A ca. 200 Ma hiatus between the Lower and Upper Transvaal Groups of southern Africa: SHRIMP U–Pb detrital zircon evidence from the Segwagwa Group, Botswana: Implications for Palaeoproterozoic glaciations

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Editor: R.W. Carlson

Abstract

The Segwagwa Group of southeastern Botswana, a correlate of the Pretoria Group of the Transvaal Supergroup of South Africa, consists of a major sequence of siliciclastic sedimentary rocks, minor carbonates and basaltic to andesitic lavas and tuffs straddling the Western and Central Domains of the Kaapvaal Craton. The Segwagwa Group unconformably overlies the Taupone Dolomite Group, a correlative of the South African Chuniespoort/Ghaap Groups of the Transvaal Supergroup. SHRIMP U–Pb analyses of 123 detrital zircons from the top, middle and bottom of the Segwagwa Group sedimentary rocks include 96 concordant to near-concordant zircons defining three main age groups: >3.0–2.9 Ga (n=12), 2.8–2.5 Ga (n=27) and 2.45–2.20 Ga (n=57). The ≥2.90 Ga zircons were sourced from granitoids emplaced before and around 2915±12 Ma and are related to the amalgamation of the Western, Northern and Central Domains of the Kaapvaal Craton. Concordant zircons with a mean age of 2781±8 Ma originate from the Gaborone Igneous Complex. The detrital zircons in the range 2.7–2.5 Ga were likely sourced from the Kalahari continental fragment made up of the Kaapvaal Craton, Limpopo Belt and the Zimbabwe Craton, specifically from the Limpopo Belt and/or the Zimbabwe Craton where igneous rocks in this age range are widespread. The igneous sources for the Palaeoproterozoic (ca. 2.45–2.20 Ga) zircons are difficult to identify since igneous rocks in that age are not widely known or documented by reliable dates in the Kalahari Craton.

The youngest zircons of ca. 2.2 Ga occur in all the sandstones and form the main group (>90%) in the sample from the top of the Segwagwa Group. The youngest detrital zircon of 2193±20 Ma sets the maximum time of deposition of the Segwagwa Group. Published data suggest that the minimum deposition age of Chuniespoort/Ghaap Group sedimentary rocks is 2431±31 Ma [D.R. Nelson, Compilation of SHRIMP U-Pb zircon Geochronological Data, 1996 Record 1997/2, pp. 189, Western Australia Geological Survey, 1997.]. Therefore, the unconformity between the Lower and Upper Transvaal represents a ~200 Ma hiatus, and the lithostratigraphic units on the two sides of the unconformity should not be grouped in the same supergroup. Detrital zircon ages suggest that the time of deposition of the Segwagwa/Pretoria Group which ranges from ca. 2.40 to 2.20 Ga is coeval with the

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Palaeoproterozoic global glacial deposits in North America, Australia and Fennoscandia; and with sedimentary rocks from the Palaeoproterozoic Magondi Belt. Therefore, the Segwagwa/Pretoria Group and the Magondi metasedimentary succession were deposited during the first global glacial period, are possibly related to the same geodynamic cycle, and should be part of the same supergroup.

Keywords: Transvaal Supergroup; Segwagwa/Pretoria Group; detrital zircon geochronology; glacial implications; Botswana; southern Africa

1. Introduction

The transition between the Archaean and the Palaeoproterozoic is formally located at 2.5 Ga by the Commission of Stratigraphy of the International Union of Geological Sciences (IUGS). However, the exact timing of the oldest Palaeoproterozoic sedimentary rocks resting on the Archaean cratons is still poorly constrained around the world, possibly because this period was not a prolific magmatic period in various cratons. This could be biased by the limited amount of reliable geochronological data available on the African continent, as there are only few igneous rocks yielding precise crystallisation ages between ~2.4 and 2.1 Ga in most African cratons and orogenic belts [2]. Hanson [3] in a paper on the Proterozoic geochronology and tectonic evolution of Africa does not show any record of igneous activity at ca. 2.4–2.2 Ga on the African continent. Similarly, Eglington and Armstrong [4] show that in the Kaapvaal Craton there are few geochronological dates indicating magmatic activity at ca. 2.4–2.3 Ga, however cratons in India, North America, Baltic Shield and Antarctica are characterized by the emplacement of flood basalts, dyke swarms and ultramafic–mafic layered complexes near the Archaean–Proterozoic boundary [5,6]. The Archaean Kaapvaal Craton in southern Africa is covered by a thick sedimentary succession – the Transvaal Supergroup – known to straddle the Archaean–Proterozoic boundary. The Transvaal Supergroup is mainly a metasedimentary succession (quartzite, carbonate and iron formation), with minor mafic volcanics, which is found in three separate basins on the Kaapvaal Craton. It is subdivided into the Lower Neoarchaean Chuniespoort/Taupone/Ghaap and Upper Palaeoproterozoic Pretoria/Segwagwa/Postmasburg groups [7,8]. The Neoarchaean Lower Transvaal sequence is separated from the Palaeoproterozoic Upper Transvaal sequence by an unconformity and contains important rock formations that include carbonate and banded iron formation, basal and intraformational low latitude glacigenic deposits and red beds [9,10]. Thus, this sedimentary succession offers a unique opportunity to document the critical transition between the Archaean and the Palaeoproterozoic, to constrain the time which separated the deposition of the last Archaean and the earliest Proterozoic geological unit, and to constrain the time of Palaeoproterozoic glaciation and oxygenation.

The Sensitive High Resolution Ion Microprobe (SHRIMP) U–Pb detrital zircon geochronology offers a powerful tool for unravelling the maximum depositional ages of sediments whereas crosscutting igneous bodies provide the minimum age of the accumulation of sediments in basins. The youngest concordant detrital zircons define the maximum deposition age of the analysed sedimentary rocks whereas the overall population of the detrital zircons represents the age spectrum of zircon-bearing rocks in the source area of the sedimentary detritus. Furthermore, the size, shape and general morphology of detrital zircons provide clues on the dynamics of the transporting media and transport distances.

Important questions relating to the evolution of the Transvaal Supergroup include: (a) what is the length of time represented by the hiatus/unconformity between the Neoarchaean Lower Transvaal known as the Taupone Dolomite Group in Botswana and the Palaeoproterozoic Upper Transvaal known as the Segwagwa Group in Botswana? (b) What is the source of sediments? (c) What was the geotectonic setting during the deposition of the Upper Transvaal (Pretoria/Postmasburg Groups in South Africa and Segwagwa Group in Botswana) rocks of southern Africa?

In this study we use SHRIMP U–Pb zircon data to shed light on: (1) The maximum depositional age of clastic sedimentary rocks of the Segwagwa/Pretoria Group; (2) The source of sediments using the age of detrital zircons along with previously published sedimentological data; (3) The implications of the data on the formation of Segwagwa/Pretoria Group in the broad Palaeoproterozoic evolution of southern Africa and; (4) The implications of the data on the first global glaciation during the Palaeoproterozoic time.

2. Geological background

The Transvaal Supergroup (Fig. 1, Table 1) forms one of the major Archaean to Palaeoproterozoic basins hosting low-grade metasedimentary and metavolcanic rocks within

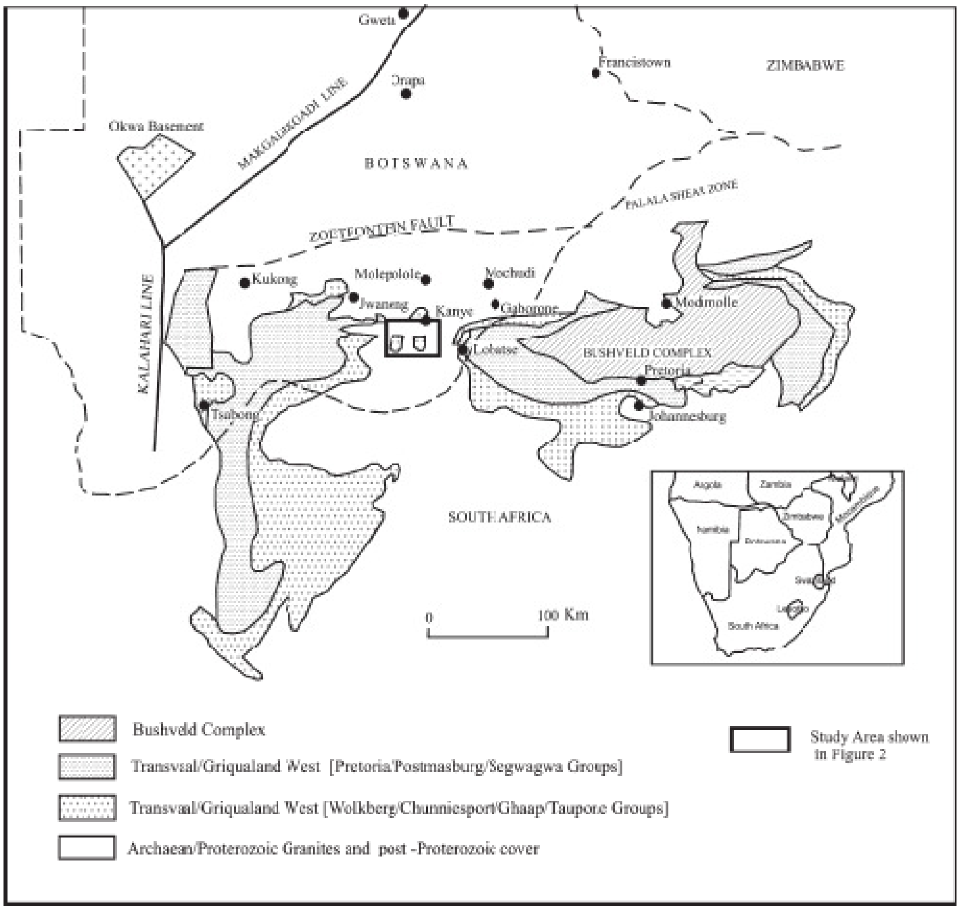

Fig. 1. Geological map of southern Africa and location of the Transvaal Supergroup.

the Kaapvaal Craton in South Africa and Botswana [11–15]. The Lower Transvaal includes the Neoarchaean Chuniespoort/Ghaap Group in South Africa and its correlative Taupone Dolomite Group in Botswana. The Upper Transvaal consists of the Palaeoproterozoic Pretoria/Postmasburg Group in South Africa and its correlative Segwagwa Group in Botswana. The Taupone/Chuniespoort Group is a carbonate sequence capped by iron formations and ironstones whereas the Segwagwa/Pretoria Group is silciclastic with minor volcanic rocks [16,17].

In Botswana, the base of the Taupone Group is a red, matrix supported conglomerate unconformably overlying siltstones and laminated shales of the Lobatse Volcanic Group [12,16,18,19]. This conglomerate forms extensive ridges and marks the base of the Black Reef Quartzite Formation. It consists of sub-rounded and angular clasts of rhyolite and vein quartz supported by a sandy matrix cemented by iron rich material. The poorly consolidated conglomerate is overlain by mature quartzite and then by a sequence of chert-rich and chert-poor dolomites. The cherty dolomites contain massive chert beds that are locally stromatolitic, with interbedded chert and dolomite grading to iron-formation(s) of the Masoke Iron Formation and chert breccias of the Kgwakgwe Chert Breccia Formation at the top [16,20]. The chemical sedimentary succession of the Taupone/Chuniespoort Group is separated from the clastic sedimentary rocks of the Segwagwa/Pretoria Group by an erosional unconformity. The

Table 1
Lithostratigraphy of the Transvaal Supergroup and correlations between the Griqualand West, Kanye and Transvaal Basins

Griqualand West Basin		Age (Ma)		Kanye Basin		Transvaal Basin	Age (Ma)
Group	Formation			Formation	Group	Formation	
	Hartley	1928±4 [81]		Segwagwa/Moshaneng		Sibasa Lavas	1.88-1.87 Ga [82]
Olifantshoek				205±9 [40]			
	Molopo Farms Complex	2044±24 [80]		205±2 [11, 39]		Bushveld Complex	2054.4±2.8 [40, 41]
Unconformity	~	~	Unconformity	~	Unconformity	~	~
						Dullstroom Lava	
	Mapedi/Gamagara					Houtenbek	
						Steenkampsberg	
						Nederhorst	
Postmasburg	Mooidraai	2394±26 [44]				Lakenvlei	
				Loengyaa		Vermont	
				Monwakofwane (RBM1/2001)		Magaliesberg	Re-Os 2322±16 [42]
			Segwagwa	Gatsepane	Pretoria	Silverton	
				Mogapinyana (RBM1/2001)		Daspoort	
						Strubenkop	
						Dwaalheuwel	
	Ongeluk	2222±13 [28],		Tsatsu		Hekpoort	2224±21 [35]
						Boshoek	
	Makganyene			Ditojana/Thamang		Time ball Hill	
				(Sample RBM2/2001)		Rooihoogte	
	Unconformity	~	Unconformity	Kgwakgwe Chert Breccia	~	Duitschland	
	Griquatown Iron	2431±31 [36]		Masoke		Penge	2480±6 [1, 36]
	Kuruman Iron	2465±7, 2460±5 [38]					2432±31 [33]
	Gamohaan	2516±4 [35], 2521±3 [37]	Taupone	Ramonnedi	Chuniespoort		2489±33 [1]
Ghaap	Kogelbeen		Dolomite			Frisco	
	Klipfontein					Eccles	
	Fairfield					Lyttelton	
	Reivilo					Montecristo	
	Monteville	2555±19 [35], 2557±49 [34]				Oak tree	2583±5 [1]
	Lokammona						2550±3 [1]
	Boomplas						
	Vryburg	2642±3 [33]		Black Reef Quartzite		Black Reef Quartzite	2642±2.3 [33]

The number in parenthesis refers to the reference of data source which describes method of dating [1,11,28,33–42,44,80–82].

unconformity rocks comprise a conglomerate with pebbles of chert (in a ferruginous matrix) known as the Bevets conglomerate Member which has also been interpreted as a glacial sedimentary unit [15,19,21,22].

