

Rooiberg revisited—the analysis of tin and copper smelting debris

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ABSTRACT: It is nearly a century since the first description of indigenous tin mines at Rooiberg. Sporadic archaeological research has not demonstrated tin mining prior to the mid-2nd millennium AD at Rooiberg, and the presence of tin bronzes at sites such as Mapungubwe and Bosutswe prior to this date could implicate other sources of tin. Nevertheless, all the southern African archaeological tin ingots analysed for their trace element composition are thought to have originated at Rooiberg, but this is not yet proven. The actual technology of tin production at Rooiberg is poorly understood, and is complicated by the production of arsenical copper and possibly also iron in the immediate vicinity. This paper summarises the published literature, presents new analyses of tin and copper production waste collected on a brief reconnaissance visit, discusses the technology of metals production at Rooiberg in the light of these new data, and poses questions for ongoing research.

Introduction

This paper contributes to developing an understanding of local tin and bronze production in southern Africa, by reporting analyses of ores and slags collected in 2005 from sites near Rooiberg (Figs 1 and 2), and discussing the results in the light of earlier published analyses. Issues of chronology are not dealt with here. They are the subject of ongoing archaeological investigation (see Chirikure *et al* 2007). Rooiberg is of significance because it is the only known location of Iron Age tin production in southern Africa (Grant 1999), and one of only two such tin sources in Africa, the other being in Nigeria (Chikwendu *et al* 1989).

At Rooiberg, in the southern Waterberg 100 km north-west of Pretoria, the mineralization is associated with the terminal emplacement of granites and felsites of the Bushveld Igneous Complex (Crocker *et al* 1976; du Toit and Pringle 1998). The Rooiberg constellation of archaeological sites includes early mines on a number of contiguous farms, smelting sites on a prominent hill called Smelterskop at the foot of the Elandsberg, and smelting debris eroding out of a nearby drainage channel known as Blaauwbank Donga (Fig 2). It is

nearly a century since the first descriptions of evidence of tin mining at Rooiberg prior to European colonisation (Recknagel 1908; Kynaston and Mellor 1909; Trevor



Figure 1: Map of the wider region, showing some of the major archaeological sites.

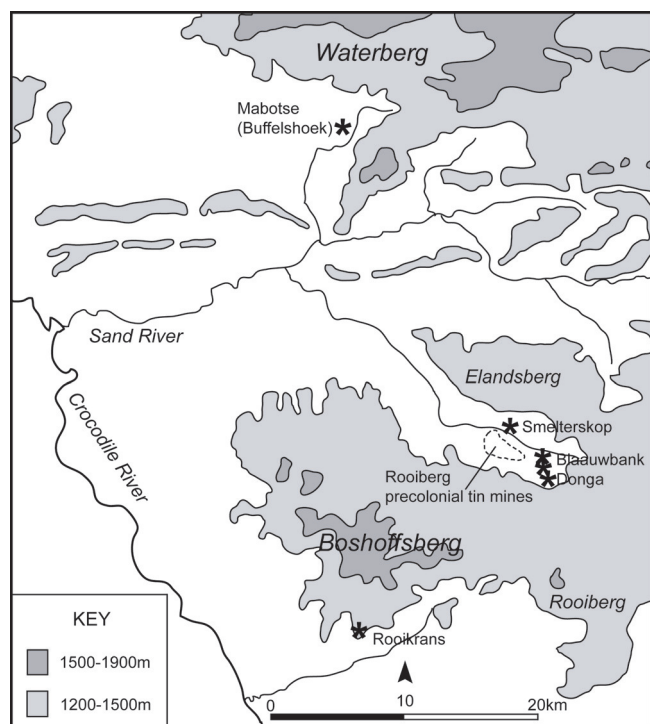


Figure 2: Map of the Rooiberg region showing the location of sites implicated in tin production.

1912; Baumann 1919a). These early descriptions of mining and smelting generated considerable discussion, mostly centred around the possible identity of the miners (Trevor 1913; Baumann 1919b; Schoch and Gray 1919; Trevor *et al* 1919; Waites 1919). Chemical analysis of tin ingots, tin bronze and arsenical bronze artefacts found at various sites in the then Transvaal province followed relatively swiftly (Wagner 1926; Wagner and Gordon 1929; Stanley 1929a and b), with another brief description of tin mining at Rooiberg (Trevor 1930). Then there was a lull in interest, until Thompson's publications describing various tin ingots and summarising the extant analyses (Thompson 1949, 1954), and Schultz's (1950) metallographic description of a number of metal artefacts from Rooiberg (Miller 1992). The 1974 issue of the *Journal of the South African Institute of Mining and Metallurgy*, devoted entirely to 'ancient mining', carried several brief descriptions of tin extraction at Rooiberg (Küsel 1974; Oxley Oxland and White 1974; White and Oxley Oxland 1974). This was followed by detailed re-assessment by Friede (1975) and Friede and Steel (1976) of evidence for indigenous tin and bronze production. In the 1980s, archaeological research in the Rooiberg area focused on establishing the Iron Age archaeological sequence (Hall 1981, 1985; Mason 1986). More recently published archaeometallurgical research has involved the detailed description, analysis, and interpretation of all the available tin and bronze ingots (Killick, 1991; Grant 1990a and b, 1994,

1995, 1999; Grant *et al* 1994). The analysis of metal assemblages from various southern African sites has revealed the unexpectedly high incidence of tin bronze in the 2nd millennium AD (Miller 2002), which once more focuses attention on the source or potential sources of the tin, the technology employed in its production and fabrication into bronze, and the role of tin and bronze in both regional and inter-regional trade.

The material described in this paper was collected during a two day reconnaissance visit, aimed at assessing the Rooiberg area for more intensive future investigation. It was all eroded out onto the surface; none of it was from controlled excavation, and so it was not assumed to be contemporaneous. The sampling aimed to collect material that appeared to be metal production waste at a number of localities described in more detail below, in order to gain an understanding of the variation of materials involved.

Rooiberg and adjacent sites

At Rooiberg itself two areas of production have been identified historically. The first is the Blaauwbank Donga, a heavily eroded area a little to the east of the central mine cluster (Fig 2). There is scattered smelting debris, mostly small irregular nodules of slag with the occasional piece of malachite ore, although the erosion may give a false impression of density. The second centre of metal production is the Smelterskop locality (site number 12/78 Hall (1981); site number 9/85 Mason (1986)) and associated areas at the foot of the Elandsberg. On Smelterskop there are several dense scatters of smelting debris. Surprisingly, much of this debris appeared to be tuyère fragments, many with slagged tips. Very few pieces of glassy-looking slag were evident, in the form of irregular lumps up to about 100mm across. It was not possible on the basis of this sparse slag material to tell if these were the remains of tap slag or not.

There is also evidence for tin working at some distance from the actual tin mines. Rooikrans (Fig 2), for example, dated to the mid-17th century is a defensive hilltop locality that is on the southern margin of the Boshoffsberg, well south of Rooiberg (Hall 1981, 1985). It preserves extensive metal working debris, crucible sherds, furnaces and trimmed tin ore caches. The hilltop site historically called Mabotse, on the Buffelshoek farm (Fig 2), about 30km north of Rooiberg is where one of the few extant tin ingots was probably recovered (Recknagel 1908). Tin slag has also been found here and tin detected in domestic ceramics (Hall and Grant 1995).

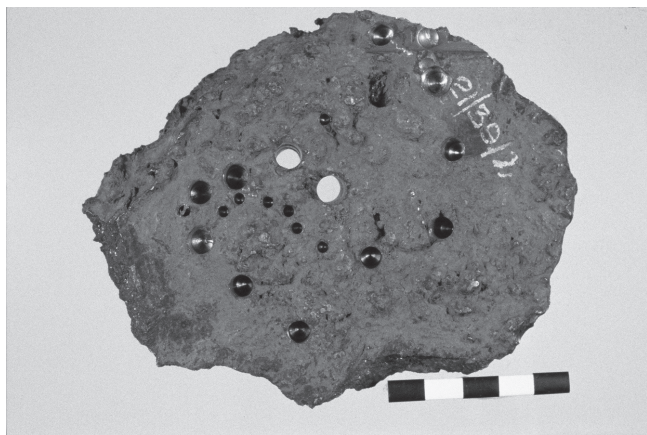


Figure 3: Arsenical bronze ingot (Wits 21/39/2) from Rooiberg. The holes were drilled by earlier analysts (scale bar 50mm)



Figure 4: Tin bun ingot (Wits 21/39/1) from Rooiberg. The central hole and the one to the right of it were drilled by earlier analysts. The other holes are gas porosity (scale bar 50mm).

