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Kimberlite indicator minerals of the Gibeon Kimberlite Province (GKP), southern Namibia: Their character and distribution in kimberlite intrusions and fluvial sediments

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The GKP of southern Namibia comprises about 75 pipes of Cretaceous age, which were emplaced off-craton. This study deals with the character and distribution of macrocrystic kimberlite indicator minerals (KIM), and how distribution was modified during transport under semi-arid conditions. Samples were taken from kimberlite intrusions (pipes/dykes) and downstream from traps within small and large rivers. Ilmenite, garnet and Cr-diopside grains occur (within the intrusions) mostly as angular fragments and more rarely as complete crystals, whereas, chromite displays resorbed corners. Ilmenite generally amounts to more than 50 % of the relative abundance of the indicator minerals, but varies from less than 1% to as much as 87%. Garnet varies from generally less than 45% up to 95%, Cr-diopside from generally less than 2% up to of 30%, while chromite-content is normally less than 1%. In addition, there is a difference between the relative abundances of KIM in the 0.5-1 mm and 1-2 mm fractions of the pipes. The finer size fraction is marked by a higher abundance of chromite, Cr-diopside and purplish pyrope garnet and the coarser fraction by ilmenite. The distance downstream from the source at which alteration products (e.g. keliphytic rims and pitting texture) and/or primary textural features (e.g. orange-peel surface) were removed or abraded from KIM grains varies at each locality. This appears to be correlated to the lithology of the country rock and to the fluvial energy of the drainage network system. Cr-diopside and orange garnet generally disappear within 3 km downstream, while ilmenite and pyrope garnet have been traced for more than 12 km. In areas where the country rock comprises quartzite and Dwyka tillites, the KIM dispersion halo is more tightly constrained around the source than in shale-dominated areas, where dispersion is wider. Milling of KIM by coarse clasts during high-energy transport, as well as the better development of trap sites in quartzites and tillites relative to shale, is a probable explanation for this circumstance.

Introduction

Kimberlitic magmas sample mantle rocks (e.g. peridotite, lherzolite, wehrlite) during ascent. These mantle rocks break up during transport and release their constituent minerals such as garnet, Cr-diopside, chromite and ilmenite. Erosion of kimberlite pipes eventually re-leases these mantle-derived minerals into secondary geomorphological cycles, e.g. soils and fluvial sediments. Mantle-derived minerals are also commonly called kimberlitic indicator minerals (KIM), because they 'indicate' the presence of a kimberlitic intrusion nearby. Diamond exploration, which aims to discover kimberlite pipes, initiates sampling programmes to recover such KIM.

The change of physical properties and distribution of kimberlite indicator minerals during transport were previously studied in glaciated terrains (Averill *et al.*, 1994), under humid climates (Afanas'ev *et al.*, 1984) and under arid conditions (Atkinson, 1984). Very minor changes (wear, rounding) were observed in KIM in till (Canada) and in fluvial sediments (Siberia). Averill *et al.* (1994) suggest that the latter was due to the rapid transport of the minerals. On the other hand in Australia, wear and degradation of KIM in soil creep and sheet wash already occurs after short transport distances.

Muggeridge (1995) suggests five trap site classes to be considered during stream sampling for KIM. These trap site classes are 'good', 'moderate to good', 'moderate', 'poor to moderate' and 'poor'. For example, a good site consists of tightly packed, poorly sorted material with boulders, whereas a poor site consists of matrix-supported (sand or silt), very loosely packed, fine gravel and no associated obstructions (Fig. 2a-d). This classification was considered in the present study and led to the collection of stream samples mainly from trap sites where a maximum accumulation of heavy minerals was anticipated. Also, harder country rock like quartzite and boudery till appears to form better trap sites than softer shale and mudstone.

The most important KIM are garnet, ilmenite, Cr-diopside and chromite. These minerals acquire distinct surface features prior to and during emplacement of the kimberlite magma. Their unique physical properties include: (a) kelyphitic alteration rims and kelyphite-lined fractures on garnet, (b) leucoxene and perovskite alteration rims on picroilmenite, (c) subalteration matte and orange-peel resorption surfaces on garnet and picro-ilmenite, (d) stepped crystalline garnet overgrowths on garnet and polygonal recrystallization within picro-ilmenite, (e) rounded, resorbed corners and edges on chromite octahedra, and (g) adhering kimberlite matrix on all minerals (Averill *et al.*, 1994).

The present study investigates the distribution and character of KIM in the Gibeon Kimberlite Province of southern Namibia and their change during transport. The study area has been marked by semi-arid conditions for the past 16 million years (Pickford and Senut, 1999). The average annual rainfall of 125 mm often precipitates during only a few thunder showers, causing the nor-mally dry rivers and streams to change into high-energy torrents, which can transport considerable sediment loads. The drainage system is well developed and marked by medium to small ephemeral rivers and their tributaries (Fig. 1), which flow into the N-S running Fish River. The fluvial sediments comprise eroded undifferentiated surficial deposits of the Kalahari Group, unconsolidated Quaternary sand and mud and erosional products from Karoo and Nama sediments. Due to the semi-arid climate, the vegetation in the Gibeon area is

