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U-Pb AGES ON SINGLE DETRITAL ZIRCON GRAINS FROM THE WITWATERSRAND BASIN: CONSTRAINTS ON THE AGE OF SEDIMENTATION AND ON THE EVOLUTION OF GRANITES ADJACENT TO THE DEPOSITORY

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INFORMATION CIRCULAR No. 208

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by

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ABSTRACT

U-Pb ages of single detrital grains from various stratigraphic horizons in the Dominion and Witwatersrand sequences provide constraints on the maximum age of sedimentation as well as indicating the pattern of age distribution of the (granitoid) basement providing detritus into the basin. Zircon ages in the Dominion sediments range from 3191-3105 Ma with a geometric mean (X) at 3153 Ma. Zircons from the lower Witwatersrand sediments (West Rand Group) range in age from 3305-3044 Ma with X = 3097 Ma. Zircons in the upper Witwatersrand sediments (Central Rand Group) are between 3207-2894 Ma old with X = 3053Ma.

Ages of detrital zircons generally decrease upwards in the stratigraphic record and $<$3000 Ma old zircons are only found in the Central Rand Group. This trend implies that younger granites may have formed in the crust at some time subsequent to lower Witwatersrand deposition, or that continued erosion of the hinterland resulted in the unroofing of sucessively younger granites developed by processes of downward vertical crustal accretion. The wide spread of zircon ages (411 Ma) evident in the data set indicates that granitic crust formed virtually continously between circa 3300-2900 Ma ago in the Witwatersrand hinterland. Forty five percent of the zircon ages fall within 30 Ma of the geometric mean of the total data set, suggesting that a major crust-forming event occurred at 3074 +/-30 Ma. Granitoids in the hinterland can be categorized into, (1) pre-Dominion basement; (2) Dominion granites, whose emplacement coincided with the extrusion of Dominion volcanics; and (3) granites formed synchronously with Witwatersrand deposition. Unconformity-bound sedimentary packages in the Witwatersrand depository probably represent the depositional responses to on-going tectono-magmatic events in the hinterland.

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1. INTRODUCTION

The Witwatersrand Basin is well known for the prodigious concentration of gold contained within the deposit. The reasons for this enrichment remain enigmatic, although it is likely that three factors, geologic age, structural setting and nature of the hinterland, have played a role in the development of the deposit. In particular, the age of the Witwatersrand Basin, and its relationship to the stages of crustal evolution in the Archaean basement of the Kaapvaal Craton, is one factor which is poorly understood.

The Witwatersrand Basin is subdivided into a lower (West Rand Group) and upper (Central Rand Group) division (Figure 1). The lower division comprises essentially shales and quartz-arenites with only minor, generally sub-economic, conglomerate horizons. The upper division, from which over 99% of the gold and uranium has been won, is dominated by quartz-arenites containing numerous intercalated conglomerate bands, but only a minor shale component.

The age of the Witwatersrand sediments is bracketed between that of basement granitoids, which form the floor of the depository, and the age of lavas of the Ventersdorp Supergroup, which immediately overlie the uppermost Witwatersrand sediments (Figure 1). Until recently, this bracket had been constrained between approximately 2800 Ma and 2300 Ma ago (Allsopp and Welke, 1986).

This range was derived from controversial age determinations involving whole rock Rb-Sr and Pb-Pb isochrons of basement granitoids (Allsopp, 1964; Barton et al., 1986), and whole rock Rb-Sr and Pb-Pb , as well as U-Pb zircon age determinations, on the Ventersdorp lavas (Harding et al., 1974; Armstrong, 1987; Van Niekerk and Burger, 1964; 1978). The uncertainty in these ages centres around the possibility that the Rb-Sr whole rock dates in the area may have been widely reset. An older age of 2643 Ma for zircons from the Ventersdorp lavas (Van Niekerk and Burger, 1978) was also viewed with suspicion because of a possible xenocrystic origin for zircons in the analysed sample (Allsopp and Welke, 1986).

Direct age determinations on Witwatersrand rocks themselves have been largely unsuccessful in helping constrain the age of sedimentation. Intercalated lavas in the succession have, to date, yielded isotope ratios indicative of open-system behaviour. Whole rock Pb-Pb data on conglomerate samples indicate that primary uranium minerals in the conglomerates are approximately 3050 Ma old (Rundle and Snelling, 1977), very similar to the estimate of 3065 Ma obtained earlier by Burger et al., (1962). These uranium minerals were also shown to have been largely reset by an event of probable Bushveld origin at approximately 2040 Ma (Rundle and Snelling, 1977).

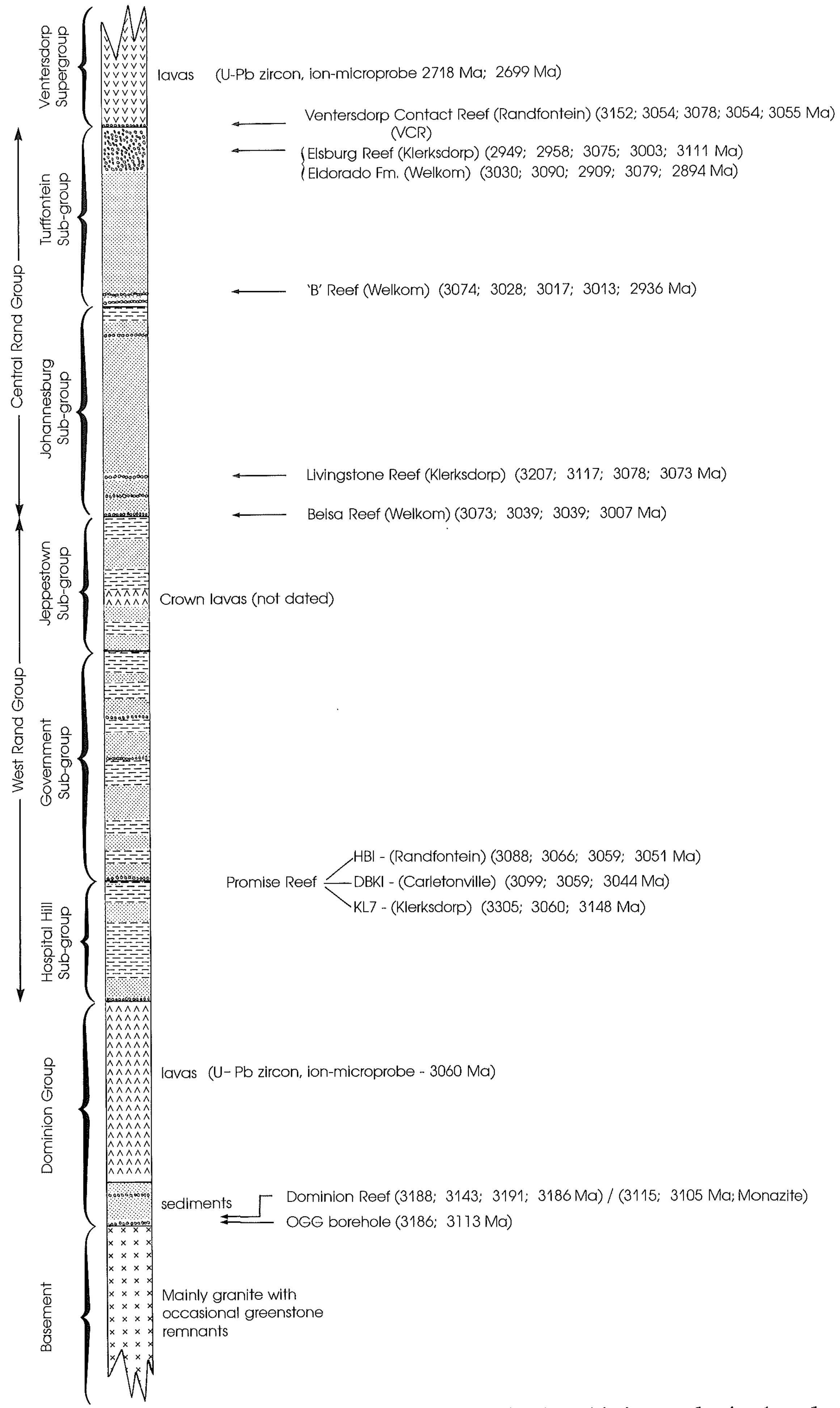

Figure 1: Simplified stratigraphic column showing sample localities and single, detrital zircon and monazite ages from each conglomerate sampled. Dominion and Ventersdorp lava ages are after Armstrong et al. (1986, 1989 and pers. comm.). Stipple represents quartz arenite, dashes represent shale, and open circles represent conglomerate horizons.

2. RECENT DEVELOPMENTS

Recent geochronological developments involving the precise dating of single grains have drastically altered the previous estimates concerning the age limits to Witwatersrand sedimentation. Dating of a non-magnetic zircon fraction from the middle Ventersdorp lavas using conventional U-Pb techniques has yielded an age of 2693 +60/-59 Ma (Armstrong et al., 1986). This age has been confirmed by recent ion-microprobe analysis of single zircon grains, which yielded a precise age of 2699 +/-16 Ma (Armstrong et al., 1986). Provisional dating of single zircons from the lower Ventersdorp Klipriviersberg lavas also recently yielded an age of 2817 +/-8 Ma (R.A. Armstrong, pers. comm.). These ages confirm the accuracy of the largely disregarded age of 2643 Ma obtained by Van Niekerk and Burger (1978), and serve to increase the previously recognized age of the Ventersdorp Supergroup by some 400 Ma. The minimum age of the Witwatersrand Supergroup can now be placed, with confidence, at circa 2700 Ma.