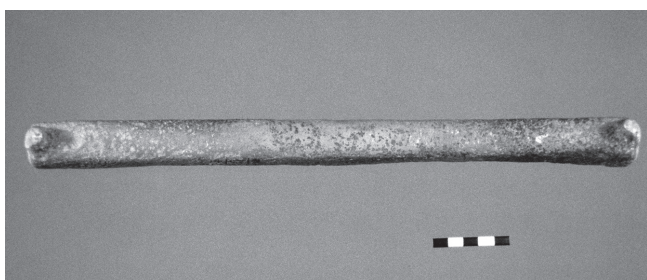


Figure 5: Tin bar ingot (Wits 14/47/3) from Malaboeh, near Potgietersrust (scale bar 50mm).

This site comprises 17th century domestic homesteads, overlain by a 19th century colonial period town. The smelting debris, that includes tin production, predates the 19th century but cannot yet be tied stratigraphically to the earlier occupation. Whatever the case, it is entirely reasonable that the ingot was produced there. Tin ingots have been found further afield (Fig 1), including at Musina (Fig 7; Killick 1991) and Great Zimbabwe (Fig 6; Miller 2002: Z581). An arsenical bronze (Fig 3) and two other tin ingots (Figs 4 and 5) are illustrated

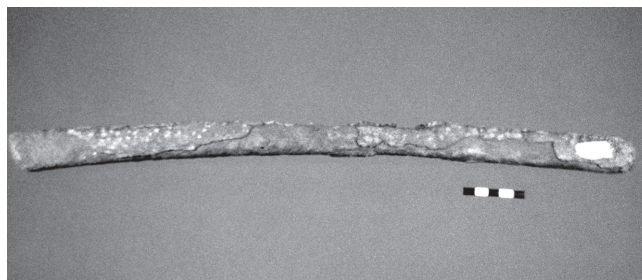


Figure 6: Tin bar ingot (Wits 2030 BD1) from Great Zimbabwe (Miller 2002:Z581; scale bar 50mm).

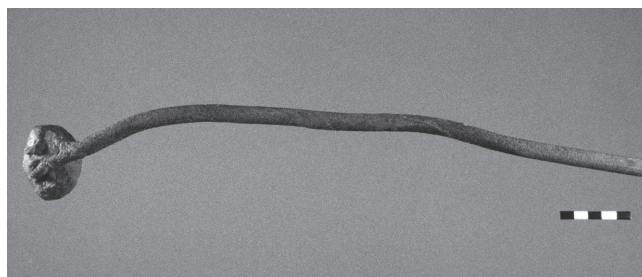


Figure 7: Tin lerale ingot from Musina (Killick 1991; scale bar 50mm).

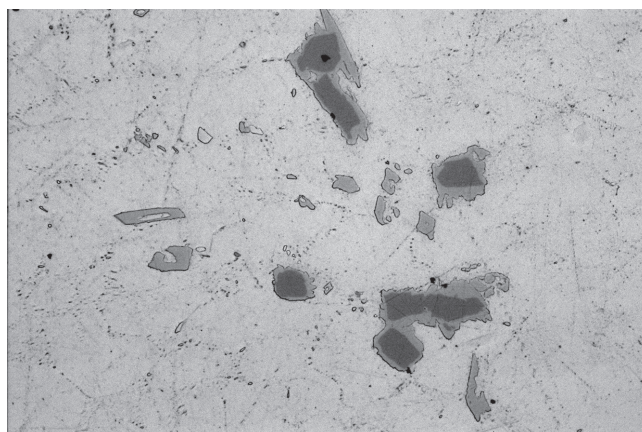


Figure 8: Polished section through tin bun ingot (Wits 21/39/1) from Rooiberg, showing typical tin/iron intermetallic hardhead inclusions (image width 0.1mm).

(‘Wits number’ for the ingots indicates the University of the Witwatersrand accession numbers). All the ingot samples studied metallographically had similar microstructures (Fig 8).

Metallographic analyses of slags

There are relatively few published analyses of archaeological tin slags from southern Africa (Wagner and Gordon 1929; Friede and Steel 1976; Mason 1986; Grant 1994). The analysis of a single fragment of tin bronze melting dross from Bosutswe in Botswana (Fig 1) has been published (Miller 2003). Because of the paucity of analysed material and the complete lack of published mineralogical identifications, the metallurgical analyses

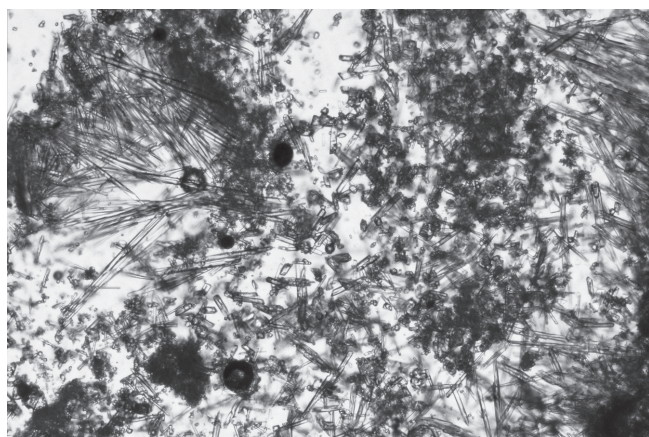


Figure 9: Thin section of slagged tuyère tip SK1 from Smelters Kop, showing light cassiterite needles and dark tin droplets in a light glass (image width 1mm).

of nine samples from Late Iron Age sites in the vicinity of Rooiberg are described here in detail. These samples represent two slagged tuyère fragments and two glassy slag nodules from Smelterskop (SK); three slag nodules from Blaauwbank Donga (BBD); and two slagged crucible sherds from Rooikrans (RK) (Table 1). The samples from Smelterskop and Blaauwbank Donga were assumed to be associated with cassiterite production at the Rooiberg mines. Those from Rooikrans were analysed because prepared tin ore had been found at the site (Hall 1981). Several slices were cut from each sample to section through slag or adhering glassy material. A polished thin section for petrographic study was prepared using one slice from each sample. A matching face slice was mounted in acrylic resin, ground and polished for metallographic study. The metallographic specimens were carbon coated and selected components analysed chemically by energy dispersive X-ray fluorescence spectroscopy (EDS) in the scanning electron microscope to confirm the identification of phases present. The EDS system used detected elements heavier than sodium, with the analytical totals normalised automatically to 100%.



Figure 10: Polished section of slagged tuyère tip SK2 from Smelters Kop, showing light cassiterite crystals in glass, with fine fayalite dendrites (image width 0.3mm).

Smelterskop, Rooiberg

SK1 was a vitrified tuyère tip which had been used in tin smelting. The ceramic body was bloated and vesicular, with cracked quartz grains embedded in a matrix of brown glass. There was a thick, vesicular glass rind containing highly birefringent, dendritic crystals with parallel extinction. These were the iron silicate fayalite (Fe_2SiO_4), a common slag mineral. The glass also contained clumps and rafts of colourless, acicular, birefringent crystals of the tin oxide cassiterite (SnO_2) and swarms of tiny droplets of metallic tin (Fig 9). EDS analysis indicated predominantly silica (SiO_2) and calcium oxide (CaO), with nearly 10% SnO_2 (Table 2:1). It is possible that light glass-forming elements like sodium or boron were present, but undetected. The colourless acicular crystals were confirmed as cassiterite (Table 2:2 and 3).

SK2 also was a vitrified tuyère tip used in tin smelting. The partly vitrified ceramic was bloated and vesicular, with cracked quartz grains in a vitrified glassy matrix, and had a thin layer of adhering, reddish-brown glassy slag. The vitrified matrix and the glassy rind contained

Table 1: Summary of analysed slags.

