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Dating detrital zircon from the gold-bearing Ventersdorp Contact Reef in the Ventersdorp Supergroup of South Africa

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ABSTRACT

The Ventersdorp Contact Reef (VCR) at the base of the >4.5 km-thick volcanosedimentary Ventersdorp Supergroup unconformably overlies the Witwatersrand Supergroup and is the second youngest mineable reef in the Witwatersrand Goldfields. The volcanic rocks of the Ventersdorp Supergroup are predominantly mafic, affected by low-grade thermal metamorphism and difficult to date. Only the Makwassie Formation in the upper Platberg Group of the main Ventersdorp repository has been reliably dated on four felsic volcanic samples at 2720 ± 2 Ma. The actual timing of Ventersdorp volcanism and the duration of the three recognised lithostratigraphic groups remains enigmatic, despite much research and heroic attempts to synthesize the available data.

In this work detrital zircon grains from VCR conglomerates were U-Pb dated in order to improve the time constraints on the Klipriviersberg Group at the base of the Ventersdorp Supergroup. The six youngest grains in VCR samples were reliably dated at 2799 ± 9 Ma. The Klipriviersberg Group and the Ventersdorp Supergroup is thus younger than 2808 Ma and the supergroup is older than the 2642 Ma Vryburg Formation at the base of the Transvaal Supergroup.

Comparisons of detrital grain dates confirm that the VCR was largely derived from erosion products of the underlying Witwatersrand Supergroup, however the youngest VCR grains are ~20 Ma younger and may have been derived directly from magmatic rocks in the provenance or a felsic facet of the synchronous komatiitic Klipriviersberg volcanism.

Multi-grain analyses of discordant grains show that recent lead loss is predominant. However about 5% of the data show the effect of complex Mesoproterozoic lead loss, which can yield ages as much as 150 Ma too young in 10% discordant data. This was found in grains with high Th-induced radiation damage, providing a criterion for data rejection.

The proposed large igneous provinces dated between 2791 and 2683 Ma, based mainly on dated mafic dykes, which are not in contact with supracrustal Ventersdorp rocks, do fit the established time constraints and might provide a key to Ventersdorp chronostratigraphy. However only the proposed 2754–2709 Ma Platberg volcanic province is based on reliably dated Platberg Group volcanic rocks.

1. Introduction

The Archean Ventersdorp Supergroup is a major volcanic and sedimentary sequence with recorded thickness of at least 4.5 km, which overlies the gold-bearing Witwatersrand Supergroup in South Africa. It is probably the most-drilled sequence in the world due to exploration for deep-lying Witwatersrand gold reefs over the past 150 years (Figs. 1 and 2).

Direct dating of the volcanic units in the Ventersdorp Supergroup is hampered by their generally mafic to komatiitic compositions which were undersaturated in zircon, so that zircon grains extracted from them are likely to be dominated by older xenocrysts. Only the intermediate to

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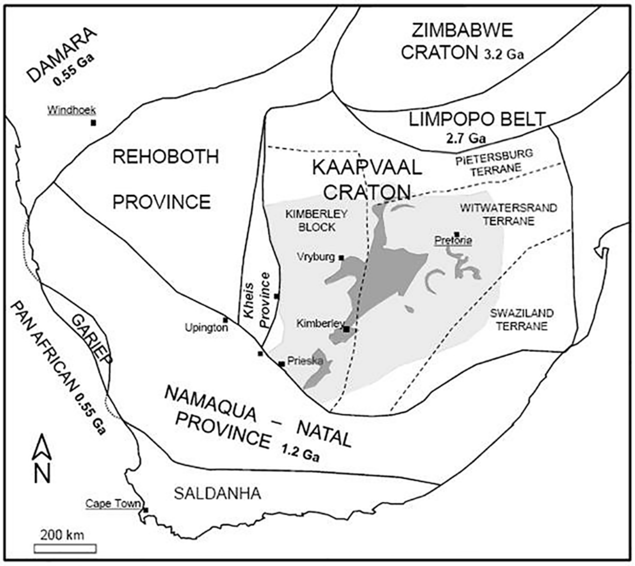

Fig. 1. Precambrian structural provinces of southern Africa and terranes of the Kaapvaal Craton, showing the outcrop area of the Archaean Ventersdorp Supergroup (dark shading) and the inferred suboutcrop area (light shading), after Cornell et al. (2017).

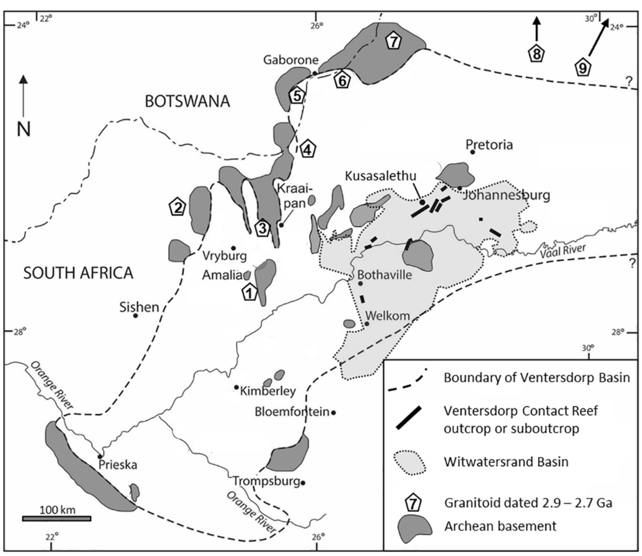

Fig. 2. The extent of the preserved (outcrop and suboutcrop) basins of the Witwatersrand and Ventersdorp supergroups on the Kaapvaal Craton of South Africa after McCarthy (1994) and Van der Westhuizen et al. (2006) respectively. The known occurrences of the Ventersdorp Contact Reef (VCR) are shown after McCarthy (1994) and the locality of Kusasalethu Mine is shown, from which the samples were taken. The numbered localities are granitoids dated between 2.9 and 2.7 Ga in the possible provenance area of the VCR, detailed in supplementary Table A1.

