the larger, whose dimensions are approximately 310 km long and 120 km wide, and whose maximum cumulative depth is approximately 3 km. This assumption yields a volume of 55 800 km³. These estimates indicate that the ratio of sediment volume in the West Rand and Central Rand Groups is approximately 3,7:1 (Figure 15).

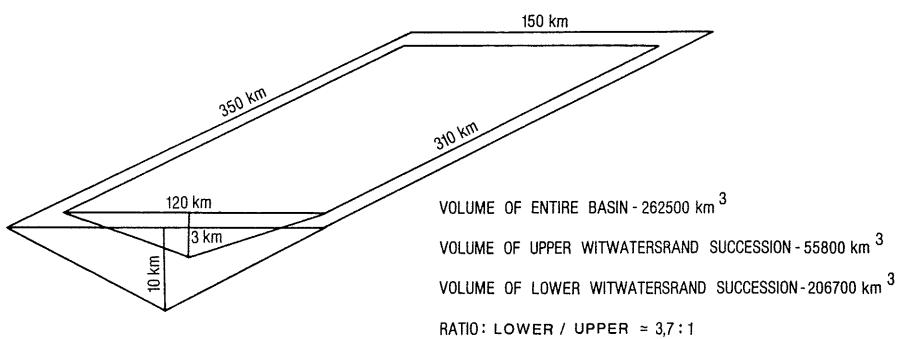


Figure 15 : Geometric model for calculating the approximate volume of the Witwatersrand Basin.

Estimates of average Au, U and Th contents in rocks from both the lower and upper successions of the Witwatersrand Basin are provided in Table II. Compilation of such data is an hazardous exercise in view of the paucity of published analyses available on lithologies other than those actively exploited for mining purposes. The data provided in Table II is the best estimate available on present data, but must be regarded as a provisional indication of bulk average values. The data nevertheless make it possible to obtain an assessment of the weighted average Au, U and Th contents in the lower and upper successions respectively, as well as in the basin as a whole. Using a shale : quartzite : conglomerate weighting of 49:49:2 for the West Rand Group provides an average of approximately 30 ppb Au, 3 ppm U and 10 ppm Th for this sediment package. By comparison, the Central Rand Group, where the ratios of shale : quartzite : conglomerate are approximately 5:85:10, the weighted averages are approximately 1 ppm Au, 30 ppm U and 8 ppm Th. An assessment of the bulk average grades can also be made for the Witwatersrand Basin as a whole, if it is assumed that the ratio of sediment volume in the lower and upper successions is approximately 3,7:1 (Figure 15). This consideration yields average contents of approximately 250 ppb Au, 9 ppm U and 10 ppm Th for the entire sedimentary sequence.

The above data, although only preliminary and approximate, is pertinent in establishing mass balances in the source area - depository system. The availability of trace element data for granites in the Barberton Mountain Land (Meyer, 1983; Meyer *et al.*, 1985; Robb and Meyer, 1985) facilitates a comparison between a Barberton-type source region and the Witwatersrand depository. The analyses of 190 granites from the Barberton region indicate average values of approximately 1 ppb Au, 2 ppm U and 9 ppm Th for a segment of the Archaean crust which must be regarded as fairly typical, at least in the southern African sub-continent. In addition, it is possible to estimate the average bulk Au content of the lithologies comprising the Barberton greenstone belt using a similar technique to that described above for the Witwatersrand Basin. Such a calculation yields a bulk Au content of 15 ppb for the entire lithological sequence with values for U and Th assumed to be negligible. If it is assumed that greenstone belts comprise at most 10% of the typical Archaean basement crust in the Kaapvaal Craton, then the weighted average Au content of a Barberton-type granite-greenstone crust is approximately 2,4 ppb.

The Witwatersrand Basin is, therefore, approximately 100X enriched in gold, and about 4,5X enriched in uranium with respect to typical granite-greenstone crust. Even if only approximate, the differences in magnitude of these varying degrees of enrichment place an important constraint on the nature of the Witwatersrand provenance. The data also indicate that erosion of an approximately equal volume of typical granite-greenstone crust to that which makes up the Witwatersrand Basin (i.e. circa 260 000 km³) cannot possibly provide all the gold that appears to have been concentrated in the depository. Consequently, a serious mass-balance problem clearly exists if a typical Barberton type granite-greenstone crust is considered as the source for the Au and U in the Witwatersrand Basin.

Finally it is pertinent to refer to the differing degrees of enrichment that exist in the accumulation of Au and U between the upper and lower Witwatersrand successions. The data indicate that Au is enriched by a factor of approximately 30X, and U by about 10X, in the Central Rand compared to the West Rand Group. By contrast, a factor of approximately 0,8X exists for Th, indicating higher thorium contents in the lower succession.