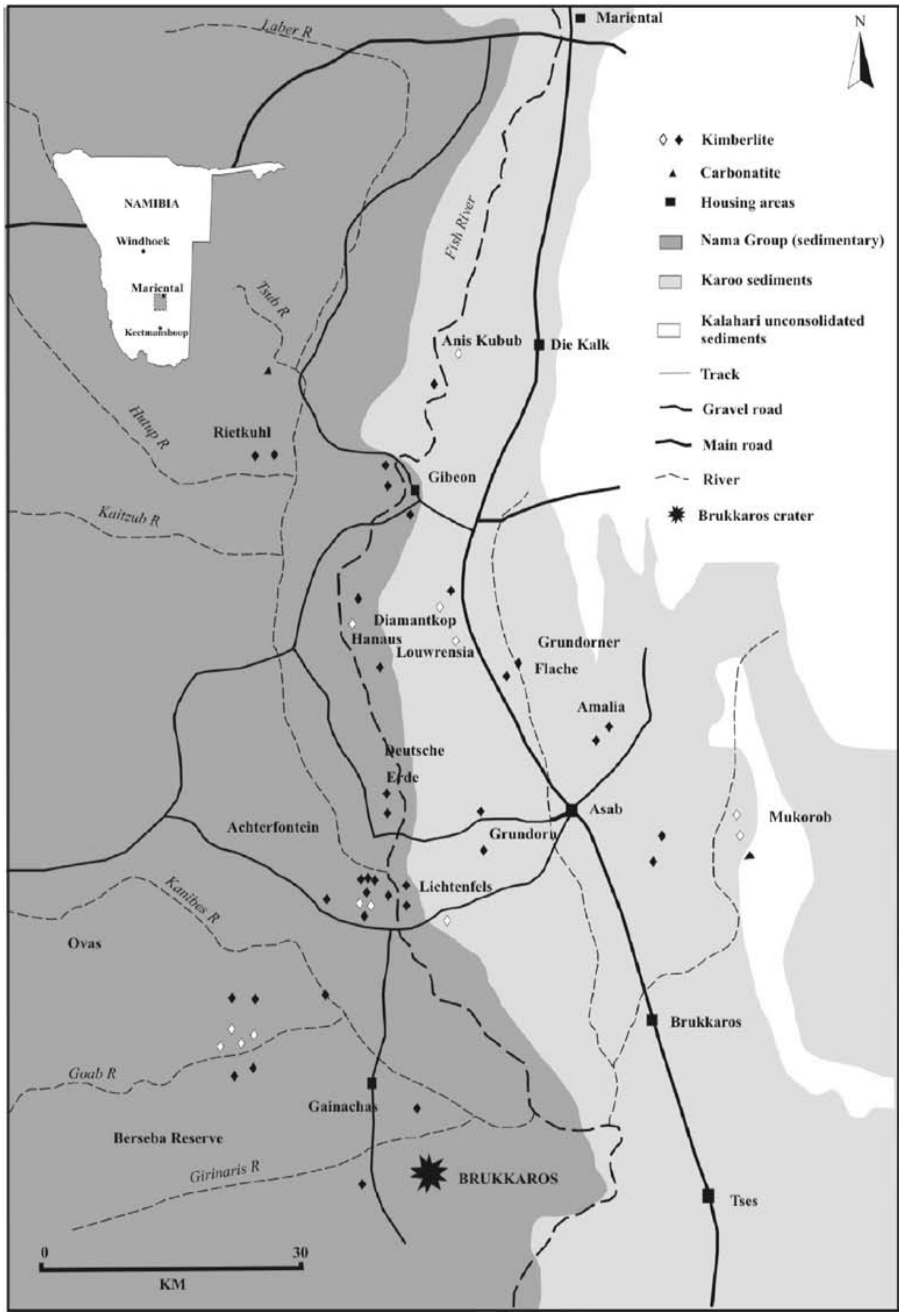


Figure 1: Gibeon kimberlite Province (modified after Janse, 1975) and location of the study area. Sampled kimberlite pipes are shown by open diamond symbols.

sparse, and generally the bedrock is only overlain by a thin cover of regolith. While there has been extensive exploration for diamonds in the area, so far no systematic study has been carried out on the variation of the geochemistry and distribution of KIM within the pipes and during secondary dispersal.

Regional geology

More than senety-five kimberlite pipes and dykes of Cretaceous age comprise the Gibeon Kimberlite Province (GKP), which is located between 25° and 26° latitude and 17°30’ and 18°30’ longitude in southern Namibia (Fig. 1). The kimberlites, which are 60-70 Ma in age, intrude shales and sandstones of the Neoproterozoic to Palaeozoic Nama Group, and tillites and mudstones of the Carboniferous Dwyka Formation (Janse, 1975; Spriggs, 1988). The Gibeon kimberlites occur as single or multiple intrusions varying in size and shape. Generally 50 to 150 m in diameter, oval or circular kimberlite

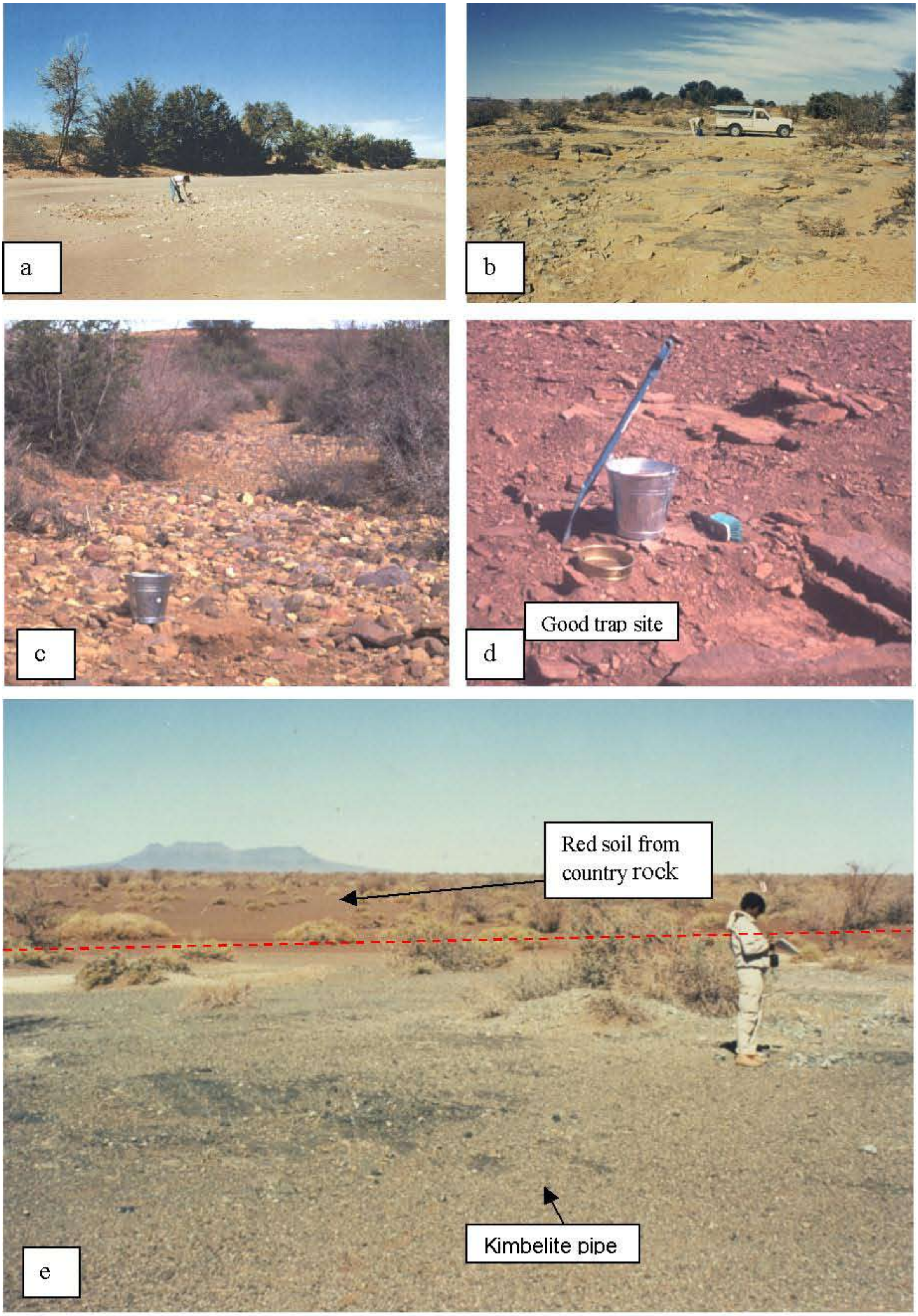


Figure 2: shows (a) the AKM-96-17 sampling site in the middle of the Kanibes river; (b) a small stream consisting of break-away slabs of the shale forming the riverbed (AKM-96-07 sampling site); (b) AKM-96-44 sampling site in a small river consisting of small boulders, rounded pebbles and cobbles; (d) a small river consisting of the shale rock that form a good trap site, AKM-96-22 ; (e) a light-coloured area in the foreground which is a weathered kimberlite pipe (sample AKM-96-26) and Mt. Brukkaros in the background.