felsic lavas from the Makwassie and Goedgenoeg formations in the Platberg Group, which forms the middle to upper part of the Ventersdorp Supergroup, have yielded abundant magmatic zircon grains. Added to that is a regional greenschist facies thermal metamorphic imprint, which corresponds broadly in age to the 2.06 Ga Bushveld Complex. This event recrystallised igneous minerals and affected many isotopic systems in the Kaapvaal Craton (Cornell, 1978; Schweitzer and Kröner, 1985; Armstrong, 1987). Conventional U-Pb zircon dating gave ages between 2.64 and 2.24 Ga for the Makwassie Formation. The ion probe investigation of Armstrong et al. (1991) was for the first time able to target unaltered zircon age domains and revised the age to 2709 ± 4 Ma (reviewed by van der Westhuizen et al., 2006).

In a recent paper we established a precise U-Pb zircon date of 2720 ± 2 Ma for four rhyolite samples from the Makwassie Formation in the Platberg Group (Cornell et al., 2017). Gumsley et al. (2020) reported U-Pb baddeleyite ages for three mafic sills and a dyke which were emplaced by intrusion into the Witwatersrand and Pongola supergroups (Table 1). They correlated them with the Klipriviersberg and Platberg groups and postulated the existence of three mafic large igneous provinces (LIPs) and a felsic volcanic province, based on these data and a review of published precise ages of many intrusive and a few extrusive rocks. These are the 2791–2779 Ma Klipriviersberg LIP, the 2754–2709 Platberg Volcanic Province, 2709–2683 Ma Allanridge LIP and the 2664–2654 Ma White Mfolozi LIP.

This work reports U-Pb data for detrital zircon from the gold-bearing Ventersdorp Contact Reef (VCR), which lies at the base of the Ventersdorp Supergroup (Fig. 3), in an effort to better constrain the age of the supergroup and to interpret the source of sedimentary material. The VCR is a conglomerate which unconformably overlies the previously lithified and variably eroded Witwatersrand Supergroup, from which much of the gold was derived. The VCR conglomerates form part of the Venterspost Formation (Fig. 3), which includes interbedded komatiitic lavas, minor sandstones and shales. There has been debate about whether the VCR should be placed at the top of the Witwatersrand Supergroup or in the Klipriviersberg Group at the base of the Ventersdorp (reviewed by van der Westhuizen et al. 2006). The latter alternative is supported by the major angular and erosional unconformity beneath the VCR, as well as its intercalation in places and soft-sediment deformation by komatiitic basalts of the overlying Westonaria Formation (Hall et al., 1997).

The mineralogy of the VCR at the Kusasalethu (then named Elandsrand) Mine, from which our samples were collected, was described by Henckel and Schweizer (1994). The VCR consists mainly of quartz or quartz-chlorite pebbles, with a matrix consisting of quartz and chlorite, with variable amounts of pyrrhotite, chalcopyrite, galena. sphalerite, zircon, carbon, chromite and gold. They regarded the mineral assemblage to reflect major recrystallisation by hydrothermal processes, evidenced by the complete replacement of original clastic pyrite grains by pyrrhotite and chlorite, together with the occurrence of authigenic tourmaline and molybdenite. Zhao et al (1999) confirmed most of these minerals in samples from the adjoining Western Deep Levels mine by X-ray diffraction and also documented major amounts of muscovite, minor albite pyrite and rutile and trace epidote and calcite. They recognised four paragenetic stages of alteration starting with pyrite-pyrrhotite-sphalerite assemblages and ending with quartz-calcite veining. They obtained K-Ar isochron ages between 1994 and 1917 Ma, which they ascribed to resetting by 350–290 °C hydrothermal alteration, broadly coeval with the intrusion of the ~2054 Ma Bushveld Complex and the ~2020 Ma Vredefort impact event.

Ion probe data for 20 detrital zircon grains from the VCR were reported by Barton et al. (1989). The age of the youngest grain (5.1) was cited by Gumsley et al. (2020) as 2780 ± 5 Ma, but that age is actually 2776 ± 102 Ma (2σ) and the point is 65% discordant. The youngest concordant grain (6.1) has an $^{207}Pb/^{206}Pb$ age of 2842 ± 80 Ma (2σ) and our re-evalution of the data gives 2785 ± 56 Ma (Table 1). This unit needs revisiting, as it can provide a useful age constraint on the lowermost Ventersdorp strata as well as its provenance.

2. Sample descriptions

Ventersdorp Contact Reef (VCR) conglomerate samples from the different reef types Kusasalethu Mine were kindly supplied by Mr Johann Ackermann of Harmony Gold Mining Co. Ltd. They were arbitrarily labelled A to D. The samples comprise mainly pale to dark quartz pebbles in a matrix dominated by quartz, and pyrite or pyrrhotite, as shown in supplementary Fig. A2.1. For zircon separation, sample D and

Table 1
Selected U-Pb zircon or baddeleyite (Bd) dates for the Ventersdorp Supergroup and possible correlates. Only supracrustal units and selected intrusive sills are listed. Bold type indicates reliable magmatic age in our opinion. Italics indicate confident correlation with the Ventersdorp sensu stricto formations. Dates in brackets are regarded as imprecise or unreliable. Dates for granitoids in the possible provenance of the VCR are listed in supplementary Table A1. A comprehensive list including intrusive rocks and rocks from outside the Ventersdorp repository can be found in Gumsley et al. (2020).