These factors place an interesting constraint on the development of the placer mineralization as it indicates that the concentration of ore zones in the upper succession cannot have been due solely to a progressive reworking of pre-existing sediments, as this would undoubtedly have resulted in reasonably consistent enrichment factors. Furthermore, the enrichment factors themselves point to a significant difference in the nature and fertility of the source region specific to the Central Rand Group sediments.

TABLE II
AVERAGE Au, U AND Th CONTENTS OF WITWATERSRAND ROCKS

		(ppm)		
		Au	U	Th
WEST RAND GROUP	(Shales	0,002 ¹	2 ²	8 ²
	(Quartzites	0,03 ⁴	4 ⁵	10 ⁵
	(Conglomerates	1 ⁷	120 ⁷	60 ⁷
CENTRAL RAND GROUP	(Shales	0,002 ³	2 ³	8 ³
	(Quartzites	0,03 ⁴	6 ⁶	5 ⁶
	(Conglomerates	10 ⁸	250 ⁹	30 ¹⁰

1. Average of five shale samples from the Government Subgroup (Meyer, 1983).
2. Average of 16 shale samples from the West Rand Group (Camden Smith, 1980; Meyer, 1983).
3. Same values as for West Rand Group shales - no published data available.
4. Average of 27 quartzite samples from the Johannesburg Subgroup (Rasmussen, 1973). [Many other data are available for quartzites, but these are invariably located in gold-enriched reef zones. The values used are the most conservative available and consequently are considered to be the best estimate of the quartzites as a whole].
5. Average of 11 quartzites from the Government Subgroup (Meyer, 1983).
6. Average of 27 quartzites from the Johannesburg Subgroup (Rasmussen, 1973).
7. Average of 99 conglomerate samples from the Promise Reefs, Government Subgroup (Meyer, 1983).
8. Average grade over 96 years of mining, obtained by dividing total metal production by total tonnage mined (Pretorius, per. comm.).
9. Average grade over 28 years of mining, obtained by dividing total metal production by total tonnage mined (Pretorius, per. comm.).
10. Average of 111 varied conglomerate samples from the Johannesburg Subgroup (Feather and Koen, 1975; Hempkins, 1969; Rasmussen, 1973; Tucker, 1980).

B. Anatomy of the Source Area

The above calculations render it possible to make generalized suggestions on the anatomy of the source area particularly with respect to the distribution and abundance of Au. In Figure 16, three possible scenarios are presented :-

(i) The first model (Figure 16 (i)) proposes that an area of equal volume to that of the Witwatersrand depository was eroded, this comprising typical Archaean granite-greenstone crust with an average of 2,4ppb Au. The additional gold required by the mass balance considerations is made up of isolated, randomly distributed, very-rich point sources of gold (i.e. large gold deposits) which collectively almost equal the amount of gold present in the basin. Clearly, accumulations of gold of this magnitude are unknown in the Archaean granite-greenstone crust, rendering this scenario unlikely. Furthermore, consideration of a "nugget" effect requires that the point sources of Au are conveniently located at all the entry points of the depository, a requisite which is also highly unlikely.

(ii) In the second model (Figure 16 (ii)) it is assumed that the Au was derived from a typical Archaean granite-greenstone crust, and that the volume of the crust eroded was at least 100X that of the depository. Again, this is unlikely as considerations of an external sink for the excess sediment are constrained by the viewpoint that the basin was closed for most of its depositional history (Watchorn, 1981). An alternate approach envisages that Au was introduced in solution, having been derived by selective leaching of a source region as large as that outlined above. Mass introduction of Au in solution has been suggested by Reimer (1984), but this contradicts the widely accepted detrital origin, not only of Au, but also the other related heavy mineral suite.

(iii) The third model (Figure 16 (iii)), and the one regarded as the most realistic, envisages a complex, multi-component source region of approximately the same volume as the depository, in which a significant proportion of the hinterland comprises rocks enriched in Au (and U) relative to typical Archaean granite-greenstone crust. In Figure 16(iii) a scenario is presented in which zones of enrichment constitute an arbitrary 30% of the volume of the source region, the latter - in terms of the mass balance considerations - containing an average of 800ppb Au.