Table 1: Sample processing weights for the studied localities in the Gibeon Kimberlite Province and the number of kimberlitic indicator mineral counts. (Ilm = Ilmenite, Garn = garnet, Cr-dio = Cr-diopside, Chr = chromite, FNC = fraction (1/2 or 1/4) of the non-magnetic concentrate, Preconc = Pre-concentrate, Conc. = concentrate, Magn. = magnetic)

Locality	Sample ID	Sample site	Distance down-stream [km]	Weight [g]					Weight [g]				FNC split	Number of grains picked						
														1.0-2.0 mm				0.5-1.0 mm		
				Total Pre-conc.	Light Frac.	Total conc.	Magn conc.	Non-Magn conc.	<0.25 mm	0.25-0.5 mm	0.5-1.0 mm	1.0-2.0 mm		Ilm	Garn	Cr-dio	Chr	Ilm	Garn	Cr-dio
Anis Kubub 96	Akm-96-43	Pipe	0	144.5	99.4	45.1	1.71	43.4	2.1	5	9.7	9.4	1\2	10	420	21	1	130	750	148
	Akm-96-44	Small stream	1.2	148.5	121.7	26.8	0.93	25.9	0.8	3.7	6	3.1		5	34	4	3	47	51	8
	Akm-96-45	Small stream	2.8	154.1	123.8	30.3	0.94	29.4	1.8	4.6	5.7	3.7	1\2	5	7	0	2	23	12	2
	Akm-96-46	Small stream	15	167.6	123.4	44.2	2.12	42.1	3.44	6.61	7.21	4.13	1\2	3	0	0	0	12	0	0
Berseba Reserve	Akm-96-01	Pipe	0	312.8	215.8	97	19.19	77.8	0.73	2.68	7.5	11.23	1\4	643	303	22	0	~2500	~1200	47
	Akm-96-02	Pipe	0	264.6	188.6	76	10.1	65.9	0.65	3.24	6.75	5.55	1\4	511	310	15	0	~3100	~1300	13
	Akm-96-03	Pipe	0	148.8	107.3	41.5	17.58	23.9			12.08	12.86	1\2	291	71	10	1	533	210	21
	Akm-96-012	Pipe	0	313.5	210.4	103.1	29.7	73.4	6.94	15.15	27.75	24.43		445	1203	433	53	~3100	~1700	~2700
	Akm-96-04	Small stream	0.5	132.5	120.7	11.8	1.39	10.41	2.04	2.08	2.78	3.45		321	53	3	0	820	128	32
	Akm-96-05	River	0.5	150.6	137.4	13.2	0.65	12.5	3.4	1.1	3.6	4		145	191	33	0	470	206	63
	Akm-96-06	River	1.5	290.4	282.3	8.1	0.42	7.49	6.62	0.57	0.33	0.11		2	5	1	0	14	12	4
	Akm-96-07	Small stream	1	155.6	104.4	51.2	5.43	45.77	1.36	6.65	22.43	15.23		1500	458	15	3	~3500	~800	104
	Akm-96-08	Small stream	1.7	149.9	100.7	49.2	4.7	44.5	2.04	11.38	21.51	9.98		203	487	43	0	~4100	~2500	123
	Akm-96-09	Small stream	1.5	153.3	106.1	47.2	6.55	40.6	0.8	2.3	8.1	10.9	1\2	718	111	12	0	~1200	317	6
	Akm-96-23	River	1.5	298.2	282.2	16	0.31	15.7	12.3	1.3	1	1		8	6	0	1	44	30	0
	Akm-96-24	River	3	161.1	132.5	28.6	0.67	27.93	1.34	0.54	3.66	8.07	1\2	856	289	5	11	1619	284	7
	Akm-96-10	Small stream	3	153.3	113.2	40.1	3.59	36.51	3.63	4.66	14.65	13.45		793	213	3	0	~3850	525	16
	Akm-96-25	River	4	157.1	133.5	23.6	6.66	22.94	4.91	1.25	5.4	11.27		537	207	10	2	1123	307	19
	Akm-96-11	Small stream	4.3	132.1	119.7	12.4	1.18	11.2	1.7	1.8	4.2	3.4		73	224	0	13	452	385	20
	Akm-96-13	River	5.3	290.5	274.9	15.6	0.52	15.1	9.6	1.3	1.8	2.3		61	83	0	1			
	Akm-96-14	River	8.5	303.3	274.1	29.2	0.84	28.4	2.6	0.7	3.3	7.9	1\2	411	83	4	5	1120	87	6
	Akm-96-15	River	12	300.1	278.1	22	0.82	21.2	13.7	1.5	3.3	2.5		233	138	3	0	1353	289	27
	Akm-96-16	River	13.5	296.5	275.7	20.8	0.73	20.1	14.3	1.81	2.5	1.3		116	89	2	2	748	89	13
	Akm-96-17	River	21.7	147.5	136.5	11	0.71	10.29	5.19	0.85	2.42	1.67		98	54	2	3	447	111	5
	Akm-96-18	River	32	293.8	280.3	13.5	0.45	13	11.4	0.6	0.6	0.4		14	13	0	0	44	30	0
Diamant kop	Akm-96-30	Pipe	0	360.5	214.6	145.9	5.01	140.8	3.39	5.83	12.24	13.29	1\4	1236	1020	33	2	~2300	~2000	145
	Akm-96-31	Small stream	0.6	307	256.8	50.2	1.44	48.76	4.54	6.65	9.76	4.15	1\2	40	640	119	0	100	~1500	423
	Akm-96-37	Small stream	3	167.5	130.8	36.7	0.37	36.3	0.7	4.5	8.6	5.1		92	173	3	2	632	211	7
Hanaus 43,44	Akm-96-47	Pipe	0	326	205.6	120.4	5.4	115	1.39	4.5	11.69	11.42	1\4	1058	137	14		~4000	578	78
	Akm-96-48	Stream	0.5	167.6	104.7	62.9	1.96	60.94	0.84	2.59	7.23	4.79	1\4	423	23	1	0	~1500	273	30
	Akm-96-49	Stream	2.8	155.9	103.9	52	1.37	50.6	1.8	6.4	12.1	5.9	1\2	313	253	11	1	~800	211	61
	Akm-96-50	Stream	5.8	145.2	116.2	29	1.18	28.8	7.7	8.7	7.1	4.2		7	11	3	1	278	311	98
Lichtenfels 10 E	Akm-96-19	Pipe	0	312	192.8	119.2	24.3	95.9	2.1	5	9.7	9.4	1\4	1151	435	8	2	~1500	839	34
	Akm-96-20	Small stream	0.8	156	110.4	45.6	4.17	41.43	0.69	1.27	3.61	4.38	1\4	307	36		8	657	157	1
	Akm-96-21	Small stream	1.3	144	114.8	29.2	2.58	26.6	3.2	4.8	8.7	9.8		438	143	3	0	1000	297	12
	Akm-96-22	Small stream	2.2	291.8	256.4	35.4	2.7	32.7	6.2	4.4	3.8	4	1\2	197	125	0	0	380	195	15
	Akm-96-40	Stream	4.8	179.3	76.6	73.99	2.61	74	1.53	4.02	6.2	6.73	1\4	343	15	0	0	1000	33	0
	Akm-96-41	Stream	5.6	155.5	45.1	43.39	1.71	43.4	5.9	6.5	6.2	5.9	1\2	105	36	3	0	300	21	3
Lichtenfels 10 W	Akm-96-26	Pipe	0	149.3	106.5	42.8	1.05	41.7	0.8	2.6	8.8	9	1\2	526	813	48	6	~2500	720	57
	Akm-96-27	Pipe	0	153.7	103.1	50.6	0.66	22.94	4.91	1.25	5.4	11.27		318	395	5	5	848	1123	45
	Akm-96-29	Small stream	0.5	164.3	96.3	68	1.19	66.81	1.82	3.85	6.68	4.28		337	251	5	4	~1300	89	43
	Akm-96-28	Small stream	1.8	167.6	111.9	55.7	1.4	54.31	1.26	2.14	5.57	4.65		83	211	10	4	500	350	43
	Akm-96-38	Small stream	4.5	180.8	94.9	85.9	0.46	85.44	2.2	6.07	6.83	5.19	1\4	52	153	2	0	~700	320	10
	Akm-96-39	Small stream	5	168.6	118	50.6	1.72	48.9	5.81	6.26	6.97	5,o2	1\2	11	3	1	0	45	25	3
Mukorob 14	Akm-96-32	Pipe	0	201.9	89.3	112.6	19.11	93.49	2.16	6.42	14.42	22.46	1\2	415	184	88	0	640	275	257
	Akm-96-33	Pipe	0	180.3	69.8	110.5	2.16	108.3	2	4.5	9.3	11.5	1\4	1085	153	68	0	~3000	207	187
	Akm-96-34	Stream	0.9	188	105	83	6.34	76.7	0.42	3.02	9.6	6.03	1\4	361	7	3	1	~3500	47	32
	Akm-96-35	Stream	4.3	173.1	112	61.1	0.49	60.6	1.72	4.58	12.25	10.72	1\2	102	85	3	1	140	97	10
	Akm-96-36	Stream	6.7	182.4	109.9	72.5	0.82	71.7	1.77	4.67	10.24	9.53	1\2	120	51	0	0	~2000	14	4
Louwrensia	Akm-96-42	Pipe	0	133.4	128	5.4	0.41	34.99	1.32	2.52	6.68	6.36	1\2	54	676	201	0	447	~3000	657