The Segwagwa Group sedimentary rocks are exposed in the Jwaneng, Kanye, Lobatse and Ramotswa areas (Fig. 2), and within the Griqualand West Basin extension in Botswana. This basin is separated from the main Transvaal Basin (South Africa) by a basement ridge including the Gaborone Igneous Complex [11,13,15]. These basins evolved separately [18,22–25], although the Hekpoort–Ditlhojana–Tsatsu–Ongeluk volcanic units provide a prominent marker horizon at the same stratigraphic position in both basins. In the Kanye area [13,20,26,27], the Segwagwa Group comprises seven formations (Table 1) exposed within a syncline around Segwagwa village and within a syncline–anticline pair southwest of Jwaneng (Fig. 2). The Segwagwa Group comprises quartzites, ferruginous sandstones, shales and a volcanic unit (basaltic to andesitic lavas and amygdaloidal basalt) known as the Tsatsu Formation. This formation is a correlate of the Hekpoort and Ongeluk Formations in the Pretoria/Postmasburg Groups of South Africa, respectively [16,17,28]. The base of the Segwagwa Group is made up of black pyritic shales, overlain by ferruginous quartzites, iron rich shales and a chert pebble conglomerate of the Ditojana and Tlaameng Formations [13,20].

In South Africa, the Pretoria Group is made up of a lower Pretoria Group comprising nine formations [29] starting with the Rooihoogte Formation made up of conglomerates, quartzite, shales and chert pebble/clast breccia known as the Bevets conglomerate Member; and an upper Pretoria Group comprising quartzites and shales. A further five formations are preserved in the east of the Transvaal Basin [9]. The Rooihoogte Formation overlies the Duitschland Formation comprising dolomitic shale, dolomite, quartzite, and chert breccias/diamictite (Bevet's Conglomerate) above the Banded Iron Formation landscape [9]. The Rooihoogte Formation is overlain by the Timeball Hill Formation, which is made up of lower

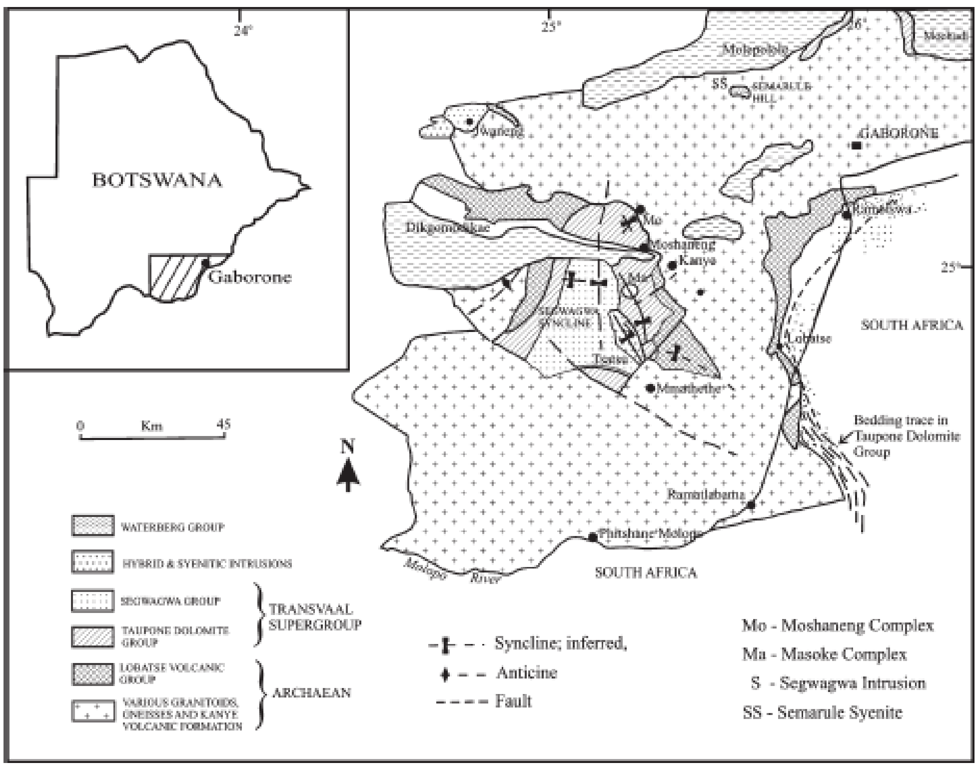

Fig. 2. Geological map of the southeast Botswana showing the Segwagwa Syncline (modified from Carney et al. [16]).

shales, quartzites, conglomerate lenses and diamictites, and upper shales. Locally, the base of the Timeball Hill Formation (Table 1) is marked by altered lavas of the Bushy Band Lava Member [22,24,30,31]. The Timeball Hill Formation is overlain unconformably by the Boshoek Formation (conglomerate, sandstone), a correlate of the Makganyane diamictite [9,10,32]. The Boshoek Formation diamictites are absent in the south of the Transvaal Basin, are up to 100 m in the east, 0–50 m in the centre and down to 0–10 m in the west [9]. The Timeball Hill Formation is a correlate of the Ditojana Quartzite of the Segwagwa Group [15,20]. The base of the Ditojana Formation has no volcanic rocks but contains pyritic and micaceous shales grading to ferruginous quartzites at the top. The Boshoek Formation is correlative with Tlaameng Formation in the Kanye Basin and principally made up of brown to yellow, ferruginous shale with discontinuous chert pebble conglomerate/diamictite below the Tsatsu Formation. Borehole intersections in the Jwaneng area show that the chert pebble conglomerate/diamictite forms a persistent marker unit with a maximum thickness of 100 cm. This chert pebble conglomerate is interpreted as a diamictite correlative to the Makganyane diamictite in the Griqualand West Basin and the Boshoek Formation in the Transvaal Basin.

The depositional age constraint for the lowermost Transvaal in the Griqualand Basin of South Africa is given by a U–Pb zircon crystallization age of 2642±3 Ma for a tuff bed in the Vryburg Formation [33]. An ID TIMS Pb–Pb date of 2557±49 Ma was obtained on limestones from the Schmidsdrift Formation of the Campbell Subgroup by Jahn et al. [34]. This date is similar to a SHRIMP U–Pb zircon igneous crystallization age of 2555±19 Ma for tuff beds in the Monteville Formation in the Campbellrand Subgroup [35]. In the Transvaal Basin, a tuff in the upper part of the Oak Tree Formation yielded U–Pb zircon igneous crystallization ages between 2583±5 and 2550±3 Ma [1]. The top of the Chuniespoort Group is marked by the Penge Iron Formation, which has a SHRIMP U–Pb zircon igneous crystallization (tuff) age of 2480±6 Ma [1,36].

Tuff beds below the contact between the Campbellrand Subgroup and the Kuruman Iron Formation in the Griqualand Basin yielded an ID TIMS U–Pb zircon igneous crystallization age of 2521±3 Ma [37], which is similar to the SHRIMP U–Pb zircon age of 2516±4 Ma for the same unit [35]. The Riries Member, a tuff bed in the Kuruman Formation, yielded U–Pb zircon crystallization ages of 2478.5±5.7, 2465±7 and 2460±5 Ma [38], the last date representing the crystallization age of felsic lavas coeval with the deposition of the Kuruman Iron Formation. The volcanic material from the Griquatown Iron Formation above the Kuruman Formation yielded the younger U–Pb SHRIMP zircon crystallization age of 2431±31 Ma [36], setting the minimum depositional age of the Lower Transvaal. In the Moshaneng sub-basin, the Taupone dolomites were intruded by Bushveld-age syenites, granites and diorites of the Moshaneng Complex, which yielded U–Pb zircon crystallization ages of 2054±2 Ma [11,39].

The Moshaneng Complex is not in contact with the Segwagwa Group supracrustal sedimentary rocks. However, the Segwagwa Group is intruded by and folded together with the Segwagwa and Masoke igneous complexes north of the Mmathethe (Fig. 2). These igneous complexes comprise syenites and diorites similar to those exposed in the Moshaneng Complex [39]. A granite from the Segwagwa Complex yielded a U–Pb zircon crystallization age of 2054±9 Ma that supports the correlation of the Segwagwa–Masoke Complexes to the Moshaneng Complex [40]. Therefore, the minimum deposition age of the Segwagwa Group sedimentary rocks is ~2.05 Ga. Similarly, in South Africa, the ca. 2.05 Ga Bushveld Complex intrudes and sets the minimum deposition age of the Pretoria Group [7,21,41].

The age and correlation of units described above with similar units in Botswana are shown in Table 1. The Vryburg Formation marks the base of the Griqualand West Supergroup and is the equivalent of the Black Reef Quartzite Formation in Botswana. The dolomites and siliceous dolomites of the Taupone Dolomite Group in Botswana correlate with the Ghaap and Chuniespoort Groups in South Africa.

The depositional age of the Segwagwa/Pretoria Group is constrained by an Re/Os age of 2322±16 Ma derived from mudstones from the Rooihoogte and Timeball Hill Formation, SHRIMP U–Pb detrital zircons age of 2324±17 Ma from the Timeball Hill Formation, and whole rock Pb–Pb isochron date of 2236±38 Ma and whole rock Pb–Pb isochron date of 2222±12 Ma for lavas of the Ongeluk Formation of the Postmasburg Group and lavas of the Hekpoort Formation in the Transvaal Basin in South Africa [42,43]. However, according to Bau et al. [44], the 2236±38 Ma date has never been reproduced nor confirmed by U–Pb zircon dating. Note that this date is similar to a low-precision Rb–Sr isochron date of 2224±21 Ma for the Hekpoort Formation in the Transvaal Basin [43,44]. Bau et al. [44] published a Pb–Pb date of 2394±26 Ma for dolomites from the Mooidrai Formation of the Postmasburg Group in the Griqualand West Basin. According to these authors, the dates for the Ongeluk Lava and by extension the Hekpoort andesite below the dated dolomites were unreliable. Catuneanu and Eriksson [45] suggested that the Bushy Bend Lavas above the unconformity between the Lower and Upper Transvaal Groups were possibly emplaced at ca. 2350 Ma, based on unpublished Pb–Pb zircon evaporation dates of the Hekpoort andesite lavas (Eriksson, pers. com. 2003).

Moore et al. [46] argued against a correlation between the Transvaal and Griqualand West Basins, based on the age of the unconformity separating the Lower Transvaal (Chuniespoort and Ghaap Groups) from the Upper Transvaal Supergroup (Pretoria and Postmasburg Groups). In this new interpretation, the unconformity which separates the Chuniespoort from the Pretoria Group appears to affect units correlated with the Pretoria Group, implying that units which were hitherto correlated with the Pretoria Group were absent in the Griqualand West Basin. For example, the Ongeluk Formation lava would be older with no equivalent in the Transvaal and Kanye Basins. The new interpretation of Moore et al. [46] is untenable in part because; first it is based on the age published by Bau et al. [44] on the Mooidraai dolostones in Griqualand West that is too old by ca. 70 Ma according to new data [42,43]; second regional studies confirm the correlation of key units in the both basins; for example, Tinker et al. [47] show on deep seismic sections that the Ongeluk and Hekpoort Formation lavas are laterally continuous; third the main units that correlate with Pretoria Group sedimentary rocks exist in the Kanye Basin Botswana which are not only adjacent to but are physically part of the Griqualand West Basin lithological units [11,15,17,20] consistent with current regional correlations of sedimentary and volcanic units in the Transvaal, Kanye and Griqualand West Basins [15,48,49]. However, in some parts of the Kanye Basin in the Jwaneng area, lithological units that normally lie between the Masoke Iron Formation (Penge Iron Formation) and the Ditojana Formation (Timeball Hill Formation) are missing in borehole intersection;, consequently the Taupone Dolomite Group is directly overlain by the post-Timeball Hill Formation rocks [Mapeo, unpublished data], an indication of complex erosion and preservation of Postmasburg/Segwagwa Group rocks in the Kanye and Griqualand West Basins.

3. Analytical procedure

Three 2–5 kg samples from the Segwagwa Group were collected at three different stratigraphic positions (bottom, middle and top) (Table 1). The samples were crushed and the zircons separated using standard heavy liquid and Frantz Isodynamic separation techniques. The final concentrate was handpicked under a binocular microscope and the zircon grains were mounted in epoxy together with the zircon standard AS3 (Duluth Complex gabbroic anorthosite [50]) and the standard SL13 of the Research School of Earth Sciences, The Australian National University. The grains were then sectioned approximately in half, polished and photographed. Cathodoluminescence imaging on a Scanning Electron Microscope (SEM) was carried out prior to the dating to aid in the selection of the best target areas for the analyses. All the zircons were analyzed on SHRIMP II, and the data have been reduced in a manner similar to that described by Williams and Claesson [51] and Compston et al. [52]. U/Pb in the unknowns were normalized to a $^{206}Pb^{*}/^{238}U$ value of 0.1859 (equivalent to an age of 1099.1 Ma) for AS3. The U and Th concentrations were determined relative to those measured in the SL13 standard. Ages were calculated using the radiogenic $^{207}Pb/^{206}Pb$ ratios, with the correction for common Pb made using the measured ^{204}Pb and the appropriate common Pb composition, assuming the model of Cummings and Richards [53]. Uncertainties in the isotopic ratios and ages in the data table (and in the error bars in the plotted data) are reported at the one sigma level, but unless otherwise stated in the text, the final weighted mean ages are reported as 95% confidence limits, with all statistical analyses and age calculations done using the Isoplot/Ex software of Ludwig [54–56].

4. Results

The grains are mostly sub-rounded and/or cracked, and are interpreted as detrital grains with no in situ growth of new metamorphic zircons (Fig. 3). The results for all the samples dated are reported in Table 2, and plotted on a Wetherill U–Pb Concordia diagram (Fig. 4a–c) and a cumulative histogram plot (Fig. 5a–c).

