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AGES OF HYDROTHERMALLY ALTERED GRANITES ADJACENT TO THE WITWATERSRAND BASIN: IMPLICATIONS FOR THE ORIGIN OF Au AND U

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by

L.J. ROBB*, D.W. DAVIS+, S.L. KAMO+ and F.M. MEYER*

(* *Department of Geology, University of the Witwatersrand, Private Bag 3, P.O. WITS 2050, South Africa.*
+ *Jack Satterley Geochronology Laboratory, Royal Ontario Museum, Toronto, Canada)*

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ABSTRACT

Many granites adjacent to the late-Archaean Witwatersrand Basin exhibit hydrothermal alteration and veining, and are characterized by Au and U enrichments well above their clarke contents. U-Pb isotope ages indicate that certain of these granites were emplaced during basin deposition and that hydrothermal alteration was coeval with intrusion. The protracted period of time (360 Myr) over which Witwatersrand sediments were deposited, coupled with on-going magmatism and fertilization of the source area during this period, provide clues to the origin of the prodigious Au and U mineralization contained within the conglomerates of this enigmatic basin.

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INTRODUCTION

The Witwatersrand Basin is a mineral province which has few equals in terms of productivity and socio-economic impact on its environs. It has produced close to 40% of all the gold that has been mined in the history of mankind and still contains reserves of c.40000 tonnes (Handley, 1990). In the late 1970's it also provided the western world with 20% of its uranium supplies (A.E.C., 1985). Conglomerates are the host rocks to particulate gold and uraninite (UO_2), which occur together with concentrations of pyrite and other heavy minerals. In spite of over 100 years of exploitation the origin of the Au-U mineralization within the Witwatersrand Basin remains a controversial issue, while the age of sediment deposition has, until recently, also been poorly constrained.

Mineralization, which is concentrated almost entirely within the upper part of the sequence (i.e. the Central Rand Group; Fig. 1), is regarded either as the result of concentration of heavy detrital minerals during sedimentation with subsequent modification of allogenic constituents during diagenesis and metamorphism (the modified placer theory; e.g. Feather and Koen, 1975), or as an epigenetic concentration of hydrothermal ores after basin formation (Phillips and Myers, 1989). Originally believed to have been early-Proterozoic (2800-2300 Myr; Allsopp and Welke, 1986) in age, more precise age constraints have recently been provided by U-Pb zircon dating of key volcanic horizons associated with the Witwatersrand sediments (Armstrong *et al.*, 1991; Fig. 1). These are 3074 $\pm$ 6 Myr for the Dominion Group immediately beneath the West Rand Group, 2914 $\pm$ 8 Myr for the Crown lava which occurs towards the top of the West Rand Group (Fig. 1), and 2714 $\pm$ 8 Myr for the Ventersdorp volcanics which immediately overlie the Central Rand Group . This indicates that deposition of the West Rand and Central Rand Groups took place over a period of 360 Myr in the late Archaean (Armstrong *et al.*, 1991).

One of the major problems in understanding the origin of Witwatersrand mineralization is the source of the prodigious concentrations of gold within the basin, a feature which is unrivalled by any other known sedimentary accumulation. Another problem relates to the age and nature of the rocks in the source area, much of which has now been eroded away or covered by younger successions. An indication of the age-range of source material has been obtained from U-Pb isotope ages of single detrital zircon grains derived from within the Witwatersrand sediments (Barton *et al.*, 1989; Robb *et al.*, 1990a). These data indicate that the source area supplying detritus into the basin was largely 3200-2900 Myr old, and that it was evolving (i.e. getting younger) as the sedimentary sequence was being laid down. This has led to the suggestion that many of the granites in the source area were intruded into the crust during basin evolution (Robb *et al.*, 1990a). The granites adjacent to the basin have also recently been shown to be characterized by an overprint of pervasive and vein-related hydrothermal alteration that results in enrichment of both gold and uranium in these rocks (Robb and Meyer, 1990). These hydrothermally altered granites (HAGs) have never been reliably dated, nor is it known when the attendant hydrothermal alteration took