No.	Unit Dated	Age Ma	±2σ Ma	Method	Comments	Reference
1	Lower Makwassie Formation	(2709)	4	Ion probe $^{207}Pb/^{206}Pb$	First hope for reliably dating the Ventersdorp, but high common lead and inconsistent with nos. 5,6,7	Armstrong et al. (1991)
2	Klipriviersberg Group	(2714)	16	Ion probe $^{207}Pb/^{206}Pb$	Minimum age, probable ancient lead loss	Armstrong et al. (1991)
3	***Kareefontein Fm., Zoetlief Gp. LNV014 Vryburg Area***	***2718***	***6***	***Laser Ablation ICPMS***	***Age of extrusion Makwassie Fm. correlate***	Cornell et al. (2017)
4	**Seekoebaard Formation conglomerate near Marydale**	**2720**	**4**	**Laser Ablation ICPMS**	**Single detrital zircon population dates volcanism, overlain by andesites which correspond geochemically to Allanridge Fm.**	Cornell et al. (2018)
5	**Upper Makwassie Formation FVM905, type area near Wolmaransstad**	**2722**	**6**	**Laser Ablation ICPMS**	**Age of extrusion**	Cornell et al. (2017)
6	**Lower Makwassie Formation FVM205_LLE Wolmaransstad Area**	**2721**	**6**	**Laser Ablation ICPMS**	**Age of extrusion**	Cornell et al. (2017)
7	**Upper Makwassie Formation VLF258, Vryburg Area**	**2723**	**6**	**Laser Ablation ICPMS**	**Age of extrusion**	Cornell et al. (2017)
8	***Phokwane Formation***	***2724***	***6***	***Ion probe $^{207}Pb/^{206}Pb$***	***Correlate of Makwassie Fm. Platberg Gp.***	***De Kock et al. 2012***
9	**Mafic sill in Witwatersrand Supergroup (PRGE)**	**2727**	**3**	**U-Pb TIMS Bd**	**Time correlate of Platberg Gp. but no field relations**	Gumsley et al. (2020)
10	***Paardefontein Formation near Amalia***	***2729***	***3***	***Ion probe discordia***	***Overlies Amalia Greenstone Belt, correlate of Makwassie Fm.***	Poujol et al. (2005)
11	***Mohle Formation, Taung Area***	***2733***	***8***	***Ion probe discordia***	***Correlate of Kameeldoorns Fm. Platberg Gp.***	De Kock et al. (2012)
12	***Ongers River Formation, Sodium Group***	***2739***	***(39)***	***Ion probe $^{207}Pb/^{206}Pb$***	***Duplicated with precision <10 Ma. Correlate of lower Platberg Group***	Altermann and Lenhardt (2012), ***Altermann personal communication with DHC***
13	Lower Goedgenoeg Formation FVM207_LLE Wolmaransstad Area	(2746)	9	Laser Ablation ICPMS	Probably xenocryst age, confirmed by new data in press.	Cornell et al. (2017)
14	Derdepoort outlier E of Gaborone	(2769)	2	Kober method $^{207}Pb/^{206}Pb$	Possible Klipriviersberg Gp., Ventersdorp Supergroup correlate	Walraven et al. (1996)
15	Felsite acribed to Kanye Formation in Derdepoort outlier E of Gaborone	(2781)	2	Ion probe $^{207}Pb/^{206}Pb$	Inferred age based on disputed field relations	Wingate (1998)
16	VCR Venterspost Fm. Youngest detrital zircon	(2785)	56	Ion probe $^{207}Pb/^{206}Pb$	Ventersdorp Contact Reef younger than this, superceded by no. 21	Barton et al. (1990) errors assessed by DHC using the original data.
17	**Middle Goedgenoeg (?) Formation LWS995, Wesselton Mine, Kimberley**	**2781**	**5**	**Laser Ablation ICPMS**	**Extrusion age, but not Goedgenoeg Fm. according to new data in press**	Cornell et al. (2017)
18	Kanye Formation (Lobatse Group) N. of Mafikeng, RSA	2781	2	Kober method $^{207}Pb/^{206}Pb$	Possible early Ventersdorp correlate, same samples as Moore et al. 1993	Grobler and Walraven (1993)
19	**Kanye Formation N. of Mafikeng, RSA**	**2785**	**2**	**Krogh Method U-PbTIMS**	**Possible Ventersdorp correlate but outside main repository**	Moore et al. (1993)
20	**Mafic sills in Witwatersrand Supergroup (AM1 & VJ1)**	**2787**	**2**	**U-Pb TIMS Bd**	**Geochemically similar to Klipriviersberg but no field relations**	Gumsley et al. (2020)
21	VCR Venterspost Fm. Youngest detrital zircons, multipoint data for 6 of 86 dated grains	2799	8	Concordia age for 17 points in 6 grains Laser Ablation ICPMS	Supercedes no. 16	This work
22	Lower Makwassie Formation LWS013, Wesselton Mine Kimberley	(2874)	16	Laser Ablation ICPMS	Interpreted as xenocryst age, one point gave 2711 ± 16 Ma	Cornell et al. (2017)

a combined A and C were processed.

3. Methods.

The samples were processed and mounted in epoxy pucks for U-Pb dating as described by Cornell et al. (2016, 2017) and the methods are documented in supplementary Table A3. Laser ablation multicollector ICPMS U-Pb analyses were done at the Department of Geosciences at Oslo University, Norway, as described by Andersen et al. (2009), with spot size of 40 µm. A second analytical run concentrating on the youngest grains was done by laser ablation quadrupole ICPMS at the University of Stellenbosch with spot size 25 µm, as described by Cornell et al. (2016). The data and radiation damage calculations are given in supplementary Table A6.

4. Results

Zircon grains were extracted and mounted from three conglomerate samples from the VCR. They are generally quite large grains (smallest 100x50, largest 400x400 microns) and most of them have a pink colour which does not seem to be correlated with age. Most grains were CL-dark as shown in Fig. 4 and only a few showed CL-brighter cores which could be older than the rims, e.g. grains 1 and 5.