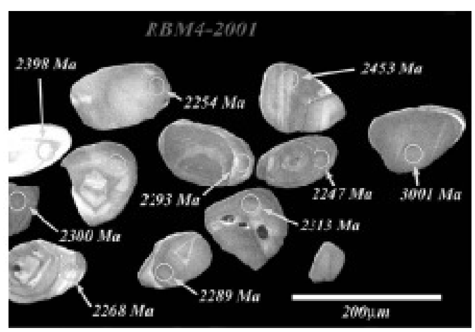

Fig. 3. Cathodoluminescence images of zircons grains from sample RBM4/2001 showing cracked and sub-rounded grain forms. Grain numbers and $^{207}Pb/^{206}Pb$ data and analytical sites are given for various grains extracted.

Table 2
Summary of SHRIMP U–Pb zircon data for samples from the Segwagwa Group SE Botswana

Grain spot	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{206}Pb^*$ (ppm)	(1) $^{206}Pb/^{238}U$ age	±	(1) $^{207}Pb/^{206}Pb$ age	±	Discordant (%)	Total $^{238}U/^{206}Pb$	± %	Total $^{207}Pb/^{206}Pb$	±%	(1) $^{238}U/^{206}Pb^*$	± %	(1) $^{207}Pb^*/^{206}Pb^*$	±%	(1) $^{207}Pb^*/^{235}U$	±%	(1) $^{206}Pb^*/^{238}U$	± %	Err corr
(a) RM42/2001																							
1.1	0.47	39	17	0.45	17.2	2639	±45	2788	±25	5	1.967	2.4	0.1996	1.2	1.977	2.4	0.1954	1.5	13.63	2.9	0.506	2.4	.849
2.1	0.01	49	28	0.60	19.7	2454	±46	2793	±19	12	2.158	2.2	0.1960	1.1	2.159	2.2	0.1959	1.2	12.51	2.5	0.463	2.2	.888
3.1	0.33	80	50	0.64	34.3	2591	±47	2795	±22	7	2.015	2.2	0.1991	0.88	2.021	2.2	0.1962	1.3	13.38	2.6	0.495	2.2	.857
4.1	0.88	356	205	0.59	71.1	1337	±18	2227	±23	40	4.302	1.5	0.14781	0.66	4.340	1.5	0.1400	1.3	4.447	2.0	0.2304	1.5	.750
5.1	0.00	57	30	0.54	11.5	1347	±18	2051	±210	56	4.302	1.5	0.130	13	4.302	1.5	0.123	13	7.37	13	0.2325	1.5	.114
6.1	0.08	168	47	0.29	51.3	2275	±49	2360	±11	4	2.362	1.5	0.15040	0.60	2.363	1.5	0.15170	0.60	8.85	1.6	0.4231	1.5	.919
7.1	–	11	13	1.20	4.36	2389	±76	2542	±65	6	2.235	3.8	0.1664	2.4	2.230	3.8	0.1684	2.7	10.41	4.7	0.449	3.8	.815
8.1	0.07	68	42	0.64	28.9	2589	±38	2632	±15	2	2.022	1.8	0.1784	0.85	2.023	1.8	0.1778	0.91	12.11	2.0	0.4942	1.8	.893
9.1	0.09	235	103	0.45	82.2	2202	±29	2251	±12	2	2.453	1.6	0.14276	0.63	2.456	1.6	0.14195	0.68	7.97	1.7	0.4072	1.6	.919
10.1	1.49	619	385	0.64	121	1312	±16	2233	±26	41	4.363	1.3	0.15371	0.42	4.429	1.3	0.1405	1.5	4.373	2.0	0.2258	1.3	.664
11.1	0.29	80	40	0.51	35.3	2672	±38	2781	±15	4	1.942	1.7	0.1971	0.74	1.947	1.7	0.1946	0.90	13.78	2.0	0.5136	1.7	.889
12.1	0.78	634	236	0.38	111	1182	±15	2253	±17	48	4.928	1.3	0.14908	0.42	4.967	1.3	0.1421	0.96	3.946	1.7	0.2013	1.3	.815
13.1	1.30	487	457	0.96	89.9	1228	±15	2401	±22	49	4.703	1.4	0.16654	0.46	4.765	1.4	0.1549	1.3	4.48	1.9	0.2099	1.4	.770
14.1	0.18	108	44	0.43	49.2	2744	±46	2790	±15	2	1.881	2.0	0.1972	0.75	1.885	2.0	0.1956	0.90	14.31	2.2	0.531	2.0	.911
15.1	0.30	49	45	0.95	23.0	2796	±46	2852	±18	2	1.836	2.0	0.2058	0.96	1.842	2.0	0.2031	1.1	15.21	2.3	0.543	2.0	.879
16.1	0.36	167	86	0.53	55.1	2090	±30	2239	±20	7	2.602	1.7	0.1441	0.81	2.611	1.7	0.1410	1.2	7.44	2.0	0.3830	1.7	.820
17.1	0.23	86	42	0.50	39.0	2719	±39	2781	±14	2	1.902	1.7	0.1966	0.72	1.906	1.7	0.1946	0.83	14.08	1.9	0.5246	1.7	.903
18.1	0.20	206	130	0.65	71.9	2191	±28	2240	±12	2	2.465	1.5	0.14281	0.59	2.470	1.5	0.1411	0.72	7.87	1.7	0.4048	1.5	.902
19.1	0.17	103	145	1.45	48.3	2801	±38	2901	±11	3	1.834	1.7	0.2109	0.64	1.837	1.7	0.2094	0.66	15.71	1.8	0.5442	1.7	.929
20.1	0.26	65	33	0.52	29.9	2712	±46	2743	±17	1	1.907	2.1	0.1924	0.98	1.912	2.1	0.1901	1.0	13.71	2.3	0.523	2.1	.899
21.1	0.47	45	9	0.21	21.8	2844	±55	2977	±21	4	1.795	2.4	0.2237	1.1	1.803	2.4	0.2195	1.3	16.79	2.7	0.555	2.4	.878
22.1	0.26	85	44	0.54	38.9	2760	±43	2786	±16	1	1.866	1.9	0.1975	0.85	1.871	1.9	0.1951	1.0	14.38	2.1	0.534	1.9	.886
23.1	0.36	74	34	0.48	32.9	2674	±43	2774	±18	4	1.938	2.0	0.1969	0.92	1.945	2.0	0.1938	1.1	13.73	2.3	0.514	2.0	.872
24.1	0.54	65	27	0.44	28.6	2725	±47	2772	±22	2	1.890	2.1	0.1984	1.0	1.901	2.1	0.1935	1.3	14.04	2.5	0.526	2.1	.845
25.1	0.05	132	112	0.87	61.3	2779	±39	2911	±11	5	1.854	1.7	0.2112	0.65	1.855	1.7	0.2107	0.69	15.66	1.8	0.5390	1.7	.927
26.1	0.29	437	245	0.58	113	1692	±21	2778	±14	39	3.323	1.4	0.1967	0.79	3.333	1.4	0.1942	0.85	8.03	1.6	0.3001	1.4	.853
27.1	0.28	56	50	0.91	21.8	2388	±38	2357	±22	−1	2.224	1.9	0.1535	1.0	2.230	1.9	0.1509	1.3	9.33	2.3	0.4485	1.9	.828
28.1	0.02	218	71	0.34	99.4	2806	±38	2810.3	±7.3	0	1.833	1.3	0.19894	0.43	1.832	1.3	0.19879	0.40	14.94	1.3	0.5449	1.3	.954
29.1	0.33	86	37	0.44	37.3	2632	±37	2764	±15	5	1.977	1.7	0.1954	0.76	1.983	1.7	0.1925	0.93	13.38	2.0	0.5042	1.7	.880
30.1	0.29	113	62	0.57	52.1	2757	±37	2785	±13	1	1.867	1.6	0.1985	0.63	1.874	1.6	0.1950	0.81	14.35	1.8	0.5336	1.6	.895
31.1	0.02	224	219	1.01	78.4	2205	±27	2758.7	±8.9	20	2.452	1.5	0.19209	0.51	2.453	1.5	0.1919	0.54	10.79	1.6	0.4077	1.5	.938
32.1	0.05	351	127	0.38	155	2679	±30	2871.2	±6.1	7	1.940	1.4	0.20603	0.36	1.941	1.4	0.20560	0.37	14.61	1.4	0.5153	1.4	.966
34.1	0.10	294	131	0.46	140	2841	±32	3264	±30	13	1.804	1.4	0.2637	1.9	1.806	1.4	0.2628	1.9	20.07	2.4	0.5538	1.4	.593
33.1	0.14	93	56	0.62	43.0	2765	±38	2770	±12	0	1.865	1.7	0.1945	0.68	1.867	1.7	0.1933	0.72	14.27	1.8	0.5356	1.7	.920
35.1	0.08	186	106	0.59	91.8	2925	±38	2913.8	±7.5	0	1.740	1.5	0.21176	0.45	1.741	1.5	0.21107	0.46	16.71	1.6	0.5742	1.5	.954
36.1	0.00	75	38	0.53	34.5	2756	±37	2786	±11	1	1.875	1.7	0.1952	0.65	1.875	1.7	0.1952	0.66	14.35	1.8	0.5333	1.7	.929
37.1	0.12	179	99	0.57	58.1	2066	±27	2248	±13	8	2.644	1.5	0.14277	0.64	2.647	1.5	0.1417	0.73	7.38	1.7	0.3778	1.5	.902
38.1	0.07	177	20	0.11	87.1	2921	±35	3010.6	±7.8	3	1.743	1.5	0.2248	0.47	1.744	1.5	0.2231	0.49	17.72	1.6	0.5732	1.5	.952
39.1	0.04	125	57	0.47	57.0	2750	±36	2784.2	±9.8	1	1.879	1.6	0.1953	0.59	1.880	1.6	0.1949	0.60	14.30	1.7	0.5319	1.6	.936
40.1	0.03	195	116	0.61	69.8	2244	±28	2268	±10	1	2.400	1.5	0.14367	0.58	2.401	1.5	0.14438	0.60	8.23	1.6	0.4165	1.5	.926
41.1	0.13	168	119	0.75	75.7	2764	±34	2788.7	±9.0	1	1.865	1.5	0.1966	0.51	1.868	1.5	0.1955	0.55	14.43	1.6	0.5354	1.5	.940
42.1	0.17	125	74	0.61	59.5	2843	±36	2789	±11	−2	1.801	1.6	0.1970	0.58	1.804	1.6	0.1955	0.65	14.94	1.7	0.5544	1.6	.925
43.1	0.20	51	24	0.49	23.2	2757	±41	2759	±14	0	1.870	1.8	0.1937	0.83	1.874	1.8	0.1919	0.87	14.12	2.0	0.5337	1.8	.903
(b) [illegible]																							
1.1	0.06	282	7	0.03	108	2900	±29	3001.0	±7.5	3	1.759	1.2	0.22333	0.44	1.760	1.2	0.2228	0.47	17.46	1.3	0.5682	1.2	.936
2.1	0.13	491	316	0.67	82.2	1148	±12	2247	±11	49	5.125	1.2	0.14282	0.56	5.132	1.2	0.14163	0.65	3.805	1.3	0.1948	1.2	.872
3.1	0.01	259	2	0.01	97.5	2340	±25	2453	±11	5	2.285	1.3	0.15989	0.56	2.285	1.3	0.1598	0.64	9.64	1.4	0.4376	1.3	.898
4.1	0.05	170	60	0.36	60.6	2237	±26	2293	±13	2	2.409	1.4	0.1459	0.71	2.410	1.4	0.1455	0.77	8.32	1.6	0.4149	1.4	.868
5.1	–	183	52	0.30	65.5	2246	±26	2313	±13	3	2.400	1.4	0.1471	0.72	2.400	1.4	0.1471	0.72	8.46	1.5	0.4167	1.4	.885
6.1	0.05	368	123	0.34	84.8	1532	±18	2289	±14	33	3.726	1.3	0.14559	0.63	3.728	1.3	0.1451	0.79	5.368	1.5	0.2682	1.3	.86[illegible]
7.1	0.03	238	126	0.55	85.5	2254	±26	2304	±11	2	2.389	1.3	0.14661	0.60	2.389	1.3	0.14638	0.61	8.45	1.4	0.4185	1.3	.899
8.1	0.09	164	38	0.24	60.3	2293	±26	2269	±19	−1	2.339	1.4	0.1442	0.73	2.341	1.4	0.1435	1.1	8.45	1.8	0.4271	1.4	.778
9.1	0.01	102	46	0.46	41.2	2491	±32	2398	±22	−4	2.120	1.6	0.1548	0.87	2.120	1.6	0.1547	1.3	10.06	2.0	0.4716	1.6	.776
10.1	0.00	340	129	0.39	110	2068	±25	2300	±18	10	2.643	1.3	0.14604	0.57	2.643	1.3	0.14604	0.61	7.62	1.5	0.3783	1.3	.909
11.1	–	88	39	0.46	31.6	2217	±50	2268	±18	2	2.438	1.6	0.1428	1.0	2.437	1.6	0.1433	1.1	8.11	1.9	0.4104	1.6	.832
12.1	0.01	309	195	0.65	89.9	1877	±22	2296	±11	18	2.958	1.4	0.14571	0.61	2.958	1.4	0.14566	0.62	6.79	1.5	0.3381	1.4	.909
13.1	–	178	62	0.36	62.9	2219	±26	2236	±13	1	2.435	1.4	0.1404	0.75	2.434	1.4	0.1407	0.77	7.97	1.6	0.4109	1.4	.874
14.1	0.08	292	195	0.69	90.6	1986	±22	2298	±13	14	2.769	1.3	0.14660	0.60	2.771	1.3	0.1459	0.73	7.26	1.5	0.3609	1.3	.868
15.1	0.02	396	80	0.21	116	1897	±20	2288.0	±8.8	17	2.923	1.2	0.14517	0.50	2.923	1.2	0.14502	0.51	6.840	1.3	0.3421	1.2	.919
16.1	0.12	166	58	0.36	50.5	1949	±27	2229	±25	13	2.829	1.6	0.1413	1.2	2.833	1.6	0.1402	1.3	6.82	2.1	0.3530	1.6	.763
17.1	0.14	73	60	0.85	27.8	2357	±36	2313	±31	−2	2.262	1.8	0.1484	1.1	2.265	1.8	0.1471	1.8	8.96	2.6	0.4415	1.8	.709
18.1	0.01	710	251	0.37	113	1094	±11	2272.3	±9.3	52	5.405	1.1	0.14378	0.50	5.406	1.1	0.14370	0.52	3.665	1.3	0.1850	1.1	.909
19.1	–	302	138	0.47	109	2270	±26	2301.4	±9.5	1	2.369	1.3	0.14605	0.56	2.369	1.3	0.14615	0.56	8.51	1.4	0.4221	1.3	.914
20.1	0.13	186	86	0.48	88.7	2843	±32	2839	±10	0	1.802	1.4	0.2027	0.56	1.804	1.4	0.2016	0.64	15.41	1.5	0.5543	1.4	.908
21.1	0.19	251	72	0.30	89.7	2238	±25	2302	±15	3	2.405	1.3	0.14790	0.61	2.410	1.3	0.1462	0.89	8.37	1.6	0.4150	1.3	.826
22.1	0.11	108	67	0.64	38.6	2194	±43	2280	±16	4	2.464	1.3	0.1433	0.73	2.466	1.4	0.1444	0.91	8.07	1.6	0.4055	1.4	.839
23.1	–	210	90	0.44	72.9	2186	±26	2259	±10	3	2.478	1.3	0.14235	0.59	2.478	1.3	0.14256	0.61	7.93	1.4	0.4036	1.3	.902
24.1	0.12	97	231	2.46	44.0	2730	±38	2721	±13	0	1.894	1.5	0.1886	0.70	1.896	1.5	0.1875	0.81	13.63	1.7	0.5273	1.5	.877
25.1	–	95	58	0.63	46.5	2904	±36	3070	±12	5	1.760	1.5	0.2312	0.66	1.757	1.5	0.2327	0.76	18.26	1.7	0.5691	1.5	.897
26.1	0.01	103	119	1.19	38.1	2304	±29	2259	±17	−2	2.327	1.5	0.1427	0.88	2.328	1.5	0.1426	0.96	8.46	1.8	0.4296	1.5	.846
27.1	0.06	454	211	0.48	80.6	1210	±13	2237	±10	46	4.841	1.2	0.14134	0.55	4.844	1.2	0.14081	0.61	4.008	1.3	0.2064	1.2	.888
28.1	–	369	150	0.42	82.9	1499	±17	2236.8	±9.3	33	3.820	1.3	0.14070	0.54	3.819	1.3	0.14078	0.54	5.082	1.4	0.2618	1.3	.919
29.1	–	148	121	0.84	52.7	2238	±26	2258	±14	1	2.411	1.4	0.1419	0.72	2.409	1.4	0.1425	0.81	8.16	1.6	0.4151	1.4	.868
30.1	0.07	56	23	0.43	29.9	3103	±45	2997	±15	−4	1.617	1.8	0.2229	0.86	1.618	1.8	0.2223	0.95	18.94	2.1	0.618	1.8	.888
31.1	0.02	315	184	0.60	59.3	1276	±14	2245	±12	43	4.567	1.2	0.14160	0.64	4.568	1.2	0.14144	0.68	4.269	1.4	0.2189	1.2	.873
32.1	0.04	131	118	0.94	65.6	2964	±33	2924	±10	−1	1.712	1.4	0.2127	0.58	1.713	1.4	0.2124	0.65	17.10	1.5	0.5838	1.4	.907
33.1	0.11	598	211	0.36	108	1234	±13	2271	±10	46	4.734	1.1	0.14461	0.54	4.739	1.1	0.14360	0.61	4.178	1.3	0.2110	1.1	.888
34.1	–	272	114	0.43	96.0	2216	±25	2311.0	±8.5	4	2.438	1.2	0.14663	0.50	2.437	1.2	0.14697	0.50	8.31	1.3	0.4103	1.2	.924
35.1	–	461	229	0.51	62.4	943	±11	2798.2	±9.8	66	6.352	1.2	0.1962	0.55	6.349	1.2	0.1966	0.57	4.269	1.4	0.1575	1.2	.906
36.1	0.15	465	227	0.50	91.8	1333	±14	2228	±15	40	4.349	1.1	0.14132	0.69	4.355	1.2	0.1400	0.85	4.434	1.4	0.2296	1.2	.806
37.1	0.04	326	63	0.20	118	2256	±25	2393	±15	6	2.385	1.2	0.1546	0.84	2.387	1.2	0.1542	0.86	8.9	1.5	0.4190	1.2	.809
38.1	–	155	130	0.86	58.8	2284	±36	2328	±13	1	2.341	1.3	0.1478	0.69	2.339	1.4	0.1484	0.74	8.75	1.5	0.4275	1.4	.878
39.1	–	75	32	0.44	30.4	2501	±33	2410	±16	−4	2.112	1.6	0.1550	0.92	2.110	1.6	0.1557	0.96	10.11	1.9	0.4739	1.6	.86[illegible]
40.1	–	445	112	0.26	101	1508	±16	2279.3	±8.9	34	3.796	1.2	0.14413	0.48	3.795	1.2	0.14429	0.52	5.242	1.3	0.2635	1.2	.918
(c) RM41/2002																							
1.1	2.38	1203	602	0.52	170	959	±11	2783	±48	66	6.086	1.1	0.21599	0.34	6.235	1.2	0.1948	2.7	4.31	3.0	0.1604	1.2	.410
2.1	7.74	197	227	1.19	71.2	2111	±45	3445	±110	39	2.382	1.2	0.3613	0.42	2.581	2.5	0.295	6.9	15.8	7.3	0.3874	2.5	.340
3.1	–	43	21	0.50	16.3	2356	±36	2329	±40	−1	2.272	1.8	0.1464	1.2	2.266	1.8	0.1485	2.5	9.04	3.1	0.4413	1.8	.594
4.1	3.89	729	147	0.21	153	1359	±17	3460	±46	61	4.097	1.1	0.3312	0.60	4.262	1.4	0.2980	2.9	9.64	3.2	0.2346	1.4	.433
5.1	0.10	130	55	0.44	48.2	2313	±27	2312	±14	0	2.315	1.4	0.1480	0.72	2.317	1.4	0.1471	0.79	8.75	1.6	0.4315	1.4	.868
6.1	–	84	29	0.35	33.7	2467	±32	2338	±16	−6	2.148	1.6	0.1483	0.88	2.145	1.6	0.1493	0.95	9.60	1.8	0.4662	1.6	.854
7.1	1.04	460	165	0.37	89.5	1400	±17	2783	±26	63	3.971	1.1	0.2021	0.32	4.096	1.4	0.1678	1.9	12.31	2.3	0.2442	1.4	.584