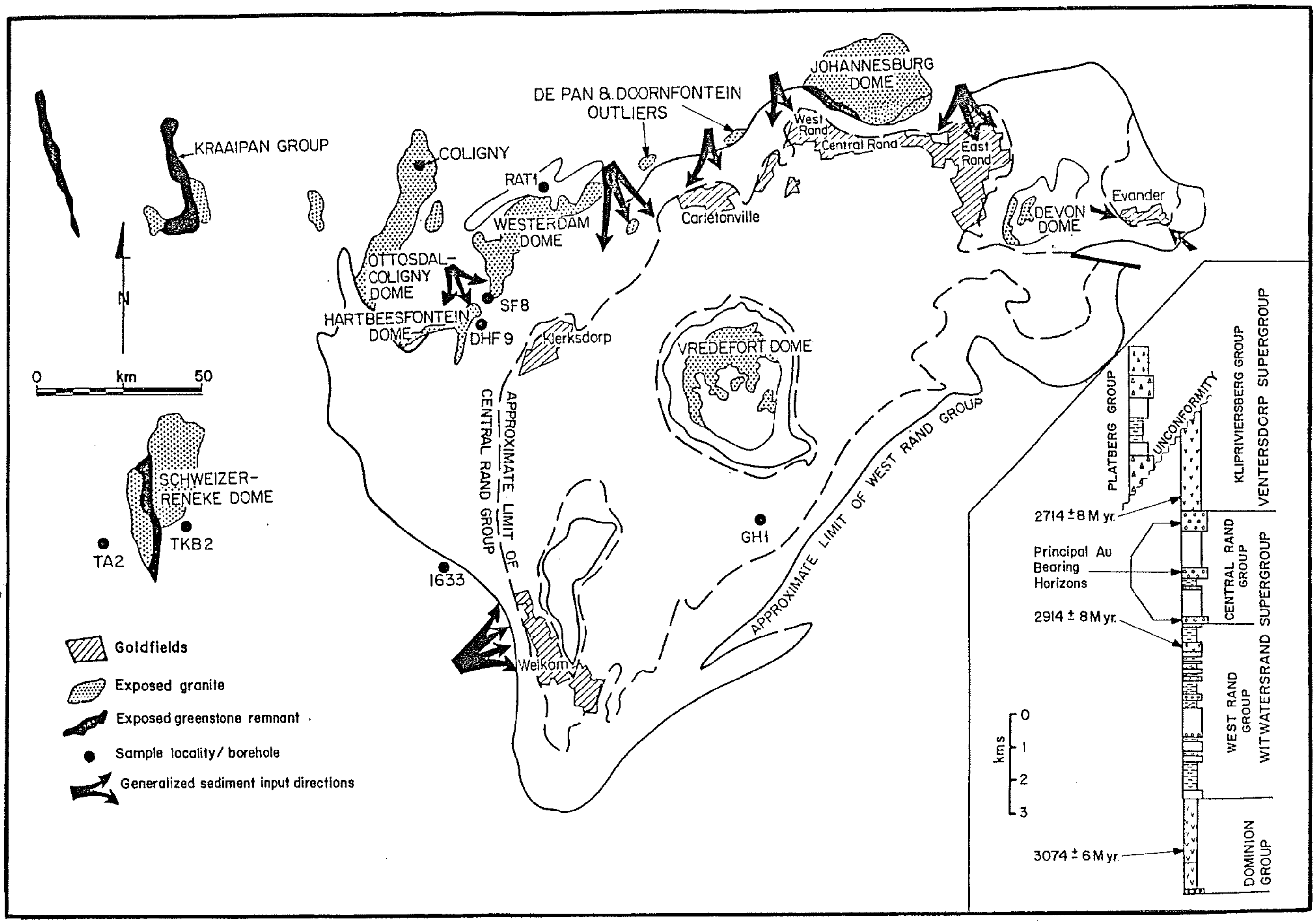

Figure 1: Schematic plan of the Witwatersrand Basin showing localities of the samples described in the text. Inset diagram shows a simplified stratigraphic column and key volcanic horizons providing chrono-stratigraphic control (from recent U-Pb zircon age determinations by Armstrong et al., 1991).

place. Here we report data demonstrating that certain of the HAGs in the source area were emplaced sporadically during the 360 Myr of Witwatersrand deposition and, thus, represent a potential source of detritus. Furthermore, it will be shown that hydrothermal alteration was associated with granitoid intrusion and subsequent cooling. Consequently, fertilization of the crust occurred during Witwatersrand Basin evolution and this must have been relevant to the source of Au and U once erosion of this material took place.

