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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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 trachytes straddling the Western and Central Domains of the Kaapvaal Craton. The Segwagwa Group unconformably overlies the Tapiene Dolomite Group, a correlate of the South African Chuniespoort/Ghaap Group 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 granitoid rocks emplaced before and around 2915 ± 12 Ma and are related to the amalgamation of the Western, Northern and Central Domains of the Kaapvaal Craton. Discordant 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 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. 119, 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 glacial deposits in North America, Australia and Fennoscandia and with sedimentary rocks from the Palaeoproterozoic Magnetit Belt. Therefore, the Segwagwa/Preotia Group and the Maganji metasedimentary succession were deposited during the first global glacial period, were possibly related to the same geodynamic event, and should be part of the same supergroup.

Keywords: Transvaal Supergroup; Segwagwa/Preotia 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 basement is still poorly constrained around the world, possibly because this period was not a prolific magmatic period in various regions. This could be linked to 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 some African continental orogenic belts [2]. Hanchar [3] in a paper on the Palaeozoic 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, Eglinton 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 crusts in India, North America, Baltic Shield and Australia are characterized by the appearance 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 volcanic rocks, which is found in three separate basins on the Kaapvaal Craton. It is subdivided into the Lower Nearchean Chinsisoport-Tennore/Ghaap and Upper Palaeoproterozoic Seiswagwa/Postmasburg groups [7,8]. The Nearchean Lower Transvaal sequence is separated from the Palaeoproterozoic Upper Transvaal sequence by an unconformity and contains important iron formations that include carbonate and banded iron formation, basal and intraformational low latitude glaciogenic 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 Palaeozoic geological units, 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 crossecting igneous bodies provide the minimum age of the accumulation of sediments in basins. The youngest concordant detrital zircons define the maximum depositional 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 in conformity between the Nearchean Lower Transvaal known as the Tenapole 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 (Preotia/Postmasburg Groups in South Africa and Segwagwa Group in Botswana) rocks of southern Africa? (d) In this study we use SHRIMP U–Pb zircon data to shed light on: (1) The maximum depositional age of classic sedimentary rocks of the Segwagwa/Preotia 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/Preotia 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
the Kaapvaal Craton in South Africa and Botswana [11–15]. The Lower Transvaal includes the Neoarchean Churiespoort/Ghaap Group in South Africa and its correlative Tauponti Palaeoproterozoic Group in Botswana. The Upper Transvaal consists of the Palaeoproterozoic Pretoria/Postmasburg Group in South Africa and its correlative Segwagwa Group in Botswana. The Tauponti/Churiespoort Group is a carbonate sequence capped by iron formations and ironstones whereas the Segwagwa/Pretoria Group is siliclastic with minor volcanic rocks [18,17].

In Botswana, the base of the Tauponti 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 diorite 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 cemented, with interbedded chert and dolomite grading to iron formation(s) of the Maseke Iron Formation and chert breccias of the Kgwagwe Chert Breccia Formation at the top [16,20]. The chemical sedimentary succession of the Tauponti/Churiespoort Group is separated from the clastic sedimentary rocks of the Segwagwa/Pretoria Group by an erosional unconformity. The
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The section on paleontological data is from the literature and data sources. The described method of dating is based on [1].
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 Helpoort–Dithlokojane–Tsau–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 Tsatsa Formation. This formation is a correlate of the Helpoort 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 Tsameng 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 Deutschland Formation comprising dolomite shale, dolomite, quartzite, and chert breccia/diamicte (Bevets Conglomerate) above the Banded Iron Formation landscape [9]. The Rooihoogte Formation is overlain by the Timeball Hill Formation, which is made up of lower