No.	Site	Material	Mass (g)	Dimensions (mm)	Magnetism
SK1	Smelterskop	vitrified tuyère tip	87.25	55 x 43 x 30	none
SK2	Smelterskop	vitrified tuyère tip	55.01	47 x 50 x 22	none
SK3	Smelterskop	glassy tin slag	55.46	50 x 35 x 20	none
SK4	Smelterskop	gassy tin slag	25.44	45 x 30 x 20	none
BBD1	Blaauwbank Donga	arsenical copper slag	43.86	47 x 20 x 24	strong
BBD2	Blaauwbank Donga	arsenical copper slag	14.60	35 x 25 x 14	moderate
BBD3	Blaauwbank Donga	copper slag	22.27	45 x 30 x 20	weak
RK1	Rooikrans	slagged crucible sherd	14.45	43 x 30 x 12	none
RK2	Rooikrans	slagged crucible sherd	8.16	50 x 22 x 7	none

feathery dendrites of fayalite. The glassy rind also contained some small opaque crystallites, which were probably magnetite (Fe_3O_4), as well as patches of colourless, acicular cassiterite crystals and drifts of tiny droplets of metallic tin (Fig 10). The chemical analysis of the glass showed it to be silica rich (Table 2:4), but

with more iron oxide than in SK1, which accounted for the magnetite dendrites. It also had much higher levels of tin; around 20% when expressed as the oxide (Table 2:4), present both as metallic tin droplets and cassiterite (Table 2:5).

Table 2: EDS analyses of slags from Smelterskop (SK) at Rooiberg, weight %, totals normalised to 100%.

No.	Sample	Material	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	V ₂ O ₅	Cr ₂ O ₃	FeO	SnO ₂	ZrO ₂	Fe	Cu	As	Sn
1	SK1	glass	2.7	9.7	47.4	4.1	15.6	1.3	-	-	9.5	9.7	-				
2	SK1	cassiterite	-	-	-	-	-	-	-	-	-	100.0	-				
3	SK1	cassiterite	-	-	3.7	-	-	-	-	-	1.2	95.1	-				
4	SK2	glass	-	8.5	41.9	2.8	5.2	2.6	-	-	18.2	20.9	-				
5	SK2	cassiterite	-	-	-	-	-	-	-	-	-	100.0	-				
6	SK3	bulk	-	4.4	22.8	-	6.5	1.5	-	-	17.8	46.9	-				
7	SK3	glass	-	3.4	22.2	-	6.3	0.8	-	-	13.4	54.0	-				
8	SK3	inclusion												16.4	-	-	83.6
9	SK3	inclusion												38.4	-	31.6	30.0
10	SK3	anorthite	-	24.1	47.6	2.4	24.1	-	-	-	1.7	-	-				
11	SK3	anorthite	-	23.7	49.0	2.1	23.6	-	-	-	1.5	-	-				
12	SK3	anorthite	-	21.7	48.3	2.2	26.3	-	-	-	1.6	-	-				
13	SK3	fayalite	9.2	-	32.3	-	1.1	-	-	-	57.4	-	-				
14	SK3	fayalite	11.7	-	34.0	-	0.7	-	-	-	53.6	-	-				
15	SK3	spinel	5.3	44.2	-	-	-	1.7	5.5	1.3	42.1	-	-				
16	SK3	spinel	4.3	36.4	-	-	-	2.1	10.4	5.4	41.4	-	-				
17	SK3	spinel	4.4	40.4	4.8	-	2.2	1.6	5.1	2.3	39.2	-	-				
18	SK3	spinel	4.5	38.4	-	-	0.8	2.9	5.9	2.7	44.8	-	-				
19	SK3	spinel	5.2	42.3	-	-	-	1.8	6.2	1.6	42.9	-	-				
20	SK3	magnetite	-	0.5	-	-	-	22.0	-	-	69.1	8.3	-				
21	SK3	magnetite	-	3.3	-	-	-	18.9	6.3	-	65.8	5.8	-				
22	SK3	magnetite	-	1.9	-	-	-	20.5	4.6	-	66.2	6.9	-				
23	SK3	magnetite	-	1.7	-	-	-	16.9	6.8	-	67.4	7.3	-				
24	SK3	augite	0.5	8.2	19.5	-	14.9	7.9	-	-	37.8	11.3	-				
25	SK3	augite	1.7	8.1	20.7	-	15.5	8.8	2.2	-	35.4	7.7	-				
26	SK3	augite	1.5	8.3	20.4	-	15.7	9.0	1.5	-	36.2	7.3	-				
27	SK3	augite	1.6	8.1	21.2	-	15.5	8.6	1.5	-	36.1	7.5	-				
28	SK4	bulk	-	3.1	38.3	2.8	10.3	18.9	-	-	12.0	14.6	-				
29	SK4	glass	-	3.2	39.2	3.1	12.6	10.2	-	-	12.5	19.2	-				
30	SK4	zircon	-	-	22.5	-	-	-	-	-	-	-	77.6				
31	SK4	rutile	-	-	-	-	-	82.1	-	-	17.9	-	-				
32	SK4	rutile	-	-	-	-	-	80.7	-	-	19.3	-	-				
33	SK4	ilmenite	-	-	-	-	1.7	62.9	5.7	4.0	9.7	2.9	13.0				
34	SK4	ilmenite	-	-	7.1	-	3.5	60.6	-	4.3	13.3	4.8	6.5				
35	SK4	ilmenite	-	-	18.8	-	5.6	45.0	-	1.9	13.1	9.9	5.7				
36	SK4	ilmenite	-	-	12.9	-	3.5	55.4	-	5.0	11.9	5.6	5.7				
37	SK4	ilmenite	-	-	6.0	-	1.6	76.9	-	1.5	2.1	3.9	8.1				
38	SK4	ilmenite	-	-	9.2	-	2.2	70.8	-	1.5	3.0	6.1	7.2				
39	SK4	zirkelite	-	-	7.8	-	8.8	36.0	-	1.6	9.1	4.6	32.0				
40	SK4	zirkelite	-	-	8.4	-	8.1	34.4	-	1.8	10.7	5.5	31.2				

Note: blank = not sought; dash = not detected



Figure 11: Thin section of tin smelting slag nodule SK3 from Smelters Kop. The light laths are fayalite in a pale glass, with stellate rosettes consisting of blades of titaniferous augite around opaque cores of spinel (image width 0.4mm).

SK3 was a nodule of dense, homogeneous, glassy tin slag whose bulk composition (Table 2:6) was very similar to the glassy matrix, a silica glass with about 50% tin oxide, and lesser iron oxide and calcium oxide (Table 2:7). It contained spherical tin droplets, some with inclusions of the dark tin/iron intermetallics known as ‘hardhead’, present in all the southern African ingots analysed (eg Fig 8). One inclusion consisted of two nested phases, the outer, lighter one being the tin intermetallic FeSn_2 (Table 2:8). The inner, darker one was an iron-tin arsenide (Table 2:9), similar in composition to the arsenical inclusions in the tin *lerale* ingot from Terblanche Hoek, 35km east of Musina (Fig 1), described by Killick (1991; Fig 7). Ten droplets of tin in this slag were analysed by laser ablation inductively coupled mass spectrometry (LA-ICP-MS). Their trace element signatures were virtually identical, both in elements present and their relative intensities (see Discussion, below, and Fig 18).

