Heavy-mineral concentrates were obtained from a recent exploration campaign for diamond in the Somabula gravels, a paleoplacer of Upper Karoo (Triassic, ~200 Ma) age near Gweru, Zimbabwe. The polymict spectrum of heavy minerals in the Somabula placers comprises staurolite, zircon, monazite, columbite–tantalite, cassiterite, chromite, native gold, platinum-group minerals (PGM), and other components, which suggests derivation from a variety of source lithologies. Age determinations revealed that most of the detrital grains of zircon, monazite, and columbite–tantalite originate from Pan-African source rocks. Altogether, 622 detrital PGM grains were identified. Pt and Pt alloys, mainly with Fe, Rh, Pd and Ru, predominate (79%), followed by Os–Ir–Ru–Rh–Pt alloys (10%), rustenburgite [Pt₃Sn] (9%), and rare Pt-rich phases (1%). The compositions of the alloys suggest high-temperature crystallization from a complex Pt–Pd–Rh–Os–Ir–Ru–Fe solid solution in a sulfur-poor magmatic environment, probably mafic–ultramafic rocks. The suite of PGM markedly differs from that of detrital PGM originating from the Great Dyke and from the primary platinum-group element mineralization of the Main Sulfide Zone of the Great Dyke. The mineralogical evidence and Os isotope data obtained for the Os–Ir–Ru alloy rule out the possible derivation of the PGM from the Great Dyke. Instead, they are likely derived from late Archaean greenstone belts of the Zimbabwe craton.

Keywords: zircon, monazite, tantalite, U–Pb dating, platinum-group minerals, Pt–Fe alloy, Os–Ir–Ru–Rh–Pt alloys, rustenburgite, gold, Os isotopes, paleoplacer, Karoo Formation, Somabula gravels, Gweru, Zimbabwe.


INTRODUCTION

Diamond was first discovered in the Somabula forest of Zimbabwe in 1903 (Phaup 1958), and no other significant diamondiferous placer deposits are known in Zimbabwe. The diamondiferous gravels were exploited intermittently until about 1930, and since then, production has been sporadic and limited. The diamond output from 1905 to 1956 was recorded as 15,886 carats (Phaup 1958, Gibson 1967). The Somabula gravels are also interesting as they are paleoplacer deposits of Karoo age. Macgregor & Zealley (1921) noted that the heavy minerals of the gravels included "osmiridium and platinum". The availability of a heavy-mineral concentrate obtained during exploration work of the Trans Hex Group allowed the present investigation of the platinum-group minerals (PGM) in the Somabula paleoplacers. Our aim is (i) to provide a comprehensive characterization of the detrital PGM in the Karoo-age paleoplacers of Somabula, and (ii) to define possible sources of the heavy mineral and PGM assemblage.

GEOLOGICAL SETTING

From about 20 km southwest of Gweru in central Zimbabwe, a tongue of Karoo sediments up to 10 km wide stretches for ca. 50 km in a northwesterly direction (Tndalaje-Biscon 1949: Fig. 1). Locally, these sediments reach a thickness of 50 m and show well-developed basal layers of gravel, up to some meters thick. Macgregor & Zealley (1921) noted that the Karoo rocks rest unconformably on an uneven surface of weathered granite. On the basis of fossil plants, Seward & Holtum (1921) assigned the gravels to the Stormberg Series of the Upper Karoo (Triassic, ~200 Ma). The country rocks consist of early to late Archean (ca. 3.5–2.6 Ga) granitic and gneissic rocks and greenstone belts (Wilson et al. 1995). The Great Dyke, dated at 2575.4 ± 0.7 Ma (Oberthür et al. 2002) crops out some 50 km east of the Somabula occurrence (Fig. 1). The diamondiferous beds are a series of fluviatile and estuarine deposits characterized by beds of gravel with very well rounded pebbles. At the base of the deposit is a “wash” containing a large proportion of rounded crystals of heavy minerals, the most abundant of which is staurolite, which constitutes more than 98% of the heavy minerals (Bührmann 1997). Andalusite, gorceixite, beryl, chromite, chrysoberyl, corundum, garnet, ilmenite, kyanite, rutile, topaz, tourmaline, zircon, native gold and “platinum” also have been reported (Macgregor & Zealley 1921, Macgregor 1941, Harrison 1980). The most characteristic feature of the diamond crystals from Somabula is the faint green tinge of the majority of the stones, which invariably is lost on cutting (Macgregor & Zealley 1921). On average, the stones weigh just under one carat, and the largest diamond of good quality weighs 36¾ carats.

The origin of the placer minerals has been in debate for some time. Macgregor & Zealley (1921) believed that the rivers that deposited the Somabula gravels flowed from the north based on the fact that staurolite, abundant in the Somabula placers, is only found in the Miami mica fields of the Lomagundi district, some 300 km to the north. Harrison (1980) recalled signs of early Karoo glaciation, and speculated that the diamond crystals may have originated from a pipe in the northern part of Zimbabwe, probably in the area of the Zambezi valley, and were transported to the south by a glacier with additions of gravel by fast-flowing rivers from the melted ice. Master (1995) re-evaluated the possible sources of the diamonds and in general supported the hypothesis of Macgregor & Zealley (1921). Master (1995) proposed that the heavy minerals were brought to the Somabula area by a major river system that flowed southwest across the Great Dyke and recrossed back in the Somabula region, in the process picking up chromite and platinum-group minerals from the Great Dyke, and gold nuggets from auriferous greenstone deposits. Some chrome may have come from the Archean chromitite deposits of Shurugwi. Master (1995) further proposed...
that the diamond crystals may originate from undiscovered kimberlites in the Miami district, but he also remarked that the source of the diamond at Somabula remains enigmatic. Sedimentological work of Bührmann (1997) showed that the paleoriver system at Somabula flowed from south to north with an overall gradient of 0.18°, which implies a southerly source of the heavy minerals. This finding contrasts with the views of most earlier authors, who favored sediment sources to the north.

**METHODOLOGY**

During exploration by the Trans Hex Group between 1994 and 1997, a heavy-mineral concentrate was continuously separated as a by-product of the diamond extraction and stored in barrels at the processing site. We screened 656 kg of this concentrate to <2 mm and treated it in Zimbabwe in 1998. The fine fraction was subsequently washed and panned to obtain fractions of the heaviest minerals. By the above treatment, the densest fraction was reduced to about 10 g of a final concentrate of the heaviest components. The PGM grains, usually having silver metallic colors, and other minerals of interest, were extracted by hand and transferred to SEM sample holders. The grains were inspected with a scanning electron microscope (SEM) equipped with an energy-dispersion system (EDAX). Out of a total of 622 PGM grains detected, 154 grains representing the various groups of PGM were embedded in araldite, polished with diamond powder on a Dürer polisher, and analyzed with a CAMEBAX electron microprobe (EPMA) at BGR. The analytical conditions were: accelerating voltage 20 kV, specimen current 30 nA, and measurement times 10 s. The following standards and X-ray lines were used: RuLα, RhLα, OsMα, IrLα, AuLα, AgLβ, NiKα, SeKα, TeLα, BiMα, SnLα (metals), PtLα and FeKα (synthetic Pt:Fe alloy), PdLα
(synthetic PdS), SKα (synthetic PtS), PbMα (galena), and SbLα (stibnite). Raw data were corrected using the PAP (Pouchou & Pichoir 1991) program supplied by CAMECA. Additional corrections were performed for overlap of the elements Rh, Pd, Ag, Cu, As, and Sb with secondary lines. Detection limits for the elements listed are 0.1 wt.%. Altogether, 232 quantitative electron-microprobe analyses (EPMA) were carried out on the 154 grains of PGM selected and on 15 grains of gold.