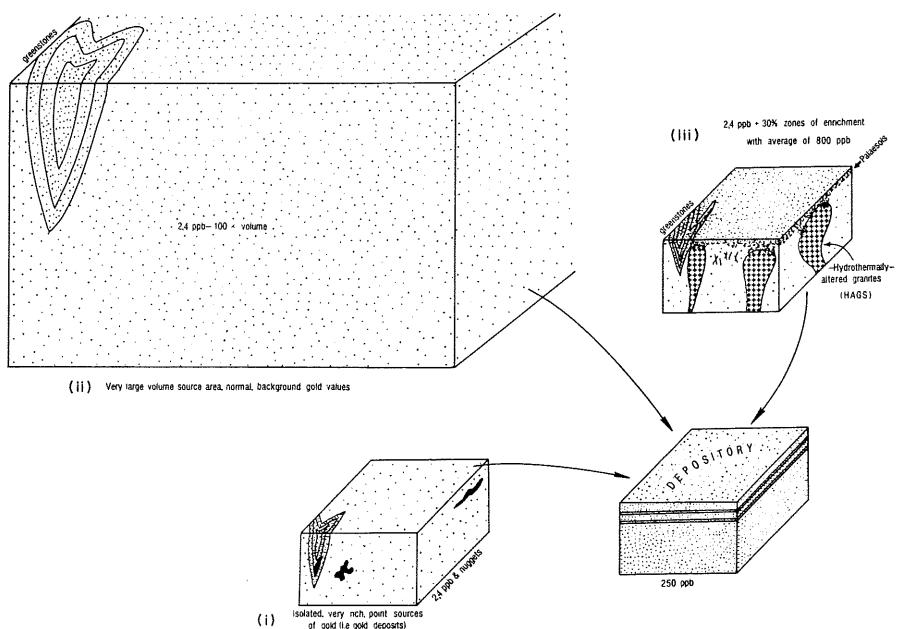


Figure 16 : Three possible scenarios for the nature of the Witwatersrand source area. For detailed description see text.

The latter model receives support from the previous descriptions of the Witwatersrand hinterland in which mention was made of the extensive zones of hydrothermally altered granites hitherto not recognized on the Kaapvaal craton. As evident in Figures 13 and 14, the HAGS are clearly enriched in Au (and U) by comparison with typical Barberton granitoids. Furthermore, the presence of a pervasive palaeoregolith in the Witwatersrand hinterland provides a further means whereby Au (and U) may have become enriched in the surficial environment (Figure 13).

Implicit in this multi-component source area model is the realization that the degree of enrichment of Au and U will differ both spatially and with respect to lithology. Greenstones, for example, may exhibit spectacular localized enrichments of Au, but are devoid of uranium. Granites, on the other hand, often show enhanced uranium concentrations but no enrichment in Au. More important than either of these, however, is the fact that the hydrothermally altered granites described previously are characterized by enrichments of both Au and U (Figure 14). The distribution of Au and U in a complex, multi-component source region, such as that described above, is reflected in the variable Au-U curves for the reef horizons shown in Figure 5. Here it was shown that the distribution of Au and U in the majority of the reefs (i.e. those with slopes of approximately one on a log scale) point to source rocks in which the two elements are concomitantly enriched. The potential for this process is only evident in the HAGS and, consequently, it is suggested that the hydrothermally altered granites represent the principal source rock type in the Witwatersrand hinterland. Rock types in which only gold or uranium is enriched are considered to represent less significant components of the source area.

In summary, the HAGS represent a newly recognized component in the Witwatersrand hinterland and have considerable significance as a source for both gold and uranium. The following sections specifically consider the geological setting of the HAGS, and their age of emplacement.

C. Geological Setting of the HAGS

In the above descriptions of the Witwatersrand hinterland a distinction was made between granites outcropping on surface and those sampled in borehole core. The main difference between the two groups is that most of the sub-surface granites are characterized by diverse styles and degrees of hydrothermal alteration which are of regional extent. In contrast, such characteristics were rarely encountered in surface outcrops of the Archaean basement domes. The reasons for this dichotomy are poorly understood as detailed geological relationships are lacking. However, if it is assumed that the granite domes represent areas of considerable uplift and erosion, a possible explanation for the geological setting of the HAGS is provided. Figure 17 is a schematic profile which illustrates aspects of differential erosion in relation to a simplified yoked-basin model. Along the active margins of such a basin it is envisaged that faulting will result in considerable uplift of the basement, exposures of which will probably reflect fairly deep levels in the crust. Certainly, zones of high level hydrothermal alteration and mineralization will have been removed by erosion and will only be preserved beneath sedimentary cover. Along the passive margins of the basin, exhumation of the basement is achieved by gentle warping and flexure, rather than by pronounced vertical tectonism. In such situations the margins of basement domes may reveal zones of high-level hydrothermal alteration (e.g. the southern tip of the Ventersdorp dome, and the northern flank of the Schweizer-Reneke dome), whereas the centres will be more deeply eroded. Thus, the preferred preservation of HAGS in subsurface outcrop is regarded as reflecting significant differential erosion in the hinterland of the Witwatersrand Basin.