A maximum estimate of the Witwatersrand age has also recently emerged from the re-dating of the Dominion Group lavas, the latter forming part of a proto-basinal sequence which immediately pre-dates deposition of the Witwatersrand sediments (Figure 1). The age of these lavas has long been equivocal and a figure of 2800 +/-60 Ma (Van Niekerk and Burger, 1969) is most often quoted. This age is regarded as a minimum estimate as it was calculated from a Pb-Pb isochron obtained by analysing six sulphide leach solutions derived from mineral separates (i.e. pyrite, chalcopyrite, rutile, fluorite etc.) considered to be of secondary derivation. The Dominion lavas recently yielded a precise U-Pb age obtained from single zircons analysed by ion-microprobe, of 3060 +/-18 Ma (Armstrong et al., 1989).

This age is regarded as being a reliable indication of Dominion volcanism and, consequently, the Witwatersrand sediments are now considered to have been deposited between 3060 Ma and 2700 Ma ago, a span of time that is considerably older than the 2800-2300 Ma interval suggested by earlier work. These constraints place the Witwatersrand squarely into the Archaean era - rather than at the Archaean-Proterozoic boundary - in spite of the fact that sedimentation occurred predominantly within an epicratonic basin.

Many of the granites in the Witwatersrand hinterland are characterized by an overprint of hydrothermal alteration (Hallbauer, 1984; Klemd and Hallbauer, 1987; Giusti, 1988; Robb and Meyer, 1989). These granites have traditionally been regarded as the floor to the Dominion and Witwatersrand sediments/lavas, and few, if any, workers have entertained the possibility that certain granitic intrusions may post-date these sequences. Barton et al. (1986) presented isotopic data (summarized in Figure 3) pointing to a major magmatic event at circa 2800 Ma ago and suggested that although it was possible that magmatism may have been concurrent with the formation of the depository, it was more likely that the maximum age of the lower Witwatersrand sediments must be circa 2800 Ma. In contrast, Robb and Meyer (1989) regarded Dominion and Witwatersrand sedimentation as distinctly episodic and suggested that the emplacement of a suite of younger granites may have post-dated deposition of the lowermost (West Rand Group) sediments and, in fact, stimulated the onset of further sedimentation to yield the upper (Central Rand Group) sequences.

Despite even the recent developments it is clear that the age of sedimentation, as well as the relationship between discrete pulses of sediment and possible events - either tectonic or magmatic - in the hinterland, are poorly constrained. This status has stimulated the present study in which single detrital zircon grains from a number of conglomerate horizons in the Dominion, West Rand and Central Rand Groups have been isotopically analysed. In particular, it was hoped to better constrain the maximum age of discrete sedimentary packages from the age of the youngest detrital zircon in that package, as well as to obtain an indication of the age distribution of the granitoid basement providing zircon detritus into the basin.

3. SAMPLING AND ANALYTICAL METHODS

A total of 11 conglomerate samples, ranging from 1-6 kg in weight was collected from four broad stratigraphic intervals in the Dominion and Witwatersrand sequences. The distribution of sampling sites is shown in the locality map in Figure 2 and also in the stratigraphic column in Figure 1.

Two samples of the lower conglomerate band from the dominantly arenaceous Rhenosterspruit Formation of the Dominion Group were obtained from the Afrikander Leases Mine and a borehole OGG1 in the western Transvaal (Figures 1 and 2). Three conglomerate samples were obtained from the same horizon in the Promise Formation of the West Rand Group (Figure 1). The samples were obtained from borehole core drilled at three different localities, between Randfontein in the east and Klerksdorp in the west, over a distance of some 100 km (Figure 2). These three samples were selected specifically to assess whether the effects of differing provenance areas on the same chronostratigraphic horizon could be detected in the distribution of zircon ages.

In the upper Witwatersrand sequence, two conglomerate samples were obtained from the lowermost Johannesburg Subgroup, specifically from the Livingstone Reef at the Vaal Reefs Mine in the Klerksdorp Goldfield (Figure 2). Both of these samples came from conglomerates developed at, or near to, the major unconformity between the lower and upper portions of the Witwatersrand sequence (Figure 1). Four conglomerate samples were obtained from the Turffontein Subgroup; these were from the 'B' Reef and the Eldorado Formation at the Loraine Mine in the Welkom Goldfield, and the Elsburg No. 5 Reef at the Vaal Reefs Mine in the Klerksdorp Goldfield (Figures 1 and 2). The fourth sample was derived from the Ventersdorp Contact Reef at the South Roodepoort Mine in the West Rand Goldfield (Figure 2). This conglomerate is developed on a major unconformity which terminates deposition of the Witwatersrand sequence and also marks the initiation of Ventersdorp volcanicity.

Crushing, mineral separation, chemistry, and isotopic analyses followed standard procedures used at the Royal Ontario Museum (Krogh, 1973, 1982;

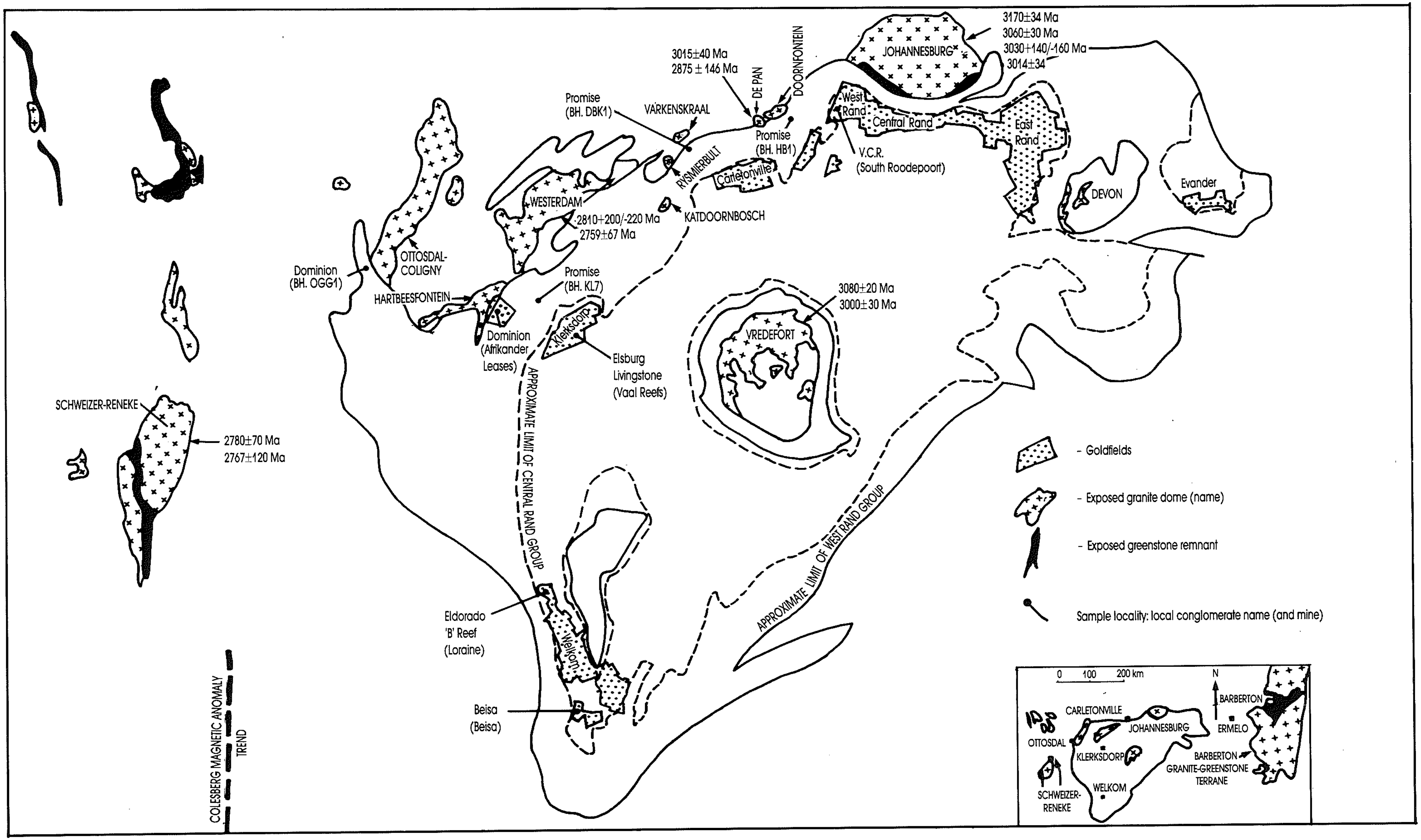

Figure 2: Simplified outline and locality map of the Witwatersrand Basin and surrounding Archaean granite-greenstone terrane. Source of granite ages from Figure 3.