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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 Braid Lava Member [22,24,30,31]. The Timeball Hill Formation is overlain unconformably by the Bushveld Formation (conglomerate, sandstone), a correlative of the Mafikeng diamictite [9,10,22]. The Bushveld Formation diamictites are absent in 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 correlative of the Ditejaa Quartzite of the Segwagwa Group [15,20]. The base of the Ditejaa Formation has no volcanic rocks but contains pyritic and micaceous shales grading to ferruginous quartzites at the top. The Bushveld Formation is correlative with Thamalakane Formation in the Kanye Basin and principally made up of brown to yellow, ferruginous shale with discontinuous chert pebble conglomerate/diamictite below the Isatou Formation. Borehole intersections in the Jeemang 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 of the Mafikeng diamictite in the Griqualand West Basin and the Bushveld 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 lime-tuff from the Subalpine Formation of the Campbell Subgroup by Jahn et al. [34]. This date is similar to a SHRIMP U–Pb zircon crystallization age of 255 ± 19 Ma for tuff beds in the Montville 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 crystallization ages between 253 ± 5 and 2550 ± 3 Ma [1]. The top of the Choniesport Formation is marked by the Pangea 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 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 [38]. The Quiver Member, a tuff bed in the Kuruman Formation, yielded U–Pb zircon crystallization ages of 2478 ± 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 Griqualand Iron Formation above the Kuruman Formation yielded the younger U–Pb SHRIMP zircon crystallization age of 2031 ± 31 Ma [39], setting the minimum depositional age of the Lower Transvaal. In the Moshaneng sub-basin, the Taipone 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 Masokwe igneous complexes north of the Mnathethe (Fig. 2). These igneous complexes comprise syenites and diorites similar to those exposed in the Moshaneng Complex [29]. A granite from the Segwagwa Complex yielded a U–Pb zircon crystallization age of 2054 ± 9 Ma that supports the correlation of the Segwagwa–Masokwe Complexes to the Moshaneng Complex [10]. Therefore, the minimum deposition age of the Segwagwa Group sedimentary rocks is ~2105 Ga. Similarly, in South Africa, the ca. 205 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 siliciclastic dolomites of the Taipone Dolomite Group in Botswana correlate with the Ghaap and Chumispoort 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 Roohoogte 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 2326 ± 18 Ma and whole rock Pb–Pb isochron date of 2222 ± 12 Ma for lavas of the Onagbule Formation of the Postnasburg Group and lavas of the Hoekpoort Formation in the Transvaal Basin in South Africa [42,43]. However, according to Bau et al. [44], the 2236 ± 3 Ma date has never been reproduced or confirmed by U–Pb zircon dating. Note that this date is similar to the low-precision Rb–Sr isochron date of 2224 ± 21 Ma for the Hoekpoort Formation in the Transvaal Basin [43,44]. Bau et al. [44] published a Pb–Pb date of 2304 ± 7 Ma for dolomites from the Mooidraai Formation of the Postnasburg Group in the Griqualand West Basin. According to these authors, the dates for the Onagbule Lava and by extension the Hoekpoort andesite below the dated dolomites were unreliable. Catuneanu and Eriksson [45]
suggested that the Bushy Bend Lava above the unconformity between the Lower and Upper Transvaal Groups were possibly erupted at ca. 2.350 Ma, based on unpublished Pb-Pb zircon evaporation dates of the Hekpoort andesite lavas (Eriksson, pens. comm. 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 (Charniespoort and Gaap Groups) from the Upper Transvaal Supergroup (Pretoria and Postmasburg Groups). In this new interpretation, the unconformity which separates the Charniespoort 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 lavas would be older with no equivalent in the Transvaal and Kanye Basins. The new interpretation of Moore et al. [46] is tenable in part because, first, it is based on the age published by Bai et al. [44] on the Moasdani 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 Basins 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 Innereng area, lithological units that normally lie between the Masoko Iron Formation (Penge Iron Formation) and the Ditjara Formation (Timeball Hill Formation) are missing in borehole intersection, consequently, the Kanye Volcanic Group is directly overlain by the post-Timeball Hill Formation rocks [Mapeo, unpublished data], an indication of complex erosion and preservation of Postmasburg/Segvagwa Group rocks in the Kanye and Griqualand West Basins.

3. Analytical procedure

Three 2-5 kg samples from the Segvagwa 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 Pluen density fractionation techniques. The final concentrate was hardpicked under a binocular microscope and the zircon grains were mounted in epoxy together with the zircon standard AS3 (Dalhousie Complex gabbronorite [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 Clasen [51] and Condomin et al. [52]. Pb-Pb in the unknowns were normalized to a 206Pb/204Pb value of 0.1859 (equivalent to an age of 1099.1 Ma) for AS3. The 206Pb/207Pb and 206Pb/208Pb concentrations were determined relative to those measured in the SL13 standard. Ages were calculated using the radiogenic 207Pb/206Pb ratios, with the correction for common Pb made using the measured 204Pb 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 three 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 IsoplotEx 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).
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4.1. Sample RBM2/2001