pipes can be distinguished clearly from the unfolded, flat-lying Nama sediments; the pipes are generally weathered into yellowish, greenish or bluish saprolite, which contrasts with the red and/or red-brown colours of the surrounding country rock (Fig. 2e). Macrocryst indicator minerals, megacrysts and xenoliths often accumulate at the surface of the pipes.

Methods

Fifty soil samples were collected in the GKP from thirteen kimberlite pipes, as well as from thirty-seven trap sites within streams and rivers on farms Anis Kubub 96, Berseba Reserve (Ovas), Diamantkop 516, Hanaus 43, Mukorob 14, Lichtenfels 10, Louwrensia and Achterfontein 60 (Fig. 1). In the following the farm name (without farm number) is used to refer to the collection site. On the farm Lichtenfels, W and E are used to distinguish between kimberlite pipes west and east of the Fish River.

The bulk samples were collected from the weathered surface of kimberlite intrusions and drainage sediments. The latter were mainly taken from trap sites in riverbeds, where maximum accumulation of heavy minerals occurs. These sites are composed of clast-supported, tightly packed and poorly sorted gravels in rivers with sandy beds. At sampling sites with exposed bedrock, the sample was taken from natural 'riffles', formed by bedrock cracks, fissures or crevices, by using a small shovel and brush (Fig. 2a-d). The stream samples were screened to <4.6 mm fraction at the sampling site and placed into plastic drums; each sample weighed about 50 kg.

The half-split samples (ca. 25 kg each), were dry-screened to obtain a <2 mm fraction (Fig. 3) in the Diamond Research Laboratory of the Geological Survey of