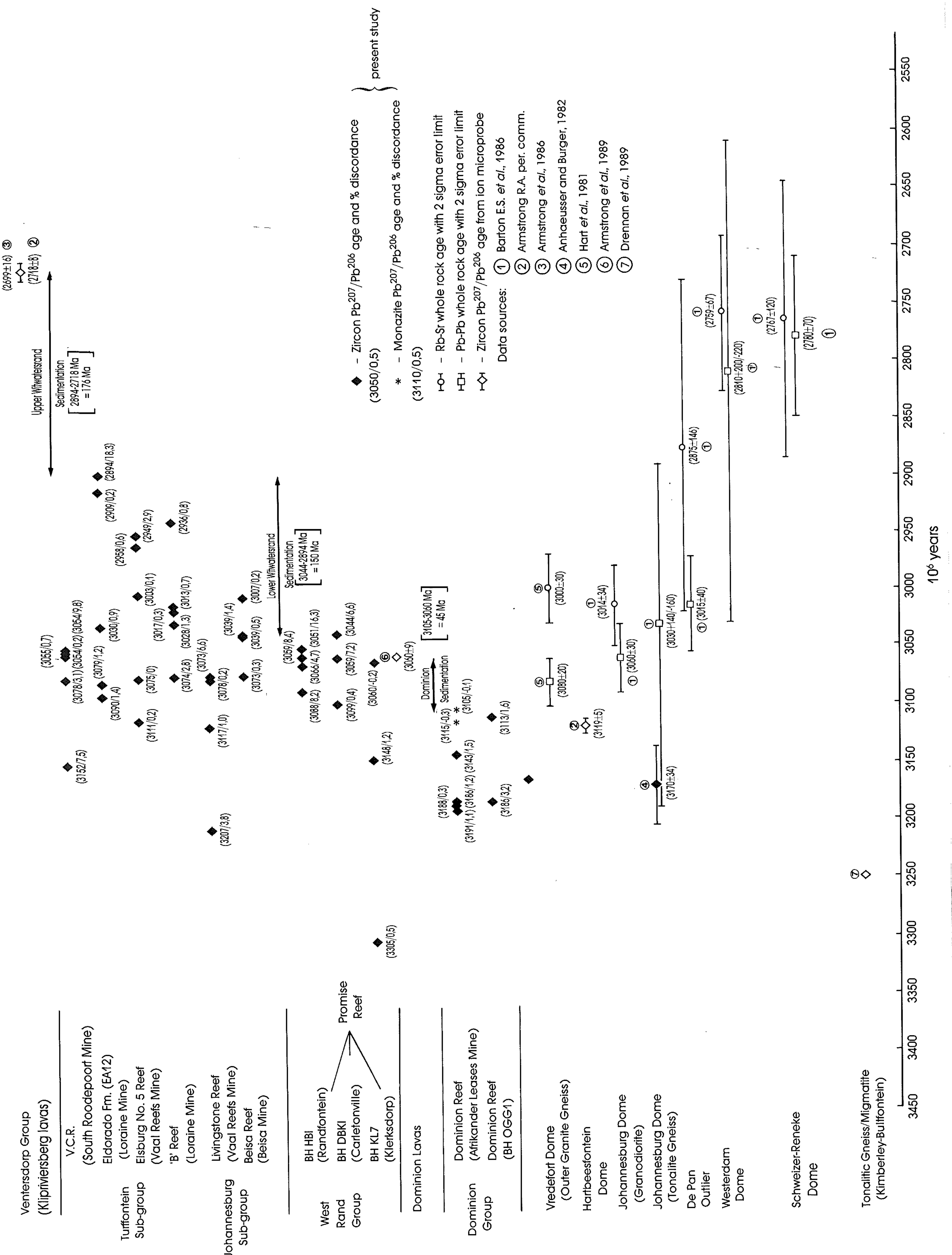

Figure 3: Summary of zircon and monazite ages relevant to the study.

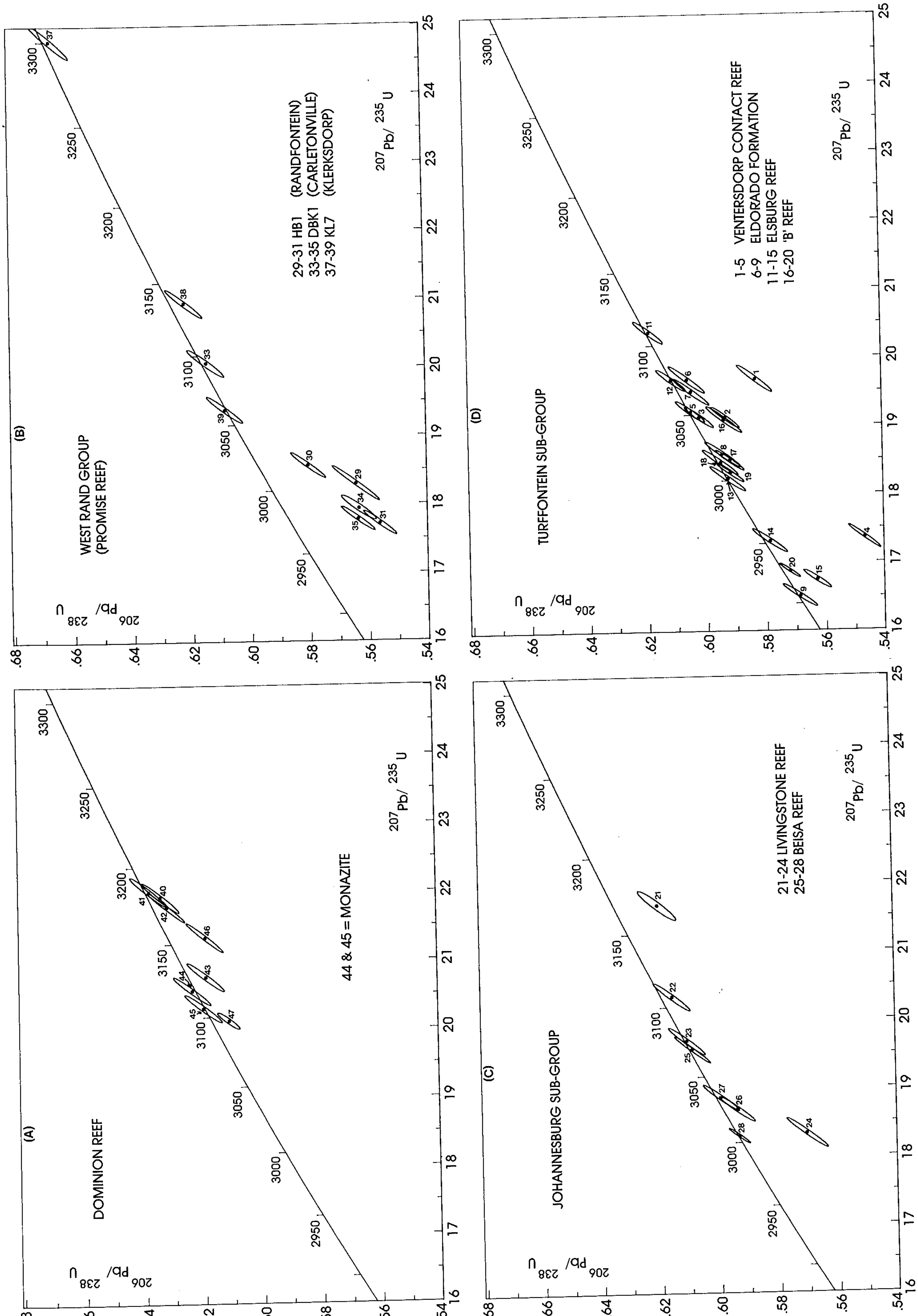

Figure 4: 206Pb/238U versus 207Pb/235U concordia diagrams for: A. the Dominion Reef; B. the Promise Reef in the West Rand Group; C. the Livingstone and Beisa Reefs in the Johannesburg Subgroup; and D. the 'B', Elsburg, Eldorado and Ventersdorp Contact Reefs in the Turffontein Subgroup. Numbers refer to the listing in Table 1.

Davis et al., 1982). At all stages extreme care was taken to prevent cross contamination. Selected, unaltered, crack-free grains were abraded to improve concordancy (Krogh, 1982). Single abraded zircons were dissolved either in teflon bombs or on thin, moulded teflon film. Dissolution blank levels were measured prior to bomb dissolution and were all in the range 2-6 pgm of lead. Isotopic measurements were carried out on a VG354 mass spectrometer using a Daly collector.

4. RESULTS

A total of 44 single zircon grains, as well as 2 single monazite grains were analysed. The ages of grains are discussed as 207 Pb/206 Pb ages, and these are plotted, together with pertinent basement ages in Figure 3. Data points are also plotted on a composite set of concordia diagrams in Figure 4, while the U-Pb isotopic data are summarized in Table 1. Age errors and error ellipses are presented at the 95% confidence level.

Analysis of individual detrital grains record age information about the zircon-bearing source rocks which contributed to the sediments. Provided the grains are free of inheritance, a date calculated from the 207 Pb/206 Pb ratio is a minimum estimate for the rock which furnished the grain. This date will be indistinguishable from the age of the source rock if the data point is concordant. All grains were carefully selected so that there were no visible cores present, and it can therefore generally be assumed that inheritance is not a factor in interpreting the ages. About 30% of the grains, however, show a degree of secondary lead loss, which does not appear to be correlated with uranium concentration (i.e. degree of metamictization). For example, grain 4 (Table 1) shows 10% lead loss although the uranium concentration of the grain was only 20 ppm. This is unusual considering the tendency in other Archaean terranes such as the Superior Province, where it has been found that crack-free, abraded zircon grains with uranium concentrations <100 ppm are almost invariably well within 1% of concordia.