Zircon and monazite grains were picked using a binocular microscope. Exterior surfaces of zircon grains were removed by air abrasion. Weights of zircon and monazite fractions, estimated by eye, should be accurate to about ±50%. This affects only U and Pb concentrations, not age information, which depends only on measurements of isotope ratios (Table 1).

Single crystals of zircon and monazite were washed in HNO₃. For all samples, a 205Pb–235U spike was added to the dissolution capsules during sample loading. Zircon was dissolved using HF in teflon bombs at 200°C. Monazite dissolution was carried out in a Savillex vial using 6N HCl. For both minerals, purification of Pb and U was carried out in HCl using 0.05 mL anion-exchange columns, following the method of Krogh (1973).

TABLE 1. U–Pb ISOTOPIC DATA ON ZIRCON, MONAZITE AND TANALITE FROM THE SOMABULA PALEOPLACER

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Weight</th>
<th>U ppm</th>
<th>Th/U</th>
<th>Pbcom</th>
<th>206Pb</th>
<th>207Pb</th>
<th>207U</th>
<th>U age Ma</th>
<th>Pb age Ma</th>
<th>Disc. %</th>
</tr>
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<tbody>
<tr>
<td>Zircon and Monazite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 ab Zrn, lpr, melt incl</td>
<td>0.0100 39 0.31</td>
<td>0.1297 0.1721 1.7731 1023.7</td>
<td>4.7 1035.6 5.5 1063.9</td>
<td>12.6</td>
<td>4.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Mnz, stby, nd, spr</td>
<td>0.0120 1055 13.0</td>
<td>23.8 3302 0.1042 0.8765 638.7</td>
<td>2.1 639.1 2.3 640.3</td>
<td>7.2</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Mnz, euh, equ</td>
<td>0.0120 826 25.1</td>
<td>24.3 2638 0.1033 0.8652 633.9</td>
<td>2.4 632.9 2.9 629.3</td>
<td>10.0</td>
<td>-0.8</td>
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</tr>
<tr>
<td>4 ab Zrn, euh</td>
<td>0.0050 69 0.57</td>
<td>0.8 2817 0.1020 0.8553 626.2</td>
<td>1.8 626.4 2.4 627.5</td>
<td>8.7</td>
<td>0.2</td>
<td></td>
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<tr>
<td>5 ab Zrn, frosted</td>
<td>0.0160 281 133</td>
<td>15.5 1897 0.1002 0.8329 615.4</td>
<td>2.1 615.2 3.3 614.7</td>
<td>12.7</td>
<td>-0.1</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>6 ab Zrn, resorbed, melt incl</td>
<td>0.0120 64 0.53</td>
<td>4.6 1081 0.0991 0.8271 609.3</td>
<td>1.0 612.0 4.9 612.9</td>
<td>20.6</td>
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<tr>
<td>7 ab Zrn, euh, spr</td>
<td>0.0030 51 0.37</td>
<td>0.2 4364 0.0987 0.8178 606.6</td>
<td>3.2 606.8 2.9 607.4</td>
<td>7.2</td>
<td>0.1</td>
<td></td>
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<tr>
<td>8 ab Zrn, frag</td>
<td>0.0160 219 0.29</td>
<td>0.5 39698 0.0902 0.7327 557.0</td>
<td>2.9 558.1 2.4 562.8</td>
<td>2.5</td>
<td>1.1</td>
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<tr>
<td>9 ab Zrn, euh, frosted</td>
<td>0.0060 162 0.22</td>
<td>1.6 3540 0.0892 0.7276 550.6</td>
<td>3.1 555.1</td>
<td>2.4 574.0</td>
<td>10.8</td>
<td>4.3</td>
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</table>

Columbite–Tantalite

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Weight</th>
<th>U ppm</th>
<th>Th/U</th>
<th>Pbcom</th>
<th>206Pb</th>
<th>207Pb</th>
<th>207U</th>
<th>U age Ma</th>
<th>Pb age Ma</th>
<th>Disc. %</th>
</tr>
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<tbody>
<tr>
<td>1 tantalite, lpr</td>
<td>0.0120 286 0.39</td>
<td>0.0149 57180 140894</td>
<td>2915.2 29.5 2755.7 63.4 2640.9</td>
<td>112.9</td>
<td>-12.9</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>2 tantalite, spr</td>
<td>0.0115 80 0.06</td>
<td>0.28 213.6 0.00590 0.7788</td>
<td>590.3 2.6 584.8 21.2</td>
<td>563.4</td>
<td>105.0</td>
<td>-5.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 tantalite, irreg shape</td>
<td>0.0129 129 -0.02</td>
<td>0.102 100.2 0.08123 0.6420</td>
<td>503.5 4.3 503.6</td>
<td>51.3</td>
<td>504.1</td>
<td>239.9</td>
<td>0.1</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>4 tantalite, spr</td>
<td>0.0114 164 0.00</td>
<td>0.75 1307.8 0.08048 0.6377</td>
<td>499.0 2.0 500.8</td>
<td>4.1</td>
<td>509.4</td>
<td>22.4</td>
<td>2.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 tantalite, square, flat</td>
<td>0.0112 209 0.02</td>
<td>0.77 166.9 0.07975 0.6358</td>
<td>494.6</td>
<td>2.7</td>
<td>499.7</td>
<td>27.5</td>
<td>522.9</td>
<td>155.3</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>6 tantalite, equant</td>
<td>0.0027 90 -0.01</td>
<td>0.33 256.4 0.06312 0.4945</td>
<td>394.6</td>
<td>1.7</td>
<td>408.4</td>
<td>14.7</td>
<td>484.5</td>
<td>96.6</td>
<td>19.1</td>
<td></td>
</tr>
</tbody>
</table>

Zrn: zircon grain, Mnz: monazite grain, ab: grain abraded, incl: inclusions, euh: euhedral, nd: rounded, frag: fragment, spr: short prismatic, lpr: long prismatic, equ: equant. Th/U is calculated from measured 206Pb/204Pb and 207Pb/204Pb age. Pbcom is total measured common Pb assuming the isotopic composition of laboratory blank. Pb/207Pb, Pb/206Pb, Pb/204Pb are measured values corrected for fractionation and spike. Pbcom/207Pb and Pbcom/206Pb age are corrected for 206Pb/204Pb age assuming a magmatic Th/U value of 4.2. %Disc.: percent discordance for the given 206Pb/204Pb age. U decay constants are from Jaffey et al. (1971).
with 6N HCl. The U solution was heated in the open Savillex vial to drive off the HBr, again leaving the H$_2$SO$_4$. This was taken up in 10 drops of 6N HCl and reloaded into the column, which had previously been re-conditioned with 6N HCl. U is strongly absorbed under these conditions. The resin was washed with 30 drops 6N HCl, followed by 10 drops 7N HNO$_3$. U was eluted back into the Savillex vial using H$_2$O. A drop of 0.5N H$_3$PO$_4$ was added to the Pb and U solutions, which were then dried down.