AGES AND CHARACTERISTICS OF HAGs

Eight localities of HAGs around the edges of the Witwatersrand Basin have been sampled (Fig. 1). Descriptions of the various granites sampled, their compositions and the

TABLE 1: Characteristics of HAGS adjoining the Witwatersrand Basin

NAME/LOCALITY	COMPOSITION/TYPE	ALTERATION (VEIN PARAGENESIS)	Au (ppb)	U (ppm)	AGE (Myr)	OVERLAIN BY
Hartbeesfontein DHF9	peraluminous granodiorite-adamellite (primary garnet)	greisen (quartz-chlorite-pyrite-chalcopyrite-molybdenite) ± uraninite	0.7 - 4.1	2 -10	3174 +9/-7	Dominion
GH1	low-Ca granite (monazite)	deuteric (abundant uraninite)	0.7 - 1.7	6 -116	3101±2	West Rand
Westerdam SF8 / RAT1	granite	(quartz-chlorite-pyrite-fluorite-carbonate)	0.6 - 7.4	1 - 21	3086±3	West Rand Dominion
Coligny	low-Ca leucogranite	minor albitization	7.4	1 - 2	3031+11/-10	Ventersdorp
TA2	tonalite gneiss	minor deuteric (contains veins derived from Schweizer-Reneke intrusion)	-	-	2927+23/-6 (metamorphic?)	Ventersdorp
Schweizer-Reneke TKB2	peraluminous adamellite-granite (monazite)	deuteric Quartz-K felspar-chlorite-rutile-pyrite-chalcopyrite) (exogeneous)	6.0 -127	1 - 34	2880±2	Ventersdorp
1633	granodiorite-adamellite	(quartz-chlorite-pyrite-chalcopyrite-galena)	1.3 - 9.6	3 - 4	2727+6/-5	mid-Ventersdorp

nature of the hydrothermal alteration affecting them are summarized in Table 1. U-Pb isotopic ratios of zircon, as well as in certain cases monazite, fluorite and rutile have been obtained for each locality, following standard procedures used at the Royal Ontario Museum (Krogh, 1973; 1982; Corfu, 1988). The zircon and monazite analyses were all carried out on abraded single grains or small samples (i.e. <3 grains) carefully selected against cracking and metamictization to improve concordancy of isotope ratios. Monazite and fluorite were dissolved in Savillex capsules using 6N HCl. U-Pb isotopic data are plotted on concordia diagrams (Fig. 2) and presented in Table 2. Concordia intersection ages and errors were determined using published correlation procedures (Davis, 1982).

Hartbeesfontein Area - Borehole DHF9

Granodiorites and adamellites of the Hartbeesfontein area are overlain by the basal conglomerates and quartz-arenites of the Dominion Group. These granitoids contain primary garnet and are peraluminous. They are commonly characterized by a pervasive greisening as well as quartz-chlorite-sulphide vein-type alteration. The vein mineral paragenesis is quartz-chlorite-molybdenite-pyrite-chalcopyrite-calcite. Uraninite is a common accessory mineral which is occasionally replaced by late kerogen (Robb and Meyer, 1990). Greisen samples exhibit U contents in the range 10-15ppm, anomalously low Th/U ratios (1-2) and depleted light REE signatures.

Zircons extracted from granodiorite intersected in borehole DHF9 yielded an upper intercept age of 3174 +9/-7 Myr (Fig. 2A). This granodiorite, therefore, represents part of the basement upon which the ca. 3070 Myr old Dominion Group was deposited. Elsewhere in the Hartbeesfontein area granites have been dated at 3120 $\pm$ 9 Myr (Armstrong *et al.*, 1991) indicating that at least two events of felsic plutonism pre-dated the Dominion sequence in this region.

Welkom Area - Borehole GH1

Borehole GH1 was drilled within the contiguous Witwatersrand Basin and intersected coarse-grained granite (*sensu stricto*) beneath West Rand Group sediments. The granite is a low-Ca variety, moderately differentiated (Rb/Sr=2-3) and characterized by an accessory mineral suite that is dominated by monazite and uraninite. Certain samples contain in excess of 100ppm (Table 1) uranium and have highly enriched U/Th ratios (>5). Granites of this type adjacent to the Witwatersrand basin would represent an obvious source of detrital uraninite in the adjacent Dominion and Witwatersrand placer deposits. Monazite extracted from the GH1 granite yielded an upper intercept age of 3101 $\pm$ 2 Myr (Fig. 2B). Ages of the two concordant data points, although close, differ slightly outside of analytical error, indicating some disturbance.

Westerdam Dome - Boreholes SF8 and RAT1

The Westerdam dome is overlain by the Dominion Group along its southeastern flank and West Rand Group sediments in the north. The Westerdam granite has been intersected