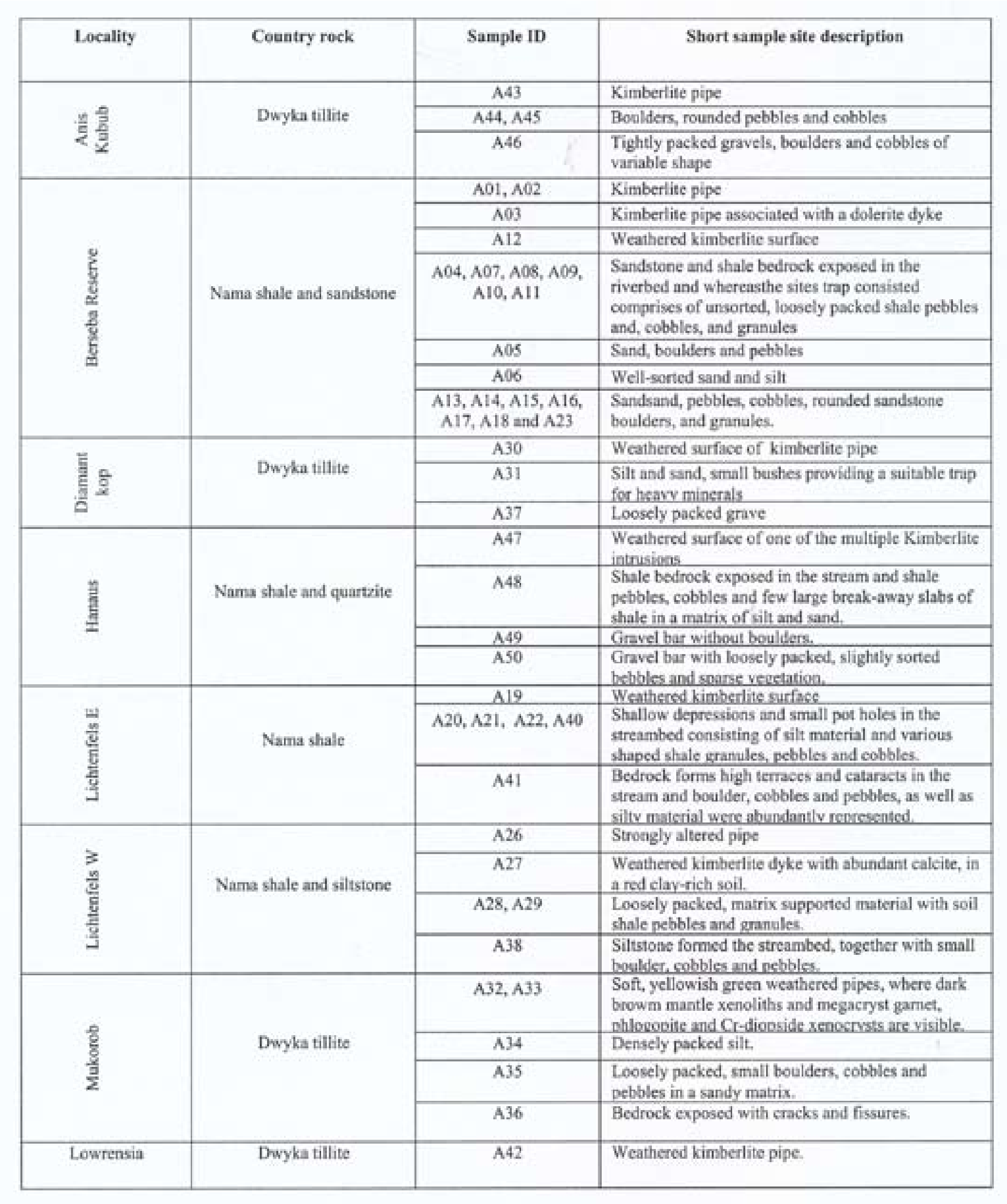
Finland (GSF). The samples were pre-concentrated with a Knelson concentrator and further processed, using methylene iodide with a specific gravity of 3.2 to produce a heavy mineral concentrate. Ferromagnetic heavy minerals were removed by using a low-intensity magnetic separator. The remaining concentrate was sieved into four fractions (<0.25 mm, 0.25-0.5 mm, 0.5-1 mm, and 1-2 mm and weighed (Fig. 3). A binocular microscope was used to examine the non-ferromagnetic heavy mineral concentrates. KIM were identified on the basis of their colour (purple, red, reddish-brown and orange gar-nets, black ilmenite, emerald-green Cr-diopside and black chromite) and other physical features unique to mantle-derived xenocrysts. The KIM were hand-picked from the 0.5-1.0 and 1-2 mm fractions. From samples with more than 20 grams of heavy mineral concentrate, only one fourth or half of the concentrate was picked.

A Frantz Isodynamic Separator was used to separate most of the ilmenite as well as some garnet and Cr-diopside from the concentrate in the 0.5-1 mm fraction, where the KIM were most abundant (Table 1). A representative number of each KIM was analysed with an electron microprobe (Cameca Camebax SX50, Standardisation: 25 kV, 48 nA and beam diameter of 5 micron) at the GSF (Nguno, 1998).

Results

The description of the sampling sites appears in Table 2, whereas the initial weights of the pre-concentrated and concentrated samples and the distribution of KIM are given in Table 1. The properties of the KIM from the 0.5-1.0 and 1.0-2.0 mm fractions are described together, unless differences between the two fractions

Table 2: Key features of the investigated sample sites and their respective sample IDs



Locality	Country rock	Sample ID	Short sample site description
Anis Kubub	Dwyka tillite	A43	Kimberlite pipe
		A44, A45	Boulders, rounded pebbles and cobbles
		A46	Tightly packed gravels, boulders and cobbles of variable shape
Berseba Reserve	Nama shale and sandstone	A01, A02	Kimberlite pipe
		A03	Kimberlite pipe associated with a dolerite dyke
		A12	Weathered kimberlite surface
		A04, A07, A08, A09, A10, A11	Sandstone and shale bedrock exposed in the riverbed and whereasthe sites trap consisted comprises of unsorted, loosely packed shale pebbles and, cobbles, and granules
		A05	Sand, boulders and pebbles
		A06	Well-sorted sand and silt
		A13, A14, A15, A16, A17, A18 and A23	Sandsand, pebbles, cobbles, rounded sandstone boulders, and granules.
Diamant kop	Dwyka tillite	A30	Weathered surface of kimberlite pipe
		A31	Silt and sand, small bushes providing a suitable trap for heavy minerals
		A37	Loosely packed grave
Hanaus	Nama shale and quartzite	A47	Weathered surface of one of the multiple Kimberlite intrusions
		A48	Shale bedrock exposed in the stream and shale pebbles, cobbles and few large break-away slabs of shale in a matrix of silt and sand.
		A49	Gravel bar without boulders.
		A50	Gravel bar with loosely packed, slightly sorted bebbles and sparse vegetation.
Lichtenfels E	Nama shale	A19	Weathered kimberlite surface
		A20, A21, A22, A40	Shallow depressions and small pot holes in the streambed consisting of silt material and various shaped shale granules, pebbles and cobbles.
		A41	Bedrock forms high terraces and cataracts in the stream and boulder, cobbles and pebbles, as well as silty material were abundantly represented.
Lichtenfels W	Nama shale and siltstone	A26	Strongly altered pipe
		A27	Weathered kimberlite dyke with abundant calcite, in a red clay-rich soil.
		A28, A29	Loosely packed, matrix supported material with soil shale pebbles and granules.
		A38	Siltstone formed the streambed, together with small boulder, cobbles and pebbles.
Mukorob	Dwyka tillite	A32, A33	Soft, yellowish green weathered pipes, where dark browm mantle xenoliths and megacryst garnet, phlogopite and Cr-diopside xenocrysts are visible.
		A34	Densely packed silt.
		A35	Loosely packed, small boulders, cobbles and pebbles in a sandy matrix.
		A36	Bedrock exposed with cracks and fissures.
Lowrensia	Dwyka tillite	A42	Weathered kimberlite pipe.