The data from the first campaign at the University of Oslo are shown on a concordia diagram in Fig. 5. The points with youngest $^{207}Pb/^{206}Pb$ ages are discordant, and in the $^{207}Pb/^{206}Pb$ age histograms there is a shift to younger ages in the more discordant data. This suggests that some or all of the discordant points may have experienced ancient lead loss, which would decrease the $^{207}Pb/^{206}Pb$ ages. This aspect was further investigated in a second dating campaign which aimed to accurately

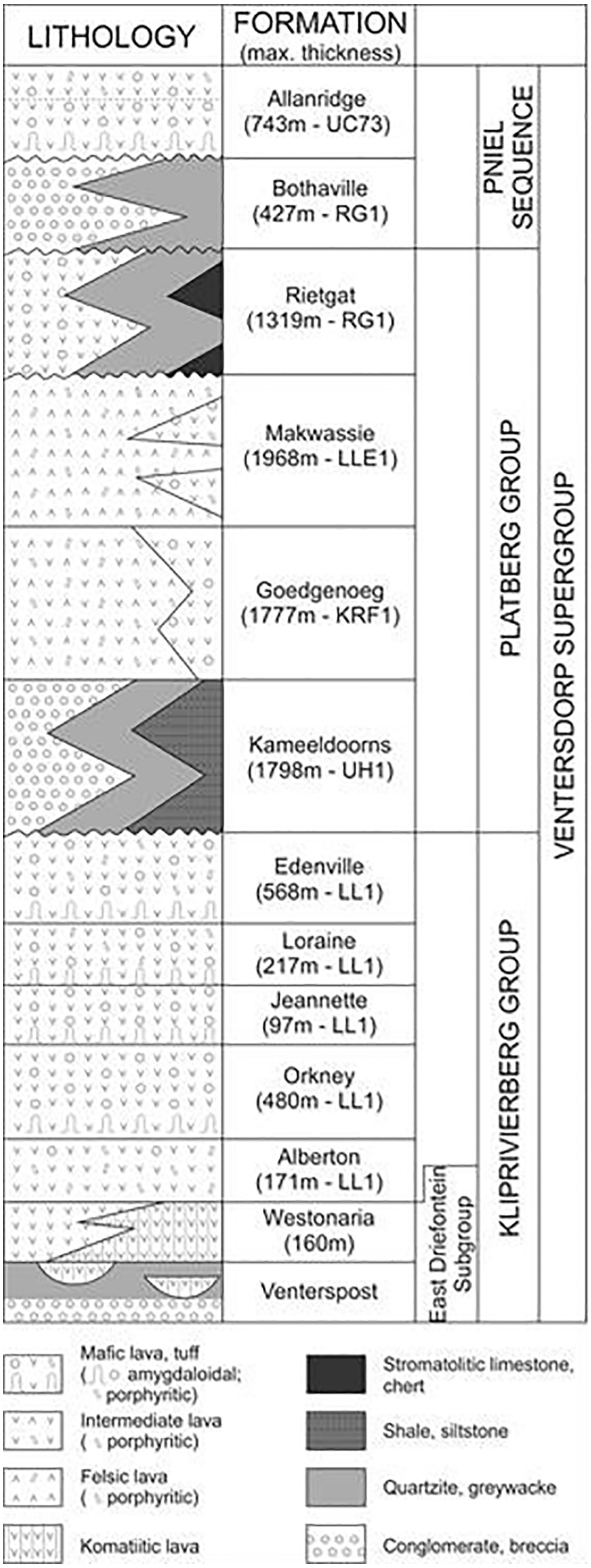

Fig. 3. Stratigraphy of the Ventersdorp Supergroup after Van Der Westhuizen et al. (2006) and references therein. The VCR is shown as conglomerate at the base of the Venterspost Formation, which lies unconformably on the Witwatersrand Supergroup. The Ventersdorp Supergroup is unconformably overlain by the Transvaal Supergroup.

define the age of the youngest grains. Eight grains, including six with the youngest $^{207}Pb/^{206}Pb$ ages, were dated at Stellenbosch University, analysing up to seven points in each grain. Fig. 6 and Table 2 shows the age calculations for each of these grains, for which the full data are given in supplementary Table A6.

5. Discussion

5.1. Age of youngest detrital zircon grains.

As shown in Table 2, the six youngest grains all yield concordia and discordia intercept ages close to 2800 Ma, the most precise being 2799 ± 14 Ma for grain D84. The discordia intercepts for 27 of the 33 points including 17 concordant ones yield an acceptable recent lead loss discordia line with upper intercept 2799 ± 11 Ma and the concordant points yield 2799 ± 9 Ma (Fig. 6A). This is a precise estimate of the age of youngest detrital zircon grains in the Ventersdorp Contact Reef.

To conclude, a reliable age for the youngest detrital zircon grains in this study of the Ventersdorp Contact Reef is 2799 ± 9 Ma. The VCR and the Ventersdorp Supergroup is younger than that. This supercedes the age of 2895 ± 22 Ma based on three imprecise ion probe analyses, reported by Barton et al. (1990).

5.2. Ancient lead loss in some domains

The six points which show complex ancient lead loss all have Th concentrations more than 170 ppm and U more than 350 ppm, whereas those conforming to recent lead loss have Th in the range 10–150 ppm and U 38–550, as shown in supplementary Fig. A2.2. Radiation dose calculations illustrated in supplementary Fig. A2.3 show that radiation damage due to Th provides a clear distinction between points which show recent lead loss ($n = 10$) or ancient lead loss ($n = 6$), whereas the total radiation dose due to U and Th is less definitive. Several grains yielded points with both types of discordance as well as concordant points ($n = 17$).