(continued on next page)

Table 2 (*continued*)

Grain spot	$^{204}Pb_c$ (%)	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{206}Pb^*$ (ppm)	(1) $^{206}Pb/^{238}U$ age	±	( ) $^{207}Pb/^{206}Pb$ age	±	Discordant (%)	Total $^{238}U/^{206}Pb$	± %	Total $^{207}Pb/^{206}Pb$	±%	(1) $^{238}U/^{206}Pb^*$	± %	(1) $^{207}Pb^*/^{206}Pb^*$	±%	(1) $^{207}Pb^*/^{235}U$	±%	(1) $^{206}Pb^*/^{238}U$	± %	Err corr
(c) BIMB2002																							
8.1	–	139	32	0.24	52.5	2711	±30	2574	±11	−1	1.913	1.3	0.1821	0.60	1.913	1.3	0.1823	0.64	13.14	1.5	0.5227	1.3	.904
9.1	0.47	147	95	0.67	53.2	2252	±28	2381	±20	5	2.390	1.5	0.1573	0.68	2.391	1.5	0.1531	1.2	8.83	1.9	0.4182	1.5	.778
10.1	7.81	978	1984	2.75	135	1713	±15	2665	±38	59	4.695	1.1	0.2458	0.92	4.851	1.2	0.2179	2.3	6.22	2.6	0.2070	1.2	.455
11.1	1.52	377	292	0.80	82.2	1437	±15	2519	±26	45	3.964	1.2	0.18592	0.51	4.004	1.2	0.1764	1.5	6.07	1.9	0.2497	1.2	.609
12.1	5.59	415	266	0.66	97.3	1478	±19	3138	±51	56	3.663	1.2	0.3260	0.34	3.880	1.4	0.2735	3.2	9.79	3.5	0.2577	1.4	.400
13.1	–	241	121	0.52	91.0	2346	±26	2312.1	±8.6	−1	2.278	1.2	0.14701	0.50	2.278	1.2	0.14707	0.50	8.90	1.3	0.4391	1.2	.924
14.1	0.11	122	42	0.35	47.1	2393	±27	2304	±16	−4	2.222	1.3	0.1474	0.72	2.224	1.3	0.1464	0.92	9.08	1.6	0.4496	1.3	.827
15.1	–	158	77	0.52	57.1	2316	±25	2308	±12	0	2.315	1.3	0.14616	0.66	2.314	1.3	0.1467	0.70	8.74	1.5	0.4322	1.3	.881
16.1	–	162	67	0.43	50.1	2310	±25	2332	±20	1	2.321	1.3	0.1484	1.1	2.321	1.3	0.1488	1.2	8.84	1.7	0.4309	1.3	.747
17.1	0.30	130	39	0.31	45.6	2199	±26	2215	±18	1	2.453	1.4	0.1416	0.78	2.460	1.4	0.1390	1.0	7.79	1.7	0.4065	1.4	.807
18.1	0.26	173	74	0.45	52.3	2287	±26	2290	±19	0	2.342	1.3	0.1475	0.78	2.348	1.3	0.1452	1.1	8.52	1.7	0.4258	1.3	.766
19.1	0.49	210	88	0.43	71.2	2134	±25	2312	±19	8	2.536	1.3	0.1514	0.80	2.548	1.3	0.1470	1.1	7.96	1.7	0.3924	1.3	.761
20.1	0.19	155	78	0.51	54.7	2202	±27	2294	±15	4	2.451	1.4	0.1472	0.76	2.456	1.4	0.1455	0.87	8.17	1.7	0.4072	1.4	.853
21.1	0.24	165	55	0.34	56.7	2152	±26	2193	±20	2	2.517	1.4	0.1394	0.81	2.523	1.4	0.1372	1.1	7.50	1.8	0.3964	1.4	.782
23.1	0.40	151	48	0.32	51.2	2112	±26	2221	±21	5	2.559	1.5	0.1430	0.83	2.580	1.5	0.1395	1.2	7.46	1.9	0.3877	1.5	.774
24.1	6.64	351	409	1.20	85.3	1636	±20	2314	±100	29	3.233	1.2	0.2062	0.52	3.463	1.4	0.1472	6.1	5.86	6.2	0.2888	1.4	.217
25.1	0.01	95	30	0.32	33.4	2192	±29	2290	±17	4	2.469	1.6	0.1453	0.95	2.469	1.6	0.1452	0.98	8.11	1.8	0.4050	1.6	.847
[illegible]	2.92	298	238	1.04	71.9	1831	±22	2302	±84	20	2.919	1.2	0.1[illegible]	2.9	[illegible]	1.4	0.1462	4.9	6.71	5.1	[illegible]	1.4	.288
29.1	0.15	111	38	0.35	40.5	2254	±28	2280	±18	1	2.386	1.5	0.1457	0.88	2.390	1.5	0.1443	1.0	8.33	1.8	0.4185	1.5	.817
30.1	0.12	285	123	0.45	97.8	2161	±22	2305	±11	6	2.508	1.2	0.14752	0.56	2.511	1.2	0.14643	0.64	8.04	1.4	0.3982	1.2	.880
31.1	0.63	88	15	0.19	31.2	2316	±28	2248	±32	−3	2.298	1.4	0.1473	0.77	2.313	1.4	0.1417	1.9	8.45	2.3	0.4323	1.4	.608
32.1	0.22	155	49	0.33	55.5	2225	±25	2210	±16	−1	2.420	1.4	0.1406	0.73	2.425	1.4	0.1387	0.91	7.88	1.6	0.4123	1.4	.839
33.1	0.17	240	61	0.26	88.4	2297	±26	2279	±12	−1	2.332	1.2	0.14874	0.60	2.336	1.2	0.14426	0.67	8.52	1.4	0.4281	1.2	.880
34.1	0.82	341	227	0.69	139	2018	±20	2283	±18	12	2.698	1.2	0.15192	0.53	2.721	1.2	0.1446	1.1	7.33	1.6	0.3675	1.2	.740
35.1	7.42	798	669	2.72	77.1	1491	±21	2141	±160	36	3.957	1.2	0.2155	2.6	3.842	1.6	0.158	9.1	5.37	9.2	0.2600	1.6	.170
38.1	0.60	111	90	0.84	39.4	2224	±28	2289	±25	3	2.413	1.5	0.1504	0.86	2.427	1.5	0.1451	1.5	8.24	2.1	0.4120	1.5	.712
39.1	0.04	282	95	0.35	99.4	2213	±22	2231	±15	1	2.441	1.2	0.1407	0.84	2.442	1.2	0.1403	0.86	7.92	1.5	0.4095	1.2	.813
40.1	0.83	49	18	0.38	18.1	2286	±40	2299	±35	1	2.330	2.1	0.1533	1.3	2.349	2.1	0.1460	2.0	8.57	2.9	0.4257	2.1	.711

Errors are 1-sigma; Pb_c and Pb^* indicate the common and radiogenic portions, respectively.Error in Standard calibration was 0.40% (not included in above errors but required when comparing data from different mounts).

Error in Standard calibration was 0.41% (not included in above errors but required when comparing data from different mounts).

(1) Common Pb corrected using measured ^{204}Pb.

(2) Common Pb corrected by assuming $^{206}Pb/^{238}U$–$^{207}Pb/^{235}U$ age-concordance.