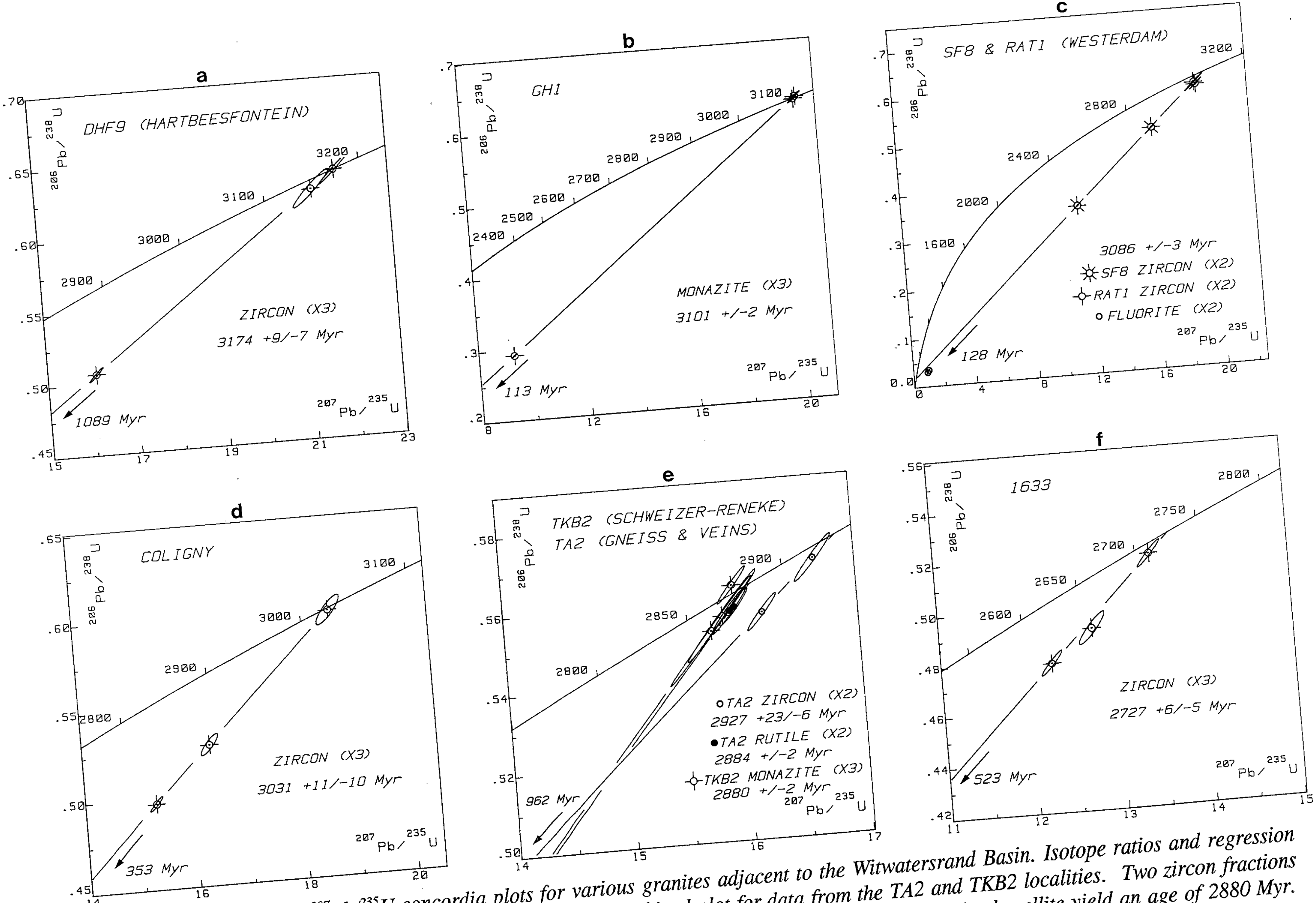

Figure 2: $^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$ concordia plots for various granites adjacent to the Witwatersrand Basin. Isotope ratios and regression data presented in Tables 1 and 2. Figure 2E is a combined plot for data from the TA2 and TKB2 localities. Two zircon fractions ... yield an age of 2927 Myr. Three monazite fractions from the TKB2 adamellite yield an age of 2880 Myr. ... gneissic banding in TA2 provide an age of 2884 Myr.