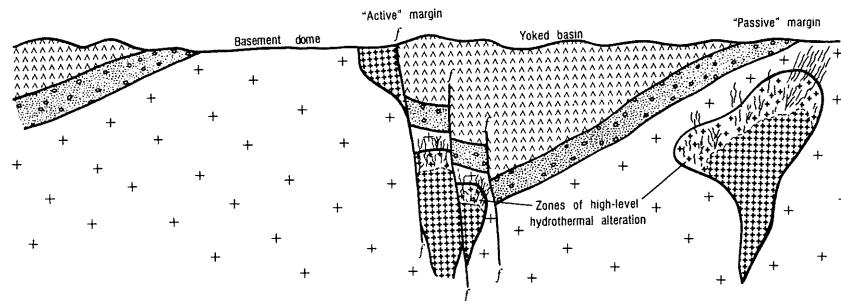


Figure 17 : Schematic model illustrating the nature of differential erosion in the Witwatersrand hinterland as an explanation for the preferential preservation of HAGS beneath a cover of early Proterozoic sediments or volcanics.

D. Age of the HAGS

The hydrothermally altered granites sampled in sub-outcrop are all unconformably overlain by early-Proterozoic sediments and volcanics spanning approximately 700 million years of earth history. Their age, therefore, is an open question and no isotopic data pertaining specifically to the HAGS are as yet available. However, geological observations in borehole core suggest that in certain areas an episode of hydrothermal alteration post-dated the deposition of basal arenites in the Dominion Group. Furthermore, in other areas the observation of cobbles of hydrothermally altered granite in mid-Ventersdorp Supergroup conglomerates provides an upper age limit for this event.

Published isotope data on granites from the Witwatersrand hinterland suggest that the region is characterized by two episodes of granite emplacement, one at circa 3,0-3,1 Ga and the other between 2,6-2,7 Ga (Allsopp, 1961; 1964; Anhaeusser and Burger, 1982). The earlier event is typified by the granites of the Johannesburg-Pretoria dome, whereas the latter episode is represented by the Schweizer-Reneke dome. The geological relationships described above, indicating a post-Dominion Group age for certain of the hydrothermal events, suggests that this episode as a whole is more likely to be related to the 2,6-2,7 Ga event than to the earlier episode of granite magmatism.

E. Comparative Mineralogy of Conglomerates on the Kaapvaal Craton

Conglomerates occur in a number of the sedimentary units on the Kaapvaal Craton (Pretorius, 1981) and these range in age from circa 3,3 Ga to 2,2 Ga. These units include, in chronostratigraphic sequence, the Moodies Group in the Barberton greenstone belt, the Pongola Supergroup, the Dominion Group, the Uitkyk Formation in the Pietersburg greenstone belt, the West Rand and Central Rand Groups of the Witwatersrand basin and the Black Reef Formation of the Transvaal Sequence. With the exception of the Moodies Group, conglomerates from all other units have been worked for gold. Production has in general, however, been very minor, with the marked exception of the Central Rand Group with its enormous accumulations of Au and U. From this comparison it would appear that specifically during deposition of upper Witwatersrand sediments vast quantities of Au were available in the source area, and that this condition prevailed neither before, nor after, Central Rand Group times. The unique time-bound character of the upper Witwatersrand source region is underlined by the fact that both the lower Witwatersrand sediments and the Dominion Group, contain far smaller quantities of Au even though they form part of the same depositional basin and presumably were accessed to a broadly similar hinterland.

In addition to the striking differences in the accumulation of gold, the upper Witwatersrand conglomerates also reveal interesting characteristics in terms of their uranium-thorium mineralogy, by comparison with older conglomerates. In Figure 18i the relative abundances of U-Th minerals are compared in conglomerates from a variety of sedimentary units arranged in chronostratigraphic sequence. It is apparent that conglomerates from the upper Witwatersrand succession contain the highest relative abundance of minerals such as uraninite, brannerite, and fly-speck carbon, but a relative paucity of minerals such as monazite and thorite. By comparison, conglomerates from the lower Witwatersrand sediments and Dominion Group contain monazite and thorite as relatively abundant accessory phases, but do not exhibit the same degree of uraninite enrichment. Consequently, the source region specific to Central Rand Group sediments must have been grossly enriched, not only in Au, but in uranium too. Furthermore, as indicated earlier the differences in relative abundance of uranium-thorium minerals between the lower and upper Witwatersrand sediments indicates that the enrichments in the latter cannot have been derived solely by reworking of underlying strata.

Mineralogical differences between Central Rand and pre-Central Rand Group conglomerates are also summarized in the U/Th plot of Figure 18ii. The older conglomerates have U/Th ratios of 1-3, whereas the upper Witwatersrand conglomerates are characterized by markedly higher U/Th ratios ($U/Th = 8-9$) reflecting the abnormally high concentrations of uraninite and brannerite. Consequently, the time-bound uniqueness of the source rocks for the upper Witwatersrand sediments is reflected, not only in their high Au contents, but also in their enrichment of U, both in absolute terms and with respect to Th.