(3) Common Pb corrected by assuming $^{206}Pb/^{238}U$–$^{208}Pb/^{232}Th$ age-concordance.

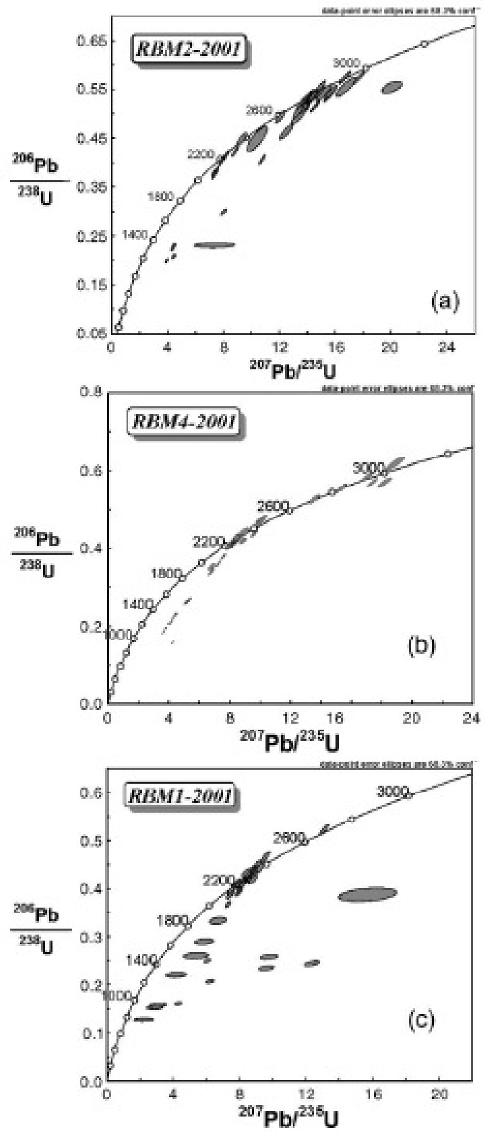

Fig. 4. U-Pb concordia plots of SHRIMP of analysed detrital zircon fractions from the Segwagwa Group. The Concordia is calibrated in Ma and only data which are >90% concordant are included in the analysis: (a) base of the Ditojana Formation (RBM2/2001); (b) top of the Mogapinyana Formation (RBM4/2001); (c) top of Monotoholwana formation (RBM1/2001).

4.1. Sample RBM2/2001

This quartzite sample was collected near the base of the Segwagwa Group immediately above the banded ironstones of the Taupone Group, west of Segwagwa village at 25°11.334′S/25°10.066′E. The quartzite is pale brown, medium- to coarse-grained, rarely with cross-beds. It occurs at the bottom of the Ditojana Formation of the Segwagwa Group, a correlate of the quartzitic units of the Timeball Hill Formation of the Pretoria Group, or with some units in the Makganyane Formation of the Postmasburg Group. Forty-three analyses were done on 43 different and randomly selected detrital grains from this sample, of which 35 are >90% concordant (Fig. 4a). All the grains ranged between 160 and 120 μm. The 35 concordant zircons are split into four main groups: ca. 2900–2700 Ma (n=25); ca. 2350–2200 Ma (n=7); ca. 2600–2500 Ma (n=2), including analyses 8.1 and 9.1 giving 2632±15 and 2542±45 Ma, respectively; and >3000 Ma (n=1) corresponding to one concordant grain of 3010.6±7.8 Ma (Table 2a). The oldest concordant zircon date of 3260±30 Ma is recorded by a 13% discordant zircon, which sets the maximum age of the source of this zircon. The probability plot for the main detrital zircon population in this sample gives a mean $^{207}Pb/^{206}Pb$ with peak at 2781±7 Ma (Fig. 5a). The youngest zircon in this sample (grain number 18.1) yielded a concordant $^{207}Pb/^{206}Pb$ date of 2240± 12 Ma (2σ) among a group of four other near concordant analyses (2251±12, 2239 ±22, 2248±13 and 2268±10 Ma) which give a weighted mean $^{207}Pb/^{206}Pb$ date of 2250+14/−15 Ma (MSWD = 0.09) for Ditojana Formation of the Segwagwa Group.

4.2. Sample RBM4/2001

This ferruginous quartzite sample was collected from a ridge close to the top of the Mogapinyana Formation of the Segwagwa Group at 25°07.696′S/25°06.890′E. The Mogapinyana Formation in Botswana is a correlate of the Daaspoort Quartzite Formation of the Pretoria Group. It comprises dark carbonaceous shales overlain by pink quartzitic sandstones. The sandstones are overlain by micaceous shales with the top marked by prominent pink to red coloured sandstones. The red sandstones are associated with a polymict, red-coloured or dark brown, poorly sorted conglomerate with subrounded clasts of chert, red to dark brown sandstones, ironstones, jaspilites and vein quartz. Forty analyses were done on 40 different and randomly selected detrital grains from sample RBM4/2001. The majority of the data plot on or near Concordia (Fig. 4b);

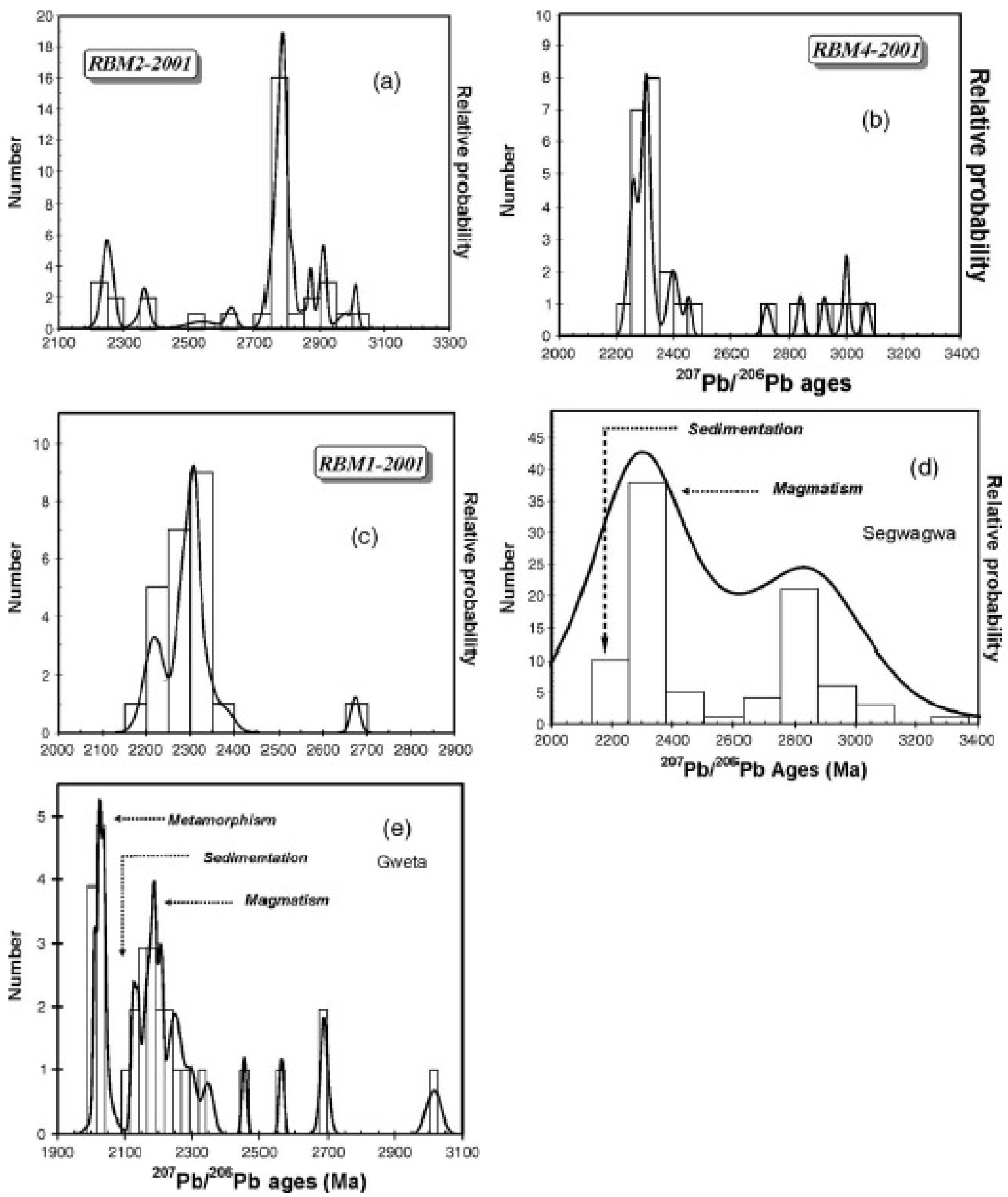

Fig. 5. Histogram and density probability curves of SHRIMP $^{207}Pb/^{206}Pb$ data for all the samples in the Segwagwa Group. (a) Base of the Ditojana Formation (RBM2/2001); (b) top of the Mogapinyana Formation (RBM4/2001); (c) top of Monotoholwana formation (RBM1/2001); (d-e) comparison of the Segwagwa Group sedimentary rocks and Gweta Gneiss using histograms and density probability curves of all SHRIMP $^{207}Pb/^{206}Pb$ data. The probability curves are calibrated in Ma.

a number of zircons are significantly discordant, and therefore in our statistical assessment of the data, only the 26 concordant to near concordant (>90%) $^{207}Pb/^{206}Pb$ dates are considered. The spread of zircon dates ranges from ca. 3.0–2.7 Ga (n=3) to ca. 2.45–2.20 Ga (n=23), reflecting the heterogeneous nature of the sources of these rocks (Fig. 5b). The largest distinct group of data falls between ca. 2450–2200 Ma. The youngest zircon grain (13.1) yielded a concordant $^{207}Pb/^{206}Pb$ date of 2236±13 Ma (2σ) (Table 2b) which is the preferred estimate for the maximum age of deposition for the Mogapinyana Formation of the Segwagwa Group.

4.3. Sample RBM1/2001

This sample from the pink to white cross-bedded quartzites of the Monotoholwane formation at the top of the Segwagwa Group was collected at 25°13.694′S/25°07.735′E and it correlates with the Magaliesberg Quartzite Formation of the Pretoria Group. This Formation is principally made up of reddish quartzitic sandstone with a sugary texture capped by unexposed shales. Forty grains in sample RBM1/2001 were analyzed, of which 33 are concordant to slightly discordant (>90%) (Fig. 4c), and the data show a bimodal distribution of $^{207}Pb/^{206}Pb$ dates (Fig. 5c). More than 90% (n=24) of the concordant zircons yielded dates between 2350 and 2190 Ma. The oldest zircon grain (8.1) is Archaean with a $^{207}Pb/^{206}Pb$ date of 2674±11 Ma (Table 2c). The youngest group of zircons comprises 24 concordant analyses, of which the youngest zircon grain (21.1) yields a $^{207}Pb/^{206}Pb$ date of 2193±20 Ma.

5. Discussion

5.1. Timing of sediments deposition

The Segwagwa/Pretoria Group contains a volcanic marker known as the Hekpoort Formation in the Transvaal Basin or the Ongeluk Formation in the Griqualand West Basin in South Africa [14,20,43], and the Tsatsu or Ditlhojana Formations in the Kanye and Ramotswa Basins of Botswana, respectively [17,23,57]. The Ongeluk and the Hekpoort Formations in South Africa yielded Pb–Pb and Rb–Sr whole-rock isochron dates of 2222±13 and 2224±21 Ma, respectively [28,57]. In contrast, a carbonate unit stratigraphically overlying the Ongeluk Formation yielded a low-precision whole-rock isochron Pb–Pb date of 2394±26 Ma [44]. This date was used to suggest that the Segwagwa/Pretoria Group sedimentary rocks were deposited between ca. 2.40 and 2.39 Ga [23,45]. New Re/Os dating of the Timeball Hill Formation indicates that this formation was deposited at 2316±7 Ma [42] whilst SHRIMP U–Pb dating of detrital zircons yielded an age of 2324±17 Ma being the maximum deposition age of the this formation [43]; suggesting the age obtained by Bau et al. [44] was too old. The youngest detrital zircons from the base (2240±12 Ma), middle (2236±13 Ma) and top (2193±20 Ma) of the Segwagwa/Pretoria Group in Botswana are, within the margin of errors, identical. These dates indicate that the maximum depositional age of the Segwagwa/Pretoria Group in Botswana is ~2.25–2.20 Ga and imply that the dated exposure of the Timeball Hill Formation by Dorland [43] did not contain any of the younger grains or alternatively the lack of a major component of ca. 2.32 Ga detrital zircons in the Kanye Basins, reflects changes in the source regions during the deposition this formation in the Kanye and Transvaal Basins.

The Rb–Sr isochron ages of ca. 2.22 Ga reported for volcanic rocks inter-bedded with the sedimentary rocks of the Segwagwa/Pretoria Group reinforce the deposition of these supracrustal sedimentary units at ≤2.25 Ga. The U–Pb zircon dates in this paper rule out the deposition of the Segwagwa/Pretoria Group at ~2.40 Ga, at least in Botswana. Taking into account the limitations of the Pb–Pb isochron technique, we believe the same may apply to the Postmasburg Group of South Africa where the Pb–Pb carbonate age of ~2.39 Ga was obtained. The minimum age of deposition of the Segwagwa/Pretoria Group is set by the crystallization age of 2055±5 Ma for the Bushveld Complex in South Africa [33,58], and coeval intrusive bodies including the Moshaneng Complex [39] and the Segwagwa Complex – intruding the Segwagwa Group – in Botswana [Mapeo et al., unpublished data].