TABLE 2
U-Pb isotopic data

Sample	Weight (mg)	U (ppm)	Pb_{COM} (pg)	MEASURED $^{207}Pb/^{204}Pb$	CORRECTED Th/U	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	% DISC.	$^{207}Pb/^{206}Pb$ Age (Myr)
DHF9, HARTBEESFONTEIN									
z, Ab, 1 gr	0.003	50	8	219	0.71	0.63653	21.797	0.0±1.6	3174.2±3.3
z, Ab, 1 gr	0.001	170	3	502	0.65	0.62409	21.256	1.6±2.0	3165.7±8.9
z, Ab, 3 gr	0.003	80	38	59.7	0.65	0.50677	16.098	16.3±1.0	3054.6±3.0
r, Ab, 20 gr	0.051	0.3	2934	20.11	1.64	---	---	-9000±6	3323±3
GH1									
m, Ab, 1 gr	0.003	1820	27	1931	36.9	0.61676	20.198	0.3±0.8	3103.3±2.6
m, Ab, 1 gr	0.001	3341	88	372	34.5	0.62138	20.286	-0.7±1.0	3098.3±3.2
m, Ab, 2 gr	0.002	400	8	447	37.6	0.29217	9.306	51.9±1.0	3059.0±3.2
SF8, WESTERDAM									
z, Ab, 1 gr	0.002	150	7	334	0.45	0.50561	16.287	17.4±1.0	3077.0±2.6
z, Ab, 1 gr	0.001	130	7	109.6	0.42	0.35306	11.211	41.7±1.0	3054.1±3.6
f, Ab, 13 gr	0.028	1.2	6	17.74	0.56	0.02973	0.8816	94.9±4.0	2944±54
RAT1, WESTERDAM									
z, Ab, 1 gr	0.005	160	5	1312	0.60	0.58961	19.286	4.6±2.0	3101.4±2.7
z, Ab, 2 gr	0.002	130	5	450	0.64	0.59246	19.173	3.4±3.0	3084.3±3.7
f, Ab, 20 gr	0.209	0.2	11	17.09	2.53	0.03490	0.9646	93.7±8.2	2830±52
COLIGNY									
z, Ab, 1 gr	0.001	20	4	65.4	1.26	0.59806	18.703	0.3±1.2	3029.6±10.8
z, Ab, 1 gr	0.001	30	2	134.7	1.50	0.52794	16.347	11.4±1.0	3013.6±8.5
z, Ab, 3 gr	0.003	40	4	226.3	1.24	0.49718	15.301	16.2±0.8	3004.0±3.5
TA2 (GNEISS PLUS VEIN)									
z, Ab, 2 gr	0.003	130	3	1077	0.59	0.56925	16.661	0.8±1.0	2923.0±3.3
z, Ab, 2 gr	0.003	170	6	597	0.68	0.55666	16.197	2.6±0.8	2913.3±2.6
r, Ab	0.604	7	126	256.4	0.01	0.55850	15.961	1.0±0.8	2884.2±3.3
r, Ab, 13 gr	0.307	5	41	305	0.00	0.55762	15.920	1.1±1.0	2882.6±3.4
TKB2, SCHWEIZER-RENEKE									
m, Ab, 1 gr	0.002	9800	22	6555	13.4	0.55647	15.857	1.2±2.0	2879.5±3.2
m, Ab, 1 gr	0.001	4200	14	2137	18.7	0.55293	15.755	1.8±2.4	2879.4±2.3
m, Ab, 1 gr	0.001	8800	83	797	24.7	0.56399	15.955	-0.7±0.8	2867.7±2.2
1633									
z, Ab, 1 gr	0.008	50	6	404	0.92	0.51904	13.439	1.3±1.0	2723.0±3.3
z, Ab, 2 gr	0.002	30	3	151.2	0.83	0.49155	12.734	6.5±1.2	2723.6±7.5
z, Ab, 1 gr	0.001	150	6	164.8	0.80	0.47889	12.254	8.1±1.0	2703.3±4.0

z - zircon; m - monazite; r - rutile; f - fluorite; Ab - abraded; Pb_{COM} - Common Pb, including blank;
Th/U calculated from $^{208}Pb/^{206}Pb$ ratio and $^{207}Pb/^{206}Pb$ age assuming concordance;
%DISC. - per cent discordance relative to $^{207}Pb/^{206}Pb$ age

in several boreholes both to its north and south. The body ranges from granodiorite to granite (*sensu stricto*) in composition and is characterized by extensive hydrothermal veining. Veins comprise a chlorite-pyrite-fluorite-calcite paragenesis. Hydrothermally altered samples of the Westerdam granite contain anomalous enrichments of uranium (10-20ppm) which is largely hosted in small, unidentified, opaque accessory minerals (possibly uraninite) and leucoxene (Robb *et al.*, 1990b).

Samples from the exposed portion of the Westerdam dome have yielded imprecise whole rock ages of 2759 $\pm$ 67 Myr (Rb-Sr) and 2810 +200/-220 Myr (Pb-Pb) (Barton *et al.*, 1986). These numbers probably reflect isotope resetting and not true emplacement ages as they clearly post-date the age of the Dominion Group. Zircons were extracted from two boreholes intersecting sub-surface Westerdam granite. Two moderately discordant data points from RAT1 differ slightly in age suggesting that inheritance may be present. However, the younger of the two points, together with two discordant data points from SF8, fit a line within error and define an upper intercept age of 3086 $\pm$ 3 Myr (Fig. 2C) which is the best available indication for the emplacement age of the granite. The Westerdam granite was, therefore, emplaced a mere 10-15 Myr prior to extrusion of the Dominion felsic volcanics and represents part of a major pulse of magmatism at this time (Robb *et al.*, 1990a).