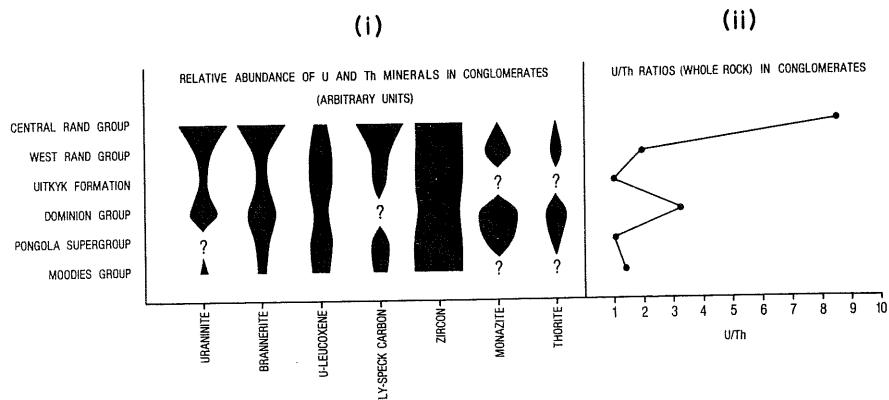


Figure 18 : Relative abundances of uranium and thorium minerals (i), and whole-rock U/Th ratios (ii), of various conglomerates ranging chronostratigraphically from the Moodies Group through to the Central Rand Group. Sources of data include Liebenberg, 1955; Ramdohr, 1955, 1958; Hiemstra, 1968; Feather and Koen, 1975; Simpson and Bowles, 1977; Muff and Saager, 1979; Saager et al., 1982; Meyer, 1983; Meyer et al., 1983; Stupp, 1984.

V DISCUSSION

A. An Evolving Source Region in the Witwatersrand Hinterland

Three important considerations, namely the potential of the HAGS as fertile Au and U source rocks, their emplacement relatively late in the evolution of the Archaean granite-greenstone crust (perhaps 2.6 - 2.7 Ga), and the striking changes in the budget of detrital mineral accumulations in the upper Witwatersrand conglomerates with respect to those in the lower Witwatersrand succession, can be regarded as being relevant to the source-area problem. In the following section a model is presented in which consideration is given to the possibility that the Archaean basement underwent a dramatic change contemporaneously with Witwatersrand deposition. Figure 19(i) illustrates a scenario in which sediments of the lower Witwatersrand succession are derived from an elevated source region consisting of an Archaean granite-greenstone crust capable of satisfying the relevant mass balance requirements. It is believed that these source rocks were weathered forming a regionally extensive regolith, the latter being transported and deposited into the basin. Deposition of the lower succession was terminated with the formation of the shale-dominated Jeppestown Subgroup (Figure 1), this indicating a waning in the energy of sedimentation as a result of the wearing-down of the hinterland (Pretorius, 1976).

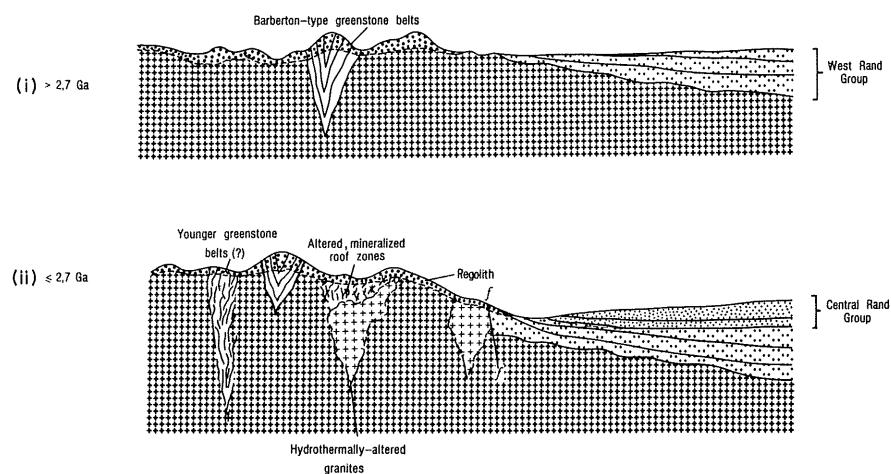


Figure 19 : Schematic model illustrating the envisaged changes in the nature of the source area of the Witwatersrand Basin during deposition of the West Rand Group (i) and Central Rand Group (ii).