5.2. Provenance of sediments

Palaeo-current studies in the Pretoria Group in South Africa indicate variable source directions of the sediments [9,21,22]; the Timeball Hill Formation has northwesterly and northeasterly sources whilst the both Hekpoort and Magaliesberg Formations have westerly sources [9]. The Botswana Segwagwa Group located northwest of the main Transvaal Basin and north of the Griqualand West Basin displays northerly sources. The oldest concordant detrital zircon grains at ~3.01 Ga could originate from Mesoarchaean basement complex lithologies exposed in the Northern and Western Domains of the Kaapvaal Craton [59,60]. The Western

Domain of the Kaapvaal Craton hosts felsic igneous rocks emplaced at 2915±9, 2879±9, 2781±4 and 2689 ±5 Ma [59,61,62]. Detrital zircons with similar ages occur in the samples RBM2/2001 and RBM4/2001. Mesoarchaean/Neoarchaean detrital zircons form the dominant (~79%) population in sample RBM2/2001 at the base of the Segwagwa/Pretoria Group and decrease upwards (~19% in the sample RBM4/2001 and 4% in the sample RBM1/2001) at the top of the succession. Note the absence of Mesoarchaean zircons in this last sample. The sample RBM2/2001 contains a large population of detrital zircons yielding an average date of 2781±7 Ma that is identical to the age of the Gaborone Igneous Complex [19,63]. This suggests that this igneous complex was the main source of the sediments, indicating a proximal source for the basal succession of the Segwagwa/Pretoria Group. This zircon population decreases up the stratigraphy, indicating either that this source region was progressively covered and not available as a source for detritus or alternatively to changes in the morphology and hydrological network patterns resulting in changes of the sediment source area (s) with time. The upward increase of the ca. 2.2 Ga zircon group may be related to a progressive unroofing of a Palaeoproterozoic igneous province and/or changes in the morphology and hydrological network patterns, resulting in the changes in the source areas of the sedimentary detritus.

5.3. Detrital zircon of uncertain provenance

The ca. 2.45–2.22 Ga detrital zircons detected throughout the Segwagwa Group cannot be tied to a known local source area. No rocks of this age range are known in the Kaapvaal Craton. Assuming that the Rb–Sr and Pb–Pb whole-rock isochron ages of the Hekpoort and Ongeluk Formations are representative of their emplacement ages [8,22,28], one can argue for a local intrabasinal source for this group of detrital zircons. However, the Palaeoproterozoic detrital zircons show a broad age spectrum between 2450 down to 2193 Ma, whereas the Rb–Sr and Pb–Pb isochron dates of the volcanic sequences in the Pretoria Group are clustered at ~2200 Ma. The Palaeoproterozoic detrital zircons of ca. 2200 Ma occur at the base of the Segwagwa/Pretoria Group sedimentary succession beneath the ca. 2.2 Ga volcanic unit. For this reason, our preferred interpretation is that these zircons are exotic, i.e. of non-local source, consistent with new data of Dorland [43], which indicate that the sedimentary rocks intercalated with Hekpoort lavas yielded U–Pb detrital zircon ages of 2225±3 Ma, suggesting the lavas are not the source of the detrital zircons. The signature of these detrital zircons is characterized by abundant grains with a broad age range between ca. 2.45 and 2.20 Ga with a peak at ca. 2300 Ma, rather than displaying ages clustered within a small age interval. Detrital zircons with ages of ca. 2.4 Ga represent <15% of zircon population in samples RBM2/2001 and RBM4/2001, whereas those between ca. 2.3 and 2.2 Ga include 93% of detrital zircons from sample RBM1/2001. The trends indicate a gradual involvement of Palaeoproterozoic igneous rocks at the source of the Segwagwa/Pretoria Group sediments. This could reflect either a gradual spatial shift of the Palaeoproterozoic igneous rock area submitted to erosion or unroofing gradually exposing a Palaeoproterozoic igneous source area.

5.4. Geological implications

Detrital zircon U–Pb age data in this study suggest that igneous Palaeoproterozoic rocks (ca. 2.4–2.2 Ga) were exposed to erosion at the source of the Segwagwa/Pretoria Group sedimentary rocks. These zircons may have been derived from a no longer preserved crustal terrain located north of the Kaapvaal Craton or west of the Zimbabwe Craton. In the Kaapvaal Craton there are no igneous rocks emplaced between ca. 2.3 and 2.2 Ga. In the Zimbabwe Craton, however, Manyeruke et al. [64] have described the results of dating of a troctolite sample from the mafic–ultramafic Chimbadzi Hill intrusion in northwest Zimbabwe, east of the Magondi Belt, which yielded U–Pb baddeleyite crystallization ages ranging from 2265.8±4.8 to 2257±9.5 Ma with an upper intercept age of 2262±2 Ma. It is parallel and to the northwest of the 2575.4±0.7 Ma Great Dyke in Zimbabwe [65]. Globally, the period ca. 2.5–2.0 Ga is characterized by the occurrence of ultramafic intrusions, dyke swarms and layered mafic complexes, indicating continental break-up [5]. In North America, the break-ups are represented by the Kaminak dyke swarms (ca. 2.54 Ga) in the Hearne Province of Canada, Matachewan and Hearst diabases (ca. 2.47–2.45 Ga) of Canada and the final dispersion at ca. 2.2–2.1 Ga is recorded by the mafic dykes and sill swarms in the Slave, Hearne, Superior and Nain Provinces [66]. This event of the development of the Earth's crust during the Palaeoproterozoic appears not to be represented in the Kaapvaal–Limpopo–Zimbabwe Province.

Detrital zircons with magmatic zircons falling in the same range as the Segwagwa Group were also recorded in the Gweta–Magondi Belt of northeast Botswana [67], a distance of ca. 700 km to the southwest of the Chimbadzi Intrusion (Fig. 6). The ca.

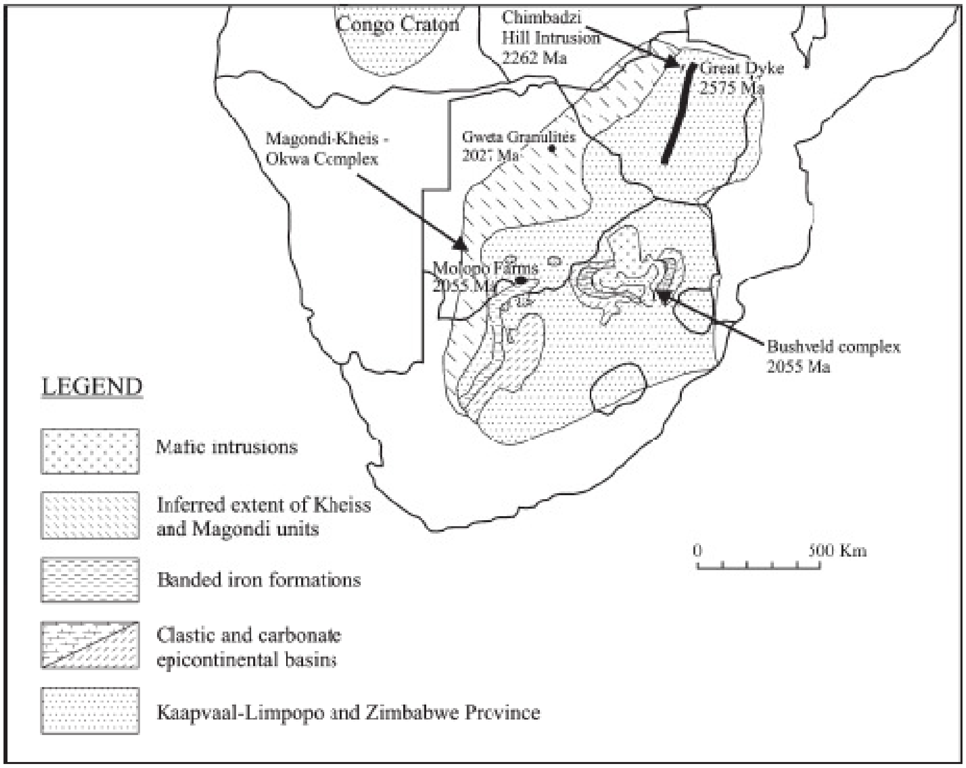

Fig. 6. Regional geological map of southern Africa showing the Transvaal Supergroup rocks and the Kheis–Magondi Belt.

2.3–2.2 Ga zircon grains documented in this paper also display strong zoning consistent with igneous origin. Reczko et al. [68] pointed out that there is no evidence for active margin tectonics during the deposition of the Pretoria Group, and proposed an intracratonic setting for the Transvaal Basin in which the Segwagwa/Pretoria sediments were deposited. Detrital zircons from the Segwagwa Group display the same ^{207}Pb/^{206}Pb fingerprint as metasedimentary rocks of the Gweta–Magondi Belt, suggesting that these two depocentres were most likely fed from the same source (Fig. 5d–e). Igneous complexes with ages between ca. 2.3 and 2.2 Ga are unknown in the Kaapvaal Craton, implying that this was not a significant sedimentary source for the Segwagwa/Pretoria Group. This is supported by palaeo-current directions pointing to a northerly, northeasterly and northwesterly source of sediments. These data imply that the main source of the Segwagwa/Pretoria Group was either the Zimbabwe Craton or a Palaeoproterozoic terrain, which was located north or northwest of the Kaapvaal Craton and west of the Zimbabwe Craton/Magondi Belt at ca. 2.2 Ga. An extensive investigation of the Zimbabwe Craton to assess the presence or not of major ca. 2.3–2.2 Ga igneous complexes is required in order to confirm these two alternatives and the role of intrusions such as the Chimbadzi Hill intrusion as source of zircon bearing detritus material during the Palaeoproterozoic time.

5.5. Significance for Palaeoproterozoic global glaciations

Our data which shows the formation age of the Upper Transvaal Supergroup at ca. 2.4–2.2 Ga provides a new, minimum age for the deposition of these units in Botswana, and confirms deposition of these and correlative units in the Transvaal and Griqualand West

Basins in South Africa during the first global glaciations during the Palaeoproterozoic. The earliest mid-latitude glaciations in southern Africa are recorded in the ca. 2.9 Ga Pongola Supergroup [69]; these were termed the Earth's oldest glacial deposits [70]. In North America (Canada and the USA), the deposition of the Huronian Supergroup between ca. 2.45 and 2.2 Ga is punctuated by three periods of glaciations (Ramsay Lake, Bruce and Gowganda Formation) [10,32,71]. This sequence is overlain by a thick sequence of sedimentary rocks of the Cobalt Group and the entire sequence is intruded by the ca. 2.22–2.21 Ga Nipissing diabase [66]; suggesting that the glacial deposits of the Huronian Supergroup were deposited much earlier than ca. 2.2 Ga. The Nipissing diabase has a similar age to the ca. 2.20 Ga detrital zircons derived from the Hekpoort Lavas, Mogapinyana (Dasspoort) and Monotoholwane (Magaliesberg) Formations of the Segwagwa/Pretoria Group and the Chimbadzi intrusion in the northwest of the Zimbabwe Craton.

Global mafic magmatism at ca. 2.45–2.40 Ga in the form of major dyke systems, flood basalts and layered mafic is an accepted event during the Palaeoproterozoic [5]. The ca. 2.45 Ga magmatism in North America predates the deposition of the Huronian Supergroup glacial sedimentary rocks, which were therefore deposited between 2.45 and 2.22 Ga, but well before the intrusion of ca. 2.22 Ga the Nipissing diabase. The Transvaal sequence of South Africa contains glacial deposits; the Makganyane Diamictite in the Postmasburg Group, the Bevets Conglomerate in the Duitschland Formation and a thin diamictite in the Boshoek Formations of the Pretoria Group [9]. The Boshoek Formation is a correlate of the Makganyane Formation in the Griqualand West Basin [10,32,42]. The data in this paper suggests the Makganyane glaciation occurred in the interval ca. 2.32–2.21 Ma in the Pretoria/Segwagwa Group. The new data suggests the period of Palaeoproterozoic glaciation within the Postmasburg/Pretoria/Segwagwa Groups ranges from ca. 2.32 to 2.20 Ga whilst other low latitudes glaciations in North America, Fennoscandia and Australia were laid down at ca. 2.45–2.20 Ga [72]. The depositions of the Makganyane glacial rocks show considerable diachroneity with those in the Huronian, Hamersley Province of Western Australia and Fennoscandia of up to ~130 Ma.

6. Palaeogeographic implications

A significant implication of the ages obtained in this study concerns the palaeogeographic relationship between the Kaapvaal Craton, the Palaeoproterozoic Magondi Supergroup and the Zimbabwe Craton between ca. 2.3 and 2.2 Ga. The current location of the Segwagwa/Pretoria Group on the Kaapvaal Craton is an original feature as shown by the unconformity relationship between the Segwagwa/Pretoria Group with the Taupone/Chuniespoort/Ghaap Groups [47]. At the northern margin of the Kaapvaal Craton, the Magondi Supergroup rocks are affected by Palaeoproterozoic contractional deformation at 2.03 Ga [73–75]. The Magondi Belt straddles the western margin of the Zimbabwe Craton, the northwest margin of the Limpopo–Shashe Belt [76] and the northern margin of the Kaapvaal Craton, indicating that these last three units amalgamated before the Eburnean Magondi orogeny. The similar maximum depositional age of the Gweta–Magondi Supergroup [64] and the Segwagwa/Pretoria Group (this paper), and their identical U–Pb zircon fingerprints (Fig. 5a) and the lack of any plate boundary between the Magondi Supergroup and the Segwagwa/Pretoria Group sedimentary units imply that they were both deposited during the evolution of an extensional basin which closed during the Eburnean Magondi orogeny. The extension of the Magondi belt in southern Botswana (western edge of the Kaapvaal Craton) is known as the Kheis belt that exposes Olifantshoek Supergroup metasedimentary rocks [45,61]. Mapeo et al. [77] have shown that the Olifantshoek Supergroup lithologies starting with the Hartley Formation volcanics (dated at 1928±7 Ma) are younger than the Magondi Supergroup rocks, and therefore not part of the same sequence. Furthermore, recognition by Beukes et al. [48] that: first the Mapedi and Lucknow Formations of the Olifantshoek Formation (below the Hartley lavas) are intruded by the ca. 2.05 Ga Bushveld Complex; second the Mapedi and Lucknow Formations contain $\delta^{13}C$ enriched carbonates similar to carbonates below the Magaliesberg quartzite in the Transvaal basin and to those in the Lomagundi Group of the Magondi Supergroup, and lastly were deformed during the Kheis–Gweta–Magondi orogeny makes these units belong to the Postmasburg Group of the Griqualand West Basin and therefore lateral correlatives of the Magondi Supergroup sedimentary rocks in the Zimbabwe Craton. This provides the clearest link between the deposition of the Postmasburg/Pretoria/Segwagwa Groups and the Magondi Supergroup; and their deformation during the Eburnean Magondi orogeny.