Pb and U from zircon and monazite were loaded together on Re filaments using silica gel. The Pb and U fractions derived from the tantalite were loaded onto separate filaments. The isotopes were measured using a VG354 mass spectrometer equipped with a Daly ion counter. The samples produced strong, smooth signals for both Pb and U. The data reported are corrected for ion-counter mass discrimination of 0.0007/AMU and a detector dead-time of 23.0 ns. The thermal mass-discrimination correction is 0.0010/AMU. A blank analysis for the tantalite procedure gave a Pb blank of 3.7 pg and a U blank of 1.5 pg. For zircon and monazite, Pb and U blanks were taken to be 1 pg and 0.1 pg, respectively. After subtraction of blank, the results were corrected for common Pb using values from the growth curve of Stacey & Kramers (1975) at the $^{206}$Pb/$^{238}$U age of the sample.

Os isotope compositions of PGM grains were analyzed at the University of Bern, Switzerland. Single PGM grains were digested in sealed Carus tubes in reverse aqua regia. After opening the Carius tubes, Os was directly distilled into chilled HBr following the method described by Nägler & Frei (1997). Os isotope compositions were determined on a NuInstruments multicollector inductively coupled plasma – mass spectrometer (MC–ICP–MS) by direct transfer of Os as OsO$_4$ into the argon stream (Schoenberg et al. 2000). The twelve Faraday collector array of the MC–ICP–MS allows simultaneous detection of all Os isotope beams in static measurement mode and also allows the monitoring of other elements that might interfere with Os isotope masses. Monitored isotopes were $^{182}$W, $^{185}$Re and $^{194}$Pt to allow for simultaneous in-run correction of their interfering isotopes $^{186}$W, $^{187}$Re, $^{190}$Pt and $^{192}$Pt, respectively. However, purification of Os by distillation (Nägler & Frei 1997) is very efficient, and neither W nor Re nor Pt was detected during the analyses. Os isotope ratios were fractionation-corrected using an exponential law and $^{182}$Os/$^{186}$Os = 3.082614 (Nier 1937).

**MINERALOGY OF THE PLACER**

Corroborating and extending earlier findings (Macgregor & Zealley 1921, Phaup 1958, Bührmann 1997), staurolite predominates (>95%) in the heavy-mineral spectrum. Staurolite grains attain several mm across. The grains are dark brown to black and opaque. According to K.-P. Burgath (pers. commun., August 2000), they contain numerous inclusions of quartz, tourmaline, hematite or magnetite, and possibly zircon. The staurolite grains are undeformed, post-kinematic poikiloblastic grains and probably formed under amphibolite-facies conditions of metamorphism (P–T range >515–680°C, >2.5 kbar; Bucher & Frey 1994).

Zircon, monazite, cassiterite, columbite–tantalite, chromite, magnetite, hematite, ilmenite, garnet, coron-}

{Zinc, monazite, cassiterite, columbite–tantalite, chromite, magnetite, hematite, ilmenite, garnet, corundum, uraninite, thorianite, native gold, and PGM are the main minerals of the heaviest fraction of the concentrate (Fig. 2). Notably, the cassiterite grains come in many different colors (transparent yellowish brown, light yellow, yellow-orange, orange-red to deep red and, rarely opaque and black). Studies by J. Götze (pers. commun., May 1998) showed that the crystals of cassiterite have (i) a low Fe content, (ii) inclusions of Ta-rich columbite, and (iii) relatively monotonous cathodoluminescence spectra, without conspicuous zoning. J. Götze (pers. commun., May 1998) concluded that the cassiterite crystals most probably originate from highly evolved granitic pegmatites.

Grains of gold are far more numerous than PGM grains. The concentrate has an estimated content of about 10 g/t Au, whereas its recalculated Pt content ranges between about 10 and 20 ppb. The grains of gold display a wide range of shapes and sizes (Fig. 2). Flat disks, flakes, rods and also round grains are present, and most grains range in size between 250 μm and 1 mm in longest dimension; the largest grain is 4 mm long. In addition to the discrete grains of gold, thin (~1–5 μm) secondary films and coatings of silver-poor gold were detected on a number of PGM grains. EPMA showed that most of the gold grains are very pure (>99 wt.% Au). However, the concentrate also contains a smaller fraction of gold grains with between 10.6 and 29.6 wt.% Ag. Some of the Ag-rich gold grains have a thin rim depleted in Ag. Other elements sought (Pd, Cu, Fe, Hg and Bi) were below the detection limit, about 0.1 wt.%.

**Age dating of zircon, monazite and columbite–tantalite**

Three single grains of pale greenish monazite, six single grains of colorless zircon, and six single grains of brownish columbite–tantalite were dated using the U–Pb method. Results of U–Pb isotopic analyses are given in Table 1 (errors at 2σ). Results are plotted on concordia diagrams on Figures 3 and 4. Error ellipses are plotted at 2σ. Average errors in the age are given at 95% confidence levels. Probabilities of fit would be expected to be 50% on average for random data with correctly chosen analytical errors. Errors in the age derived from $^{206}$Pb/$^{207}$Pb are quoted at 2σ.

Both zircon and monazite are very fresh. Most grains are rounded or subrounded. A few have frosted surfaces typically produced by detrital transport, but most have smooth reflective surfaces. Regarding zircon and monazite, eight data points are concordant or near-concor-
dant, with a range of $^{206}\text{Pb}/^{238}\text{U}$ ages between 639 ± 2 Ma and 551 ± 3 Ma (Fig. 3). One zircon crystal gave a distinctly older, slightly discordant data-point with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1061 ± 13 Ma. A line running through this point and the middle of the distribution of the younger crystals of zircon would have an upper concordia intersection of 1100 ± 23 Ma (Fig. 3).

The age range of most of the grains matches that of Pan-African rocks. Since almost all of the zircon and monazite is similar in appearance, these ages may be typical of the whole population. The calculated Th/U values are indicative of a probable magmatic, rather than metamorphic, origin for both zircon and monazite. The high abundance of monazite suggests that the source rocks were derived from crustal melts, such as S-type granitic rocks. The moderate level of discordance of the older zircon, which seems very fresh and is unlikely to have suffered low-temperature loss of Pb, suggests that it has been disturbed by a thermal event. If so, this might indicate that part of the basement to the orogen was about 1100 Ma in age.

Concentrations of uranium in the columbite–tantalite grains are fairly high, but concentrations of common Pb also proved to be generally high and variable. Only one grain yielded a highly radiogenic datum, which is concordant with a $^{207}\text{Pb}/^{235}\text{U}$ age of 499.0 ± 2.0 Ma (Table 1). The high proportion of common Pb in the other analyses causes a substantial increase in the $^{207}\text{Pb}/^{235}\text{U}$ errors (Fig. 4). This level of common Pb is well above the blank and may be due to inclusions that are not visible owing to the opaque nature of the grains.