Subsequent to the termination of West Rand Group deposition, the model envisages reactivation of the source area by a major tectono-magmatic event (Figure 15ii). At approximately 2,6-2,7 Ga it is envisaged that the earlier granite-greenstone crust was intruded by numerous highly-evolved granitoids, the upper portions of which were characterized by zones of hydrothermal alteration. In addition these intrusions were probably responsible for the emplacement of mineralized breccia- and vein-type alteration systems, both in the granites themselves and in the surrounding country rocks. Furthermore, it is conceivable that this major event initiated the extrusion of basic volcanics into linear rift systems, the latter representing the occurrence of younger greenstones such as those of the upper Bulawayan succession in Zimbabwe and dated at between 2,53-2,72 Ga (Hawksworth *et al.*, 1975). Epigenetic mineralization in both older and younger greenstone belt types may also have been stimulated by this event. The uplift of the source region caused by this tectono-magmatic event reactivated the sedimentary process resulting in deposition of the high-energy arenaceous and rudaceous sediments of the Central Rand Group. The emplacement of HAGS, and possibly also a coeval greenstone belt-related mineralization, added a volumetrically significant fertile component hitherto not present in the Witwatersrand hinterland, and which was responsible for the spectacular enrichments of Au and U specific to the Central Rand Group. The newly-introduced fertile components in the source region were all emplaced at a high level in the crust and were, therefore, easily accessible to weathering and erosion. Again, denudation of the hinterland will have been accompanied by the formation of regionally extensive palaeosol or palaeoregolith within which a preconcentration of U and/or Au might also have occurred.

Although conjectural, the above model finds support from a number of observations. The model relies principally on the existence of volumetrically-significant zones of enrichment in the source area of the upper Witwatersrand sediments, with mass-balance considerations requiring average concentrations of 800 ppb Au in at least 30% of the rocks comprising the source region (Figure 16). As indicated earlier (Figure 14) the HAGS certainly do represent extensive zones of enrichment, but mean Au abundances do not approach the required 800 ppb, at least with respect to the present data set. Clearly, therefore, there is a need, in order to satisfy the mass balance requirements, for zones in which even higher concentrations of Au occur. The latter are in all likelihood represented by gold "deposits" which occur both in greenstones as well as in the more abundant granites. Highly altered gold-pyrite zones associated with the cupolas of high-level granitoid intrusions are not uncommon in Archaean granite-greenstone terranes (Foster, 1985; Boyle, 1979; Anhaeusser, 1985) and preserved relics of such mineralization are known to occur in the Murchison and Pietersburg greenstone belts of the northeastern Transvaal, where Au is exploited at grades of up to 5 ppm (Willemse, 1938, Meyer *et al.*, in prep.). It is, therefore, feasible that Au mineralization in vein and stockwork systems, and in cupolas, was associated with the regionally extensive, hydrothermally altered granites of the Witwatersrand hinterland. Thus, the real significance of the HAGS, lies, not so much in contributing to the required mass balance, but in revealing the presence of an extensive environment in which significant enrichment of Au could have occurred.

In the case of uranium it is also apparent that certain of the HAGS exhibit U contents considerably in excess of those characterizing typical Archaean granitoids (Figure 14) and this, too, argues in favour of the role which the hydrothermally altered granite have played as source rocks to the upper Witwatersrand sediments. Perhaps more important than the enhanced U contents, however, is the fact that the HAGS very often exhibit low Th/U ratios implying a decoupling, with uranium having been enriched in the hydrothermal environment at the expense of thorium. As indicated in Table II, and in Robb and Meyer (1985), conglomerates in the upper Witwatersrand sequence are also characterized by very low Th/U ratios, a factor which reflects the abundance of uraninite and brannerite, and the extreme paucity of thorium-bearing minerals, in the reef horizons. This discrepancy is almost certainly related, in part, to the nature of U and Th distribution in the source rocks and, consequently, evidence for U and Th decoupling in the HAGS argues in favour of their substantial presence in the source area.

Another facet of the model outlined in Figure 19 is the suggestion that emplacement of the HAGS in the Witwatersrand hinterland was accompanied by tectonism which resulted in rejuvenation of the source region. The rejuvenation of the source area is reflected in the contrasting nature of the lower and upper Witwatersrand lithologies (Figure 1) with sediments of the upper sequence being deposited in a higher energy environment than those of the lower sequence. This is not inconsistent with the suggestion of significant rejuvenation of the source area immediately prior to Central Rand Group times. It is also pertinent to mention that morphological studies of detrital Au particles in the reef horizons indicate small transport distances, with figures of as low as circa 30 km having been suggested (Hallbauer and Utter, 1977). The upper Witwatersrand detritus, therefore, appears to have been derived from source rocks that were located very close to the margins of the depository, and not from a distant source requiring possibly several cycles of transport and intermediate pre-concentration. These observations also argue in favour of tectonic (and magmatic) rejuvenation of the source area along the active margins of the Witwatersrand Basin.