The dominant group of detrital zircons in the youngest sedimentary rocks in the Segwagwa/Pretoria Group and the Magondi Supergroup rocks (Fig. 5) suggests that the source of these sediments was most probably the same. Taking into account the fact that the sedimentary transport direction points to a northerly source for the Segwagwa/Pretoria Group sedimentary rocks in Botswana, and that the Segwagwa/Pretoria Group type platform sedimentary rocks are unknown in the Zimbabwe Craton, the most likely palaeomorphology is that of a highland west of the Zimbabwe Craton which is the potential source of sediments of both Segwagwa/Pretoria Groups and Magondi Supergroup. The Magondi Supergroup was involved in a major Palaeoproterozoic (~2.0 Ga) crustal shortening event and high-grade granulite facies metamorphism. In contrast, the presumably coeval and lateral correlative, the Segwagwa/Pretoria Group, evolved under greenschist facies metamorphism, with a minimum shortening. This difference is here taken to reflect a major rheological and different geotectonic position of the shortened crust at ~2.0 Ga. The Segwagwa/Pretoria rests on the Kaapvaal Craton, and, presumably, the thick lithosphere related to the strong Archaean mantle keel beneath the craton [78] protected the craton and the sedimentary blanket during the Eburnean orogeny. The Magondi Supergroup was presumably a pristine Palaeoproterozoic basin not underlain by Archaean lithosphere at the early stage of Eburnean contractional deformation, and thus possibly represents a section that was affected by inversion at ca.<2.2 Ga and before 2.0 Ga. The Segwagwa/Pretoria Group is interpreted as a continental back-arc sequence, associated with rifting leading to deposition of the minor mafic and intermediate to felsic metavolcanics and metasedimentary rocks [79]. The initial intracratonic rifting is indicated by the Bushy Bend lavas (absent in Botswana), and other indications of the cyclic nature of the rifting are shown by the Ongeluk/Hekpoort/Ditlhojana/Tsatsu lavas within the Segwagwa/Pretoria Group sedimentary rocks [30,46]. The Segwagwa/Pretoria Group deposition occurred between 2193±20 and 2054±9 Ma, which is the depositional time range of the Magondi Supergroup sedimentary rocks [67].

7. Conclusions

The main results of this study are as follows:

(1) New SHRIMP U–Pb geochronology dates the maximum depositional age of the Segwagwa/Pretoria Group at 2193±20 Ma. The minimum age of this group is set by crosscutting Bushveld-age Segwagwa Igneous Complex emplaced at 2055±5 Ma. These dates indicate that the Segwagwa/Pretoria Group is entirely Palaeoproterozoic and consists of detritus derived from a variety of sources, mainly of Palaeoproterozoic age with minor inputs from Archaean sources.

(2) The data indirectly demonstrates the existence in the neighbourhood of the Kalahari Craton of a crust of ca. 2.30–2.20 Ga in the source regions of the Segwagwa/Pretoria Group sediments. The older zircons (>2.4 Ga) are minor and suggest the bulk of the sediments which make up the Segwagwa/Pretoria Group in southeast Botswana were from distal sources.

(3) The majority of the zircons from the upper parts of the Segwagwa/Pretoria Group show a narrow age spectrum with well-defined Palaeoproterozoic ages (ca. 2.30–2.20 Ga). This pattern is similar to that of sediments deposited in the Gweta–Magondi Basin. Sedimentary rocks of the Magondi Supergroup were deposited after or at 2125±6 Ma and metamorphosed during the Eburnean Magondi orogeny at ca. 2027±8 Ma. The deposition ages of the Segwagwa/Pretoria Group and the Magondi Supergroup (Gweta–Magondi Basin in northeast Botswana) show overlapping age spectrums, suggesting that these two basins received detritus of similar age and probably developed during the same extensional tectonic cycle marking the development of the Pretoria–Segwagwa–Gweta–Magondi sequences at ~2.2–2.05 Ga.

(4) The maximum age of deposition of the Lower Transvaal Supergroup is 2431±31 Ma, the age of the Kuruman Formation. Therefore, the length of the unconformity between the Lower Transvaal and the Upper Transvaal ranges from 2431±31 to 2190±20 Ma, suggesting the hiatus between the Taupone/Chuniespoort/Ghaap and Pretoria/Segwagwa Groups is ~200 Ma. This extremely long hiatus indicates that the Lower (Taupone/Chuniespoort/Ghaap) and Upper (Segwagwa/Pretoria) Transvaal Groups cannot be part of the same supergroup.

(5) The Segwagwa/Pretoria Group glacial deposits (Makganyane and Boshoek Formation diamictites) accumulated at ca. 2.32–2.1 Ga, and are thus younger than Palaeoproterozoic glacial rocks in North America, Western Australia and Fennoscandia, which formed at ca. 2.45–2.20 Ga. The detrital zircon ages therefore show a major diachroneity in the deposition ages of the Palaeoproterozoic glacial deposits in the Kaapvaal Craton (ca. 2.32–2.1 Ga) and North American cratons (ca. 2.45–2.2). The data further suggests that the low latitude glacial deposits of the Makganyane and Boshoek in southern Africa, Huronian in North America, Hamersley in Western Australia and Karelian in Finland and Western Russia represent "snowball–earth" conditions attained at different times during Palaeoproterozoic.

Acknowledgements

This study was carried out as part of the revision of the Mmathethe Sheet (QDS 2525A) by the Department of Geological Survey of Botswana. Thanks are due to the Director, Department of Geological Survey, and R.M. Key, former Principal Geologist in the Regional Geology Division. SHRIMP work was supported by the University of Botswana/FoS-RPC (Project #R034) for Research on the Transvaal Supergroup of southeast Botswana. Richard A. Armstrong would like to thank the Electron Microscopy Unit at Austualian National University for access to their facilities. This paper is published with the authorization of the Minister of Minerals, Energy and Water Affairs, and of the Director of the Geological Survey Department, Botswana. The authors are indebted to the Earth and Planetary Science Letters reviewers (Dr. M. Schmitz) whose critical reviews materially improved this manuscript.

References

[1] D.R. Nelson, Compilation of SHRIMP U–Pb Zircon Geochronological Data, 1996 Record 1997/2, Western Australia Geological Survey, 1997, p. 189.

[2] S.F. Olson, The Proterozoic evolution of Africa, Economic Geology Research Institute, Information Circular, vol. 343, University of the Witwatersrand, Johannesburg, South Africa, 2000, pp. 1–40.

[3] R.E. Hanson, Proterozoic geochronology and tectonic evolution of southern Africa, in: M. Yoshida, B.F. Windley, S. Dasgupta (Eds.), Proterozoic of East Gondwana: Supercontinent Assembly and Breakup, vol. 206, Geological Society of London Special Publication, 2003, pp. 427–463.

[4] B.M. Eglington, R.A. Armstrong, The Kaapvaal Craton and adjacent orogens, southern Africa: a geochronological database and overview of the geological development of the craton, S. Afr. J. Geol., 107 (1/2) (2004) 13–32.

[5] L.M. Heaman, Global mafic magmatism at 2.45 Ga: remnants of an ancient large igneous province, Geology, 25 (1997) 299–302.

[6] L.M. Heaman, 2.5–2.4Ga global mafic magmatism: remnants of supercontinent or product of superplumes? Denver Annual General Meeting, USA, 2004, p. 105-5.

[7] SACS, Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophutatswana, Transkei and Venda, Geological Survey of South Africa, Pretoria, 1980.

[8] P.G. Eriksson, J.K. Schweitzer, P.J.A. Bosch, U.M. Schreiber, M.J.L. Van Deventer, C.J. Hatton, The Transvaal sequence: an overview, J. Afr. Earth Sci., 27 (1993) 349–358.

[9] P.G. Eriksson, W. Altermann, C. Catuneanu, R. Van der Merwe, A.J. Bumby, Major influences on the evolution of the 2.67–2.1 Ga Transvaal Basin, Kaapvaal Craton, Sediment. Geol., 141–142 (2001) 205–231.

[10] R.E. Kopp, J.L. Kirschvink, I.A. Hilburn, C.Z. Nash, The Palaeoproterozoic snowball earth: a climate triggered by the evolution of oxygenic photosynthesis, Proc. Natl. Acad. Sci. U. S. A., 102 (1999) 1131–1136.

[11] D.T. Aldiss, A.R. Tombale, R.B.M. Mapeo, M. Chiepe, The Geology of the Kanye Area: an Explanation of the Quarter Degree Sheet 2425C, Botswana Geological Survey, Lobatse, 1989, 170 pp.

[12] R.M. Key, N. Ayers, The 1998 edition of the national geological map of Botswana, J. Afr. Earth Sci. 30 (2000) 427–451.

[13] R.B.M. Mapeo, The Geology of Molobo and Mabule Areas: an Explanation of Quarter Degree Sheet 2524B and Part of 2524D Which Lies in Botswana, Botswana Geological Survey, 1990, 33 pp.

[14] P.G. Eriksson, P.J. Hattingh, W. Altermann, An overview of the geology of the Transvaal sequence and Bushveld Complex, South Africa, Miner. Depos. 30 (1995) 98–111.

[15] R.M. Key, The Geology of the Area Around Gaborone and Lobatse, Kweneng, Kgatleng and Southern District, Botswana Geological Survey, Lobatse, 1983, 230 pp.

[16] J.C. Carney, D.T. Aldiss, N.P. Lock, The Geology of Botswana, Botswana Geological Survey, Lobatse, 1994, 113 pp.

[17] P.G. Eriksson, B.F.F. Reczko, A.J. Boschoff, U.M. Schreiber, M. Van der Nuit, C.P. Snyman, Architectural elements from Lower Proterozoic braided-delta and high-energy tidal flats in the Magaliesberg Formation, Transvaal Supergroup, South Africa, Sediment. Geol. 97 (1994) 99–117.

[18] R.N. Crocket, The Transvaal system in Botswana: its geotectonic and depositional environments and special problems, Trans. Geol. Soc. S. Afr. 75 (1972) 275–291.

[19] D.F. Grobler, F. Walraven, Geochronology of the Gaborone Granite Complex extension in the area north of Mafikeng, South Africa, Chem. Geol. 105 (1993) 319–337.

[20] A.R. Tombale, Geological Map of the Jwaneng Area (QDS 2424D) (1:125000) with brief explanation, Botswana Geological Survey, Lobatse, 1986.

[21] P.G. Eriksson, J.P. Engelbrecht, M. Res, R.E. Harmer, An overview of the geology of the Transvaal sequence and the Bushveld Complex, South Africa, Miner. Depos. 30 (1995) 98–111.

[22] P.G. Eriksson, B.F.F. Reczko, The sedimentary and tectonic setting of the Transvaal Supergroup floor rocks to the Bushveld Complex: tectonic setting derived from basin-fill geometry, inferred volcanic processes and sedimentation systems, J. Afr. Earth Sci. 21 (1995) 487–504.

[23] P.G. Eriksson, U.M. Schreiber, M. Van der Nuit, A review of the sedimentology of the early Proterozoic Pretoria Group, Transvaal sequence, South Africa: implications for tectonic setting, J. Afr. Earth Sci. 13 (1991) 107–119.

[24] P.G. Eriksson, Sedimentology of the Rooihoogte Formation, Transvaal sequence, S. Afr. J. Geol. 93 (4) (1988) 477–489.

[25] P.G. Eriksson, D. Twist, C.P. Snyman, L. Burger, The geochemistry of the Silverton Formation, Transvaal sequence, S. Afr. J. Geol. 93 (3) (1990) 454–462.

[26] D.J. Cullen, Geology of the Dikgomo-Di-Kae Area, Bechuanaland Protectorate Geological Survey, for 1956, Lobatse, 1958, 5-11 pp.

[27] A.R. Tombale, Brief explanation of the geology, Mmathethe, quarter degree sheet 2525A. Geological Survey, Lobatse Botswana. Unpublished internal Report ART/6/86, 1986.

[28] D.H. Cornell, S.S. Schutte, B.L. Eglington, The Ongeluk Basaltic Andesite Formation in Griqualand West, South Africa, Precambrian Res. 79 (1996) 101–123.

[29] P.G. Eriksson, B.F.F. Reczko, Tectonic setting of the Pretoria Group, Transvaal Supergroup, in: J.M.J. Barton, Y.E.

Copperthwaite (Eds.), Centennial Geocongress, vol. 1, Geological Society of South Africa, Johannesburg, South Africa, 1995, pp. 508–511.

[30] P.G. Eriksson, R.R.W. Merkle, U.M. Schreiber, J.P. Engelbrecht, M. Res, C.P. Snyman, Early Proterozoic black shales of the Timeball Hill Formation, South Africa: volcanogenic and palaeoenvironmental influences, J. Afr. Earth Sci. 97 (1994) 325–337.

[31] P.G. Eriksson, J.P. Engelbrecht, R.E. Harmer, The Bushy Band Lavas, a new volcanic member of the Pretoria Group, Transvaal sequence, S. Afr. J. Geol. 97 (1994) 1–7.

[32] D.A.D. Evans, N.J. Beukes, J.L. Kirschvink, Paleomagnetism of a lateritic paleoweathering and overlying Paleoproterozoic red beds from South Africa: implications for the Kaapvaal apparent polar wander and a confirmation of atmospheric oxygen enrichment, J. Geophys. Res. 107 (12-2326) (2002) 1–22.