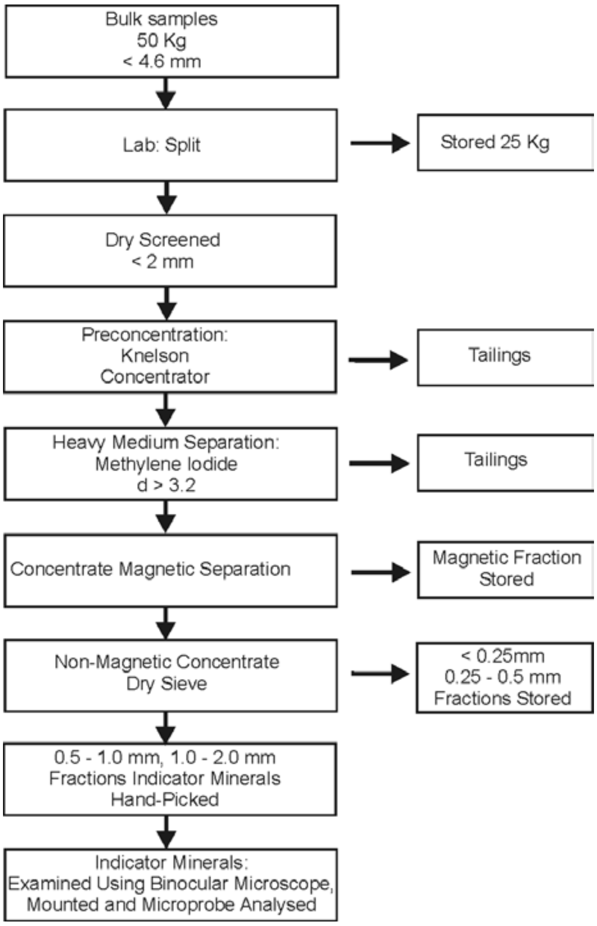


Figure 3: Sampling processing flow sheet for the recovery of kimberlite indicator minerals from the stream sediments and weathered kimberlite intrusions.

were observed.

Physical features of the KIM

Kimberlite pipes

Most KIM are broken and only a few complete preserved crystals were found. Garnets (Fig. 4a) often have a kelyphitic layer and ilmenites (Fig. 4f) a preserved leucoxene coating. Intergrowths of ilmenite, garnet and Cr-diopside are observed locally. Conchoidally fractured garnets predominate (Fig. 4c), whereas orange-peel textured garnet surfaces are less common; internally fractured garnets (Fig. 4b) were rarely recovered. The colour varies from predominantly deep red (Berseba area) to less abundant purple and orange (Hanaus and Diamantkop areas). However, occasionally the purple and orange garnet varieties occur in similar proportions (Mukorob area). In the Berseba Reserve cluster, samples AKM-96-01 and AKM-96-02 are just one kilometre apart from sample AKM-96-03 which features mainly purple pyrope (and no reddish-brown) garnet, whereas the former contain mainly red pyrope garnet. Sample AKM-96-012 (from Berseba Reserve) shows a larger variation of garnet grains, ranging from orange, red, deep red, purple to deep purple garnets. Cr-diopside (Fig. 4k) mostly is of pale green colour, although deep emerald green colours were also observed; the latter lo-cally shows leucoxene coating and/or orange peel surfaces. Isomorphic octahedral chromite occurs mostly in the 0.5-1 mm fraction (Table1) and sometimes displays leucoxene coating. Ilmenite (Fig. 4 e, f and g) occurs mainly as conchoidally fractured grains, which are marked by a fresh black metallic lustre and pitted surfaces (Fig. 4e), while dark-grey ilmenite without a pitted surface was found only in a few pipes.

The relative proportions of KIM vary considerably within the studied pipes. Garnet ranges from > 90% (Anis Kubub, Fig. 5a). to about 50% (Diamantkop, Fig. 5b), ilmenite from > 60% (Berseba Reserve, Mukorob, Lichtenfels E,) to < 14% (Anis Kubub, Fig. 5a) and Cr-diopside from 34-13% (Berseba Reserve, Louwrensia, Anis Kubub, Mukorob) to generally less than 2%, concentrated in the finer fraction. Chromite is rare, with maximum concentrations of 1-4% in the samples from Lichtenfels E (AKM-96-019) and Berseba Reserve (AKM-96-03, AKM-96-012).

Trap sites in rivers

Samples taken from rocky river beds tend to have higher total pre-concentrate weights, as well as higher concentrate weights in the finer fraction (0.5-1.0 mm), than samples from sandy river beds (Tables 1, 2). In ad-dition, the coarse (1.0-2.0 mm) and fine-grained fractions differ considerably in composition, degree of rounding and preservation of primary structures. The coarse-grained fraction is generally marked by well-polished grains with an oxidized or a weathered surface, which obscures the typical properties of ilmenite of mantle origin. A general decrease in the proportion of Cr-diopside and purple and orange garnet is evident with increasing distance from the pipe. Hence, purple, bluish-purple and red pyrope garnet and ilmenite are the major constituents at a distance greater than 2.5 km.

In contrast, KIM of the fine-grained fraction are only slightly polished or unpolished, with preserved leucoxene coatings and kelyphitic layers. The proportion of Cr-diopside and purple garnet may increase in proximal trap sites, before it decreases in distal trap sites.

Influence of the country rock

The study area is drained by a network of fairly mature ephemeral rivers (e.g. Fish River, Goab, Kanibes) and their braided, more immature tributaries. Bedrock lithology within the riverbeds varies from coarse-clastic Dwyka tillites to sandstones and shales of the Nama Group. Accordingly, the fluvial sediments range widely in character, comprising boulders, cobbles, pebbles and granules within a sand or silt matrix (Fig. 2, Table 2). The survival of the KIM appears to depend largely on the grain size of the co-transported sediments.