The five youngest data are concordant or nearly so, but have $^{206}\text{Pb}/^{238}\text{U}$ ages that vary in the range 395–590 Ma (Table 1, Fig. 4). Three cluster around 500 Ma but are slightly outside of error range. A sixth grain yielded a much older datum, with a $^{206}\text{Pb}/^{238}\text{U}$ age of 2915 ± 30 Ma. However, this is distinctly to the left of concordia, suggesting either isotopic disturbance or an incorrect choice of correction for common Pb. This sample also showed an extremely high level of common Pb compared to the others. If the discordance is due to isotopic disturbance (differential mobility of U and Pb), then the true age of the grain may be closer to the $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2641 ± 113 Ma. The discordance would be much reduced if the analysis were corrected for a more recent common Pb isotopic composition, and the age would approach 2600 Ma. This approach would also reduce the calculated Th/U value to nearly zero, in accord with the other analyses.

Romer & Smeds (1996) observed that HF treatment did not differentially leach Pb or U from columbite. However, the roughly linear trend of the younger data from Somabula and the reversely discordant older datum suggest that U and Pb may have been mobile. If the spread of ages for the younger data is due to recent U–Pb disturbance, the upper concordia intersection of a zero-age line through them should give the best estimate of age. This is 511 ± 20 Ma (Fig. 4). The line is not well

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**Fig. 2.** Back-scattered electron image of part of the final heavy-mineral concentrate from Somabula. Polished section of sieve fraction <125 µm. White grains are gold (Au) except one grain each of Pt–Fe alloy (Pt–Fe) and uraninite (U). Other components are zircon (zr, darkest grey), monazite (mon), cassiterite (cas), and columbite–tantalite (col).
constrained because most of the data have large $^{207}\text{Pb}/^{235}\text{U}$ errors. This is the most conservative interpretation, but it is also possible that each grain has a different age, as with the zircon and monazite grains from this sample. Columbite–tantalite grain 1 (Table 1), despite its relatively high uncertainty, clearly has a much older late Archean age.

Collectively, the age range of most of the zircon, monazite and columbite–tantalite grains matches that of Pan-African rocks. Therefore, the Pan-African Zambezi and Mozambique belts to the north and east have to be envisaged as potential sources.

Platinum-group minerals (PGM)

A total of 622 PGM grains were extracted from the heavy-mineral concentrates. Their morphology and composition were studied under the SEM with an attached energy-dispersion analytical system (EDAX). In all, 154 selected PGM grains were analyzed by EPMA. The grain sizes (maximum diameters) range from ca. 100 to 850 μm. The spectrum of PGM consists of Pt and Pt alloys with Fe, Rh, Pd, and Ru (79%), Os–Ir–Ru–Rh–Pt alloys (10%), rustenburgite [Pt$_3$Sn] (9%) and other Pt–rich compounds (1%). Most PGM grains are monomineralic. Intergrowths of different PGM are rare, and even rarer are mineral inclusions in the PGM.

Pt and Pt alloys

The following mineral proportions by numbers were obtained by SEM surface analysis using the energy-dispersion system (EDAX) attached to the SEM (altogether, 492 Pt-rich grains): 43.3% Pt, 49.2% Pt–Fe alloy, 4.1% Pt–Rh–Fe alloy, 2.2% Pt–Pd–Fe alloy, and 1.2% Pt–Ru–Fe alloy. Our selection from these 492 grains for EPMA was somewhat biased toward grains having unusual compositions.

The grains of Pt and Pt–Pd alloy are very similar in external appearance. They are the "softest" PGM grains and are mostly present as flat disks, some with contorted edges. Flakes, irregular particles and rarer rounded grains may have slightly porous parts and smaller cavities. Typically, the surfaces of the Pt and Pt–Pd alloy grains are mostly rough. In polished sections, many grains display variable internal porosity. The grains of Pt and Pt–Pd alloy reach the largest sizes (up to 850 μm) of all PGM grains (Figs. 5a, 6a). Occasionally, a thin crust of iron hydroxide covers parts of the grains. Other grains locally have a thin (up to 5 μm) film of Ag-poor gold deposited on their surface or intergrown with gold (Fig. 6c).

Grains of Pt–Fe alloy attain 600 μm across and are mainly equidimensional, and commonly well-rounded ("potato shapes"), with smooth convex, polished, silver-white surfaces. Some grains have orthogonal outlines ("bricks") with polished surfaces and rounded corners (Fig. 5b), and other grains show thin cracks. Internally, the Pt–Fe grains are generally homogeneous. Intergrowths with Pt–Rh–Fe alloy (Fig. 6d) or with rustenburgite (Fig. 6e) are rare.

The rarer alloys containing Pt–Pd–Fe, Pt–Rh–Fe, and Pt–Ru–Fe are mainly represented by round grains, either with smooth surfaces or with etch pits on their surfaces. In general, they have a similar appearance to...
the grains of Pt–Fe alloy. They reach about 350 μm in size. These alloys host the few exsolution lamellae and inclusions observed. Figure 7b shows lamellae of osmium in Pt–Pd–Fe alloy, and Figure 7c, oriented exsolution-induced lamellae of ruthenium in Pt–Rh–Fe alloy.

Figures 8a and 8b show the results of 99 analyses of grains of Pt and Pt alloy, in at.%, in terms of Pt – (Pd + Ru + Rh + Os + Ir) – (Fe + Cu + Ni). Figures 8a contains the compositions of (i) Pt, (ii) Pt–Pd alloy, (iii) Pt–Pd–Fe alloy (defined as: concentration of Pd > Ru, Rh, Os or Ir), and (iv) Pt–Fe alloy (Ru, Os or Ir <3 at.%). Figure 8b shows the compositions of (i) Pt–Rh–Fe alloy (concentration of Rh > Pd, Ru, Os or Ir; triangles), (ii) Pt–Ru–Fe alloy (concentration of Ru > Pd, Rh, Os or Ir; squares), and (iii) one grain with Ir > Pd, Rh, Ru or Os (diamond).

Chemically, the Pt grains are very pure (>98 wt.% Pt; Table 2, no. 67; Fig. 8a) and only rarely contain traces of Ir (up to 0.7 wt.%; Table 2, no. 51), Fe (up to 0.5 wt.%), or Rh (up to 0.2 wt.%). The grains of Pt–Pd alloy may contain up to 0.9 wt.% Pd, 0.4 wt.% Rh, and 1.3 wt.% Sn (Table 2, no. 26). Contents of Fe + Cu + Ni range between 25 and 29 at.%. Therefore, the compositions plot in the range between Pt3Fe and Pt5Fe (Fig. 8a). Cabri et al. (1996) observed a

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**TABLE 2. SELECTED ELECTRON-MICROPROBE DATA PERTAINING TO Pt AND Pt–Pd–Ru–Rh–Fe ALLOYS, SOMABULA GRAVELS, ZIMBABWE**

| Anal. | 67 | 1 | 2 | 21 | 31 | 185 | 27 | 84 | 158 | 206 | 212 | 215 | 173 | 181 | 190 | 195 | 165 | 172 |
|-------|---|---|---|----|----|-----|---|---|----|----|----|----|----|----|----|----|----|----|----|
| Pt    | 1.10% 0.78% 0.67% 0.73% 0.64% 0.48% 0.38% 0.35% 0.52% 0.42% 0.22% 0.23% 0.56% 0.49% 0.70% 0.33% 0.29% |
| Pd    | 0.16% 0.31% - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Ru    | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Os    | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Ir    | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Fe    | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Cu    | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Ni    | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Au    | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Sn    | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |


---

**FIG. 5.** Scanning electron microscope (SEM) images of PGM grains from Somabula. a. Large discoid, flat and slightly porous grain of Pt–Pd alloy with contorted rims. b. Hypidiomorphic grain of Pt–Fe alloy. c. Grain of rustenburgite showing growth steps and only little abrasion. d. Rounded grain of iridium with bent edges and internal negative hexagonal crystal (probably formerly a platelet of osmium). e. Well-rounded grain of osmium. f. Aggregate consisting of hexagonal platelets of osmium cemented by a matrix of Pt–Fe alloy.
similar narrow compositional range of Pt–Fe alloy only in samples from the Rio Condoto area, Colombia.