Coligny Granite

The Coligny granite crops out in the northern portion of the Ottosdal-Coligny dome (Fig. 1). This granite (*sensu stricto*) is characterized by high SiO_2 contents (>75%), low CaO contents (<0,5%) and extremely fractionated Rb/Sr ratios (>15). It contains primary muscovite, but is deuterically altered and exhibits minor albitization and interstitial fluorite.

The Coligny granite is unconformably overlain by the ca. 2700 Myr old Ventersdorp Supergroup. Zircons yield an upper intercept U-Pb age of 3031 +11/-10 Myr (Fig. 2D). This granite was, therefore, emplaced into the crust some 40 Myr after deposition of the Dominion volcanics, probably just prior the onset of West Rand Group sedimentation.

Schweizer-Reneke Dome - Borehole TKB2

The Schweizer-Reneke dome is granodioritic-to-adamellitic in composition and is unconformably overlain on all sides by the Ventersdorp Supergroup. It is reasonably well exposed, revealing light-to-moderate deuteric alteration at surface. Exogeneous, sulphide-bearing, hydrothermal veins associated with the emplacement of the Schweizer-Reneke granite are preserved in older basement gneisses adjacent to the dome (see later). These veins may be markedly enriched in gold (Robb and Meyer, 1990) and in the present samples contain in excess of 100 ppb (Table 1). The granite is characterized by monazite-group accessory minerals and only scarce zircon. A sub-surface borehole intersection (TKB2) of the Schweizer-Reneke granite reveals a zone of intense phyllic and argillic alteration immediately beneath mid-Ventersdorp arenites and conglomerate. Monazite grains extracted from below this zone yield extremely concordant data points. Two of these agree within error, but a third which shows slight reverse discordance differs outside of error (Fig. 2E). The two monazite points in agreement define an age of 2880 $\pm$ 2 Myr which is the best estimate for emplacement of the granite. The Schweizer-Reneke granite was, therefore, emplaced in post-West Rand Group times, and was exhumed, eroded and subsequently covered by Ventersdorp-aged sediments within 165 Myr of its formation.

Welkom Area - Borehole 1633

Borehole 1633 was drilled close to the present western edge of the basin and intersected medium-grained granodiorite-adamellite beneath mid-Ventersdorp volcanics. This granite is characterized by hydrothermal veins comprising quartz-chlorite-pyrite-chalcopyrite-galena. Zircons extracted from this granite yielded an upper intercept age of 2727 +6/-5 Myr (Fig. 2F). The three data points do not fit a line within error possibly because of different lead-loss histories. Nevertheless, because the best data point is near concordant this result is probably reliable and implies emplacement only a few million years prior to cessation of Witwatersrand sediment deposition and outpouring of Ventersdorp volcanics at 2714 Myr (Armstrong *et al.*, 1991). It is pertinent to note that Central Rand Group sediments along the western edge of the Welkom Goldfield were structurally deformed (and in places overturned) just prior to Ventersdorp volcanism suggesting that the 1633 granite was either the cause of this disturbance, or was emplaced along major structures associated with the deformation.

AGES OF HYDROTHERMAL ALTERATION

The timing of hydrothermal alteration adjacent to the Witwatersrand Basin is difficult to determine since fluid movements have been complex and long-lived, given the wide-ranging ages of granite emplacement, the different alteration parageneses and the post-depositional effects superimposed onto the basin sediments themselves. In several areas, however, U-Pb isotope dating provides an indication that the age of hydrothermal alteration was synchronous with the emplacement of the granites.

The western edge of the Schweizer-Reneke dome comprises a complex suite of tonalite gneisses and migmatites which are intruded by an array of hydrothermal veins comprising quartz-microcline-chlorite-pyrite-chalcopyrite-rutile. These veins cut across the foliation and compositional banding in the gneisses/migmatites and, therefore, post-date migmatization of the host rocks. Zircons extracted from tonalitic gneisses intersected in borehole TA2 yield an imprecise age of 2927 +23/-6 Myr (Fig. 2E). This may represent the age of migmatization rather than the crystallization age of the protolith since similar gneisses and migmatites dated further to the south have yielded tentative ion-microprobe ages of 3250 Ma for zircon cores and 2940 Ma for metamorphic overgrowths (Drennan *et al.*, 1990).