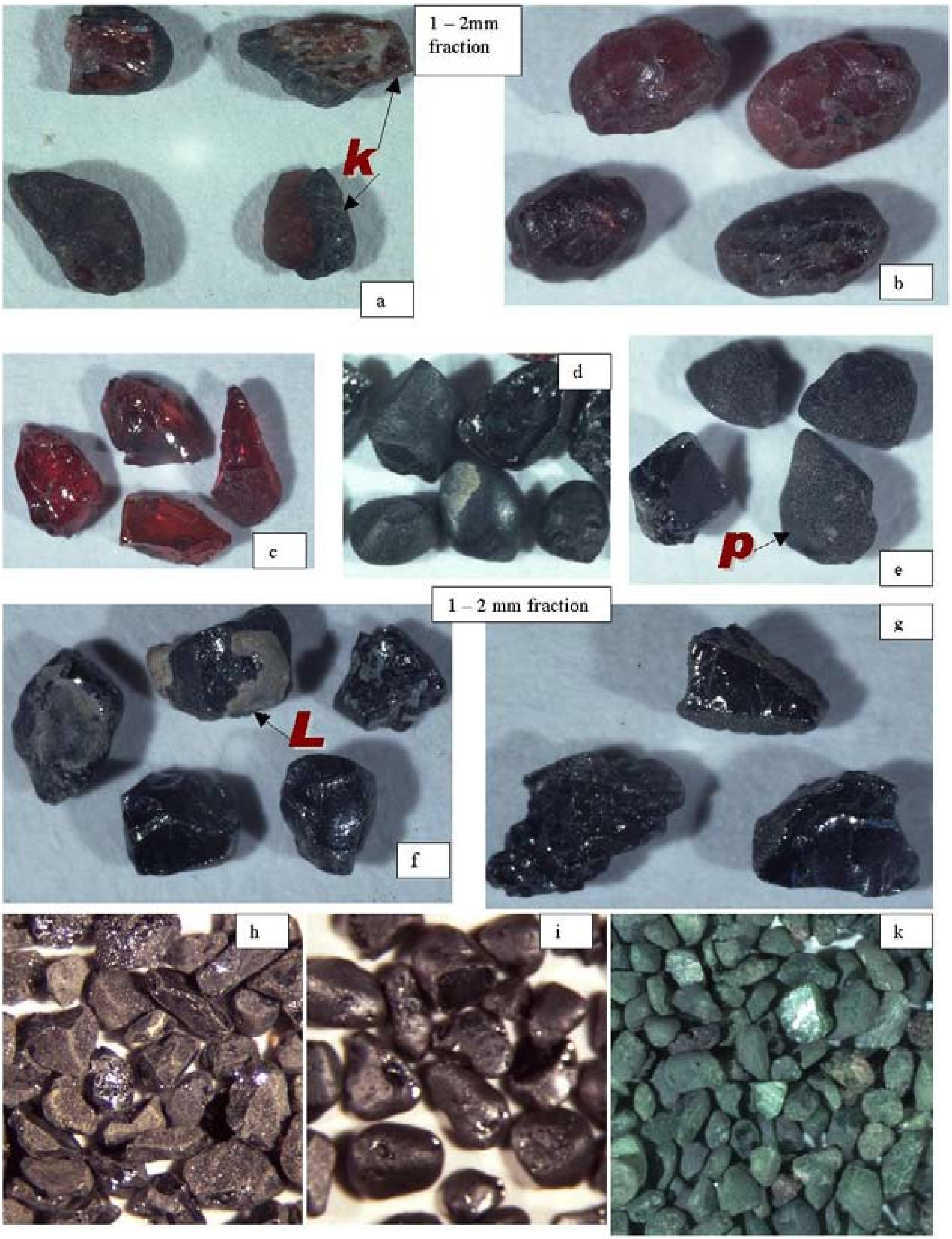


Figure 4: Physical properties of kimberlitic indicator minerals (1-2 mm fraction): (a) garnet grains with kelyphitic (K) layers (rims); (b) red and purple internally fractured complete garnets grains; (c) conchoidally fractured deep red garnets; (d) Chromite grains; (e) three complete ilmenit crystals with pitted (P) texture and one partially broken crystal; (f) resorbed ilmenite grains and the three grains (above) with leucoxene (L) alteration; (g) polycrystalline grain and two grains showing a typical ilmenite black metallic lustre; (h) slightly weathered ilmenite grains from a site close to the pipe; (i) weathered ilmenite grains from a site far from the pipe; (j) deep emerald green Cr-diopside grains.

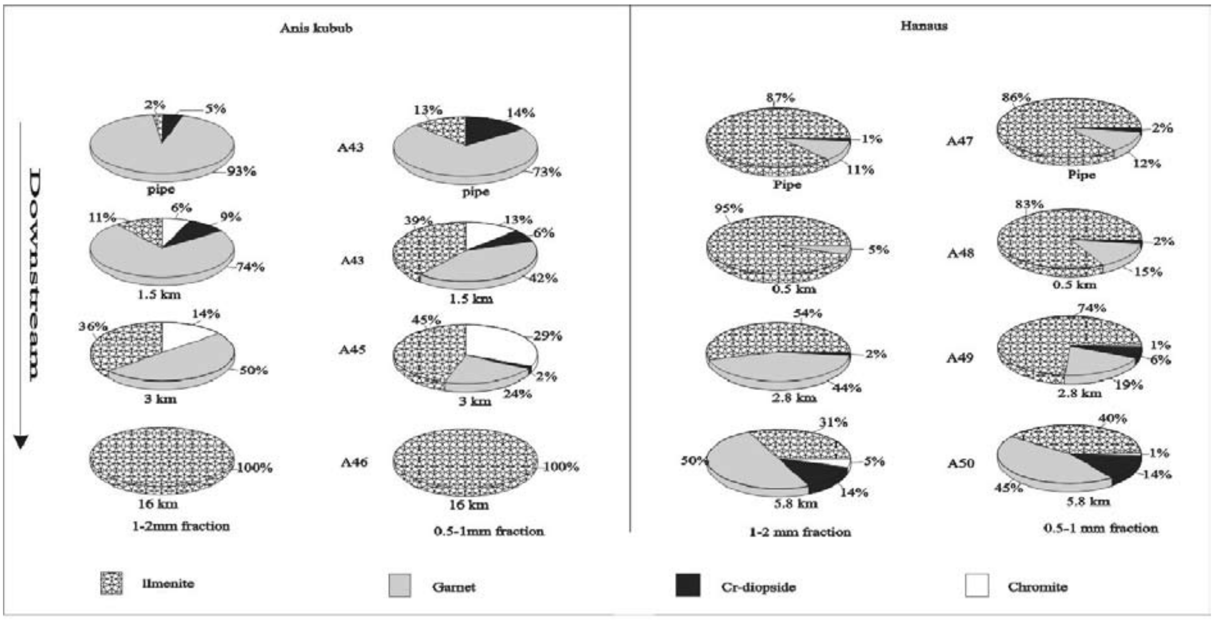


Figure 5a. shows the distribution of macrocrystic indicator minerals in the Anis Kubub and Hanaus kimberlite pipe and stream (small stream and ephemeral river) sediments at varying distances from the pipe.