Can the ancient lead loss be related to geological events? The imprecise lower intercept of 818 ± 130 Ma, shown in Fig. 6, probably represents more than one event. Baughman and Flowers (2020) showed that the central Kaapvaal Craton had been at the surface about 1.4 Ga and buried beneath ≥ 3.7 km-thick sediment derived from mountains in the adjoining Namaqua-Natal Province after 1.2 Ga. This process and the subsequent denudation probably gave rise to complex lead loss in radiation-damaged zircon domains. Zircon dating of Ventersdorp Supergroup zircon grains has been plagued from the outset by lead loss and common lead problems. Our data shows that these can be resolved by well-controlled microbeam analysis and the acquisition of enough data.

5.3. Source of VCR zircon grains

Referring only to the < 10% discordant data in Fig. 6B and 7A and bearing in mind the histogram channel width of 20 Ma, there are major age groups at 3080–2960, 2940–2840 and 2800 Ma and minor groups at 3360–3300, 3200, and 3120 Ma. The obvious source for most of the VCR conglomerate is the unconformably underlying Central Rand Group of the Witwatersrand Supergroup, for which Kositcin and Krapež (2004) published a detailed study of detrital zircon U-Pb ages in eight samples from six formations, compiled data shown in Fig. 7B. Their data shows quite large differences in age histograms between and within formations, with varying similarity to that of the VCR. Their three samples from the Krugersdorp Formation, near the base of the Central Rand Group are a fairly good match for our VCR data (not shown). However, the three samples from Mondeor and Elsburg Formations near the top of the Central Rand Group do not correspond well, as two of them have a major peak at 3440 Ma, not seen in the VCR (not shown). The probability plot shown in Fig. 6B for the Eldorado Reef, uppermost mined reef in the Central Rand Group, using data from Koglin et al. (2010), also

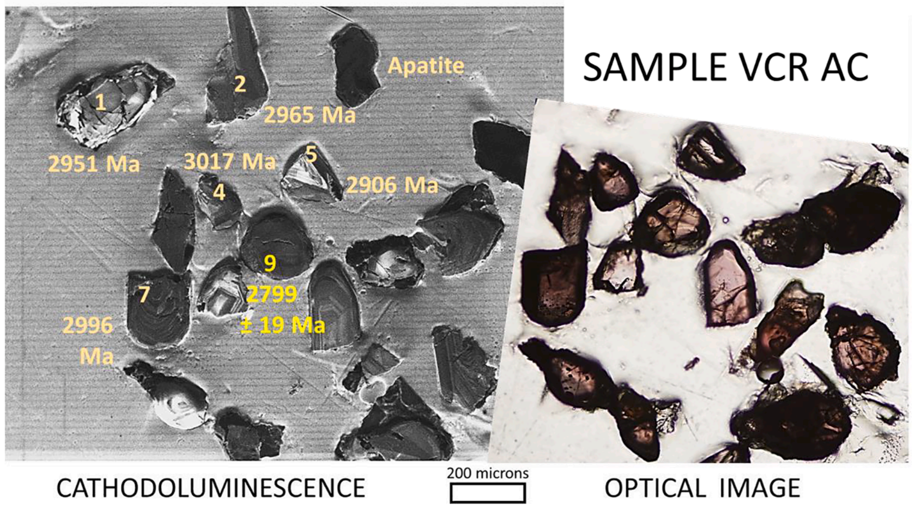

Fig. 4. Cathodoluminescent and optical images of zircon grains extracted from the Ventersdorp Contact Reef sample AC. Note the generally pink colour of the zircon grains, unrelated to age. $^{207}Pb/^{206}Pb$ ages are shown in tan font; shown in yellow is a multi-point concordia age.

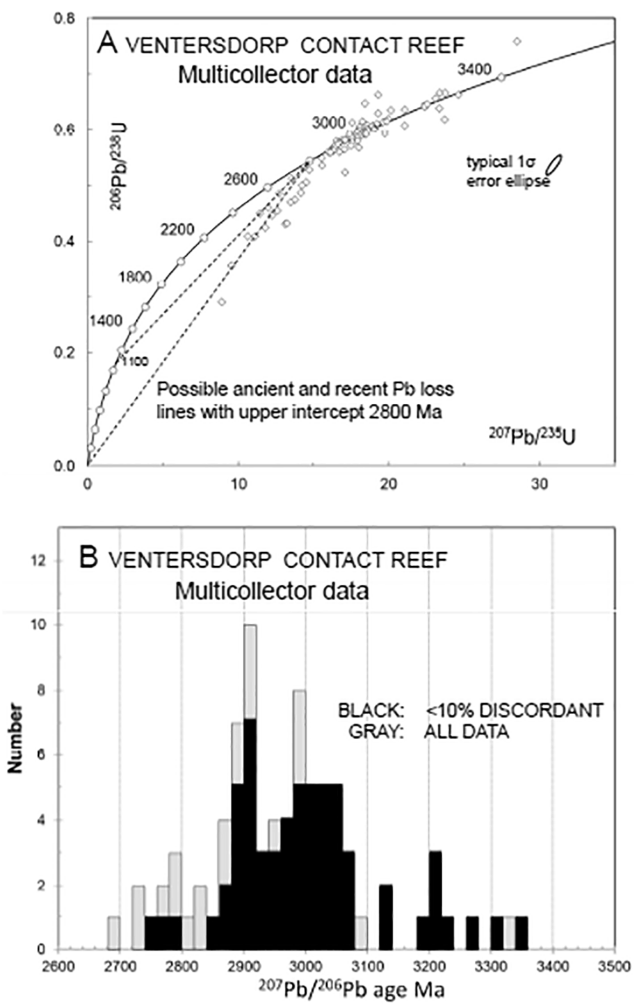

Fig. 5. Multicollector U-Pb data for detrital zircon grains from Ventersdorp Contact Reef samples AC and D. A: concordia diagram, B: histogram, showing $^{207}Pb/^{206}Pb$ ages for all data and data points with <10% discordance.