Excessive ($>30\%$) degrees of discordance have, however, also been recorded for zircons from the Barberton Mountain Land (Tegtmeyer and Kröner, 1987) where even gem-quality grains such as those from the Kaap Valley tonalite are unusually discordant. Large degrees of lead loss are also found in heavily weathered, unglaciated areas such as the Brazilian Shield (N.Machado, pers. comm.), although the Witwatersrand conglomerate samples were all collected underground or from drill core and should, therefore, be free of weathering effects. Lower intercept ages measured from discordia lines from the Barberton region by Tegtmeyer and Kröner (1987) varied from about 100-600 Ma, a range which is typical of Archaean zircons. Accordingly, ages for individual analysis in this study have been calculated by extrapolating a line with a lower intercept of 500 Ma upward through the data point to concordia. These ages are listed along with the 207 Pb/206 Pb ages in Table 1. The lower intercept variation makes little difference to points within 2% of concordia, but ages of more discordant points are progressively less reliable.

TABLE 1

U-Pb ISOTOPIC DATA FOR SINGLE DETRITAL ZIRCON GRAINS IN THE WITWATERSRAND BASIN

	WEIGHT (mg)	U (ppm)	COMMON Pb[a] (pg)	$^{207}Pb/^{204}Pb$ [b]	$^{208}Pb/^{206}Pb$ [c]	$^{206}Pb/^{238}U$ [c]	$^{207}Pb/^{235}U$ [c,d]	$^{207}Pb/^{206}Pb$ [c,e]	500 Ma[f] INTERCEPT AGE (Ma)
VENTERSDORP CONTACT REEF, SOUTH ROODEPOORT MINE									
1.	0.004	35	2	391	0.267	0.58308	19.685 (1.00)	3152 (0.21)	3168 (7.5)
2.	0.015	28	2	470	0.204	0.59330	19.122 (0.80)	3078 (0.17)	3084 (3.1)
3.	0.019	85	3	1603	0.155	0.60213	19.131 (0.80)	3055 (0.20)	3056 (0.7)
4.	0.021	20	3	371	0.197	0.54668	17.361 (1.00)	3054 (0.16)	3076 (9.8)
5.	0.007	36	4	399	0.218	0.60506	19.213 (0.80)	3054 (0.20)	3055 (0.2)
ELDORADO FORMATION, LORAINE MINE									
6.	0.015	43	4	1041	0.260	0.60607	19.679 (1.00)	3090 (0.20)	3094 (1.4)
7.	0.005	83	4	864	0.121	0.60468	19.501 (1.00)	3079 (0.20)	3082 (1.2)
8.	0.020	59	3	2386	0.125	0.59428	18.584 (1.00)	3030 (0.20)	3032 (0.9)
9.	0.010	37	3	639	0.077	0.56894	16.513 (1.00)	2909 (0.20)	2910 (0.2)
10.	0.005	59	5	393	0.136	0.46304	13.313 (1.00)	2894 (0.20)	2943 (18.3)

Table 1 (contd)

				ELSBURG NO. 5 REEF, VAAL REEFS MINE					
11.	0.008	57	2	833	0.092	0.61904	20.375 (0.80)	3111 (0.20)	3112 (0.2)
12.	0.016	103	54	265	0.135	0.61146	19.672 (0.80)	3075 (0.20)	3075 (0.0)
13.	0.009	235	3	3259	0.172	0.59267	18.226 (1.00)	3003 (0.20)	3003 (0.1)
14.	0.017	65	3	955	0.220	0.57884	17.316 (1.00)	2958 (0.21)	2960 (0.6)
15.	0.024	7	3	165	0.140	0.56302	16.750 (0.80)	2949 (0.21)	2956 (2.9)
				"B" REEF, LORAINE MINE					
16.	0.002	190	6	530	0.105	0.59368	19.090 (1.00)	3074 (0.20)	3080 (2.8)
17.	0.020	18	3	727	0.237	0.59186	18.495 (0.80)	3028 (0.16)	3031 (1.3)
18.	0.015	30	4	677	0.136	0.59521	18.468 (1.00)	3017 (0.20)	3018 (0.3)
19.	0.020	106	3	2694	0.195	0.59198	18.324 (0.80)	3013 (0.16)	3015 (0.7)
20.	0.025	52	15	643	0.076	0.57215	16.877 (0.60)	2936 (0.12)	2937 (0.8)
				LIVINGSTONE REEF, VAAL REEFS MINE					
21.	0.006	56	6	587	0.233	0.62005	21.678 (1.00)	3207 (0.31)	3215 (3.8)
22.	0.003	51	5	292	0.129	0.61557	20.337 (1.00)	3117 (0.21)	3119 (1.0)
23.	0.001	125	5	252	0.128	0.61070	19.687 (1.00)	3078 (0.21)	3079 (0.2)
24.	0.006	120	6	1113	0.115	0.57049	18.327 (1.20)	3073 (0.21)	3087 (6.6)

Table 1 (contd)

				BEISA REEF, BEISA MINE					
25.	0.018	49	2	1995	0.122	0.60889	19.566 (1.00)	3073 (0.14)	3074 (0.3)
26.	0.004	37	2	420	0.130	0.59406	18.690 (1.00)	3039 (0.21)	3042 (1.4)
27.	0.018	34	2	1436	0.173	0.59935	18.855 (1.00)	3039 (0.20)	3040 (0.5)
28.	0.019	153	2	4103	0.096	0.59337	18.295 (0.60)	3007 (0.10)	3007 (0.2)
				BOREHOLE HB1, PROMISE REEF (RANDFONTEIN)					
29.	0.007	108	3	1656	0.189	0.56419	18.298 (1.40)	3088 (0.20)	3106 (8.2)
30.	0.008	105	3	1835	0.177	0.58029	18.569 (1.00)	3066 (0.20)	3076 (4.7)
31.	0.003	153	4	928	0.200	0.55622	17.717 (1.00)	3059 (0.21)	3078 (8.4)
32.	0.003	91	4	539	0.148	0.50650	16.049 (1.00)	3051 (0.21)	3090 (16.3)
				BOREHOLE DBK1, PROMISE REEF (CARLETONVILLE)					
33.	0.003	64	7	276	0.146	0.61472	20.071 (1.00)	3099 (0.25)	3099 (0.4)
34.	0.002	71	5	267	0.184	0.56328	17.939 (1.00)	3059 (0.31)	3074 (7.2)
35.	0.005	101	12	359	0.240	0.56358	17.782 (1.00)	3044 (0.20)	3058 (6.6)
36.	0.003 (4 rutile grains)	3	3	35.5	0.154	0.73988	17.556 (1.20)	2578 (2.10)	---- (-50.5)

Table 1 (contd)

				BOREHOLE KL7, PROMISE REEF (KLERKSDORP)					
37.	0.007	57	22	223	0.227	0.66652	24.793 (1.00)	3305 (0.21)	3306 (0.5)
38.	0.007	97	5	1246	0.145	0.62183	20.944 (1.00)	3148 (0.20)	3150 (1.2)
39.	0.007	114	12	633	0.167	0.60841	19.386 (1.00)	3060 (0.21)	3059 (-0.2)
				DOMINION REEF, AFRIKANDER LEASES MINE					
40.	0.008	59	5	766	0.322	0.63357	21.930 (1.00)	3191 (0.21)	3193 (1.1)
41.	0.017	70	5	1668	0.312	0.63748	22.015 (1.00)	3188 (0.20)	3188 (0.3)
42.	0.004	70	33	99	0.301	0.63155	21.790 (1.00)	3186 (0.14)	3189 (1.2)
43.	0.014	41	6	653	0.487	0.61864	20.767 (1.00)	3143 (0.21)	3146 (1.5)
44.	0.005 (1 monazite grain)	858	12	3624	5.895	0.62331	20.566 (1.00)	3115 (0.20)	3115 (-0.3)
45.	0.010 (1 monazite grain)	253	58	353	37.373	0.61953	20.308 (1.00)	3105 (0.21)	3105 (-0.1)
				BOREHOLE OGG1, DOMINION REEF					
46.	0.002	39	4	180	0.306	0.61872	21.343 (1.00)	3186 (0.16)	3192 (3.2)
47.	0.002	94	4	436	0.197	0.61101	20.126 (0.60)	3113 (0.20)	3116 (1.6)

Table 1 (contd)

NOTES: Ab= abraded fraction

[a]Corrected for 0.117 mole fraction of common lead in the ^{205}Pb spike.
(Except fractions 4, 10, 11, 13, 14 and 19 which were analyzed using a new spike, free of common lead.)
All common lead is assumed to be blank.

[b]Measured value.

[c]Corrected for fractionation and common Pb (blank)
U blank= 3.8 pg (large column), 0.5 pg (small column)
Pb blank approximately 8 pg (both columns)
Pb and U fractionation correction= 0.13%/amu

[d]Numbers in brackets refer to % 2 sigma error in Pb/U.

[e]Numbers in brackets refer to % 2 sigma error in $^{207}Pb/^{206}Pb$ age.
0.1% corresponds to an error of 1.6 Ma.