This quartzite sample was collected near the base of the Segwagwa Group immediately above the banded ironstones of the Taupane Group, west of Segwagwa village at 25°11.334'S/25°01.066'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 Tineba Hill Formation of the Pretoria Group, or with some units in the Malaganyane 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 207Pb/206Pb with peak at 2781±7 Ma (Fig. 5a). The youngest zircon in this sample (grain number 18.1) yielded a concordant 207Pb/206Pb 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 207Pb/206Pb date of 2250±14 Ma (MSWD = 0.99) 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 Mogapitsana Formation of the Segwagwa Group at 25°07.696'S/25°06.890'E. The Mogapitsana Formation in Boiswana is a correlate of the Dasspoort 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 surrounded clasts of chert, red to dark brown sandstones, ironstones, jaspilites and vei 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 Segwa Group. (a) Base of the Dikojuma Formation (RBMO/2001); (b) top of the Mesqotyana Formation (RBMO/2001); (c) top of Mootsholwama Formation (RBMO/2001); (d-e) comparison of the Segwa Group sedimentary rocks and Gweta Gneis 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 20 concordant zircons considered (<90%) 206Pb/
238U Pb dates are considered. The spread of zircon date
ranges from ca. 3.0–1.7 Ga (n=3) to ca. 2.45–2.20 Ga
(n=23), reflecting the heterogeneous nature of the
sources of these rocks (Fig. 3b). The largest distinct
group of data falls between 2.450–2.200 Ma. The
younger zircon grain (13.1) yielded a concordant
206Pb/238U Pb date of 2316±13 Ma (2σ) (Table 2b) which
is the preferred estimate on the maximum age of
deposition for the Mogapitsi Formation of the
Segwagwa Group.

4.3. Sample RBMI/2001

This sample from the pink to white chiselled
quartzites of the Monolokovane 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 redish quartzite
sandstone with a muddy texture capped by unexposed
shales. Forty grains in sample RBMI/2001 were
analyzed, of which 33 are concordant to slightly
discordant (<90%) (Fig. 4c), and the data show a
bell-shaped distribution of 207Pb/206Pb dates (Fig. 4c).
More than 90% (n=24) of the concordant zircons
yielded dates between 2350 and 2199 Ma. The oldest
zircon grain (8.1) is Archaean with a 207Pb/206Pb date
of 2677±11 Ma (Table 2a). The younger group of
zircons comprises 24 concordant analyses, of which
the younger zircon grain (21.1) yields a 206Pb/207Pb 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 Onhlok formation in the
Griqualand West basin in South Africa [14,20,23], and
the Tsetse or Dithloko formations in the Kanyene
and Ramotswa basins of Botswana, respectively [17,23,57].
The Onhlok and the Hekpoort formations in South
Africa yielded 206Pb/207Pb and 207Pb/206Pb whole-rock zircon
ages of 2222±13 and 2224±21 Ma, respectively
[28,37]. In contrast, a carbonate unit metamorphically
overlying the Onhlok formation yielded a low-
precision whole-rock zircon 206Pb/207Pb date of 2394±50
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 [23,43]. New
Rb-Sr 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 2334±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 Kendve Basins, reflects
changes in the source regions during the deposition
this formation in the Kendve and Transvaal Basins.

The Rb–Sr isochron ages of ca. 2.22 Ga reported for
volcanic rocks inter-beded with the sedimentary rocks
of the Segwagwa/Pretoria group reinforce the deposi-
tion 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 Pongostart 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 2058±5 Ma for the Bushveld Complex in South
Africa [33,58], and coeval intrusive bodies including the
Moshina complex [99] and the Segwagwa Complex
introducing the Segwagwa Group... in Botswana [Mapes
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 [29,22,21]. The TIMEBALL Hill Formation has
northwesterly and northeasterly sources while the both
Hekpoort and Magaliesberg formations have wes ternly
sources [9]. The Botswana Segwagwa Group located
northwest of the main Transvaal Basini and north of the
Griqualand West Basin displays northerly sources.
The oldest concordant detrital zircon grains at ~3.01 Ga
could originate from the Mesaoarchean basement complex
intrusives 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 2894 ± 5 Ma [56, 61, 62]. Detrital zircons with similar ages occur in the samples RBM2/2001 and RBM4/2001. Mesoarchaean–Neoarchaean detrital zircons form the dominant (~7%) population in sample RBM2/2001 at the base of the Segwagwa/Pretoria Group and decrease upwards (~1%) in the sample RBM4/2001 and 4% in the sample RBM1/2001) at the top of the succession. Note the absence of Mesaochaean 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 that either the source region was progressively eroded 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 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 [82, 228], 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 structural 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, Manyenyere et al. [64] have described the results of dating of a troctolite sample from the maar–ultramafic Chimbadzi Hill intrusion in northwest Zimbabwe, east of the Magendi mass, which yielded U–Pb biotite–zircon zircon ages ranging from 2265.8 ± 4.8 to 2257 ± 9.5 Ma with an upper intercept age of 2262 ± 2 Ma. It is parallel to the northwest of the 2575 ± 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 Kaminik dyke swarms (ca. 2.54 Ga) in the Hearne Province of Canada, Metalward and Hearst diabases (ca. 2.47–2.45 Ga) of Canada and the final dispersal 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.
2.3–2.2 Ga zircon grains documented in this paper also display strong zoning consistent with igneous origin. Ruzza 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 *206*Pb/*207*Pb fingerprint as metasedimentary rocks of the Gwaia-Magondi Belt, suggesting that these two depositional settings 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 of 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 a 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 Bushveld, 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 Palaeanoproterozoic. 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) [16,32,71]. 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 Helsport Lavas, Mogupanyana (Dasspoort) and Monotohwane (Magaliesberg) Formations of the Segwagwa/Prentoria Group and the Chimbadzi intrusion in the northwest of the Zimbabwe Craton.