[33] F. Walraven, J.E.J. Martini, Zircon Pb-evaporation age determinations of the Oak Tree Formation, Chuniespoort Group, Transvaal sequence: implications for the Transvaal–Griqualand West Basin correlations, S. Afr. J. Geol. 98 (1995) 58–68.

[34] B.M. Jahn, J. Bertrand-Sarfati, N. Morin, J. Mace, Direct dating of stromatolitic carbonates from the Schmidtdrift Formation (Transvaal Dolomites). South Africa, with implications on the age of the Ventersdorp Supergroup, Geology 18 (1990) 1211–1214.

[35] W. Altermann, D.R. Nelson, Sedimentation rates, basin analysis and regional correlations of the three Neoarchaean sub-basins of the Kaapvaal Craton as implied by precise SHRIMP U–Pb ages from the volcanic sediments, J. Sediment. Geol. 120 (1998) 225–256.

[36] A.F. Trendall, W. Compston, I.S. Williams, R.A. Armstrong, N.T. Arndt, N.J. McNaughton, D.R. Nelson, M.E. Barley, N.J. Beukes, J.R. De Laeter, E.A. Retief, A.M. Thorne, Chronological Comparison of the Volcano-Sedimentary Sequences of the Kaapvaal and Pilbara Cratons between 3.2 and 2.4 Ga, Third Archaean Symposium, Perth Australia, 1990.

[37] D.Y. Summer, S.A. Bowring, U–Pb geochronology constraints on the deposition of the Campbell Rand Subgroup, Transvaal Supergroup, South Africa, Precambrian Res. 79 (1996) 25–35.

[38] A.L. Pickard, SHRIMP U–Pb zircon ages for the Palaeoproterozoic Kuruman Iron Formation, northern Cape Province, South Africa: evidence for simultaneous BIF deposition on the Kaapvaal and Pilbara cratons, Precambrian Res., 125 (2003) 275–315.

[39] R.B.M. Mapeo, A.B. Kampunzu, L.V. Ramokate, F. Corfu, R.M. Key, Bushveld-age magmatism in southeastern Botswana: evidence from U–Pb and titanite geochronology of the Moshaneng Complex, S. Afr. J. Geol. 107 (2004) 219–232.

[40] R.B.M. Mapeo, M.T.D. Wingate, Ion-microprobe U–Pb determination on zircons from the Bushveld-age Segwagwa igneous intrusion of SE Botswana, 20th Colloquium on African Geology Abstract, BRGM, Orleans, France, 2004, p. 281.

[41] F.J. Hartzer, Transvaal inliers: geology, tectonic development and relationship with the Bushveld Complex, in: J.M.J. Barton, Y.E. Copperthwaite (Eds.), Centennial Geocongress, vol. 1, Geological Society of South Africa, Johannesburg, South Africa, 1995, pp. 516–519.

[42] J.L. Hannar, H.J. Stein, A. Bekker, J.J. Wilkinson, N.J. Beukes, H.S. Van Niekerk, Primitive Os and 2316 Ma age for marine shale: implications for Paleoproterozoic glacial events and the rise of atmospheric oxygen, Earth Planet. Sci. Lett. 225 (2005) 43–52.

[43] H.C. Dorland, D. Phil. Thesis, Rand Afrikaans University, Johannesburg, South Africa, 2004.

[44] M. Bau, R.L. Romer, V. Luders, N.J. Beukes, Pb, O and C isotopes in silicified Mooidraai Dolomite (Transvaal Supergroup, South Africa): implications for the comparison of Palaeoproterozoic seawater and "dating" the increase of oxygen in the Precambrian atmosphere, Earth Planet. Sci. Lett. 174 (1999) 43–57.

[45] O. Catuneanu, P.G. Eriksson, The sequence stratigraphic concept and the Precambrian rock record: an example from the 2.7–2.1 Ga Transvaal Supergroup, Kaapvaal Craton, Precambrian Res. 97 (3–4) (1999) 215–251.

[46] J.M. Moore, H. Tsikos, S. Polteau, Deconstructing the Transvaal Supergroup, South Africa: implications for Palaeoproterozoic palaeoclimate models, J. Afr. Earth Sci. 33 (2001) 437–444.

[47] J. Tinker, M.J. de Wit, J. Grotzinger, Seismic stratigraphic constraints on Neoarchaean–Palaeoproterozoic evolution of the western margin of the Kaapvaal Craton, South Africa, S. Afr. J. Geol. 105 (2002) 107–134.

[48] N.J. Beukes, H. Dorland, J. Gutzmer, M. Nedachi, H. Ohmoto, Tropical laterites, life on land and the history of atmospheric oxygen in the Paleoproterozoic, Geology 30 (2002) 491–494.

[49] P.G. Eriksson, M.A. Martins-Neto, D.R. Nelson, L.B. Aspler, J.R. Chiarenzelli, O. Catuneanu, S. Sarkar, W. Altermann, C.J.d.W. Rautenbach, An introduction to Precambrian basins: their characteristics and genesis, Sediment. Geol. 141–142 (2001) 1–35.

[50] J.B. Paces, J.D. Miller, Precise U–Pb ages of the Duluth Complex and related mafic intrusions, northeastern Minnesota: geochronological insights to physical, petrogenic, palaeomagnetic and tectonomagmatic processes associated with the 1.1Ga midcontinental rift system, J. Geophys. Res. 98B (1989) 13997–14013.

[51] I.S. Williams, S. Claesson, Isotopic evidence for the Precambrian provenance and Caledonian metamorphism of high-grade paragneisses from Seve Nappes, Scandinavian Caledonides: SHRIMP II ion microprobe Zircon–U–Th–Pb, Contrib. Miner. Petrol. 97 (1987) 205–217.

[52] W. Compston, I.S. Williams, J.L. Kirschvink, Z. Zhang, G. Ma, U–Pb ages for the early Precambrian time-scale, J. Geol. Soc. (Lond.) 149 (1992) 171–184.

[53] G.L. Cummings, J.R. Richards, Ore lead isotope ratios in a continuously changing earth, Earth Planet. Sci. Lett. 28 (1975) 155–171.

[54] K.R. Ludwig, SQUID 1.00: a users manual, Berkeley Geochronological Centre Special Publication, Berkeley Geochronological Centre, California, 2000, p. 75.

[55] K.R. Ludwig, Isoplot/Ex version 2: geochronological toolkits for Microsoft Excel, Berkeley Geochronological Centre Special Publication, Berkeley Geochronological Centre, California, 1999, p. 43.

[56] K.R. Ludwig, On the treatment of concordant uranium–lead ages, Geochim. Cosmochim. Acta 62 (1998) 656–676.

[57] P.G. Eriksson, U.M. Schreiber, M. Van der Nuit, H. Labuschagne, W. Van der Chyff, G. Potgieter, Alternative marine and fluvial models for the non-fossiliferous sandstones of the Proterozoic Daspoort Formation, Transvaal sequence, southern Africa, J. Afr. Earth Sci. 16 (1993) 335–366.

[58] R.A. Armstrong, W. Compston, E.A. Retief, I.S. Williams, H.J. Welke, Zircon ion microprobe studies bearing on the age and evolution of the Witwatersrand Triad, Precambrian Res. 53 (1991) 243–266.

[59] M. Poujol, C.R. Anhaeusser, R.A. Armstrong, Episodic Archaean granitoid emplacement in the Amalia–Kraaipan Terrane,

South Africa: new evidence from single zircon U–Pb geochronology with implications for the age of the western Kaapvaal Craton, J. Afr. Earth Sci. 35 (2002) 147–161.

[60] C.R. Anhaeusser, F. Walraven, Episodic granitoid emplacement in the western Kaapvaal Craton: evidence from the Archaean Kraaipan granite–greenstone terrain, South Africa, J. Afr. Earth Sci. 28 (1999) 289–309.

[61] R.B.M. Mapeo, R.A. Armstrong, A.B. Kampunzu, L.V. Ramokate, SHRIMP U–Pb zircon ages of granitoids from the western domain of the Kaapvaal Craton, southeastern Botswana: implications for the crustal evolution, S. Afr. J. Geol., 107 (2004) 159–172.

[62] W.U. Reimold, R.A. Armstrong, C. Koebel, A deep drill-core from the Morokweng Impact Structure, South Africa: petrography, geochemistry and constraints on the crater size, Earth Planet. Sci. Lett. 201 (2002) 221–232.

[63] F. Walraven, D.F. Grobler, R.M. Key, Age equivalence of the Plantation Porphyry and the Kanye Volcanic Formation, south east Botswana, S. Afr. J. Geol. 99 (1996) 23–31.

[64] T. Manyeruke, T. Blenkinsop, P. Buchholz, D. Love, Oberthür, U. Vetter, D.W. Davis, The age and petrology of the Chimbadzi Hill Intrusion, NW Zimbabwe: first evidence for early Paleoproterozoic magmatism in Zimbabwe, J. Afr. Earth Sci., Middle East 40 (2004) 281–292.

[65] T. Oberthür, D.W. Davis, T. Blenkinsop, A. Höhndorf, Precise U–Pb mineral ages, Rb–Sr and Sm–Nd systematics for the great Dyke, Zimbabwe—constraints on late Archaean events in the Zimbabwe craton and Limpopo belt, Precambrian Res. 113 (2002) 293–305.

[66] L.B. Aspler, J.R. Chiarenzelli, Two Neoarchaean continents? Evidence from the Paleoproterozoic, Sediment. Geol. 120 (1998) 75–104.

[67] R.B.M. Mapeo, R.A. Armstrong, A.B. Kampunzu, SHRIMP U–Pb zircon geochronology of gneisses from the Gweta borehole, northeast Botswana: implications for the Palaeoproterozoic Magondi belt in southern Africa, Geol. Mag. 138 (2001) 299–308.

[68] B.F.F. Reczko, J.D. Oberholzer, M. Res, P.G. Eriksson, U.M. Schreiber, A revaluation of the Palaeoproterozoic Pretoria Group (Kaapvaal Craton) and hypothesis on basin development, J. Afr. Earth Sci. 21 (1995) 505–519.

[69] B.N.J. Modie, A glacigenic interpretation of Neoarchaean (~2.78 Ga) volcanogenic sedimentary sequences in the Nywaane Formation, Sikwane, southeast Botswana, J. Afr. Earth Sci. 35 (2002) 163–175.

[70] M.G. Young, V. voon Brunn, D.J.C. Gold, W.E.L. Minter, Earth's oldest reported glaciation: physical and chemical evidence from the Archaean Mozaan Group (~2.9 Ga) of South Africa, J. Geol. 106 (1998) 523–538.

[71] I.A. Hilburn, J.L. Kirschvink, E. Tajika, R. Tada, Y. Hamano, S. Yamamoto, A negative fold test on the Lorrain Formation of the Huronian Supergroup: uncertainty on the paleolatitude of the Paleoproterozoic Gowganda glaciation and implications for the great oxygenation event, Earth Planet. Sci. Lett. 232 (2005) 315–332.

[72] D.M. Martin, Depositional setting of Paleoproterozoic glaciomarine sedimentation in the Hamersley Province, western Australia, Geol. Soc. Amer. Bull. 111 (1999) 189–203.

[73] T. Manyeruke, T. Blenkinsop, P. Buchholz, D. Love, T. Oberthür, K. Vetter, D.W. Davis, The age and petrology of the Chimbadzi Hill Intrusion, NW Zimbabwe: first evidence for early Paleoproterozoic magmatism in Zimbabwe, J. Afr. Earth Sci. 40 (2004) 281–292.

[74] H. Munyanyiwa, A. Kroner, P. Jaeckel, U–Pb and Pb–Pb single zircon ages for charno-enderbites from Magondi belt, northwest Zimbabwe, S. Afr. J. Geol. 98 (1995) 52–57.

[75] T. Majaule, R.E. Hanson, R.M. Key, S.J. Singletary, M.W. Martin, S.A. Bowring, The Magondi belt in NE Botswana: regional relations and new geochronological data from the Sua Pan area, J. Afr. Earth Sci. 32 (2001) 257–267.

[76] R.T. Ranganai, A.B. Kampunzu, E.A. Atekwana, J.G. King, B.K. Paya, D.I. Koosimile, E.H. Stettler, Gravity evidence for a larger Limpopo Belt in southern Africa and geodynamics implications, Geophys. J. Int. 149 (2002) 221–232.

[77] R.B.M. Mapeo, L.V. Ramokate, A.R. Armstrong, A.B. Kampunzu, U–Pb zircon age of the Palapye Group (central eastern Botswana) and regional implications, J. Afr. Earth Sci. (1–2) (2004) 571–586.

[78] D.E. James, M.J. Fouch, J.C. Van Decar, S. Van Der Lee, T.K.S. Group, Tectospheric structure beneath southern Africa, Geophys. Res. Lett. 28 (2001) 2485–2488.

[79] S. Master, Geodynamic evolution and correlation of the Magondi belt (Zimbabwe): implications for the Palaeoproterozoic history of Botswana, Botsw. J. Earth Sci. 2 (1993) 25–32.

[80] F.J. Reichardt, The Molopo Farms Complex, Botswana: history, stratigraphy, petrography, petrochemistry and Ni-Cu-PGE mineralization, Expl. Mining Geol. 3 (1994) 264–284.

[81] D.H. Cornell, R.A. Armstrong, F. Walraven, Geochronology of the Hartley Basalt Formation, South Africa: constraints on the Kheis tectonogenesis and the Kaapvaal Craton's earliest Wilson cycle, J. Afr. Earth Sci. 26 (1998) 8–27.

[82] R.E. Hanson, W.A. Gosse, J.L. Crowley, J. Ramezani, S.A. Bowring, D.S. Bullen, R.P. Hall, J.A. Pancake, K. Mukwakwani, Paleoproterozoic intraplate magmatism and basin development on the Kaapvaal Craton: Age, paleomagnetism and geochemistry of the ~1.93 to ~1.87 Ga post-Waterberg dolerites, S. Afr. J. Geol. 107 (1/2) (2004) 233–254.