The grains of Pt–Pd–Fe alloy (Fig. 8a) mainly plot into a field bordered by Pt4Fe and Pt3Fe. Up to 22.3 wt.% Pd substitutes for Pt (Table 2, no. 158). Minor elements amount to 3.2 wt.% Ir, 2.4 wt.% Ru, 1.5 wt.% Rh, and 0.2 wt.% Os.

Rhodium substitutes for Pt in the Pt–Rh–Fe alloy (Fig. 8b), although to a lesser degree than Pd in the grains of Pt–Pd–Fe alloy. Figure 6d shows an intergrowth of Pt–Fe alloy in the core and Pt–Rh–Fe alloy with varying composition in the rim. The content of 6.0 wt.% Ir, 3.7 wt.% Os, and 2.5 wt.% Ru in this alloy (Table 2, no. 190) may be due to submicroscopic inclusions of Os–Ir–Ru alloy, although the surface has a homogeneous appearance both under reflected light and in the BSE image. The only sulfides and tellurides of unnamed phases (see below, Table 6, nos. 223 and 224) observed are inclusions in Pt–Rh–Fe alloy (Fig. 7d). Notably, the compositions of some grains plot distinctly outside the field bordered by Pt3Fe and Pt2Fe (Fig. 8b).

A second group of Pt–Rh–Fe alloy plots close to the line of PtFe (tetraferroplatinum) compositions (Fig. 8b, Table 2, nos. 165, 172, 173). In these grains, Rh substitutes for Pt (maximum 26.1 wt.% Rh), and at the same time, Fe is replaced by substantial amounts of Ni (up to 6.4 wt.% Ni). One grain (Table 2, no. 173) contains more Rh than Pt, resulting in the formula (Rh0.54Pt0.47Pd0.02Ir0.02)/H90181.05(Fe0.75Cu0.01Ni0.21)/H90180.97. The phase could be the Rh equivalent of tetraferroplatinum or of ferronickelplatinum.

Grains of ruthenium-rich Pt–Ru–Fe alloy contain up to 23.7 wt.% Ru. They are shown as squares in Figure 8b, and typical results of analyses are given in Table 2, no. 206 and 215. The composition of one Ir-rich grain (11.8 wt.% Ir) is shown in Figure 8b (diamond) and given in Table 2 (no. 212). Similarly unusual Pt alloys, in this case with elevated contents of Ru (up to 21.9 wt.%), Ir (up to 26.8 wt.%), and Os (up to 12.9 wt.%), were reported by Tolstykh et al. (1999) from northwestern Salair, Russia. In general, however, similar exotic compositions of Pt–Fe alloys with highly elevated contents of Pd, Ru and, above all, Rh, have only sporadically been reported previously (cf. Cabri et al. 1996), making these grains somewhat enigmatic constituents of the Somabula placers.

Hongshiite

Five grains of hongshiite were detected; they are elongate and roundish, with a diameter between ca. 150 and 270 μm. One grain has a smooth surface, the others show signs of etching. Chemical compositions are close to PtCu for most grains; however, one grain has an elevated content of Rh (3.8 wt.%), Pd (2.0 wt.%), and Ir (1.2 wt.%) (Table 3, no. 214).

Pt–Pd–Au–Cu alloy

Grains of alloy in the system Pt–Pd–Au–Cu are very rare in the samples from Somabula. One rounded single grain 200 μm long consists of 48.7 wt.% Pt, 9.9 wt.% Pd, and 40.8 wt.% Au. The formula corresponds to (Pt0.45Pd0.17Cu0.01 Au0.41) (Table 4, no. 6).

Figure 6c shows a composite grain of Pt alloy and corroded Pt–Au alloy 150 μm in diameter. Electron-microprobe analyses of the latter gave a composition of 82.7 wt.% Pt and 15.9 wt.% Au. No other elements were detected (Table 4, no. 47). This composition corresponds to the formula Pd0.88Cu0.16. According to Hansen & Anderko (1958), such solid solution is stable only above 1050°C.

Fig. 6. Back-scattered electron images of PGM and gold alloys from Somabula. a. Rhythmically zoned grain of Pt83Pd17 alloy (light grey) and Pt68Pd32 alloy (darker grey). b. Schlieren-like grain of Pt (light grey), Pt69Fe31 alloy (medium grey), and Pt66Fe34 alloy (dark grey) with two roundish inclusions of Au–Pd–Cu alloy (white). c. Composite grain of Pt (homogeneous areas) and corroded Pt48Ru45 alloy (medium grey), and Pt46Fe45 alloy (dark grey) with two roundish inclusions of Au–Pd–Cu alloy (white). d. Intergrowth of Pt75Fe25 alloy (light grey), Pt57Rh18Fe25 alloy (medium grey), and Pt49Rh31Fe20 alloy (dark grey). e. Composite grain of Pt–Fe alloy (light grey) and Pd-bearing rustenburgite (dark grey). f. Intergrowth of Ru-rich Pt–Fe alloy (darker grey), Pd-rich Pt–Fe alloy (light grey), and iridium (white).

<table>
<thead>
<tr>
<th>Table 3: Selected Electron-Microprobe Data Pertaining to Hongshiite and Rustenburgite, Somabula Gravels, Zimbabwe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anal. no.</td>
</tr>
<tr>
<td>Pd</td>
</tr>
<tr>
<td>Pt</td>
</tr>
<tr>
<td>Sn</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

n.d.: not detected, αPPB atoms per formula unit.
Droplike inclusions in Pt–Fe alloy (Fig. 6b) have a composition of an alloy in the system Pd–Pt–Au–Cu. They contain 7.6 wt.% Pd, 2.9 wt.% Pt, 5.0 wt.% Cu, 0.2 wt.% Fe, 83.3 wt.% Au, and 0.3 wt.% Ag. The formula is calculated to be (Pd_{0.48} Pt_{0.10} Cu_{0.53} Fe_{0.03})_{1/2.85} (Au_{2.84} Ag_{0.01})_{1/2.85} or, ideally Au_3 Pd (Table 4, no. 33).

**Rustenburgite**

This is the first report of rustenburgite as a ubiquitous detrital component in placers at Somabula. Detrital rustenburgite in placers was previously only reported by Törnroos et al. (1998) from Finnish Lapland.