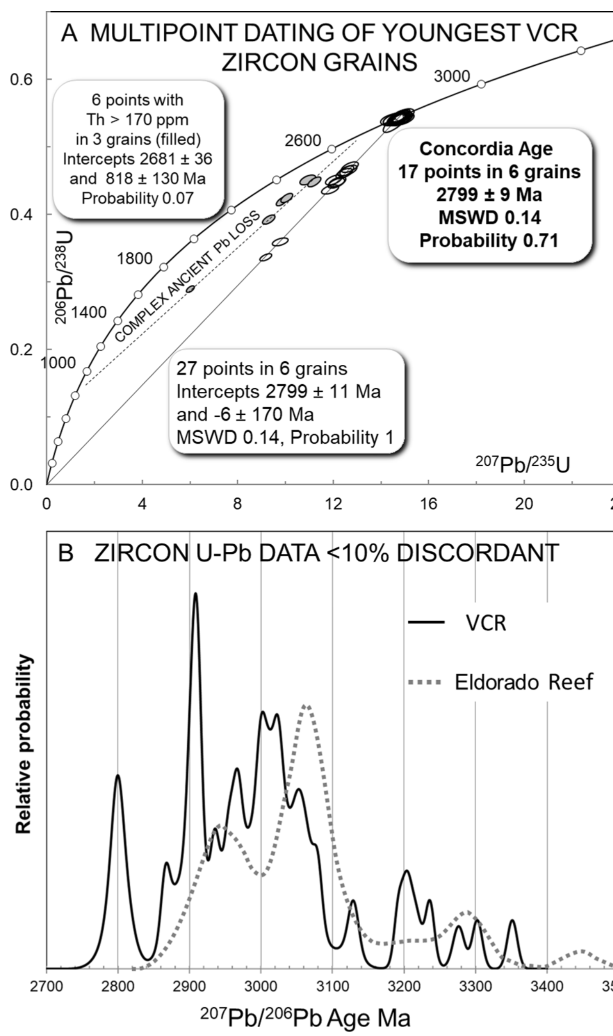

Fig. 6. A: Concordia diagram showing quadrupole multipoint data for the youngest zircon grains in the Ventersdorp Contact Reef samples AC and D. B: probability plot showing all the < 10% discordant data from both instruments, with duplicate grains removed.

Table 2
Age calculations for the six youngest and two older grains analysed by LA-ICP quadrupole mass spectrometer.

Youngest grains		Discordia age calculations [Ma]						Concordia calculations				
Grain	Points analysed	Upper	±2σ	Lower	±2σ	Probability	No.	age	±2σ	Probability	no. points	Comments
AC9	6	2806	29	-7	220	0.98	6	2799	19	0.56	4	2 points show recent Pb loss
AC15	5	2785	54	20	970	0.37	3	2788	37	0.8	1	2 points show recent, 2 show ancient Pb loss
AC27	7	2804	35	83	540	0.99	7	2797	25	0.49	2	Recent Pb loss, low Th/U suggests metamorphic
D4	5	2804	35	207	810	0.96	4	2802	24	0.86	3	1 point with 343 ppm Th shows ancient Pb loss
D82	4	2795	210	1256	740	0.04	4	2804	31	0.93	1	3 points scatter about ancient Pb loss line
D84	6	N/A						2799	14	0.83	6	All concordant, precise age for one grain
Wtd. Means	**6**	**2803**	**17**			**0.97**	**5**	**2798**	**9**	**0.99**	**6**	**Weighted mean of above calculations**
All points	**33**	**2799**	**11**	**-6**	**170**	**1**	**27**	**2799**	**9**	**0.71**	**17**	**Six points with Th >170 ppm scatter about ancient Pb loss line**
Grains interpreted as older												
D80	6	3053	18	11	1400	0.9	6	3052	15	0.83	5	Older grain, conforms to recent Pb Loss
D182	4	2860	46	152	260	0.78	4	2804	45	0.43	1	Two age domains in CL, core may be older. .

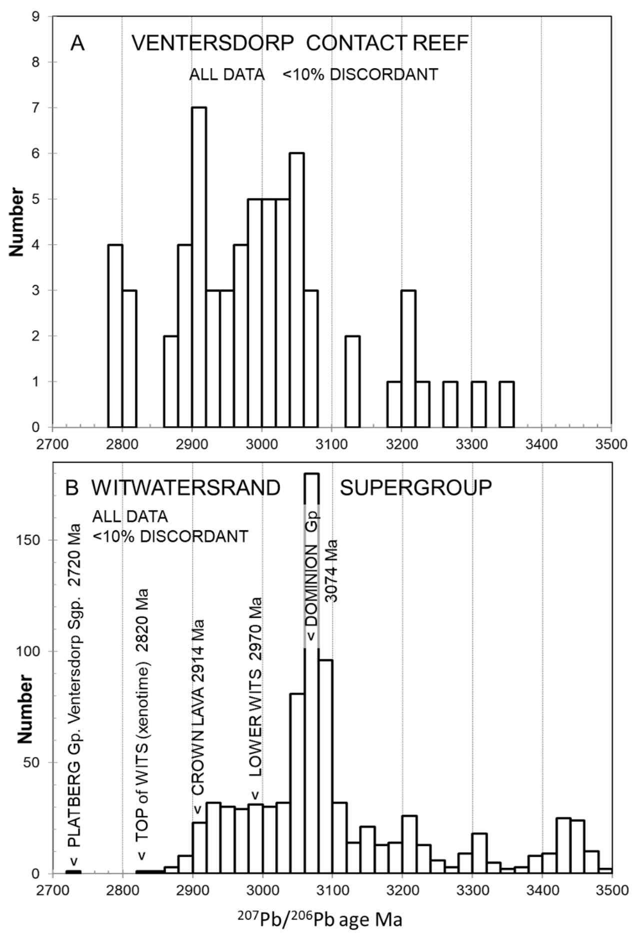

Fig. 7. Histograms of $^{207}Pb/^{206}Pb$ ages. A: detrital zircon grains in the Ventersdorp Contact Reef using only < 10% discordant data and excluding duplicate points, compared with B: all the data for the Witwatersrand Group from Kositicin and Krapež (2004), also showing the ages of other relevant units.