The other phases in the glass were a variety of silicates and oxides. Towards one edge there were a few groups of colourless, euhedral, rectangular silicates of low relief, with single axial twin planes (simple Carlsbad twinning). These were the calcium feldspar anorthite (Table 2:10–12), not before reported in southern African slags (Miller and Killick 2004). Pervasive throughout the glassy matrix were laths of fayalite, with characteristically high interference colours and typical dendritic morphology. Their analysis showed about 10% MgO substitution for FeO in the formula (Table 2:13 and 14). The most conspicuous crystalline components in transmitted light were stellate rosettes consisting of three phases (Fig 11). The central core of each rosette was a dark green, euhedral, isotropic crystal of spinel. These consisted primarily of equal weight percent of FeO and Al_2O_3 , as expected of a spinel with a composition approaching



Figure 12: Polished section of tin smelting slag nodule SK4 from Smelters Kop, showing blocky zircon crystals (medium grey) and laths of rutile (light grey) in glass (image width 0.3mm).

the common slag mineral hercynite (FeAl_2O_4), but they also contained about 7% V_2O_5 , 5% MgO, 3% Cr_2O_3 , and 2% TiO_2 (Table 2:15–19). The corners, and sometimes also the edges of these octahedral crystals had epitaxial overgrowths of an opaque, isotropic phase with higher reflectivity. These were titaniferous magnetite (nominally Fe_3O_4), with about 20% TiO_2 and 6% V_2O_5 (Table 2:20–23). These little central clusters of spinel were surrounded by radiating sprays of red rhombohedral platelets, which were birefringent, with strong brown to dark red pleochroism. Optically they looked like haematite (Fe_2O_3), but they contained only 36% FeO (Table 2:24–27). They were the chemically most complex phase in the assemblage, containing in addition to the iron 20% SiO_2 , 15% CaO, 8.5% TiO_2 , 8% Al_2O_3 , 8% SnO_2 , 2% V_2O_5 , and 1% MgO. These crystals were probably blades of titaniferous augite ($(\text{Ca,Mg,Fe,Al,Ti})_2(\text{Al,Si})_2\text{O}_6$), with substitutional tin and vanadium. This slag was the result of rather inefficient tin smelting. Unlike copper smelting, fluxing with iron ore to return a higher tin yield is not feasible because of the reaction of tin and iron to produce undesirable hardhead inclusions in the tin (Grant 1994).

SK4 was an irregular nodule of inhomogeneous, glassy flow slag, with angular charcoal impressions. One area contained included, cracked quartz grains, surrounded by glass. The remainder had a glassy matrix with a variety of crystalline phases. The bulk composition and the glass compositions were very similar to each other (Table 2:28 and 29) with higher silica, titania and lime, and less than half the tin content of SK3 (cf Table 2:6 and 7). The most conspicuous crystalline mineral consisted of large, blocky, translucent, colourless crystals. They were optically positive, with very high relief, and strongly birefringent with high interference colours

(Fig 12). These were zircon ($ZrSiO_4$) (Table 2:30). The large crystals had irregular margins with small embayments, and the appearance of some degree of reaction with the glassy matrix. Some of these embayments had tiny droplets of metallic tin in the enclosing glass. There was also another generation of zircon crystals, either single or in small clusters. These were far smaller, and euhedral, with very sharp margins. They were very fresh and must have crystallised from the glassy slag. Their presence was surprising, because zircon is a high temperature mineral. Presumably in this slag the small crystals formed by reaction of dissolved ZrO_2 with silica in the tin-rich glass, well below the melting temperature of zircon, which is above 1700 °C.

There were other crystalline phases present. The glass was pervaded by elongated, dendritic, birefringent laths of fayalite, with typical high interference colours and straight extinction. Another conspicuous phase consisted of masses of acicular crystals, some separate, some in parallel sheaves. These were reddish brown and

translucent, strongly birefringent, and bireflectant. The chemical analyses showed them to be rutile (TiO_2) with up to 20% FeO (Table 2:31 and 32). Other titanium-rich crystals were completely opaque in transmitted light and formed slightly globular dendritic arrays and hollow crystals. These were of somewhat variable and complex composition (Table 2:33–38) containing on average 62% TiO_2 , and were ilmenite (nominally $FeTiO_3$). In places the rutile and ilmenite were accompanied by swarms of small reddish brown crystals, octahedral and often twinned, and isotropic under crossed polars. These contained almost equal amounts of TiO_2 and ZrO_2 (Table 2:39–40) and were probably zirkelite ($(Fe,Ca)O \cdot 2(Zr,Ti)O_2$), an isometric reddish-brown mineral with octahedral habit (Larsen and Berman 1934, 64).

This extraordinary slag probably originated from the smelting of a heavy mineral sand, containing detrital zircon, ilmenite, rutile and cassiterite. Alternatively, the zirconium and titanium could have been added fortuitously with a detrital granitic sand used as a source of

Table 3: EDS analyses of slags from Blaauwbank Donga (BBD) at Rooiberg, weight %, totals normalised to 100%.

No.	Sample	Material	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	V ₂ O ₅	Cr ₂ O ₃	FeO	Cu ₂ O	As ₂ O ₃	Fe	Cu	As	Sn
41	BBD1	bulk	3.2	22.0	5.6	-	2.1	-	-	-	66.8	-	-				
42	BBD1	drop												3.0	87.3	6.9	2.7
43	BBD1	dendrite												-	92.0	8.0	-
44	BBD1	eutectic												0.8	77.2	22.0	-
45	BBD1	dendrite												-	71.3	28.7	-
46	BBD1	dendrite												-	71.3	28.7	-
47	BBD1	eutectic												-	80.3	19.7	-
48	BBD2	bulk	3.0	34.0	1.1	0.6	1.2	-	-	-	58.2	1.9	-				
49	BBD2	fayalite	1.3	34.8	-	0.9	0.6	-	-	-	62.4	-	-				
50	BBD2	fayalite	2.0	34.3	-	1.3	0.8	-	-	-	61.6	-	-				
51	BBD2	fayalite	-	28.2	-	0.3	0.4	-	-	-	71.2	-	-				
52	BBD2	glass	-	100.0	-	-	-	-	-	-	-	-	-				
53	BBD2	magnetite	-	-	-	-	-	-	-	3.6	96.4	-	-				
54	BBD2	drop												0.7	84.0	15.3	-
55	BBD2	drop												1.1	86.5	12.4	-
56	BBD2	drop												0.9	88.8	10.3	-
57	BBD3	glass	8.1	60.0	-	6.4	-	-	-	-	23.4	2.1	-				
58	BBD3	oxide	-	-	-	-	-	-	-	-	68.8	31.2	-				
59	BBD3	metal												4.5	95.5	-	-
60	BBD3	drop												2.3	97.7	-	-
61	BBD3	drop												2.3	97.7	-	-
62	BBD1-1	malachite	-	3.7	0.8	-	-	-	-	-	0.6	64.0	31.0				
63	BBD2-1	malachite	-	1.1	2.8	-	-	-	-	-	-	65.5	30.6				
64	BBD3-1	malachite	-	0.5	0.9	-	-	-	-	-	0.8	67.1	30.8				
65	BBD4-1	haematite	9.7	20.2		4.4	-	0.5	0.4	-	64.3	0.5	-				
66	BBD5-1	olivine	-	1.3	1.2	-	-	-	-	-	-	60.0	37.6				

Note: blank = not sought; dash = not detected

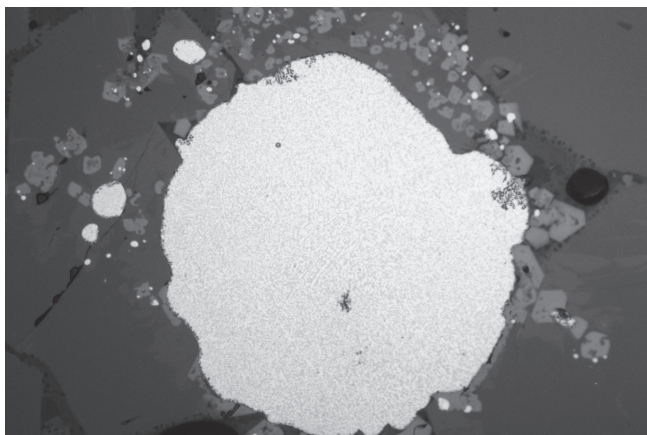


Figure 13: Polished section of copper smelting slag nodule BBD1 from Blaauwbank Donga, showing arsenical copper droplet with fine eutectic intergrowths, in a matrix of fayalite (medium grey), magnetite (light grey) and glass (dark grey) (image width 0.5mm).