The individual grains mostly have a smooth surface and are variably rounded. Some grains show cavities or negative cubic crystals on their surfaces. Some well-crystallized grains, even cubes, also are present (Fig. 5c). The grains mainly have sizes around 100 μm (maximum ca. 250 μm), and some grains of rustenburgite were found to be intergrown with Pt–Fe alloy (Fig. 7c).

Most grains are close to the ideal composition (PtSn). Some grains, however, also show considerable contents of the atokite component PdSn, indicating substantial solid-solution between rustenburgite and atokite (Fig. 6e, Table 3, nos. 35, 161).

**Grains of Os–Ir–Ru–Rh–Pt alloy**

Many grains of Os–Ir–Ru–Pt–Rh alloy are characterized by excellent rounding (“potato”- and “bean”-shaped, rarer flat disks), smooth surfaces, and sizes of up to 350 μm (Fig. 5e). Os-rich grains occasionally display a hexagonal outline (Fig. 5d). Under the SEM, we found a number of coarse intergrowths of Os plates with Pt–Fe alloy (Fig. 5f), and of Ru plates (70 and 150 μm) with Pt–Fe–Rh alloy. In reflected light, the grains of Os–Ir–Ru–Pt–Rh alloy are mostly cream-white with a light bluish tinge and variably anisotropic depending on crystal orientation. Cubic crystals are subordinate. Most grains are optically homogeneous, both under reflected light and in back-scattered electron images. They are devoid of inclusions, and composite grains of various alloys are rare. Exsolution lamellae of osmium and ruthenium were detected in only three grains of Pt–Pd–Fe and Pt–Rh–Fe alloy (Figs. 7b, c).

**EPMA** of the individual grains show the presence of phases in the systems Os–Ir–Ru (Fig. 9a), Rh–Ru–Pt (Fig. 9b), Rh–Ru–Ir (Fig. 9b), Ru–Ir–Pt (Fig. 9c), Ir–Os–Pt, Ru–Os–Pt, and Os–Ir–Rh. Osmium is the dominant phase (44%), followed by ruthenium (25%) and iridium (23%). Rutheniridosmine and platinum alloy, representing 4% each, are subordinate. Only single data-points plot into the other triangular diagrams mentioned above. In 27% of the analyzed grains, Rh is the third element and substitutes significantly for Os, Ir or Ru in the various phases.

The composition of osmium varies between 40.6 and 68.8 at.% Os, 11.1 and 46.1 at.% Ir, and 3.3 and 38.9 at.% Ru (Fig. 9a). The grains furthermore contain up to 1.9 wt.% Rh, 1.8 wt.% Pt, 0.26 wt.% Pd, and only occasionally up to 1.3 wt.% Fe. Lamellae of osmium in Pt–Pd–Fe alloy have the composition Os_{0.65} I_{0.19} R_{0.16} and contain traces of Pt (4.2 wt.%) and Fe (0.2 wt.%), with no significant difference in composition compared to the single grains of osmium.

The grains of ruthenium are mostly Rh-rich and plot in the Rh–Ru–Pt diagram (Fig. 9b). To our knowledge (cf. Cabri et al. 1996), these are the first minerals to be reported in this system. Only a few grains have compositions plotting in the field of Os–Ir–Ru (Fig. 9a) and Os–Ru–Pt alloys. Lamellae in grains of Pt–Pd–Fe and Pt–Rh–Fe alloy represent an alloy in the system Ru–Pt (Fig. 7c, Table 5, nos. 198 and 209). Figure 7e shows a composite grain of coexisting Rh–Ru–Pt and Os–Ru–Pt alloys (Table 5, nos. 74 and 75). The composition of the grains of ruthenium in the Rh–Ru–Pt field varies normally between 50.6 and 87.6 at.% Ru, 5.7 and 36.8 at.% Pt, and 6.7 to 12.6 at.% Rh (Fig. 9b). Maximum contents of other elements reach up to 10.5 wt.% Os, 9.9 wt.% Ir, 0.4 wt.% Pd, and 0.4 wt.% Fe. Some grains

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**TABLE 4. SELECTED ELECTRON-MICROPROBE DATA PERTAINING TO PGE–AUS ALLOYS, SOMABULA GRAVELS, ZIMBABWE**

<table>
<thead>
<tr>
<th>Anal. No.</th>
<th>6</th>
<th>47</th>
<th>33</th>
<th>6</th>
<th>47</th>
<th>33</th>
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<tbody>
<tr>
<td>Ru wt.%</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>Ru appr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rh</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>Rh</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pd</td>
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<td>n.d.</td>
<td>7.59</td>
<td>Pd</td>
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<td>-</td>
</tr>
<tr>
<td>Os</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>Os</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ir</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>Ir</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pt</td>
<td>48.70</td>
<td>82.66</td>
<td>2.89</td>
<td>Pt</td>
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<td>0.836</td>
</tr>
<tr>
<td>Fe</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.25</td>
<td>Fe</td>
<td>-</td>
<td>0.030</td>
</tr>
<tr>
<td>Cu</td>
<td>n.d.</td>
<td>n.d.</td>
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<td>Cu</td>
<td>-</td>
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</tr>
<tr>
<td>Ni</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>Ni</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Au</td>
<td>40.78</td>
<td>15.04</td>
<td>83.23</td>
<td>Au</td>
<td>0.376</td>
<td>0.160</td>
</tr>
<tr>
<td>Ag</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.27</td>
<td>Ag</td>
<td>-</td>
<td>0.017</td>
</tr>
<tr>
<td>Total</td>
<td>99.37</td>
<td>98.60</td>
<td>99.36</td>
<td></td>
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</tr>
</tbody>
</table>

n.d.: not detected, appr.: atoms per formula unit.
FIG. 8a. Compositions of (i) Pt, (ii) Pt–Pd alloys, (iii) Pt–Pd–Fe alloys (defined as: concentration of Pd > Ru, Rh, Os or Ir), and (iv) Pt–Fe alloys (Ru, Os or Ir < 3 at.%) projected in the triangular diagram Pt – (Pd + Ru + Rh + Os + Ir) – (Fe + Cu + Ni).

FIG. 8b. Compositions of (i) Pt–Rh–Fe alloys (concentration of Rh > Pd, Ru, Os or Ir; triangles), (ii) Pt–Ru–Fe alloys (concentration of Ru > Pd, Rh, Os or Ir; squares), and (iii) one grain with Ir > Pd, Rh, Ru or Os (diamond) projected in the triangular diagram Pt – (Pd + Ru + Rh + Os + Ir) – (Fe + Cu + Ni).
are nearly pure ruthenium (Fig. 9b, Table 5, no. 163). The single grain in the Os–Ir–Ru diagram (Fig. 9a) has 47.8 at.% Ru, 29.1 at.% Os and 23.1 at.% Ir, as well as 4.0 wt.% Pt and traces of Rh (1.0 wt.%), Pd (0.4 wt.%), and Ni (0.15 wt.%).