B. Regional Setting of the Witwatersrand Hinterland

As suggested earlier the HAGS are considered to have been emplaced relatively late in the evolutionary history of the Archaean crust in the Kaapvaal Craton, possibly at circa 2,6-2,7 Ga ago prior to the deposition of the upper Witwatersrand sediments. It is, therefore, pertinent to examine the occurrences of granitoids of this age in order to assess whether their distribution concurs with that of the Witwatersrand hinterland. A preliminary attempt at synthesizing the age distribution patterns of granitoids on the Kaapvaal Craton was carried out by Hunter (1975) who delineated at least two broad zones of granite magmatism with differing ages (Figure 20). As mentioned earlier the few age determinations available for Archaean granites of the southwestern Transvaal indicate a bimodality of granitic events at circa 3,0-3,1 Ga and 2,6-2,7 Ga, this being the breakdown used by Hunter in his early compilation. A considerable amount of more recent work, however, particularly in the eastern and northeastern Transvaal (Barton *et al.*, 1983; Barton, 1984) indicates that granitoid ages in the Kaapvaal Craton are by no means simply bimodal, but may either reflect a more complex distribution (Barton, 1983) or span a continuum of ages between circa 3,5-2,5 Ga. Consequently, in the compilation of Figure 20 outcropping granitoids are simply subdivided into granites > 2,7 Ga and granites < 2,7 Ga. It is apparent that the broad zonation suggested by Hunter (1975) is still upheld in terms of this subdivision and the map region is seen to comprise of a northern belt in which there is an abundance of < 2,7 Ga granitoids, and a southern zone in which most granitoids are > 2,7 Ga in age. This zonation also accords with the major subdivision established by SACS (1980) in which a distinction is made between the Swazian Erathem (circa 3,0 Ga) and the Randian Erathem (circa 3,0 - 2,6 Ga). It is pertinent to note that Hunter's (1975) boundary (Figure 20) runs along the northern and western edges of the Witwatersrand Basin, and points to a coherence between the sediment source region (cf. Figure 2) and the zone of dominantly < 2,7 Ga granitoids. Therefore, if the < 2,7 Ga granitoids do post-date the deposition of the lower Witwatersrand succession, then their distribution not only controlled the geometry of the upper Witwatersrand basin, but their emplacement stimulated the onset of successive sedimentary pulses and their fertility provided the budget of ore minerals in the reef horizons.

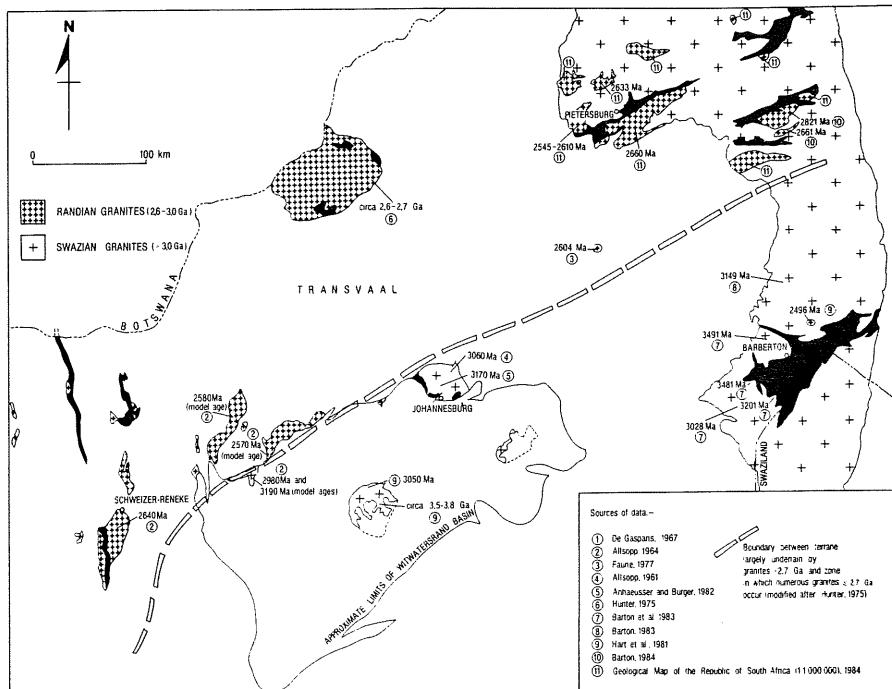


Figure 20 : Map showing distribution of exposed Archaean granite (crosses) - greenstone (black) basement on the Kaapvaal Craton. A summary of pertinent age determinations, and the sources of data, are also shown. The major dashed line delineates an approximate boundary between terrane underlain largely by granites > 2.7 Ga in age, to the south (i.e. Swazian granites) and a zone to the north in which numerous granites < 2.7 Ga occur (i.e. Randian granites).

One question which remains to be answered concerns the geotectonic framework responsible for the generation of the large zone of < 2.7 Ga granitoids shown in Figure 20. Burke *et al.*, (1985) have suggested that the Witwatersrand sediments were deposited in a foreland basin on the continental side of a major suture zone represented by the Limpopo Province. Left-lateral shearing associated with continent-continent collision is considered to have initiated a major northeast-southwest trending rift system within which the extensive Ventersdorp volcano-sedimentary succession was deposited. During the initial stages of this event significant crustal thickening and anatexis probably occurred (Burke *et al.*, 1985) which may well be related to the < 2.7 Ga granitoids in the Witwatersrand hinterland and elsewhere. This scenario is still highly debatable but nevertheless provides a plausible framework which accords with the models discussed above.