Two fractions of dark, euhedral rutile extracted from a hydrothermal vein cutting the tonalitic gneiss/migmatite in TA2 have also been analysed and yield overlapping concordant data points with a $^{207}Pb/^{206}Pb$ age of 2884 $\pm$ 2 Myr (Fig. 2E). This age is the same, within error, to that of the Schweizer-Reneke granite in borehole TKB2 (2880 $\pm$ 2 Myr; Fig. 2E). Given the close proximity of the latter to the TA2 borehole, it seems likely that the veins cutting tonalitic gneisses and migmatites in borehole TA2 represent an exogeneous hydrothermal manifestation of the nearby Schweizer-Reneke granite intrusion.

Additional evidence which indicates that hydrothermal alteration was contemporaneous with granite emplacement comes from isotopic analyses of rutile in DHF9 and fluorite fractions in SF8 and RAT1. The rutile contains a radiogenic lead component which is presently unsupported by uranium, but which gives a $^{207}Pb/^{206}Pb$ age of 3323 Myr assuming an initial Pb isotopic composition on the Stacey and Kramers (1975) growth curve. This age is dependent on the value chosen for initial Pb and could be made to agree with the age of the granite itself (3174 +9/-7 Myr) by the choice of a more evolved initial Pb composition. Furthermore, any additional U loss at a non-zero time would have the effect of further increasing the $^{207}Pb/^{206}Pb$ age. Consequently, the most likely interpretation is that the rutile formed contemporaneously with granite emplacement.

Similarly, isotopic analyses of fluorite fractions from the Westerdam granite (Table 2) yield $^{207}Pb/^{206}Pb$ ages of 2944 $\pm$ 54 Myr (SF8) and 2830 $\pm$ 52 Myr (RAT1). The fluorite data points also plot close to the Pb loss line for zircons from the Westerdam granite (Fig. 2C). Although the fluorite ages are imprecise due to the small quantities of Pb and the high levels of discordance, the data suggest that the age of hydrothermal alteration here was not significantly different from that of granite emplacement.

IMPLICATIONS FOR THE ORIGIN OF Au AND U

The tectonic framework within which the Witwatersrand Basin was deposited is still much debated although there is now general agreement over the main events. Proto-basinal development (i.e. the Dominion Group) was initiated 3070 Myr ago when crustal extension and rifting resulted in the deposition of thin basal quartz arenite and conglomerate units overlain by a 2500m thick bimodal tholeiite-andesite and dacite-rhyolite continental volcanic sequence (Stanistreet and McCarthy, 1991; Marsh *et al.*, 1989). After thermal collapse of the Dominion Basin, and with the progressive merging of the Zimbabwe and Kaapvaal Cratons, a compressional regime ensued resulting in the formation of an epicontinental cover sequence (lower West Rand Group) followed by transgression of a foreland basin to form the upper West Rand and lower Central Rand Groups between c. 3000-2900 Myr ago (Stanistreet and McCarthy, 1991). Collision of the two cratons resulted in extensive alluvial fan sedimentation to form the upper Central Rand Group, a process that was abruptly terminated 2714 Myr ago by the outpouring of the Ventersdorp flood basalts, possibly during an event of impactogenal rifting (Stanistreet and McCarthy, 1991). Although these models remain tentative because of the generally poor exposure in the hinterland, they do receive impetus from the data presented above, which demonstrate that the processes of basin formation were accompanied by magmatic activity in the source area. Voluminous granitoid plutonism occurred for at least 40 Myr before and after Dominion volcanism (Robb *et al.*, 1990a; 1991). The compression-related depositional episodes that gave rise to the Witwatersrand Basin are now also shown to have been accompanied by granitoid plutonism that occurred in the hinterland, as well as very close to the edge of the Central Rand Group basin.

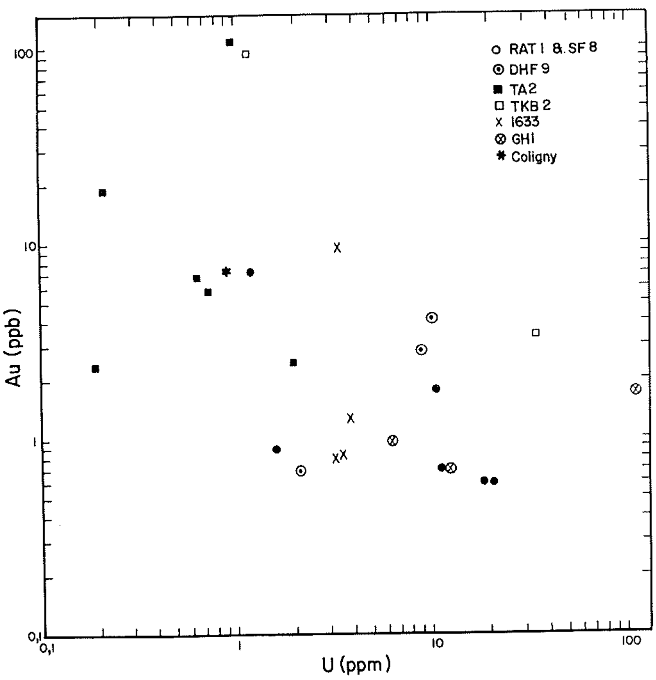

Figure 3: Plot of Au versus U contents of hydrothermally altered granites described in the text. Data obtained by instrumental neutron activation analysis.