shows little similarity to that of the VCR. These differences can be explained by the major erosional unconformity beneath the VCR, which in places removed most of the ~2.9 km-thick Central Rand Group, well-illustrated by the seismic reflection data of Manzi et al. (2013). The VCR also represents the second youngest reef, (after the Black Reef in the Transvaal Supergroup) which is mined for gold, probably derived mainly from erosion of the underlying reefs, as reviewed by Chunnett (1994).

Could all of the VCR zircon grains come from the WitwatersrandSupergroup? The Crown Lava in the middle of the Witwatersrand Supergroup is dated at 2914 Ma (reviewed by Eglington and Armstrong, 2004). Weighted mean $^{207}Pb/^{206}Pb$ ages for the three youngest concordant detrital zircon grains from the Central Rand Group, Witwatersrand Supergroup, dated by Kositcin and Krapež (2004) are 2872 ± 12 Ma and for the three youngest detrital xenotime grains 2820 ± 5 Ma (our calculations), possibly derived from non-zircon-bearing magmatic source rocks. According to Kositcin et al. (2003), diagenetic xenotime was growing in the Central Rand Group sedimentary rocks at 2778 ± 2 Ma (our calculation), so the Witwatersrand Supergroup is older than that. These dates suggest that the very youngest 2799 ± 9 Ma VCR zircon grains were not reworked from the Witwatersrand Supergroup, which was being eroded at that time. Five of the six youngest zircon grains are euhedral crystals, whereas most of the older grains are subhedral or broken. The youngest grains were possibly directly derived from plutonic magmatic rocks in the region, or their volcanic equivalents. A possible source is the 2797 ± 2 Ma Rooibokvlei Granodiorite exposed in the Makoppa Dome ~200 km north of Kusasalethu Mine (Age no. 7 in Fig. 2, reviewed by Anhaeusser, 2019).

This assumes that the provenance lay to the north of the present VCR occurrences, to the west is the 2791 ± 8 Ma Mosita Adamellite (Age no. 1 in Fig. 2).

Kositcin et al. (2004) also dated a few xenotime grains in the VCR, but got different ages within the same grains, which might reflect detrital, diagenetic or hydrothermal events.

5.4. *Sediment transport by water or ice?*

Most recent authors invoke a mainly fluvial transport mode for the Witwatersrand and VCR sedimentary rocks. (e.g. Frimmel, 2019; Kositcin and Krapež, 2004). However, there is evidence of glaciation on the Kaapvaal Craton during that time interval, very well-documented in the 2.94–2.87 Ga Mozaan Group in Kwazulu-Natal by Young et al. (1998) and correlated with the Witwatersrand Supergroup by Beukes and Cairncross (1991). Most of the gold reefs, including the VCR, lie unconformably on diamictites, striated pebbles were found associated with the Government and Coronation reefs (Rogers, 1922, Camden-Smith, 1980, Tankard et al., 1982), subglacial folding and varved shales are also recorded (Wiebols, 1955, McCarthy 2020). Literature evidence for glaciation in at least four reefs of the upper and lower (now West Rand and Central Rand Groups) Witwatersrand Supergroup was reviewed by Harland (1981). Recurring glacial ice sheets could account for the regional extent of the gold reefs and the long transport distances of detrital material suggested in the following section.

The extensive weathering documented by Nwaila et al. (2017) in many Witwatersrand Supergroup shales could be ascribed to a warm climate, negating a glacial hypothesis. However, the likelihood of acidic conditions in rain and groundwater, enhanced by sulphur-rich volcanism, could also account for the high weathering and alteration indices which they reported. The action of acidic water on freshly ground glacial material could have enabled the dissolution and mobility of gold, which enhanced the grade of gold reefs, as proposed by Horscroft et al. (2012) and Heinrich, (2015).

5.5. How much younger could the VCR be?

There are a few known felsic magmatic rocks younger than 2900 Ma, which could have supplied zircon to the VCR after 2900 Ma, with localities numbered in Fig. 2 and detailed in supplementary Table A1. The VCR is interbedded with and was covered by Klipriviersberg Group mafic lavas. The 2714 ± 16 Ma ion probe U-Pb date of Armstrong et al. (1991, Table 1) for zircon from Klipriviersberg basalt is probably too young, as reviewed by Gumsley et al. (2020). Two mafic sills in the Witwatersrand Supergroup, which they dated at 2787 ± 2 Ma and 2789 ± 4 Ma on baddeleyite (Table 1), are plausible feeders to the Klipriviersberg mafic lavas and do correspond geochemically. If these ages do represent Klipriviersberg volcanism, the youngest VCR detrital zircons could also represent that event, although felsic lavas have not been recorded in the Klipriviersberg Group. However, in our opinion the sillsare not unequivocally Klipriviersberg correlates.