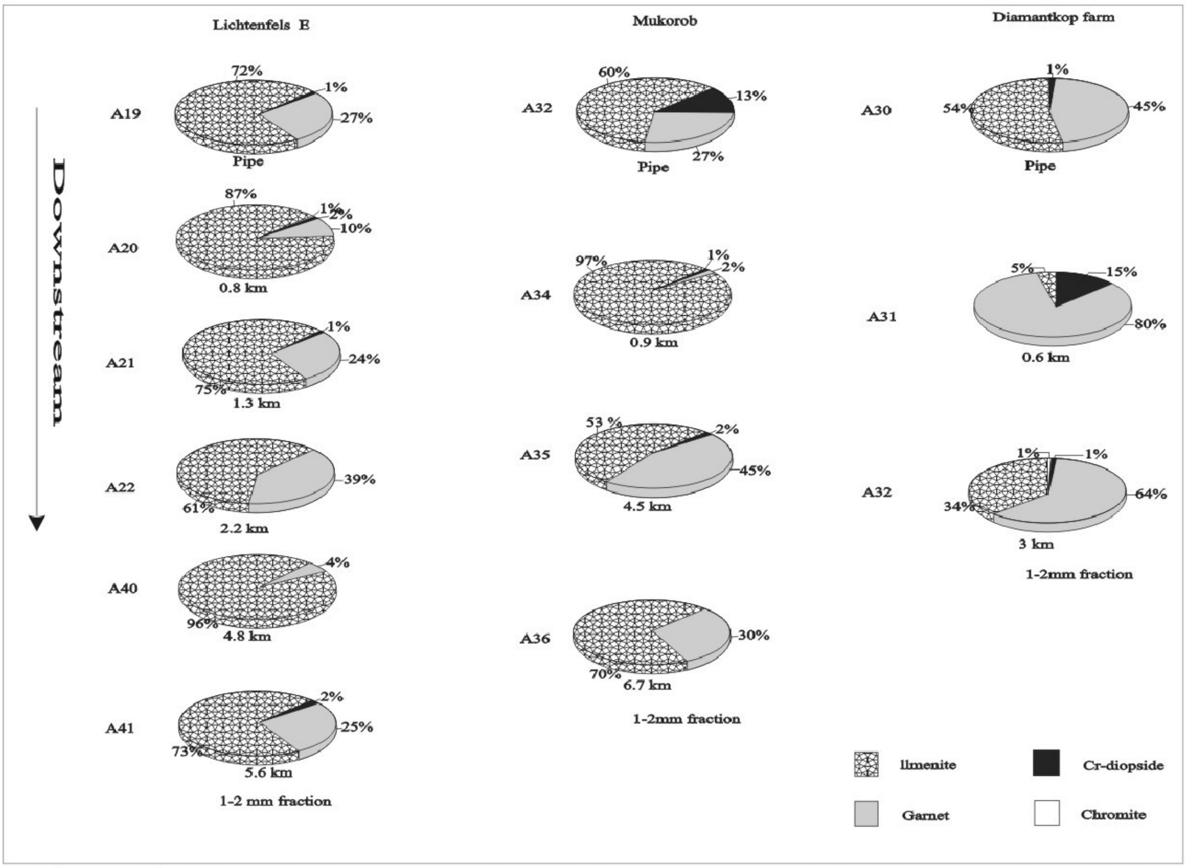


Figure 5b: The relative proportion of the macrocrystic indicator minerals from the three kimberlites that were samples localities (Lichtenfels E, Mukorob, and Diamantkop) sampled kimberlite pipes and stream sediments. and their abundances in stream sediments at varying distances from the pipes.

The KIM in the Lichtenfels E area have been collected from trap sites in a small stream crosscutting shale of the Nama Group, where fluvial sediments comprise dominantly silt. Indicator minerals with alteration products were recovered as far as 2.2 km downstream from the pipe. In contrast, in the Beserba Reserve area the country rocks consists mainly of sandstone, so that fluvial sediments are dominated by sand and gravel (Fig. 2a). Here, KIM with alteration products were only recovered from trap sites less than 1.5 km downstream from the pipe.

Discussion

1. The physical properties and distribution of KIM in the Gibeon Kimberlite Province and their change during transport are a function of various parameters. A high variation of the proportions of ilmenite, garnet, Cr-diopside and spinel occurs already in the kimberlite pipes themselves, with no apparent spatial correlation or systematic trends between individual pipes or pipe clusters. This extreme variation suggests random sampling of KIM during ascent of the kimberlite magma; therefore the majority of KIM are considered to be xenocrysts derived from disaggregated mantle xenoliths entrained by the kimberlite. Most of the grains are broken, although textures indicating mantle origin are still preserved (i.e. pitted surface, orange peel texture). In contrast to former models of violent ascent of kimberlitic magma, Kurtzlaukis *et al.* (1998) demonstrated that hot magma rises rather quietly from the mantle and only reacts violently, when it comes into contact with groundwater, i.e. by phreatomagmatism. Hence, fragmentation of the KIM in the Gibeon pipes occurs either during the phreatomagmatic stage or during ascent and depressurization of the kimberlitic magma.

2. Subsequent transport from the pipes results in rounding of the KIM and their destruction. In the semi-arid climate of southern Namibia only a few major floods during the rainy season are characterised by high transport energies, increased sediment loads and lack of sorting of the sediments. Therefore, if the country rock contains cobbles and/or pebbles (e.g. the Dwyka tillite), milling of the KIM occurs and they are destroyed close to their source. In contrast, fine-grained sediments (e.g. shales of the Nama Group) have little milling effect on the KIM. Accordingly, KIM are found at greater distances from the source here than in the case of pipes em-placed into tillite. Unfortunately, however, the input of KIM from pipes downstream often offset this trend, and no systematic study has been carried out to demonstrate this influence.

3. Mechanical abrasion affects the coarser (1-2 mm) fraction of the KIM more severely than the finer (0.5-1 mm). Larger grains are commonly well-polished and subrounded or rounded after only a few kilometres transport, while sharp edges and other primary features, such as pitted surfaces and orange-peel textures, are preserved up to 3 km downstream on smaller grains. This is due to a different mode of transport for KIM of different grain size: smaller grains are transported in suspension with little or no friction between the particles, whereas coarser grains roll along the bottom of the stream and are abraded by milling. Experimental studies on kimberlite xenocrysts yielded similar results (McCandless, 1990). Decreasing transport energy in the waning stage of major flood events results in a separation of fine and coarse particles.

4. The individual resistance of the KIM to erosion plays a major role in the composition of the heavy mineral concentrate. This study shows that there is a rapid increase in ilmenite and a decrease of first Cr-diopside and later garnet in trap sites downstream from the kimberlite pipe. This is in contrast to the behaviour of Cr-diopside in till, where it increases proportionally with transport from the source (Averill *et al.*, 1994). Again, these minerals are concentrated preferentially in the fine-grained KIM fraction, and the general trend is often offset by new influx from other pipes. In contrast to ilmenite and garnet, Cr-diopside is marked by a good mineral cleavage, which renders it more susceptible to weathering. Also, in garnet the mineral chemistry seems to be of some importance, i.e. red and purple pyrope sur-vives greater transport distances than orange or brown-reddish garnets. Furthermore, bluish-purple pyrope garnet tends to become more abundant further downstream.

5. The geometry of the trap site seems to be of importance for the accumulation of KIM; in one locality (AKM-96-06) close to a pipe only insignificant amounts of heavy minerals were recovered, whereas traps further downstream yielded much more concentrate (AKM-96-024, AKM-96-025). Muggeridge (1986, 1995) and White (1995) both stressed the importance of the sampling site selection.

In conclusion, the distance to the source, the composition of the country rock, the geometry of the trap as well as grain size, influence the composition and absolute amount of KIM found in trap sites. Generally the relative amount of ilmenite increases with distance from the source, whereas Cr-diopside decreases first, followed by garnet. In addition, because of different transport mechanisms, KIM are better preserved in the smaller fraction of the heavy mineral concentrate.

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