Although the majority opinion favours a syngenetic origin for the conglomerate-hosted Au-U mineralization with later remobilization of ore during diagenesis and metamorphism, continuing assertions for an epigenetic origin derive much of their stimuli from the inability of the modified placer model to account for the enormous quantities of Au and U that must have been present within the source area. Previous thoughts on the nature of the rocks that actually supplied the detrital gold and uraninite into the Witwatersrand Basin have generally referred to early Archaean (3500-3200 Myr) granite-greenstone terranes, such as the Barberton Mountain Land, as the source since these sequences typify much of the exposed pre-Witwatersrand Kaapvaal Craton. Although remnants of early Archaean granite-greenstone environments undoubtedly exist (Robb and Meyer,1990), these terranes in the Witwatersrand hinterland were drastically modified by addition of new crust. Singly analysed detrital zircon grains from within the Dominion and Witwatersrand sequences clearly indicate that the source area was predominantly 3200-2900 Myr old (Barton *et al.*, 1989; Robb et al. 1990a). Consequently, the early granite-greenstone source area model is inapplicable, and detritus appears to have been derived from a younger, more evolved, source than that which is represented by the Barberton terrane.

The data presented above suggest that fertilization of the Witwatersrand hinterland was the product of extensive, syndepositional, hydrothermal activity resulting from the intrusion of numerous granitoid bodies, the remnants of which are still recognizable as the HAGs. Those granitoids characterized by differentiated chemical signatures and/or peraluminous compositions tend to be uranium-enriched (Fig. 3) and probably represent an adequate source of uraninite for the Witwatersrand deposits (Robb *et al.*, 1990b). These peraluminous granitoids tend to be circa 3200-3000 Myr old, somewhat older than the metaluminous variety which often contain vein-type alteration. The presence of HAGs with gold-enriched sulphide-bearing veins (e.g. TA2; Fig. 3) do not themselves represent an adequate source of gold but possibly identify the roots of high-level systems that have largely been eroded away. Voluminous quantities of felsic volcanic rocks are now known to occur in the hinterland and these remain an unknown factor in the Witwatersrand source area enigma. Examples include the 3074 Myr old upper Dominion Group comprising dacitic to rhyolitic flows and sub-volcanic quartz-feldspar porphyries, and the felsic volcanics and agglomerates of the Kraaipan Group which is tentatively dated at c.3070 Myr (L. J. Robb *et al.*, in prep.). In addition recent U-Pb zircon age determinations on the Gaborone granite and associated Kanye rhyolite province (D. W. Davis et al., in prep.) have shown that both units are identical in age at 2785 Ma. This data reveals the presence of another major plutonic-volcanic event in the Witwatersrand Basin hinterland which was emplaced during Central Rand Group deposition (i.e. between 2914 Ma and 2714 Ma; Armstrong *et al.*, 1991). It is well known that epithermal gold deposits, occur in metallogenic provinces associated *inter alia* with felsic volcanics. The erosion of high-level felsic suites mineralized by epithermal-to-mesothermal fluids would seem, in the light of our data, to offer a reasonable solution for the source of Witwatersrand gold.

CONCLUSIONS

The protracted and complex sequence of events over 360 Myr involving uranium specificity, consecutive phases of granitoid plutonism, periods of felsic magma extrusion and hydrothermal alteration offer an explanation for the prodigious concentration of Au and U within the Witwatersrand depository by providing a framework within which primary concentration of metals in the source area might have taken place. Several, uraninite-bearing, peraluminous granites remain preserved in the source area and these could have supplied uraninite into the basin. Hydrothermal alteration and veining associated with consecutive phases of granitoid plutonism indicate moderate to high levels of intrusion with attendant vapour saturation, factors which usually lead to mobilization and enrichment of metals near the surface. The protracted emplacement of granite bodies up until late in the depositional history of the basin and the trend of increasingly younger detrital zircon grains upwards in the stratigraphic succession indicate that the Witwatersrand source area was evolving continuously during basin formation. This might be the most important reason why mineralization is almost entirely concentrated in the Central Rand Group, while the underlying West Rand Group remains largely barren.

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