[f]Numbers in parenthesis refer to % discordance for the given $^{207}Pb/^{206}Pb$ age.
^{238}U decay constant= 0.15513×10^{-9} /year
^{235}U decay constant= 0.98485×10^{-9} /year
$^{238}U/^{235}U$= 137.88

A. Dominion Group

Six zircon and two monazite grains were analysed from the two conglomerate samples of the Dominion Group. These detrital grains span 86 Ma between 3191 Ma and 3105 Ma old. The geometric mean of the ages is 3153 Ma (Table 2). These data constrain the age of Dominion sedimentation between 3105 Ma and 3060 Ma (Figure 3). Photomicrographs showing the range in size and morphology of the "best-picked" Dominion zircon population, as well as the four abraded grains ultimately selected for analysis from the Afrikander Leases sample, are shown in Figure 5.

B. West Rand Group

Ten zircon grains from three Promise Reef samples in the West Rand Group were analysed. These grains span 261 Ma between 3305 Ma and 3044 Ma old (Figure 3). The geometric mean of the ages in 3097 Ma (Table 2). The oldest zircon detected in the present study (i.e. 3305 Ma) was derived from the Promise Reef sample in the Klerksdorp area. This sample also contains the youngest concordant zircon date in the Promise Reef, of 3060 +/-12 Ma. The discordancy in certain grains from the Carletonville and Randfontein samples may arise from the fact that these grains were not as effectively abraded as others yielding more concordant results.

A fraction consisting of 4 authigenic rutile grains was also recovered from the Promise Reef (borehole DBK1), and these yielded a 207 Pb/206 Pb age of 2578 +/-34 Ma. The isotope ratios plot about 50% above concordia, indicating that the rutile has probably lost uranium.

C. Johannesburg Subgroup

Eight zircons from two reefs in the lower portion of the Johannesburg Subgroup were analysed. These grains span 200 Ma and range between 3207 Ma and 3007 Ma old. The geometric mean of these ages is 3079 Ma. The youngest zircon grain, from the Beisa Reef in the Welkom Goldfield, is 3007 +/-3 Ma old, a figure which places a maximum constraint on the deposition of the Johannesburg Subgroup. Six of the zircons analysed from the Johannesburg Subgroup have almost concordant isotope ratios ($<$ 1,4% discordant) and only two grains were $>$3% discordant.

D. Turffontein Subgroup

A total of 20 zircons from 4 selected conglomerate horizons in the Klerksdorp and Welkom Goldfields were analysed. Fifteen zircons yielded ages that fall in the same broad range as those from lower stratigraphic levels (i.e. 3152-3003 Ma), but a distinct population of 5 zircons yielded younger 207 Pb/206 Pb ages in the range 2958-2894 Ma. The geometric mean of the Turffontein Subgroup zircon ages is 3027 Ma (Table 2). The youngest zircon in the entire data set was derived from the Eldorado Formation at the Loraine Mine, and although discordant, yielded an age of 2894 Ma. The next youngest zircon, at 2909 +/-3 Ma, is concordant and provides a reliable maximum age constraint for deposition of the Turffontein Subgroup.

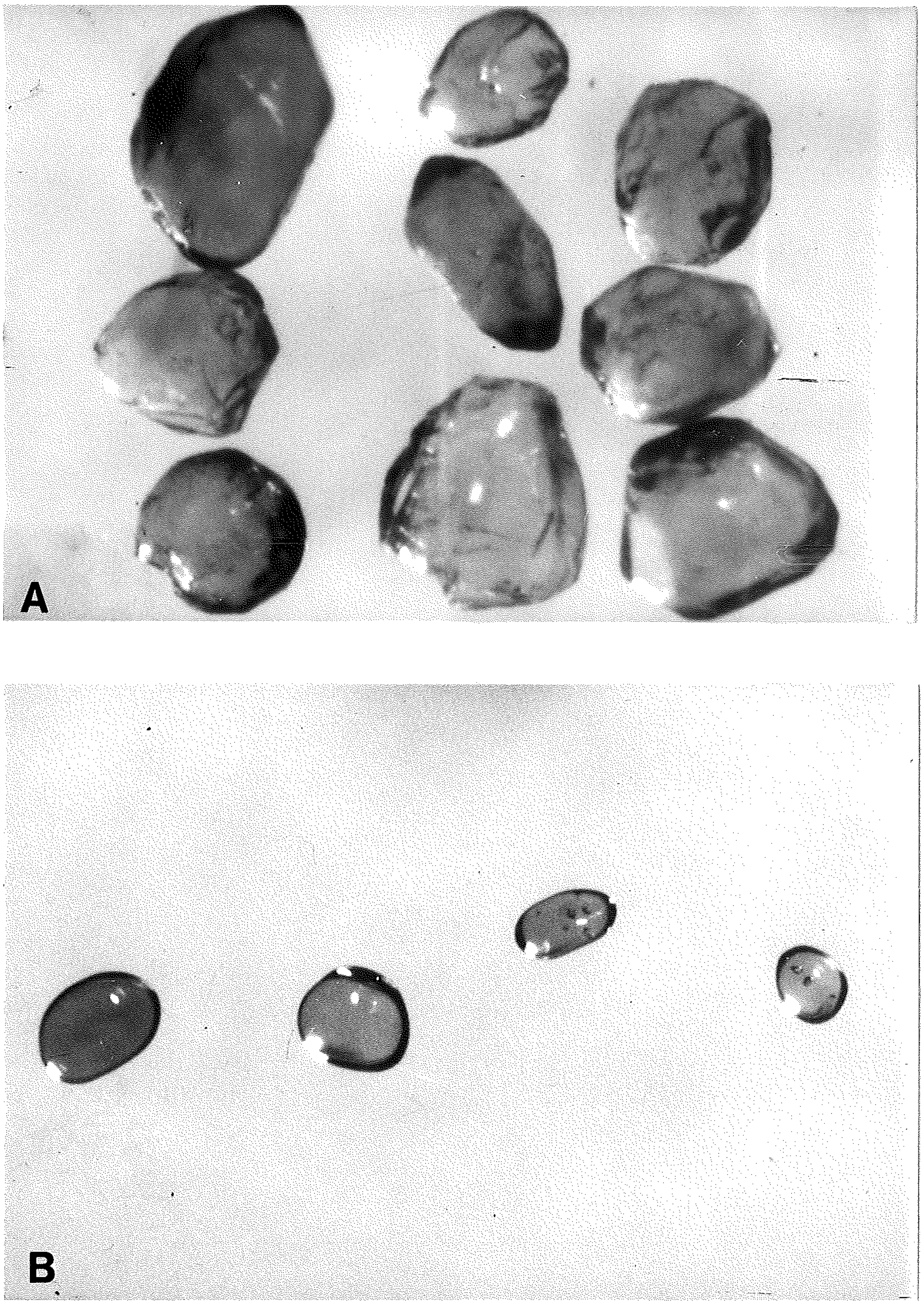

Figure 5: Zircon grains from the Dominion Reef at the Afrikander Leases Mine: A. "best-picked" sub-rounded, pre-abraded population: B. final selection of four abraded zircon grains.

TABLE 2

SUMMARY OF U-Pb AGES (Ma) FOR SINGLE DETRITAL ZIRCON AND MONAZITE GRAINS FROM VARIOUS STRATIGRAPHIC UNITS IN THE WITWATERSRAND AND DOMINION SEDIMENTS

	Dominion Group	West Rand Group	Johannesburg Sub-Group	Turffontein Sub-Group	Total Population
Sample size	8	10	8	20	46
Average	3153	3098	3079	3028	3074
Median	3164	3063	3073	3042	3073
Mode	3186	3059	3073	3054	3059
Geometric mean	3153	3097	3079	3027	3073
Variance	1471	6232	3755	4753	6260
Standard deviation	38.4	78.9	61.3	68.9	79.1
Standard error	13.6	25.0	21.7	15.4	11.7
Minimum	3105	3044	3007	2894	2894
Maximum	3191	3305	3207	3152	3305
Range	86	261	200	258	411
Skewness	-0.25	2.41	1.36	-0.44	0.20
Kurtosis	-2.36	6.15	2.44	-0.41	1.06

5. DISCUSSION

As a method of defining the age of a sedimentary provenance, detrital zircons are extremely useful, although subject to a number of potential biases. Firstly, the zircons will only provide the age of zircon-bearing lithologies in the source area, and there is, therefore, likely to be a bias towards felsic compositions. Secondly, the necessity for producing near-concordant data points in order to obtain reliable ages requires that only absolutely clear, crack-free grains with no evidence of alteration are chosen for analysis, and these normally constitute only a very small fraction of the zircon population. In addition, the analyses are made easier by choosing the largest possible grains, although some attempt was made in this study to also analyse the smaller fractions.

Finally, because conventional isotope analysis of zircons is time-consuming and expensive, only a limited number of grains can be analysed from each unit. Consequently, the detrital grain age distribution obtained in this study represents only a fragmentary glimpse of the age distribution for the provenance of the Witwatersrand and Dominion sediments. Nevertheless, they provide important constraints on the timing of sedimentation, and on the age distribution in the source area.

A. Constraints on the Age of Sediment Deposition

The youngest concordant zircon in each sedimentary unit provides an estimate of the maximum age of deposition of that unit. The reliability of such an age constraint depends on a number of factors, including: (1) whether or not the youngest zircon has in fact been analysed; (2) the lapse in time between the last magmatic event in the hinterland and the onset of sedimentation; and (3) the rapidity of uplift in the source area and the time elapsed before erosion and transferral of detritus into the depository. The factors may combine to reduce the efficacy of depositional age estimates from the youngest obtained zircon age. Nevertheless, the present data provide several additional constraints over previous estimates even though the youngest zircon ages may still be considerably older than the true onset of sedimentation.