The composition of iridium scatters over a wide range, with most compositions in the system Os–Ir–Ru (Fig. 9a), and single compositions in the systems Ru–Ir–Pt (Fig. 9b), Rh–Ir–Ru (Fig. 9c), Os–Ir–Pt (Table 5, no. 119), and Os–Ir–Rh (Table 5, no. 203). The grains of iridium that fall in the system Os–Ir–Ru contain between 67.1 and 84.4 at.% Ir, 8.0 and 26.3 at.% Os, and 6.5 to 20.0 wt.% Ru, up to 2.4 wt.% Pt, 0.4 wt.% Rh, and 0.7 wt.% Fe.

The two analyzed grains of rutheniridosmine have a composition similar to osmium and lie close to the boundary with osmium (Fig. 9a).

Two individual grains consist of Pt–Rh–Ru alloy with traces of Ir, Os, Fe and Cu (Table 5, no. 175), and Pt–Ru–Ir alloy with 5.0 wt.% Os, 2.5 wt.% Rh, 0.3 wt.% Pd, and 1.7 wt.% Fe (Fig. 9c).
Pt–Pd sulfides

PGM of the cooperite – braggite – vysotskite series are the only detrital PGE sulfides in the concentrate. There are two rounded grains, 120 and 160 μm in diameter, rich in Pd (19.2 and 31.6 wt.%), and one grain contains 0.6 wt.% Se. The corresponding formulae are \((\text{Pt} 0.64 \text{Pd} 0.36 \text{S} 1.00 \text{Se} 0.01)\) and \((\text{Pd} 0.54 \text{Pt} 0.46 \text{S} 1.00)\) (Table 5, nos. 103 and 116).

Unnamed PGM

One grain of Pt–Rh–Fe alloy contains two tabular, roundish inclusions up to 20 μm long consisting of Rh (73.7 wt.%), S (20.1 wt.%), Ru (2.1 wt.%), and Pt (2.0 wt.%). The formula \((\text{Rh} 1.00 \text{Ru} 0.03 \text{Pt} 0.01 \text{S} 0.91)\) is close to RhS (Table 6, no. 223). A PGM with a similar composition was encountered by Feather (1976) in the Witwatersrand ores, South Africa.

The same Pt–Rh–Fe alloy grain hosts a number of irregularly shaped inclusions, up to 15 μm long, rich in Rh (32.2 wt.%), Pd (22.6 wt.%), and Te (36.2 wt.%), and containing subordinate Pt (5.1 wt.%), and S (3.2 wt.%). The following formula is calculated: \((\text{Rh} 1.68 \text{Pd} 1.14 \text{Te} 1.52 \text{S} 0.53)\) or, ideally, \((\text{Rh}, \text{Pd})_2 \text{Te}_2\). An unnamed Rh$_2$Te$_2$ was described by Hagen et al. (1990) in the form of drop-like inclusions in Pt–Fe alloy from placer deposits in Burma.

Os Isotope Compositions

A number of different PGM grains (Pt, Pt–Fe alloy, Pt$_3$Sn and Os–Ir–Ru alloy) were analyzed for their Os isotope compositions. However, only the grains of Os–Ir–Ru alloy had sufficient contents of Os to allow interpretation of the data. Os–Ir alloys are considered to be free of Re and are therefore ideal for characterization of the Os isotope composition of their source magma (Bird et al. 1999).
The Os–Ir–Ru alloy grains no. 3815, 3959, 3961 and 3978 form a distinct homogeneous group with respect to their 187Os/188Os values (range 0.10707–0.10754; Table 7, Fig. 10), indicative of a pristine source in the mantle. The 187Os/188Os values are significantly lower (i.e., well outside the 2σ uncertainties) than the range determined for chromite separates from seams of massive chromitite in the Great Dyke (Schoenberg et al. 1999) (initial 187Os/188Os values between 0.1106 and 0.1126). These initial Os compositions are just slightly above the value of the contemporaneous chondritic mantle, 0.1094 (Shirey & Walker 1998). In addition, an Os isotope analysis of one detrital Os–Ir–Ru alloy grain from a river draining the Great Dyke gave an 187Os/188Os value of 0.110275 (J.D. Kramers, written commun., 2001), well in the range of initial 187Os/188Os values (average 0.1112) of the chromitites of the Great Dyke (Mukasa et al. 1998, Oberthür et al. 2002).

The maximum values for the initial 187Os/188Os signature of the Somabula PGM grains are significantly lower (i.e., well outside the 2σ uncertainty limits) than the initial Os-isotope composition of the Great Dyke magma. Therefore, a derivation of the Os–Ir–Ru grains from the Great Dyke is precluded (Fig. 10). Depending on the model used, the grains either originate from a mafic–ultramafic complex 2.91 to 2.78 Ga old derived from a chondritic mantle, or from a mafic–ultramafic intrusion 2.64 to 2.46 Ga old with Os characteristics of the subcontinental lithospheric mantle (SCLM). Nota...
bly, all greenstone belts of the Zimbabwe craton investigated by Nägler et al. (1997) clearly reflect Os signatures from the SCLM.

Grain 3993 displays a somewhat higher $^{187}$Os/$^{188}$Os value, 0.12067. It is not clear whether the evolved Os-isotope composition of grain 3993, compared to that of the other Os–Ir–Ru grains, is due to in situ growth of Re, reveals another magmatic source, or is a combination of both.

In conclusion, the Os isotope compositions of detrital Os–Ir–Ru grains are useful tracers of their origin. The Os isotope compositions of the Os–Ir–Ru grains from Somabula point to a source of the Os in the pristine mantle. Furthermore, derivation of these grains from the Great Dyke appears improbable; rather, they originate from ultramafic–mafic rocks in late Archean greenstone belts of the Zimbabwe craton.

**DISCUSSION AND CONCLUSIONS**

**Source-area aspects**

The polymict spectrum of heavy minerals in the Somabula paleoplacers indicates lithologically complex source-areas. Unfortunately, there are no direct clues to the hinterland exposed in Karoo times, some 200 Ma ago, and probably eroded now. It is beyond the scope of this paper to relate all heavy minerals to specific sources. However, some evidence gained during the study will be discussed in order to show the complexity of this pale placer.

The ubiquitous staurolite suggests an amphibolite-facies metamorphic source-terrane. The mineral is widespread in northern Zimbabwe only, in the Miami mica fields (Fig. 11), in the Urungwe, Mount Darwin and Mtoko areas (Warner 1972).

The age range of most zircon, monazite and columbite–tantalite grains matches that of Pan-African rocks. Since almost all of the zircon and monazite is similar in appearance, these ages may be typical of the whole population. The calculated Th/U values are indicative of a probable magmatic, rather than metamorphic, origin for both zircon and monazite. The high abundance of monazite suggests that the source rocks were formed from crustal melts, such as S-type granitic rocks. The presence of abundant detrital monazite, which is a relatively soft, easily abraded mineral, suggests that the Pan-African source was not very distant. The Pan-African Mozambique and Zambesi belts to the east and north (Fig. 11) are potential sources. These results suggest that part of the Pan-African belts near Zimbabwe formed a high-standing terrain during the Triassic when the sediment was eroded and transported.