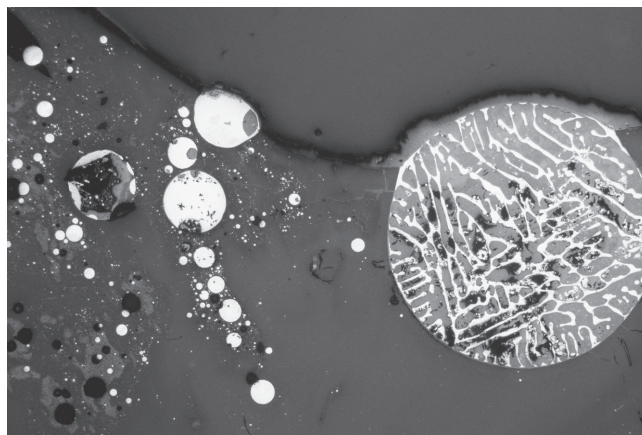


Figure 15: Polished section of copper smelting slag nodule BBD3 from Blaauwbank Donga, showing a large copper drop with a coarse intergrowth of mixed copper and iron oxides, in a glassy matrix with numerous smaller two-phase copper droplets (image width 1mm).

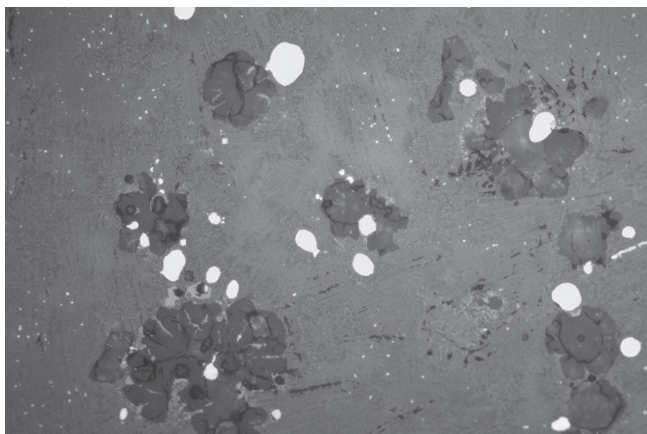


Figure 14: Polished section of copper smelting slag nodule BBD2 from Blaauwbank Donga, showing single-phase copper droplets (bright), clustered around globules of silica glass (dark grey) in a fine grained matrix of fayalite and glass with tiny copper droplets (image width 0.7mm).

silica to flux a cassiterite ore, but this seems less likely because of the concentrations involved.

Blaauwbank Donga

BBD1 was a nodule of black, arsenical copper smelting slag, with very glossy fracture surfaces and small charcoal impressions on the outside. It was inhomogeneous and crowded with metallic droplets, with areas consisting predominantly of blocky fayalite and glass, and other areas with larger volumes of magnetite (Fig 13). The magnetite formed small blocky to skeletal crystals, with only iron detectable in the EDS analysis (not recorded). The bulk composition of a fayalite and glass area was unremarkable except for the relatively high phosphorus content of 5.6% P_2O_5 (Table 3:41). A small copper droplet trapped between fayalite crystals near one margin contained 87% copper, 7% arsenic, 3% tin and 3% iron (Table 3:42). All the larger copper droplets

consisted of more than one phase. In some the copper-rich phase, containing 92% copper and 8% arsenic (Table 3:43), formed thick dendrites in an eutectic matrix with an average composition of 78% copper and 22% arsenic (Table 3:44). In other droplets the situation was reversed, with globular blue dendrites with 71% copper and 29% arsenic (Table 3:45 and 46) in an eutectic matrix of 80% copper and 20% arsenic (Table 3:47). The eutectic matrix composition was strikingly similar to that of the enigmatic Rooiberg arsenical copper bun ingot (Fig 3) with 20% arsenic reported by Grant *et al* (1994). Notably, no sulphur was detected in BBD1, precluding the smelting of a sulphide ore, and tin was detected in only one small metal droplet.

BBD2 was an irregular nodule of black flow slag, with rounded protuberances and charcoal impressions. It was clearly a homogeneous copper smelting slag, consisting predominantly of very fine fayalite laths in glass, with numerous small copper droplets (Fig 14). The bulk chemical analysis of an area avoiding large copper droplets (Table 3:48), confirmed that the ground mass consisted predominantly of fayalite with a composition not significantly different from that of individual larger laths analysed (Table 3:49–51). The isotropic glass globules contained nothing detectable but silica (Table 3:52), although undetected lighter glass-forming elements were probably present. The analysis of a blocky oxide crystal confirmed that it was magnetite, with 3.6% Cr_2O_3 (Table 3:53). Analysis of three of the two-phase copper droplets indicated between 10% and 15% arsenic, with negligible iron, and no detectable tin (Table 3:54–56). This slag was the product of smelting an arsenical copper ore.

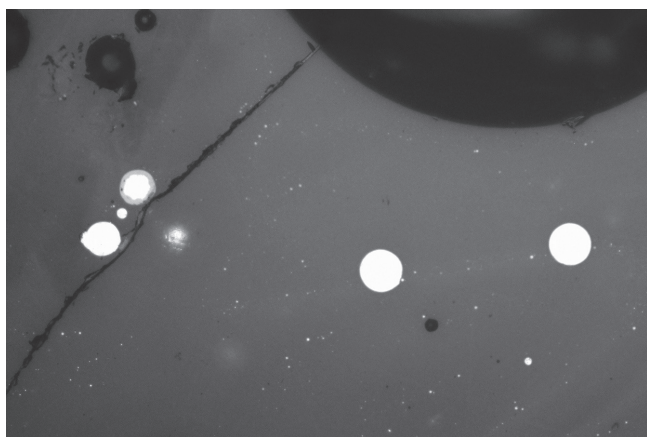


Figure 16: Polished section of slagged crucible sherd RK1 from Rooikrans, showing copper droplets in glass. (image width 0.2mm).

BBD3 was a greenish, vesicular copper smelting slag nodule with a rough exterior. It was an inhomogeneous glassy slag with included cracked quartz grains, and permeated by dendritic fayalite laths with numerous small droplets of copper, many of them with two-phase eutectic structures (Fig 15). The chemical analysis of a glassy area, avoiding obvious copper droplets, reflected the mixture of fayalite and the silica-rich glass itself (Table 3:57). One 2mm copper drop with a very coarse dendritic texture had lamellae of mixed copper and iron oxides (Table 4:58) as well as metal. The metal in this nodule and two other single-phase drops contained only copper with between 2.3% and 4.5% iron (Table 3:59–61). High levels of iron in copper imply high smelting temperatures (Craddock and Meeks 1987) and unnecessarily high reducing conditions. Neither arsenic nor tin were detected in this sample. This was the product of smelting a non-arsenical copper ore.

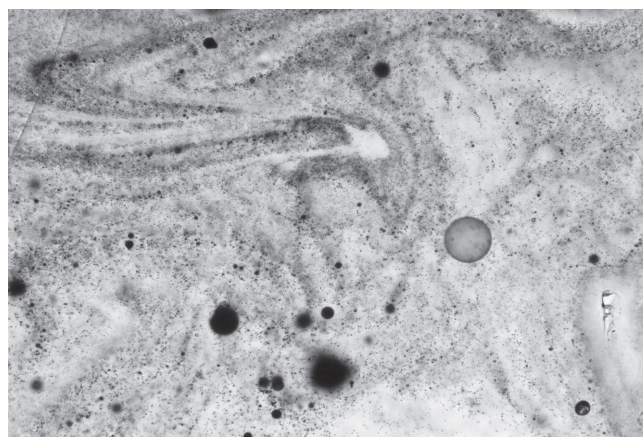


Figure 17: Thin section of slagged crucible sherd RK2 from Rooikrans, showing swirls of numerous metal droplets in glass (image width 0.3mm).

Rooikrans

RK1 was a ceramic crucible sherd from Rooikrans (Hall 1985), with a thick coating of vesicular glassy slag on the inner surface. The ceramic was dense and largely unvitified. The glass rind contained numerous copper droplets (Fig 16), ranging up to 1mm in diameter. Some of the larger droplets had two-phased eutectic structures. The glass itself had high levels of silica and lime (Table 4:67), distinguishing it from the copper smelting slags from Blaauwbank Donga. The metal droplets contained mostly copper, with about 2.5% iron and 2–4.4% arsenic. No tin was detected in these droplets. This slag was derived from the crucible melting of an arsenical copper, but with much lower levels of arsenic than the arsenical copper samples from Blaauwbank Donga.