Dominion Group sedimentation post-dates 3105 +/-3 Ma, the age of the youngest detrital monazite and is, therefore, bracketed between 3105 +/-3 Ma and 3060 +/-9 Ma, the latter representing the age of the overlying Dominion lavas (Armstrong et al., 1989).

Sedimentation in the West Rand Group must post-date the underlying Dominion lavas. The youngest reliable age from the West Rand Group is 3060 +/-2 Ma, although if lead loss from the zircons was recent, deposition may have post-dated 3044 Ma. The rutile age from the West Rand Group presumably represents a later hydrothermal event at about 2600 Ma. This age is unfortunately too young to place a useful lower limit on sedimentation. Initiation of upper Witwatersrand sedimentation in the Johannesburg Subgroup post-dated 3007 +/-3 Ma, while the youngest reliable detrital age from the overlying Turffontein Subgroup is

2909 +/-3 Ma. Deposition of the upper part of the Witwatersrand Supergroup is therefore bracketed between 2909 +/-3 Ma and 2700 Ma, the age of the overlying Ventersdorp Group lavas (Armstrong et al., 1986).

The age constraints discussed above are to a certain extent dependent on the accuracy of the 3060 Ma age (Armstrong et al., 1989) for the Dominion lavas. If these lavas are younger (i.e. 2800 Ma), as suggested by the data of Van Niekerk and Burger (1969), then all of the zircons presently analysed from the Dominion and Witwatersrand sediments could have been derived from granites constituting the floor to these sequences. The older 3060 Ma age for the Dominion lavas is, however, supported by the present study because detrital zircon and monazite grains in the underlying sediments are invariably older than 3100 Ma. Had the Dominion lavas been significantly younger than 3060 Ma it is likely that at least some of the detrital grains in the underlying Dominion sediments would have been as young (i.e. 3100-2800 Ma) as those abundantly evident in the detritus of the West Rand and Central Rand Groups.

It is also relevant to consider the age constraints outlined above in terms of the ages of basement granites which underlie either the Dominion or West Rand Groups. In the Vredefort structure (Figure 2), vertical to over-turned Dominion and West Rand sediments rest unconformably on the 3080 Ma Outer Granite Gneiss, whose Rb-Sr systematics appear to have been reset some 3000 Ma ago (Hart et al., 1981; Figure 3). In the Johannesburg dome, the West Rand Group unconformably overlies the Linden tonalite dated at 3170 Ma (Anhaeusser and Burger, 1982), but which is also reset in the Rb-Sr system at 2268 Ma (Barton et al., 1986). In the Hartbeesfontein area (Figure 2) the Dominion sediments unconformably overlie a granite which yielded a U-Pb zircon age of 3119 Ma (R.A. Armstrong, pers. comm.). These granitoid ages are all consistent with Dominion sediments being deposited onto a basement that was at least as old as 3080 Ma, the age of the Outer Granitic Gneiss in the Vredefort structure. If the latter age is accurate then the deposition of Dominion sediments can be further constrained to between 3080 and 3060 Ma. However, along the northern flank of the Westerdam dome (Figure 1) the West Rand Group appears to unconformably overlie a granite which, where sampled in the centre of the dome, yielded whole rock Pb-Pb and Rb-Sr ages of 2810 +200/-220 Ma and 2759 +/-120 Ma, respectively (Barton et al., 1986). Although relatively imprecise, these ages appear to indicate that West Rand Group deposition commenced sometime after approximately 2800 Ma ago. This constraint is at variance with the age limits presented above, where it is suggested that West Rand Group deposition was terminated by approximately 2900 Ma ago. Furthermore, it is also apparent from the present data that no young zircons (i.e. in the range 3000-2900 Ma) were detected in either the West Rand Group or even in the Johannesburg Subgroup. This indicates that no young granites (i.e. <3000 Ma) were present, or had been unroofed, during deposition of the West Rand Group. Consequently, it is suggested that the existing whole rock ages from the Westerdam dome may reflect isotope resetting, as evident in many of the other granitoids in the region, and that the true age of this granite pre-dates the maximum age of West Rand Group deposition (i.e. 3044 Ma; Figure 3). Alternatively, it is also possible that the portion of the Westerdam dome that was actually dated intrudes and post-dates the basement upon which the West Rand Group was deposited.

B. Distribution of Zircon Ages

The pattern of ages in detrital grains throughout the Witwatersrand and Dominion sequences is remarkably consistent considering the small number of grains analysed from each unit. This pattern has important implications which are relevant to the magmatic and tectonic evolution of the region.

A frequency distribution pattern for the zircon (and monazite) ages obtained in the present study is presented in histogram form in Figure 6. Rather surprisingly for a diverse population, the zircon ages define a normal distribution with high kurtosis, in which the various measures of central tendency are all remarkably similar (Table 2). The geometric mean of the data is 3073 Ma and close to 45% of the population fall within +/-30 Ma of the mean. The range of ages spans 411 Ma, from 3305 to 2894 Ma.

If the zircon population is assumed to be a representative random sample, the data imply that a significant proportion (i.e. nearly one half) of the Witwatersrand hinterland was formed over a relatively short 60 Ma time span between 3105 Ma and 3045 Ma ago. This time span coincides with (but may not necessarily be genetically related to) an event in the Barberton Mountain Land, referred to as the Second Magmatic Cycle, during which time voluminous sheet-like granodioritic - to - adamellitic batholithic complexes were emplaced at an intermediate level of the crust (Anhaeusser and Robb, 1981). A smaller proportion (approximately one third) of the Witwatersrand hinterland appears to have been composed of older granitoids (i.e. >3105 Ma), which formed the floor to both Dominion and Witwatersrand sediments. A small proportion of the hinterland also appears to have been made up of younger granites whose ages fall in the range 3025-2900 Ma and which appear to have been emplaced synchronously with Witwatersrand deposition. The frequency distribution of zircon ages questions the contention of Barton et al. (1988) that the age distribution of Witwatersrand hinterland granites is essentially bimodal, and represented by two events at circa 3050 Ma and 2800 Ma.

A second age distribution pattern, which is evident in Table 2, indicates that mean zircon ages systematically decrease with stratigraphic height in the Dominion and Witwatersrand sequences. In a plot of relative stratigraphic height versus zircon and monazite ages, this trend is emphasized by the regression curve through the youngest zircon with the most reliable (concordant) age at each stratigraphic level (Figure 7). This trend has important implications for certain of the pre-existing notions concerning the origin of the Witwatersrand sediments.

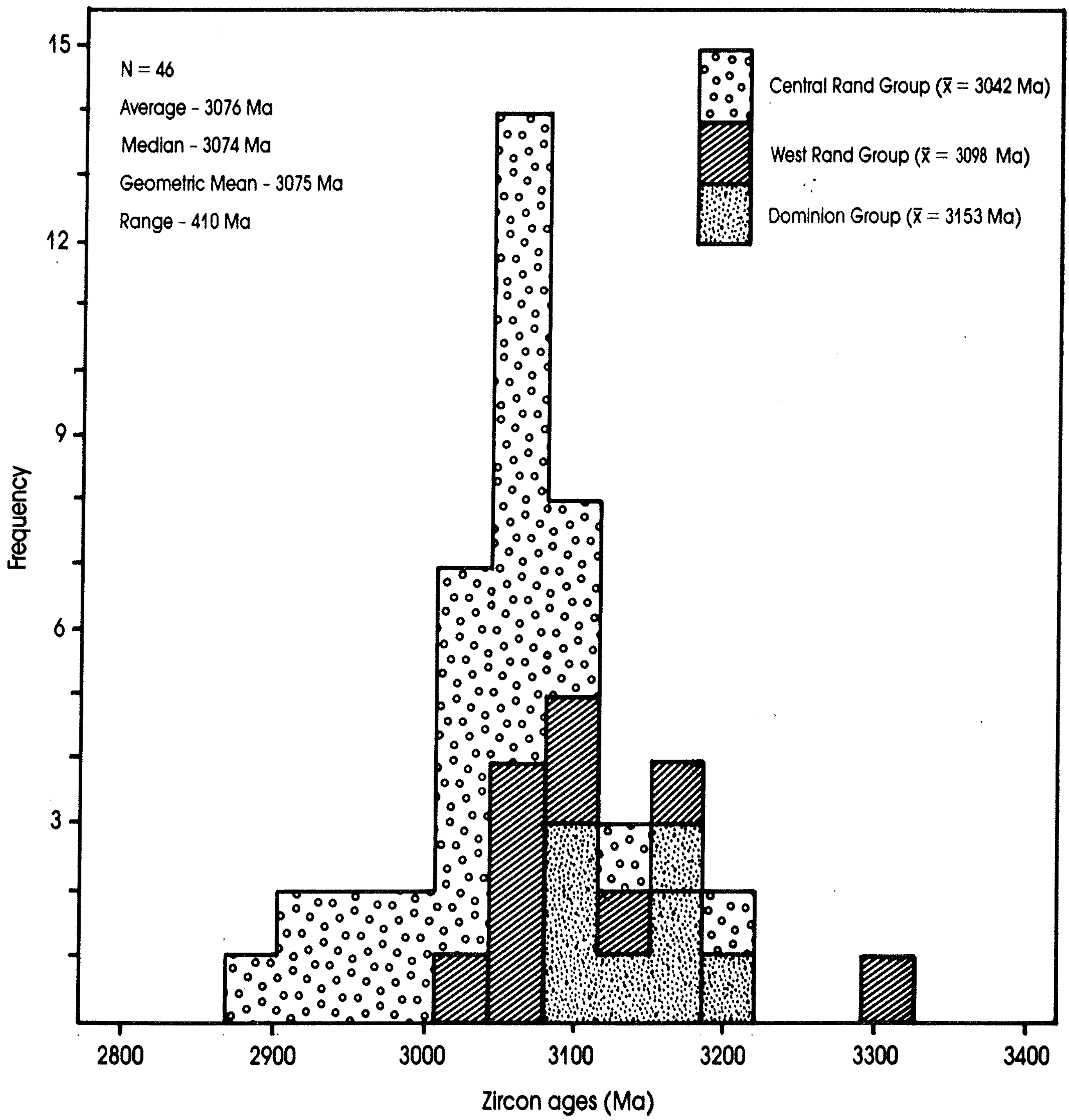

Figure 6: Frequency histogram showing the distribution of single, detrital zircon ages from the Dominion and Witwatersrand sequences.