Cassiterite and uraninite probably originate from granitic rocks and associated pegmatites of unknown age. Magnetite and hematite have many possible origins, and may have been derived from banded iron-formations, prominent in the Archean greenstone belts of the Zimbabwe craton. The most probable source of native gold has to be sought in areas of hydrothermal mineralization, abundant in the Archean greenstone belts exposed in proximity of Somabula (Figs. 1, 11). The diamond crystals probably have their origin in kimberlites. Notably, kimberlite pipes occur some 50–100 km to the southwest of Somabula, and also in the Limpopo belt (Fig. 11).

In conclusion, the wide spectrum of heavy minerals in the Somabula placers and the specific data collected in this study indicate a diversity of source lithologies. Repeated stages of reworking have to be envisaged, and the various components from specific sources may have been added to the heavy-mineral spectrum at any time during the prolonged history of the sediment. Furthermore, the Pan-African ages of some minerals suggest that part of the Pan-African belts to the north and east of the Zimbabwe craton formed a high-standing terrain during the Triassic when the sediment was eroded and transported.

**Platinum-group minerals**

The PGM assemblage found in the Somabula placers is distinctly different from the PGM of the Main Sulfide Zone of the Great Dyke (dominantly Pt,Pd bismuthotellurides, sperrylite and cooperite–braggite; Farahmand 1974, Johan et al. 1989, Coghill & Wilson 1993, Oberthür et al. 1998, Weiser et al. 1998), and the detrital PGM originating from the Great Dyke (mainly sperrylite, Pt and Pt–Fe alloys; Oberthür et al. 1998, 1999). Furthermore, the Os isotope compositions of the Os-rich grains from Somabula suggest that their source rocks such as ultramafic–mafic rock successions or intrusions of late Archean age of the Zimbabwe craton were derived from the mantle, without crustal contamination. The Os isotope ratios rule out the possibility that the Somabula PGM were derived from the Great Dyke.

However, the combination of unknown sources, unknown events of weathering and sedimentary transport, and unknown post-depositional history of the placers, pose severe problems in pointing to specific sources of the PGM. Mertie (1969) reported that platinum alloys rarely migrate far downstream from their bedrock sources, unless they are so fine-grained as to be moved by swift water or floated by surface tension. Thus, except for unusual situations (e.g., glaciation), placers of the precious metals may be assumed to lie within a few km of their bedrock sources (Mertie 1969). Most of the PGM at Somabula appear to be original grains that have experienced only subordinate chemical and physical alteration during transport and following deposition. Therefore, the sizes of the PGM grains (between 100 and 850 μm) favor transport as bedload, not in suspension, and according to Mertie (1969) would point to source rocks relatively close to Somabula (up to some tens of km).
The overall PGM assemblage, ca. 90% Pt-rich minerals and 10% Os–Ir–Ru–Rh–Pt alloys, is grossly comparable to that of many modern placers that have primary sources in Alaskan or Alpine-type mafic–ultramafic complexes (e.g., Cabri et al. 1996). Notable at Somabula are (i) the near-absence of platinum-group element (PGE) sulfides, (ii) the exceptional compositions of Pt and Pt alloy grains with Pd, Rh or Ru, (iii) the wide range of compositions of the Os–Ir–Ru–Rh–Pt alloy grains, (iv) the presence of Pt–Pd–Au alloys, and (iv) the presence of rustenburgite, not yet reported to be so prevalent from placers.

Textures of PGM at Somabula, their intergrowths and inclusions, the specific compositions of minerals of multicomponent Pt and Os–Ir–Ru–Rh–Pt alloys, and the Os isotope compositions, provide evidence of a high-temperature, magmatic origin of most of the PGM grains. Only the grains of pure Pt, and the rhythmically zoned, porous Pt–Pd alloys, may have formed by the dissolution of less stable PGE-bearing phases or PGM and subsequent reprecipitation of Pt or Pd at ambient temperatures, in the weathering environment. Also, changes during weathering, fluvial transport or by groundwaters after deposition may have to be taken into account, and both leaching and accretion may have taken place (Cousins & Kinloch 1976, Bowles 1986, 1995, Augé et al. 1995, Cabri et al. 1996).

The near-absence of PGE sulfides as detrital grains and as inclusions in other PGM may point to a primary ore-forming environment of low sulfur fugacity. Alternatively, PGE sulfides may have been destroyed during weathering and fluvial transport. However, the absence of inclusions of PGE sulfides, the presence of Ru-rich alloy, and at the same time the absence of laurite, contradict the hypothesis that PGE sulfides were originally more common in the source rocks. Therefore, the PGM assemblage most probably represents PGM grains that formed at magmatic conditions in low-sulfur mafic–ultramafic rocks or chromitites, whereas a derivation from magmatic Ni-sulfide deposits may be ruled out.

The multicomponent alloys of Pt with Pd, Rh and Ru probably formed from complex PGE-dominant solid solutions at low sulfur fugacities and at magmatic temperatures. In case of elevated sulfur fugacities, one would expect that the large proportions of Rh, Ru and Ir found in many of the alloys would form sulfides, but these are missing at Somabula. Similarly, the Os–Ir–Ru–Rh–Pt alloys, which display a wide scatter of compositions, indicate that they formed from complex PGE-dominant solid solutions. The Os isotope compositions...
lithologies in the Archean greenstone belts of Zimba-
possibly of komatiite affinity, which are widespread
ably originates from low-sulfur mafic–ultramafic rocks,
semblage of detrital PGM found at Somabula most prob-
of the PGM grains at magmatic temperatures. The as-
fluence points to the formation of most
inclusions, the specific mineral chemistry and the com-
ter of PGM at Somabula, their intergrowths and
lications of PGM at Somabula indicates that they
of Os–rich grains point to a pristine mantle source. We
therefore suggest that basic–ultrabasic rocks, possibly
omatite, represents, the likely magmatic environments
which these PGM formed.
Pt–Pd–Au solid solutions are only stable above
1050°C (Hansen & Anderko 1958). Therefore, the pres-
tence of such alloys at Somabula indicates that they
formed in a magmatic environment. Rustenburigate is a
are primary PGM, e.g., in the magmatic ores of the
Bushveld Complex in South Africa (Mihálik et al. 1975)
and the Norilsk deposit in Russia (Distler et al. 1993),
but had until now been known as a ubiquitous detri-
tal constituent of placer deposits. Our limited knowl-
edge on the mode of formation and stability of rusten-
burigate only allows us to loosely link this mineral to
primary magmatic ore-forming environments. However,
the occasional intergrowths of rustenburigate and Pt al-
loys indicates a common genesis and high-temperature
formation of these PGM.
In conclusion, except perhaps for the Pt and Pt–Pd
alloy grains, most of the PGM grains at Somabula have
experienced only subordinate chemical and physical
alteration prior to and following their deposition. Os
isotope compositions of Os–Ir–Ru alloys indicate prin-
tic mantle sources and no crustal contamination. Tex-
tures of PGM at Somabula, their intergrowths and
clusions, the specific mineral chemistry and the com-
positions of the multicomponent Pt and Os–Ir–Ru–Rh–
Pt alloys are interpreted to point to the formation of most
of the PGM grains at magmatic temperatures. The as-
semblage of detrital PGM found at Somabula most prob-
ably originates from low-sulfur mafic–ultramafic rocks,
possibly of komatiite affinity, which are widespread
thologies in the Archean greenstone belts of Zimba-

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