RK 2 was a ceramic crucible sherd with a thin vesicular glassy slag on the inside and on the vitrified rim. This

Table 4: EDS analyses of slags from Rooikrans (RK), weight %, totals normalised to 100%.

No.	Sample	Material	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	V ₂ O ₅	Cr ₂ O ₃	MnO	FeO	Al	Si	P	S	Fe	Ni	Cu	As	Sn	
67	RK1	glass	0.5	10.2	50.8	5.8	20.6	1.6	-	-	1.3	9.3										
68	RK1	drop											-	-	-	-	2.2	-	96.1	1.7	-	
69	RK1	drop											-	-	-	-	2.5	-	93.1	4.4	-	
70	RK1	drop											-	-	-	-	2.6	-	94.9	2.4	-	
71	RK2	glass	-	15.8	50.9	2.5	15.6	0.8	-	-	0.6	13.8										
72	RK2	drop											-	-	0.6	-	95.9	0.5	1.3	-	1.6	
73	RK2	drop											-	-	6.5	-	85.4	5.5	-	-	2.6	
74	RK2	drop											0.8	2.4	-	-	2.7	7.7	49.7	-	36.8	
75	RK2	drop											-	-	0.8	-	96.0	-	1.9	-	1.3	
76	RK2	drop											-	0.8	-	0.6	20.8	0.7	29.3	-	47.7	
77	RK2	drop											-	-	7.5	-	90.4	0.9	-	-	1.2	
78	RK2	drop											-	-	1.3	-	17.7	1.1	53.0	-	26.9	

Note: blank = not sought; dash = not detected

Table 5: Published analyses of Iron Age tin ores and slags from Rooiberg, weight % (after Friede and Steel 1976).

No	Location	Material	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	Cr ₂ O ₃	MnO	Fe ₂ O ₃	ZrO ₂	Sn	Total
A1	Rooiberg	'tin feed'	0.46	5.28	14.52	27.35	0.50	0.27	4.13	0.45	0.11	<0.10	15.68	0.25	30.88	99.98
A4	Rooiberg	'tin feed'	0.39	3.57	11.76	15.69	0.27	0.14	3.53	0.30	0.15	0.39	30.04	0.21	24.92	91.36
B1	Rooiberg	slag	-	1.45	7.53	33.70	1.02	0.95	0.61	0.10	<0.10	0.18	38.17	<0.10	1.98	85.89
B3	Smelterskop	slag	-	1.29	32.27	37.04	2.41	0.34	11.13	1.58	<0.10	<0.10	11.11	0.16	0.13	97.66
B4	Smelterskop	slag	0.50	1.44	15.61	56.65	2.29	1.49	2.27	0.57	0.10	<0.10	8.68	0.23	10.01	99.94
B6	Smelterskop	slag	0.50	2.97	14.16	25.75	0.33	2.51	3.39	0.76	0.12	0.72	34.64	0.27	12.96	99.08
A2	Blaauwbank	'tin feed'	0.20	5.45	10.53	32.82	0.14	0.78	3.24	0.23	0.13	0.15	19.13	0.25	15.26	88.31
I	Blaauwbank	slag	3.32	2.67	17.34	33.72	-	-	2.12	-	-	0.12	35.23*	-	4.06	98.58
II	Blaauwbank	slag	0.22	0.65	7.87	32.51	-	-	0.80	-	-	-	9.26*	-	38.29	89.60
B2	Blaauwbank	slag	-	0.53	2.32	53.89	0.30	0.35	1.32	<0.10	<0.10	<0.10	28.86	<0.10	0.14	88.11

Notes: dash = not reported; * = FeO

glassy layer contained swirls of numerous small metal drops (Fig 17). The analysis of the glass showed it had a high level of iron (Table 4:71). This was due to the fact that most of the metal drops were predominantly iron, containing in addition some phosphorus, nickel, copper and tin (eg Table 4:72). Most of these iron drops had small adhering blobs of copper alloy. Three such pairs were analysed (Table 4:73–74, 75–76, 77–78). The iron forming the bulk of each drop contained up

to 7.5% phosphorus, 5.5% nickel, 2.6% tin and 2% copper (Table 4:73, 75 and 77). The subordinate copper alloy droplets contained between 27% and 48% tin, up to 7.7% nickel, and in only one case a trace of sulphur (Table 4:74, 76 and 78). Although it was sought, no arsenic was detected. This crucible slag originated from melting a tin bronze with substantial iron contamination. At present the chemistry cannot distinguish between sources for the copper and tin, and there is no way of

Table 6: Published analyses of Iron Age tin ores and slags from Rooiberg, weight % (after Mason 1986).

No	Location	Material	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	ZrO ₂	Sn	Total
103	Smelterskop	slag	-	2.7	11.6	40	0.3	2.35	5.3	1	-	16.2	0.7	13.5	93.65
104	Smelterskop	slag	-	2	7	49	0.3	1.9	4.7	6.2	-	8.2	7.8	8	95.10
TI B4	Smelterskop	slag	-	1.4	15.6	56.6	2.3	1.5	2.3	0.6	-	8.7	0.2	10	99.20
107	Elandsberg	slag	-	0.25	9.4	60	0.2	1.9	0.9	4	-	8.1	5.3	5.4	95.45
108	Elandsberg	slag	-	0.3	13.6	65	-	2.3	0.6	0.7	0.27	10.4	0.7	3.6	97.47
111	Elandsberg	slag	-	2.4	11.7	27	0.1	1.2	1.8	0.67	0.2	31.4	0.9	16.3	93.67
113	Elandsberg	slag	-	-	2.5	19	0.1	0.8	3.6	-	0.9	78.5	1.3	0.05	106.75
7/86	Blaauwbank	'tin feed'	-	1.4	11	43	0.06	-	-	0.2	-	8.8	0.7	20.2	85.36
TI A2	Blaauwbank	ore	-	5.4	11	32	0.14	0.8	-	0.2	0.15	19	0.25	15.26	84.20
slag IV	Blaauwbank	slag	-	-	3	17	-	-	0.6	-	0.2	78.2	-	-	99.00
slag I	Blaauwbank	slag	3.3	2.6	17	34	-	-	2.2	-	0.1	35*	-	5.2	99.40
109	Blaauwbank	slag	-	-	1.7	17	-	-	0.6	-	2.4	84.5	1.5	0.04	107.74

Notes: dash = not reported; * = FeO; data for slag IV and slag I are from Wagner and Gordon (1929); data for TI A2 and TI B4 are from Friede and Steel (1976); nos 109 and 113 are not tin slags but may represent either iron or copper smelting.

Table 7: Published analyses of Iron Age tin ores and slags from Rooiberg, weight % (after Grant 1994).

No	Material	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O (+Na ₂ O)	CaO	TiO ₂	Mn ₂ O ₃	Fe ₂ O ₃	SnO ₂	Total
1	ore	0.86	5.91	12.8	0.10	0.67	0.28	0.22	0.46	19.5	35.1	75.9
2	ore	3.76	13.4	28.1	0.34	1.01	0.61	0.40	0.45	33.1	8.04	89.21
3	ore	2.63	14.8	21.6	0.04	0.80	0.35	0.61	0.25	12.7	33.2	86.98
2	slag	0.91	31.4	38.2	2.42	0.35	9.64	1.55	0.15	15.1	1.11	100.83
3	slag	1.85	14.8	41.0	0.18	2.78	1.66	0.88	0.10	17.6	16.9	97.75
6	slag	0.65	7.87	32.5	nd	0.22	0.80	nd	0.00	10.3	48.6	100.94

Note: nd = not determined

Table 8: Point count analyses, in percent, conducted on tin ingots under the optical microscope (500 points, 0.05mm increments).