The "inverted stratigraphy" model (Pretorius, 1976; Viljoen et al., 1976) regarded the Dominion and West Rand Group sediments as having been derived from the erosion of high-level, evolved granite-greenstone crust. Continued erosion of deeper crustal levels during Central Rand Group deposition would have exposed the basal, auriferous greenstone successions as well as the, generally older, tonalite-trondhjemite suite of granites. The younging of zircon ages upwards in the stratigraphy (Figure 7) militates against the inverted stratigraphy model and argues in favour of detritus being derived from unroofing and erosion of successively younger granites as the basin developed. This suggests that younger granites may have been emplaced at some stage during or subsequent to the deposition of the earlier sedimentary successions. In this case Witwatersrand deposition must have been intimately related to the magmatic, as well as tectonic, evolution of the hinterland, and sedimentation would probably have followed closely after emplacement of the most recently formed source rocks. Although the true depositional ages are still somewhat loosely constrained, it is apparent in this scenario that many of the Witwatersrand source rocks post-date formation of the Dominion Group and are at least synchronous with West Rand Group deposition. Alternatively, the younging trend observed in the ages of detrital grains may also be explained if the crust evolved by a process of downward vertical accretion and successively deeper crustal levels were subsequently exposed through continued erosion of the hinterland. A profile of this nature has recently been demonstrated by Corfu (1987) for portions of the Superior Province, where successively deeper crustal levels were characterized by a systematic decrease in the ages of granitoid emplacement.

C. Ages of Provenance Areas

Marked differences in the age, and presumably in the nature, of provenance areas to different portions of the Witwatersrand Basin are apparent in both the lateral and vertical distribution of zircon ages. These differences are exemplified in the three samples obtained from the Promise Reef in the West Rand Group (Figure 1). Conglomerate samples from the Promise Reef in the Randfontein and Carletonville area yielded zircons whose ages all fall in a fairly tight range between 3099 Ma and 3044 Ma. The Promise Reef sample obtained from the Klerksdorp area, however, yielded zircons of entirely different age, falling in a range between 3305 and 3060 Ma (Figure 3). The source area shedding detritus into the Promise Formation in the Klerksdorp region would appear, therefore, to have been significantly older than the area being eroded further to the east. Detailed mineralogical studies of the Promise Reef have also shown that the heavy mineral assemblage in the Klerksdorp area contains a higher proportion of chromite compared to the same conglomerate in the Randfontein area which is characterized by a higher relative proportion of zircon (Meyer, 1983). The Klerksdorp hinterland during West Rand Group deposition may, therefore, have comprised a significant component of older, relictual, granite-greenstone crust compared to a younger, more evolved, granitoid hinterland further east.

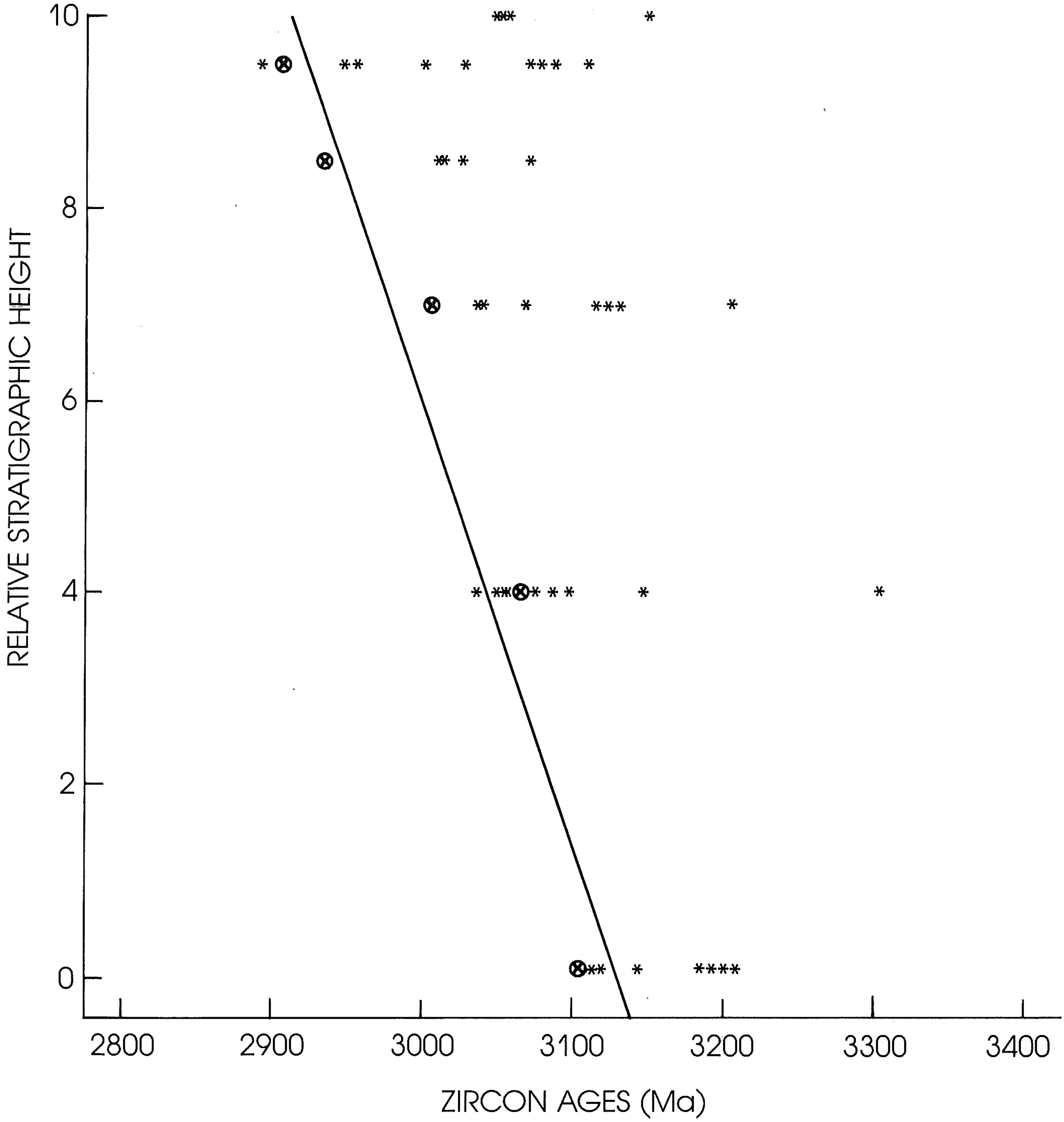

Figure 7: *Plot of zircon ages versus relative stratigraphic height. Encircled crosses represent the youngest, near-concordant zircon age from each stratigraphic horizon (with the exception of the uppermost unit, the Ventersdorp Contact Reef, in which no young zircons were detected).*

The Ventersdorp Contact Reef from the South Roodepoort Mine is the highest stratigraphic unit sampled. According to the trend in Figure 7, this unit might have been expected to yield some of the youngest zircons. This is not, however, the case and zircons from this locality are significantly older (i.e. 3152-3054 Ma) than several grains from the Turffontein Subgroup sampled further west in the basin (Figure 3). Thus, although a suite of younger granites was apparently shedding detritus into the westerly portions of the upper Witwatersrand Basin, the same granites did not appear to exist in the provenance area of the Turffontein Subgroup in the central portions of the basin.

D. Evolution of the Granitic Crust in the Witwatersrand Basin Hinterland

Formal chronostratigraphic subdivisions in the Archaean Eon of southern Africa (Kent, 1981) recognize two eras termed the "Swazian" (>2870 Ma) and the "Randian" (2870-2620 Ma). Intrusives of the Swazian era are generally regarded as representing the basement complex upon which intracratonic sequences such as the Dominion and Witwatersrand sediments were deposited. Randian intrusives are younger in age and occasionally intrude early intracratonic sedimentary sequences, as in the case of the late granite plutons in Swaziland which cut the Pongola Supergroup (Robb, 1983). The new Dominion and Ventersdorp ages now available (Armstrong et al., 1986; 1989), as well as the age constraints for Witwatersrand deposition presented above, indicate that the existing Archaean chronostratigraphic subdivisions applicable to the Kaapvaal Craton require expansion and modification.