Apart from the 2797 Ma Rooibokvlei Granodiorite and 2791 Ma Mosita Adamellite referred to above, which are coeval with the 2799 ± 9 Ma youngest VCR zircon grains, several zircon-bearing rock units which occur in the same areas (nos. 2 and 7 in Fig. 2), are significantly younger than that and may post-date the VCR. West of Amalia (No. 2 in Fig. 2), about 130 km from the nearest known VCR occurrence, four granitoids are dated at 2882 ± 7, to 2854 ± 7 Ma (Cornell et al., 2011). The 2785 ± 2 Ma Kanye Formation felsic lavas (Moore et al., 1993), and slightly younger 2781 ± 5 Ma Gaborone Granite (Walraven et al., 1996) crop out some 250 km north of the nearest VCR occurence (no. 5 in Fig. 2). If these rock units do post-date the VCR, they are time-correlates of the Ventersdorp Supergroup, as proposed by Gumsley et al. (2020) and discussed below.

5.6. Constraints on age correlations of the Ventersdorp Supergroup with other units

The time period in which the Ventersdorp Supergroup formed is now constrained between 2799 ± 9 Ma, the maximum age of the VCR, and 2642 ± 4 Ma, the age of volcanic rocks in the Vryburg Formation at the base of the Transvaal Supergroup (Walraven and Martini, 1995), which unconformably overlies the Ventersdorp rocks. In our opinion, the only reliable age for supracrustal rocks of the Ventersdorp Supergroup *sensu stricto* is 2720 ± 2 Ma for four samples of the Makwassie Formation in the Platberg Group, according to Cornell et al. (2017). Some other precise dates have been published on rocks which crop out outside the main repository and may be Ventersdorp correlates (reviewed by Gumsley et al., 2020).

Cornell et al. (2017) reported a 2874 ± 16 Ma zircon date from a sample ascribed to the Makwassie Formation at Kimberley. This date is unlikely to represent volcanism of the Ventersdorp Supergroup, because it is older than the VCR. Either that sample is coeval with the Witwatersrand Supergroup (detrital zircon grains 2872 ± 12 Ma and xenotime 2820 ± 5 Ma), or more likely, the zircon grains dated were xenocrysts, supported by one grain in that sample dated at 2711 ± 16 Ma.

The two zircon dates of 2781 ± 5 Ma and 2746 ± 9 Ma, reported by Cornell et al. (2017) for the Goedgenoeg Formation at Kimberley and Wolmaransstad respectively, are within the possible age range for the Goedgenoeg Formation, although they might both be xenocrystic dates. They are unlikely to both be extrusion ages, because a minimum 21 million year duration of Goedgenoeg volcanism is considered to be unrealistic.

The Kanye Formation in eastern Botswana, which was dated at 2785 ± 2 Ma by Moore et al. (1993), could be a time correlative of the Klipriviersberg Group in the lower Ventersdorp Supergroup, as suggested by Gumsley et al. (2020). However, its felsic composition is at odds with the komatiitic to basaltic composition of the Klipriviersberg Group.

The chronostratigraphic framework for the Ventersdorp Supergroup proposed by Gumsley et al. (2020) comprising a 2791–2779 Klipriviersberg LIP, a 2754–2709 Platberg volcanic province and a 2709–2683 Allanridge LIP does fit the time constraints for the Ventersdorp Supergroup. However, it is based largely on precise U-Pb baddeleyite dates on mafic rocks from sills which intrude the Witwatersrand and Pongola Supergroups, the Amsterdam Formation (which might be a Makwassie correlate) and older gneisses. In particular the Klipriviersberg LIP is based on two dated sills which are thought to represent feeders to the as-yet undated Klipriviersberg lavas. None of these intrusive rocks are directly linked to volcanic strata of the Ventersdorp repository. A significant group of 2730–2701 Ma granitoids and two mafic dykes within the region up to 400 km east of the Ventersdorp basin are clearly time correlates of the Makwassie Formation, justifying the proposed Platberg volcanic province. In our opinion, the older and younger limits of Ventersdorp volcanism and the validity of the LIPs are still a matter for discussion.

6. Conclusions

The youngest group of six of 80 detrital zircon grains we dated in the Ventersdorp Contact Reef (VCR), from the base of the Ventersdorp Supergroup, are reliably dated at 2799 ± 9 Ma by laser ablation ICPMS. Thus the VCR was deposited after 2808 Ma and before 2720 ± 2 Ma, the age of the Makwassie Formation in the Platberg Group of the Ventersdorp Supergroup.

Zircon in the VCR probably originated largely as erosion products of the underlying Witwatersrand Supergroup. The VCR age histograms most closely resemble those of the Krugersdorp Formation, which is in the middle of the Central Rand Group, whereas histograms from units above that are less similar. This reflects the large erosional unconformity between the Witwatersrand Supergroup and the VCR, which in places cuts out most of the Central Rand Group.

The youngest 2799 ± 9 Ma zircon grains found in the VCR do not have known age-equivalents in the Witwatersrand Supergroup and may have been derived directly from magmatic rocks such as the 2797 ± 2 Ma Rooibokvlei Granodiorite or volcanic rocks, transported into the VCR repository by fluvial and possibly also by glacial processes.

Zircon grains from conglomerate samples from the VCR predominantly yield concordant U-Pb ages. However about 15% of our data was discordant and conformed to the recent lead loss model, so that $^{207}Pb/^{206}Pb$ ages are not affected by discordance. Another 5% of the data showed complex Mesoproterozoic lead loss and those data points all have higher Th (>170 ppm) and generally higher U than the other points. This means that discordant data has to be carefully evaluated by analysing several points in each grain, as in this case 10% discordance due to lead loss at ~1000 Ma may lead to ages about 150 Ma too young.

The two large igneous provinces dated between 2791 and 2683 Ma, which have been proposed, based on the dating of mafic dykes outside the Ventersdorp repository, do fit the time constraints and might be related to Ventersdorp stratigraphy. However only the proposed 2754–2709 Ma Platberg volcanic province is coeval with reliably dated Platberg Group volcanic rocks of the Ventersdorp Supergroup *sensu stricto*. The validity of the other proposed LIPs and correlations is still under discussion.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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