VI SUMMARY

(i) The hinterland of the Witwatersrand Basin, a broad contiguous zone mainly to the north, northwest and west of the depository, reveals a number of up-domed exposures of the Archaean granite-greenstone basement. A variety of granitoids, ranging in composition from tonalite through to granite (*sensu stricto*), occur, with limited isotopic data suggesting ages of emplacement of either circa 3.0-3.1 Ga or 2.6-2.7 Ga. Greenstone remnants are sporadically exposed and either resemble the lower portions of the circa 3.5 Ga old Onverwacht Group in the Barberton greenstone belt, or are lithostratigraphically correlatable with the Kraaipan Group in the western Transvaal and northern Cape provinces. The proportion of greenstone to granite in the Witwatersrand hinterland is low, probably less than 10%.

(ii) Borehole intersections of the sub-surface Archaean basement in the Witwatersrand hinterland reveal the existence of a wide-spread component of hydrothermally altered granitoids. Alteration styles are diverse and include sericitization, chloritization, argillic alteration, muscovitization propylitization, extensive CO₂ vein-type alteration and replacement, pyritization, as well as hydraulic fracturing often involving fluorite. The fact that the HAGS are only observed beneath a protective capping of early Proterozoic sediments or volcanics indicates that these rocks have not been subjected to weathering or erosion since burial. Consequently, it is suggested that the HAGS represent the cupolas of high-level intrusions, or altered roof zones above younger granitoid intrusions at depth, and that their absence in domal surface outcrops indicates removal by erosion during uplift of the latter. Geological relationships constrain the age of the HAGS at post-Dominion to pre Ventersdorp. The HAGS may be related to the emplacement of a large number of 2.6-2.7 Ga granitoids in the Witwatersrand hinterland.

(iii) A further component in the Witwatersrand hinterland is a regionally extensive palaeoregolith also observed beneath a protective capping of early Proterozoic sediments or volcanics. The regolith is zoned, comprising an upper, bleached quartz + sericite layer and a lower, darker, quartz + sericite + chlorite layer. The palaeoregolith represents a zone within which indications of surficial chemical processes during the early Proterozoic are preserved and is regarded as a potentially important site of Au and U preconcentration in the Witwatersrand hinterland. It is suggested that the regolith represents the type of material which was ultimately deposited into the basin.

(iv) Granitoids and palaeoregolith from the Witwatersrand hinterland exhibit differences in their Au and U contents with respect to a wide range of granite types from the Barberton region. Surface granites contain similar mean values and ranges for Au as do the Barberton suite. With respect to U, however, the surface granites are enriched by comparison with earlier Barberton granitoids but show similar mean values and ranges to more evolved units of the latter suite. By contrast, the HAGS are significantly enriched in both Au and U with respect to all Barberton granitoids. The palaeoregolith is also enriched in Au, but shows similar mean U values as the more evolved granites from Barberton. Th/U ratios in the HAGS are lower, by a factor of 2x, than the Barberton granitoids, indicating significant enrichment of U with respect to Th in the hydrothermal environment.

(v) The source area of the Witwatersrand sediments is considered to be a geologically complex region in which a significant proportion of the material was enriched in Au, and to a lesser extent U. Mass balance considerations indicate that if 30% of the source area is regarded as being enriched, then it would require an average of 800ppb to account for the gold accumulated in the basin. The HAGS, the palaeoregolith and the greenstone belts although representing zones of enrichment, collectively do not satisfy this requirement. However, the presence of high-level, hydrothermal alteration in granites points to the existence of an extensive environment within which gold (and U) mineralization - with enrichments well in excess of 800ppb - could have occurred. The HAGS are considered to represent the principal source rock type in the Witwatersrand hinterland, firstly because of their widespread distribution and secondly, because the hydrothermal processes therein are capable of concentrating both gold and uranium.

(vi) The remarkable concentration of both Au and U that is unique to the Central Rand Group is considered to reflect a major, catastrophic change in the nature of the source region at some time towards the termination of lower Witwatersrand sedimentation and prior to the onset of upper Witwatersrand deposition. This change involved the emplacement, at a high level in the crust, of volumetrically significant, fertile granitoids, the upper portions and roof zones of which were characterized by intense hydrothermal alteration and attendant mineralization. The development of younger, mineralized, greenstone successions in linear rift systems may also have been more or less coeval with this event. The presence of an extensive zone of HAGS in the Witwatersrand source area is not in dispute, but the exact timing and magmatic-tectonic framework within which this event took place still needs to be evaluated.

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