In the present study the evolution of the granitic crust in the Witwatersrand Basin hinterland is considered in the light of the zircon age distribution, and presented in terms of a four-fold subdivision of granite-forming episodes. This subdivision is proposed, not so much as an alternative to the existing chronostratigraphic subdivision , but more as a basis for considering the relationships between crust-forming processes in the Witwatersrand hinterland and the depositional responses within the basin itself.

(i) Pre-Dominion granites (>3105 Ma): a significant proportion of the granites in the Witwatersrand hinterland clearly qualify as "basement" and pre-date the 3105 Ma depositional maximum provided by the present data set for the Dominion sediments. Granites in this category are widespread in the Kaapvaal Craton and are well developed in the Barberton Mountain Land and portions of Swaziland (Anhaeusser and Robb, 1981). They were emplaced during the early stages of the formation and stabilization of the Archaean crust.

(ii) Dominion granites (3105-3044 Ma): it is apparent from the frequency distribution of zircon ages that a major crust forming event occurred in the Witwatersrand hinterland at 3075 +/-30 Ma. The age of the Dominion lavas at 3060 +/-18 Ma (Armstrong et al., 1989) falls within this bracket, indicating that this event is represented, not only by granitoid plutonism, but also by extrusive volcanic activity. It is pertinent to note that the Syferfontein Formation of the Dominion Group is dominated by lavas of acidic composition, suggesting that some of the granites forming at this time may have had extrusive and/or sub-volcanic equivalents in the Dominion sequences.

(iii) Randian granites (3044-2718 Ma): the constraints on Witwatersrand deposition outlined above (Figure 3) also imply that a significant number of crust-forming events occurred synchronously with Witwatersrand sedimentation. A number of zircons from the Central Rand Group yield ages that fall within the time span inferred for lower Witwatersrand deposition (i.e. 3044-2894 Ma; Figure 3). Furthermore, at least 5 zircons with ages <3000 Ma were detected within the Turffontein Subgroup, indicating that granites supplying this detritus were either not present, or had not been unroofed, prior to deposition of this sequence. It is also apparent in Figure 3 that ages obtained from the hinterland granites themselves also suggest that certain intrusions may even have been synchronous with upper Witwatersrand deposition. The Schweizer-Reneke and Westerdam domes have, for example, yielded imprecise whole-rock ages of circa 2800 Ma (Barton et al., 1986). Although the Westerdam age may have been isotopically reset (see earlier), there is no evidence to suggest that the Schweizer-Reneke granite was not actually emplaced 2780 Ma ago (Figure 3), and is, therefore, a syn-Turffontein Subgroup intrusion.

(iv) Ventersdorp granites (< 2718 Ma): the onset of volcanic activity at 2700 Ma (Armstrong et al., 1986; 1989) signalled the beginning of a craton-wide magmatic event apparently triggered by subduction-related melting of a mantle source (Crow and Condie, 1988). Although no granitoids in the environs of the Witwatersrand Basin hinterland have as yet yielded ages of <2700 Ma, a number of plutons from elsewhere in the Kaapvaal Craton have provided imprecise whole-rock ages that are broadly synchronous with, or post-date, the Ventersdorp event (Barton et al., 1983; De Gasparis, 1967; Oosthuysen, 1970).

If subduction processes are generic to the Ventersdorp event, it is likely that a number of related felsic intrusions will also eventually be identified in the Witwatersrand hinterland.

E. Inferences Regarding the Origin of Witwatersrand Gold

The prodigious amount of gold in the Witwatersrand Supergroup and the large accumulations of detrital pyrite and vein quartz, suggests that the original source of gold may have been related to a vast hydrothermal system in the hinterland (Robb and Meyer, 1989). The wide spectrum of ages obtained from detrital zircons in the Witwatersrand sediments permit certain constraints to be placed on the origin of the gold source.

With the exception of one zircon grain from the Promise Reef, all the detrital zircon ages are younger (i.e. <3207 Ma) than the Onverwacht Group volcanics and the early tonalite-trondhjemite gneiss (TTG) plutons in the Barberton Mountain Land, which typically fall in the range 3450-3230 Ma. This strongly suggests that the detritus feeding into the Witwatersrand Basin, and hence the gold too, was not derived from the early Archaean granite-greenstone terranes of the Kaapvaal Craton, but from a younger more evolved source. It is also apparent in Figure 3 that the Dominion, West Rand and Central Rand Groups all contain zircons which display a commonality of ages ranging between 3200-3050 Ma. Despite this overlap, it is clear that the Central Rand Group is unique in that it is the only sequence containing zircons with ages that are younger than 3040 Ma.

Since the overwhelming majority of Witwatersrand gold stems from the Central Rand Group, and the underlying successions are comparatively barren, it is reasonable to suggest that an age determinant applies to considerations of the primary source of gold. Thus, not only was the Witwatersrand gold source largely unrelated to Onverwacht volcanism and early TTG plutonism, but it appears to be linked to an event which coincided with the emplacement of granitoids that are younger than circa 3000 Ma, but older than approximately 2700 Ma.

Two further considerations appear to be relevant in attempting to understand the relationships between Archaean and Witwatersrand metallogenesis. Firstly, if the source of gold is to be linked to the emplacement of <3000 Ma old granitoids, then some evidence is required that indicates that such granitoids were a viable source rock. Recent work has, in fact, shown that many Witwatersrand hinterland granites are characterized by hydrothermal, vein-related alteration and are enriched in gold over typical background values (Hallbauer, 1984; Klemd and Hallbauer, 1987; Robb and Meyer, 1989). Although most of these hydrothermally altered granites have not been accurately dated, preliminary zircon work (Robb and Davis, in prep.) indicates that many of them do fall in the range 3000-2700 Ma, a feature also supported by the available whole-rock Rb-Sr and Pb-Pb age determinations (Barton et al., 1986). These fertile granites may, therefore, have represented a voluminous source of low-grade gold for the Witwatersrand deposits. It is also feasible that these granites were the origin and stimulus for high-level epithermal gold mineralization that was subsequently rapidly eroded into the adjacent depository (Robb and Meyer, 1989).

Secondly, it is now apparent that most of the major Canadian and Western Australian lode gold deposits come from late Archaean, bimodal "rift phase" greenstone belts such as the southern Abitibi belt in the Superior Province (Ludden et al., 1986) and the Norseman-Wiluna belt of the Yilgarn Block (Groves and Batt, 1984). In southern Africa the Kaapvaal Craton had, by 3000 Ma ago, evolved to the extent that stable intracratonic platformal sequences such as the Dominion, Pongola and Witwatersrand basins were being deposited. The late Archaean (2800-2700 Ma) greenstone belts typical of the Superior and Yilgarn cratons did not form on the Kaapvaal block and this period of time was already marked by the termination of Witwatersrand deposition and the inception of Ventersdorp flood-basalt volcanism. However, the Witwatersrand Basin hinterland does consist of a number of linear, essentially north-south trending, greenstone belts (Figure 2) whose ages are unknown. These greenstone belts, which are known to contain minor, largely BIF-hosted, gold mineralization (Vearncombe, 1986), may have formed in response to a rift-related event in the Witwatersrand hinterland at some time prior to Central Rand Group deposition. Although speculative, it is conceivable that the copious felsic magmatism indicated by the peak of zircon age distributions at 3075 +/-30 Ma (Figure 6) was also accompanied by basaltic volcanism, remnants of which are preserved in the isolated greenstone remnants of the Witwatersrand hinterland (Figure 2). The development of late, rift-related greenstones in the western Kaapvaal Craton, which together with their gold deposits may have been substantially eroded away, may be an element in the Witwatersrand source-area enigma that has been largely overlooked. Attempts to date zircons from felsic volcanic units in the Amalia greenstone belt within the Schweizer-Reneke pluton (Figure 2) are currently underway.

6. CONCLUSIONS

In summary, certain of the traditional viewpoints concerning the relationship between the Witwatersrand depository and its hinterland are challenged by the data presented above. In particular, static concepts, such as the belief that the granite basement invariably represents the floor to the Dominion and Witwatersrand sequences no longer apply, and clearly, a significant proportion of the granitoid crust in the hinterland formed in post-Dominion times and synchronously with Witwatersrand deposition. The notion of inverted stratigraphy, whereby successively younger depositional units are derived from older, deeper crustal levels, is now also open to modification and it appears likely that successively younger sequences may have formed soon after the emplacement of the most recent, syn-depositional granitoids. It is also now unlikely that the early Barberton-type volcanic assemblages and the primitive TTG plutonic suites - previously considered to represent the most viable primary gold source - contributed much towards Witwatersrand mineralization, and detritus appears to have been derived largely from a younger, more evolved source. In particular it is significant that the $<$ 3000 Ma zircons detected in the Central Rand Group were not found in the underlying successions. The primary source of gold may, therefore, be related to the emplacement of fertile granitoids emplaced after 3000 Ma ago. Single detrital zircon ages reveal a continuum of crust-forming events suggesting that the source area was evolving concomitantly with the deposition of sediments. A mobilistic scenario, in which a succession of unconformity-bound sedimentary packages formed the depositional responses to on-going tectono-magmatic events in the hinterland, may form the basis for future work in the Witwatersrand Basin.

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