Ingot	Wits No	Fig No	White tin matrix	Dark FeSn	Light FeSn ₂	Arsenical inclusions	Speckled eutectic
Rooiberg bun ingot	21/39/1	4	97.2	0.6	2.2	-	-
Rooiberg bun ingot	21/39/3	-	97.2	-	2.2	0.6	-
Malaboch rod ingot	14/47/1	-	98.6	0.2	1.2	-	-
Malaboch rod ingot	14/47/2	-	99.6	-	0.4	-	-
Malaboch bar ingot	14/47/3	5	99.8	-	0.2	-	-
Zimbabwe bar ingot	2030 BD1	6	94.8	-	0.2	-	5
Messina lerale ingot	-	7	83.8	5.2	11	-	-

knowing if the iron originated as a contaminant in the copper or as hardhead in the tin.

Discussion

Tin slags

The previously published values for archaeological ores and tin slags from the Rooiberg area are listed in Tables 5 to 7. Most of the totals vary significantly from 100%, making direct comparison of these analyses with the values in Tables 2 to 4 impossible. Nevertheless, some general observations can be made.

The production of tin in the smelt is proportional to the iron content of the furnace metal (Grant 1994). Given that the reducing conditions for SnO and FeO are very similar, it is difficult to avoid the reduction of iron oxide to iron and its reaction with tin to form undesirable hardhead. A potential tin ore needs a high SnO₂ to Fe₂O₃ ratio to produce a reasonable yield of tin with low iron contamination, under equilibrium smelting conditions. An ore with an SnO₂ to Fe₂O₃ ratio of 7:1 has been calculated to produce a yield of only 37% if the tin is to contain less than 0.1% iron (Grant 1994). None of the ore or 'tin feed' analyses in Tables 5 to 7 meet this criterion. This could be explained in two ways. First, smelting must have taken place under non-equilibrium conditions, with much of the iron remaining in an oxidised state in the slag and not available for reaction with the tin. This clearly was the case, given the mineralogy of the slags and the FeO values in the slag analyses. Second, analysed tin ingots contain variable amounts of hardhead, up to 3.76% iron in the case of the Musina *lerale* ingot (Table 8). Some of the ingots have much lower iron contents, less than 0.5% (Grant 1994). Evidently, relatively high levels of hardhead were tolerated in primary production, and primary tin may have been refined through dressing or liquation to reduce the iron content when desired (Killick 1991).

The tin content in analyses of the supposed tin slags from Rooiberg varied widely, from nearly 47% SnO₂ (eg Table

2:6) to values ranging down to less than 10% Sn (eg Table 5:B3; Table 6:104, 107, 108). The higher values indicate that tin smelting was inefficient and much tin was trapped in the slags, as has been noted before (Wagner and Gordon 1929; Friede and Steel 1976). With an abundance of ore, such losses may not have been a concern. Alternatively, high-tin slag may have been recycled into the furnace charge, but the iron content of these slags may have mitigated against this (Grant 1994). Some published Rooiberg slag analyses, containing nothing significant but iron oxide and silica, clearly are not tin smelting slags but may represent copper or iron smelting (eg Table 6:113). This is corroborated by twelve published chemical analyses of 'ore' from the Smelterskop and Elandsberg sites, containing minimal tin (all below 0.25%) but in some cases up to 90% Fe₂O₃ (Mason 1986, 310).

The high levels of titanium and the large zircon inclusions in the tin slag SK4 from Smelterskop (Table 2), suggest the use of an alluvial ore containing zircon, rutile, and/or ilmenite. The Smelterskop and Elandsberg slag analyses reported by Mason (1986) had ZrO₂ values up to 7.8%, with a strong positive correlation between ZrO₂ and TiO₂ (Table 6), which implies a granitic detrital source for at least part of the furnace charge. Wagner and Gordon (1929) reported that alluvial cassiterite had been found in smelter 'feed'. Alternatively, granitic sand containing ilmenite, rutile and zircon may have been added as a flux for its silica content. Either way, it is evidence for the exploitation not only of hard rock ores, for which there is plenty of direct evidence in the form of extensive underground mining at Rooiberg, but also alluvial deposits.

According to early reports (Wagner 1926, Wagner and Gordon 1929), the nearby Blaauwbank Donga is associated with both copper and tin metallurgy. Up to forty furnaces were reported, including smelting or 'hearth' furnaces and crucible furnaces. Some smelting furnace bottoms reportedly contained prills of tin, and iron may have been smelted in similar furnaces. Copper and tin

ore, and slags were scattered over a 'large area'. The crucible furnaces consisted of rock supports for ceramic bowls, one apparently with a bronze prill attached to it. The Blaauwbank area is now very eroded and discrete furnace remains are no longer identifiable, but similar crucible supports for metal refining have been reported from the copper smelting precincts at Marothodi (Fig 1; Hall *et al* 2006).

The two Blaauwbank ores and 'tin feed' analyses published by Friede and Steel (1976) and Mason (1986) had tin contents of 15% and 20% (Tables 5 and 6). These, and some of the slag analyses (Table 5:I and II), clearly indicate some tin smelting activity. The other historical Blaauwbank slag analyses with very low or no tin contents (*eg* Table 6:slag IV and 109) could represent either copper or iron smelting, which often are difficult to distinguish on the basis of chemical analysis alone (Miller and Killick 2004).

Copper ores and slags

Most of the analyses of ore and slag from the Blaauwbank Donga reported here (Table 3) indicate copper production. Five ore fragments were analysed by EDS. A blocky piece of haematite (Table 3:65) could imply either iron smelting or fluxing of a copper smelt with iron ore. The remaining ore nodules consisted of arsenic-rich malachite (Table 3:62–64) and a nodule of olivenite crystals (Table 3:66). To our knowledge, the mineral olivenite ($\text{Cu}_2\text{AsO}_4\cdot\text{OH}$) has not been reported previously from the Rooiberg area

(Cairncross and Dixon 1995). Together, these were the ores smelted to produce the arsenical copper droplets trapped in the analysed copper slags (Table 3:BBD1 and BBD2). Very few Rooiberg 'bronze' analyses have been reported to date and they all contained high levels of arsenic (Trevor 1912; Wagner and Gordon 1929; Stanley 1929b; Friede 1975). The large plano-convex copper ingot (Fig 3, Wits 21/39/2) with 20% arsenic has been the subject of several analyses and much speculation (Stanley 1929b; Friede and Steel 1976; Grant *et al* 1994). As pointed out a long time ago by Stanley (1929b), this composition approximates the Cu-As eutectic, with a melting point of about 700°C (Grant *et al* 1994). It is the same as many of the prills trapped in one of the analysed slags (Table 3:44 and 47) and the composition one would expect to form first from smelting a highly arsenical copper ore. It has been suggested that these arsenical coppers are the result of smelting copper ore contaminated with the green nickel arsenate annabergite (Wagner 1926; Wagner and Gordon 1929; Grant *et al* 1994). This is refuted by the absence of detectable nickel in both the metals and the analysed slags with arsenic-rich copper droplets (see Table 3), and the presence of olivenite on the site. This solves a puzzle introduced in 1926 by Wagner's suggesting that the locally available green nickel arsenate annabergite might have been smelted. In the case of Wits 21/39/2, confusion of olivenite for malachite ore produced a uselessly brittle ingot, which evidently was discarded. Less intractable, lower-arsenic copper alloy nodules may have been refined by melting to drive off the arsenic.