Global tectonic magnatism 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 Palaeanoproterozoic [5]. The ca. 2.45 Ga magnatism 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 Danmiette in the Postmasburg Group, the Reehes Conglomerate in the Ditholzland Formation and a thin diamictite in the Boshoek Formations of the Prentoria Group [9]. The Boshoek Formation is a correlate of the Makganyane Formation in the Griquasand 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 Prentoria/Segwagwa Group. The new data suggests the period of Palaeanoproterozoic glaciation within the Postmasburg/Prentoria/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 deposits of the Makganyane glacial rocks show considerable diachronity 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 Palaeaeonoproterozoic Magondi Supergroup and the Zimbabwe Craton between ca. 2.3 and 2.2 Ga. The current location of the Segwagwa/Prentoria Group on the Kaapvaal Craton is an original feature shown by the unconformity relationship between the Segwagwa/Prentoria Group with the Taupole/Chainespoort/Chap Group [47]. At the northern margin of the Kaapvaal Craton, the Magondi Supergroup rocks are affected by Palaeaeonoproterozoic contractual 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 [54] and the Segwagwa/Prentoria 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/Prentoria 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 Olfantsheu Supergroup metasedimentary rocks [45,61]. Mapeo et al. [77] have shown that the Olfantsheu Supergroup lithologies starting with the Hardley 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 Beakes et al. [48] that: first the Mapedi and Lucknow Formations of the Olfantsheu Formation (below the Hardley lavas) are intruded by the ca. 2.05 Ga Bushveld Complex; second the Mapedi and Lucknow Formations contain δ13C 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 Griquasand 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/Prentoria/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/Prentoria 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 Segwawa/Pretronia Group sedimentary rocks in Botswana, and that the Segwawa/Pretronia 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 Segwawa/Pretronia 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 Segwawa/Pretronia Group evolved under granulite facies metamorphism, with no minimum shortening. This difference is here taken to reflect a major geological and different geotectonic position of the shortened crust at ~2.0 Ga. The Segwawa/Pretronia rocks on the Kaapvaal Craton, and, presumably, the thick lithosphere related to the strong Archaean mantle keel beneath the craton [58] 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 crust that was affected by inversion at ca.~2.2 Ga and before 2.0 Ga. The Segwawa/Pretronia Group is interpreted as a continental back-arc sequence, associated with rifting leading to deposition of the minor mafic and intermediate to felsic metavolcanic and metasedimentary rocks [79]. The initial sinistral rifting is indicated by the Bulky Bend lavas (absent in Botswana), and other indications of the cyclic nature of the rifting are shown by the Ongeluk/Helpoort/ Dithlojama/Isatsu lavas within the Segwawa/Pretronia Group sedimentary rocks [30,46]. The Segwawa/ Pretronia Group deposition occurred between 2193±20 and 2054±3 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 Segwawa/Pretronia Group at 2193±30 Ma. The minimum age of this group is set by crosscutting Bushveld-age Segwawa Iguana Complex emplacement at 2055±5 Ma. These dates indicate that the Segwawa/Pretronia Group is an early 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 southeast Botswana of a crust of ca. 2.30–2.20 Ga in the source regions of the Segwawa/ Pretronia Group sediments. The older zircons (~2.4 Ga) are minor and suggest the bulk of the sediments which make up the Segwawa/Pretronia Group in southeast Botswana were from distal sources.

(3) The majority of the zircons from the upper parts of the Segwawa/Pretronia 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 2.25±0.6 Ma and metamorphosed during the Eburnian Magondi orogeny at ca. 207±1 Ga. The deposition ages of the Segwawa/Pretronia 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 east-western tectonic cycle marking the development of the Pretronia–Segwawa–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 Kuniman 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 Taungtse/Chinsprechspoot/Ghaap and Pretronia/Segwawa Groups is ~200 Ma. This extremely long hiatus indicates that the Lower (Taungtse/Chinsprechspoot/Ghaap) and Upper (Segwawa/ Pretronia) Transvaal Groups cannot be part of the same supergroup.

(5) The Segwawa/Pretronia Group glacial deposits (Makganyene and Boskhe 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 derived zircon ages therefore show a major diachrony in the deposition age 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 Makganyene and Boskhe in southern Africa, Huronian in North America, Llanberis in Western Australia and Karelian in Finland and Western Russia represent "snowball–earth" conditions attained at different times during Palaeoproterozoic.
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