Table 9: Trace element signatures of selected tin ingots determined by laser ablation inductively coupled mass spectrometry, showing partitioning of trace elements between the tin metal matrix and the hardhead inclusions (data courtesy of Anglo American Research Laboratories)

	Malaboch		Malaboch		Malaboch		Rooiberg		Rooiberg		Messina	
	14/47/1		14/47/2		14/47/3		21/39/1		21/39/3		lerale	
	matrix	inclusions	matrix	inclusions	matrix	inclusions	matrix	inclusions	matrix	inclusions	matrix	inclusions
Ti										√		
Cr												√
Fe		√		√		√		√		√	√	√
Co	√	√	√	√		√		√			√	√
Ni											√	
Cu	√	√	√	√	√	√	√	√		√	√	√
Zn				√								
Ga				√		√		√				
As	√	√	√	√	√		√				√	√
Zr												√
Sn	√	√	√	√	√	√	√	√	√	√	√	√
Sb	√	√	√	√	√	√	√	√	√	√	√	√
W												√
Pb	√		√		√		√				√	√
Bi	√	√	√	√	√	√	√	√	√	√	√	√

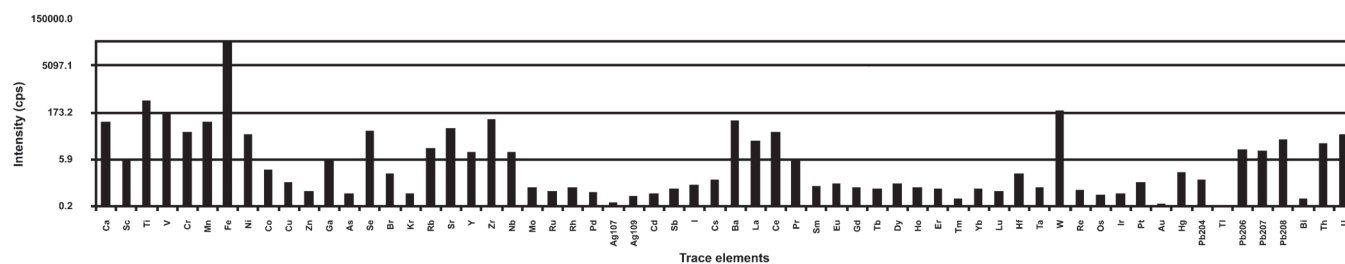


Figure 18: Trace element fingerprint of tin droplets in smelting slag SK3 from Smelters Kop, determined by laser ablation inductively coupled plasma mass spectrometry.

Nevertheless, the production of arsenical copper may have been accidental (Wagner and Gordon 1929). The arsenical malachite samples collected at the Blaauwbank Donga site are a bit light in colour, but otherwise indistinguishable by eye from ordinary malachite. The olivenite is a yellowish green and only the coarser crystals distinguish it visually from malachite. The actual source for this material is unknown, but it probably originated from the weathering of an arsenical copper sulphide body. Occurrences of copper and arsenical pyrite have been reported from Rooiberg (Recknagel 1908; Baumann 1919a; Wagner and Gordon 1929) and they must be the geological source of the hydrated arsenical copper ores. Recknagel (1908) described 'old workings' on a weathered copper sulphide deposit on the farm Vellefontein, close to the S.E. beacon of Hartebeestfontein, both immediately west of Blaauwbank (Fig 2).

It is still not entirely clear what processes were conducted at Blaauwbank, but the available evidence shows that at least two different copper ores were being smelted in the 'hearth' furnaces, one arsenic-rich (BBD1 and BBD2), the other not (BBD3). The well-described and photographed crucible furnace remains (Wagner and Gordon 1929, plate VI) may have been used for refining copper, refining tin, or alloying copper and tin to make bronze. This is an obvious subject for future investigation.

Tin sourcing

Rooiberg clearly is one source for southern African archaeological tin, in the form of ingots and bronze alloys, but there are other possible geological sources, some less likely candidates than others. These include various other tin-bearing localities of the Bushveld Complex (eg Zaaiplaats) and in Swaziland (Fig 1; Du Toit and Pringle 1998), Cornucopia in Zimbabwe (Prendergast 1979), and possible imports from Nigeria or India. So far, identifying the source(s) of southern African tin has been approached by trace element analysis of tin ingots and Rooiberg ores (Grant 1995; 1999). The quantitative determination of trace elements in tin is difficult, not least because of compositional inhomogeneity, and various complementary analytical techniques were employed

to arrive at credible results (Grant 1995). Without comparative chemical signatures from all possible sources it is impossible to determine the significance of differences between individual trace element signatures, but on the basis of available geochemical data Grant (1999) argued that the uniformly low tantalum/scandium ratios for all the analysed tin ingots pointed to Rooiberg as the source. Exploratory attempts to determine tin ingot trace element composition by solution ICP-MS at Harvard University were compromised by the difficulty of ensuring that all the chemical components were in solution (Miller, unpublished data). Anglo American Research Laboratories (AARL) fingerprinted several tin ingots by laser ablation ICP-MS (Smith *et al* 1997). The results showed a superficial similarity between the rod and bar ingots from Malaboeh (near Potgietersrust; Fig 1) and the bun ingots from Rooiberg (Table 9). The Musina *lerale* ingot had a distinct trace element profile, but the significance of this is unknown at present. The AARL LA-ICP-MS results also clearly demonstrated the partitioning of some elements between the tin matrix and the hardhead inclusions, also recorded by Grant (1995). In particular, iron appears consistently in the hardhead and lead in the tin. The ten trace element fingerprints for tin droplets in slag SK3, determined by LA-ICP-MS at the University of Cape Town, were almost identical to each other. The averaged results, plotted in Figure 18, represent the best trace element signature across the periodic table we have at present for Rooiberg tin.

There is poor correspondence between the presence of particular trace elements in Table 9 and Figure 18, and on the basis of this data it is not possible to confirm or exclude Rooiberg as the source of the other tin ingots. This is partly due to differing detection limits with the different analytical techniques, and underlines a fundamental flaw in this approach. Apart from this difficulty, given the mineralogical complexity of the Rooiberg tin fields, no single set of trace elements should be expected to work simplistically as a reliable signature of Rooiberg tin. Even when comparable data is available from other potential sources, more subtle inferences will be needed to distinguish significant trace element groupings whose

presence or absence is meaningful geochemically. If this is not successful, then the expensive and arduous process of fully quantitative trace element determination in conjunction with lead isotope analysis may be the only solution to the tin sourcing problem.

Bronze sourcing

The issue of bronze sourcing is even more complicated than sourcing tin, because of the additional copper content. Bronze has now been reported from a substantial number of Late Iron Age sites in southern Africa, including Rooiberg and Rooikrans, Great Zimbabwe (Stanley 1929b; Miller 2002), Mapungubwe (Miller 2001), Thulamela (Miller 2002), sites in the Marico district (Miller, Boeyens and Küsel 1995), Marothodi (Hall *et al* 2006), and Bosutswe (Miller 2002) (Fig 1). Even if all the tin originated at Rooiberg, which is unproven, it is unlikely that all the alloyed copper also originated there. Elemental analysis alone is unlikely to identify the sources of tin or copper in southern African bronzes. For instance, nickel cannot be used as a discriminator because it is present in potential copper ores from both Rooiberg and Marothodi (Wagner 1924; Schweltnus 1935; Hall *et al* 2006), as well as the Phoenix, Selkirk, and Selibi-Phikwe ore bodies in eastern Botswana (Johnson 1986; Molyneux and Reinecke 1983; Miller 1996). Lead isotope analysis coupled with geochemically significant trace element ratios, as employed by Grant (1999) to try to identify the source of tin ingots, may be a more successful approach.

Unresolved questions

A hundred years of research at Rooiberg has only scratched the surface. In 1919 Baumann deplored the fact that 'the value of Smelters Kop as a record of the past was not recognised and that no attempt was made to properly investigate the smelting site'. Amazingly, until very recently this was still true. The tin smelting process employed is still largely unknown, and basic chronological and technological questions remain unanswered. When did tin exploitation start? What is the full chronological sequence represented by the Smelterskop smelting debris? What is the make up of the Smelterskop debris? Is it all smelting debris or was secondary working of tin undertaken there? What ores were smelted? What were the characteristics of the furnaces? Was slag recycled? Are the domestic remains on Smelterskop associated with the tin production or are the two stratigraphically separate? What are the chronological and metallurgical relationships between the smelting sites at Smelterskop and the Blaauwbank Donga? What is the chronology and metal-

lurgical make up of the Blaauwbank Donga debris? Is it all smelting or was secondary production undertaken there as well? Is there any persuasive evidence for alloying tin and copper at Rooiberg, or was all the tin exported from the area to be alloyed elsewhere? What is the spatial relationship between mines, smelting sites, habitation and burial sites? Can all the extant tin ingots be sourced reliably to Rooiberg? What is the precise chronology of tin smelting activities outside the immediate Rooiberg basin and where did the casting of tin ingots take place? These questions are the subject of ongoing investigations being led by David Killick and Simon Hall.

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