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KIMBERLITES FROM CENTRAL ANGOLA: A CASE STUDY OF EXPLORATION FINDINGS

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INTRODUCTION

The 3000 km^2 Dando-Kwanza concession (joint venture between De Beers, Endiama, Gedebe and Sombo Mining) is situated within the Central Zone of the Angolan Shield, in the incised highlands of Bié Province (Fig. 1a). An aerial reconnaissance survey conducted in 2005 drew attention to established artisinal alluvial diamond diggings, in the vicinity of 6 kimberlite occurrences discovered during colonial times. Exploration commenced in 2007 and the subsequent 3 year work programme led to the discovery of 38 new kimberlite occurrences. Some of these are exposed at surface, whereas others are buried beneath a veneer of Cenozoic sediments including duricrusts and colluvial and terrace deposits. This study details the exploration process, and the geological setting and characteristics of the kimberlites.

EXPLORATION

The topography of the area is incised with an elevation that varies from 1800 m in the SW to 1100 m in the NE (Kwanza River valley, Fig. 1b). The Lubia River flows for a distance of ~35 km through the area and active artisinal mining activities persist along its entire length and across a significant width of the river valley. The Lubia is a small river, with a moderate gradient and diamonds are likely introduced to the river and its tributaries by means of erosion of local kimberlites.

Reconnaissance geological studies, stream sampling and airborne geophysical surveys formed the basis of the exploration program. Stream samples provided early information on the probable presence of different kimberlite sources: (a) a northern source (Lubia-Lucuta catchments, Fig. 1b) characterized by Ilm > Gar > Spi > Cpx and presence of moderate-high interest G9 and G10 garnet populations and associated artisinal mining; and (b) a southern source (Nduluma-Cambei-Mbambi catchments, characterized by Spi > Ilm > Gar > Cpx and predominance of low interest G9 and G1 garnets.

The background geology is characterized by a quiet magnetic response over Paleozoic sediments and a noisy response over exposed basement lithologies, with high amplitude curvilinear anisotropies and changes in magnetic relief and texture. Targets were selected from a follow-up airborne magnetic (AM) survey flown in 2007 (100m line spacing, 30m flight height) and a SPECTREM airborne electro-magnetic survey flown in 2008 (150m line spacing, 100m flight height). Targets were followed up by site surveying and ground geophysics (magnetics, gravity and EM), 2D size assessment, and core drilling. Most of the discoveries were made in 2008 and 2009. Samples were collected from the kimberlites for petrography, recovery and analysis of indicator minerals and geochronology. Selected kimberlites were sampled using a large diameter drill rig and treated for micro-diamond analysis.

The majority of the kimberlites (27 of 44) are Grade 1 or 2 magnetic anomalies, many of which show coincident gravity response. Twelve of the kimberlites are EM anomalies, 5 of which lack a magnetic response. Thirty-eight of the kimberlites are located within a 15km radius in the northern part of the area (Lubia cluster, Fig. 1b), and all are magnetic anomalies. Six of the kimberlites are located in the southern part of the area (Nduluma cluster) and are EM anomalies, without magnetic responses.

SHRIMP II U–Pb zircon analyses were conducted at the Research School of Earth Sciences, Australian National University on 13 samples from key stratigraphic units to assess the extent of Archaean basement and to provide age constraints on the nature and timing of magmatic, tectonic and sedimentation events. Isotopic analyses on mantle zircons from 14 kimberlites of the Lubia cluster were conducted using a LA-ICP-MS at the De Beers analytical laboratory facilities in Johannesburg. Kelyphite fragments from garnet megacrysts from two additional kimberlites were analyzed using $^{40}Ar/^{39}Ar$ laser probe step-heating analysis at University of Melbourne.

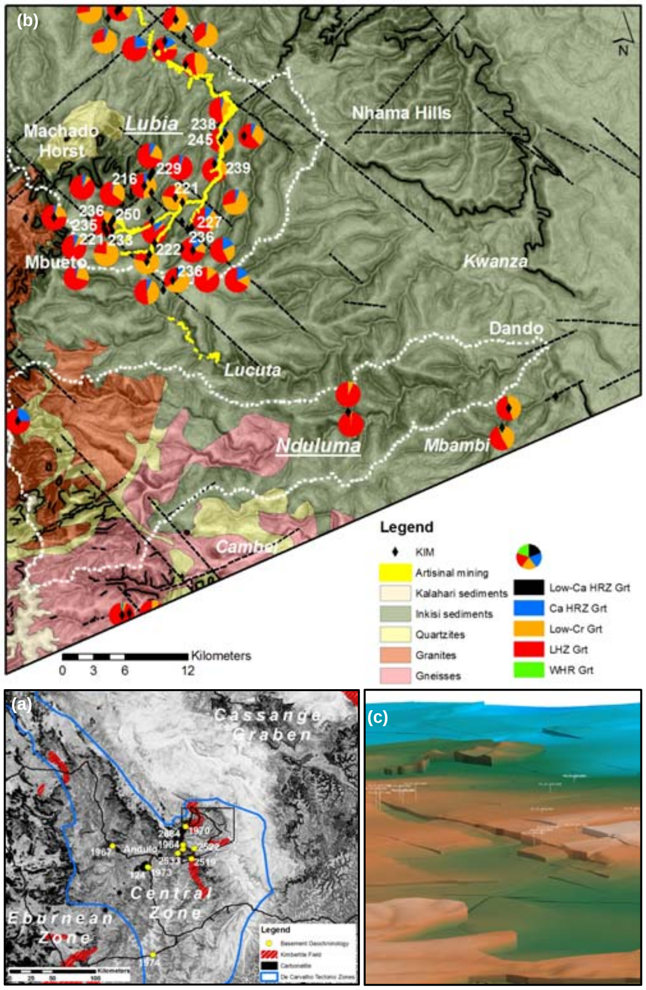

Figure 1: (a) Location of the concession area against slope-filtered SRTM, with tectonic zones, distribution of kimberlite fields and carbonatites and geochronology results for basement samples. (b) Geology and structure of the area, with Lubia and Nduluma drainage catchments, kimberlite garnet classification (GEMOC) and age constraints for mantle zircons and garnet kelyphite rims. (c) 3D model of the host geology of the Lubia cluster, showing the pre-Inkisi basement surface, faults sets and kimberlites.

REGIONAL GEOLOGY

Basement Geology

The Central Zone of the Angolan Shield is bound to the west by the Eburnean Zone. Both tectonic zones comprise remnant Archaean gneisses, granites, and greenstones. Palaeoproterozoic intrusive granitoids and coeval (sub)-volcanic and volcano-sedimentary varieties are dominant basement constituents west of Andulo town and have been related to subduction-accretion processes along an active Eburnean continental margin. Exposed basement in the area comprises biotite gneisses and granites, with zircon crystallization ages between 2682 and 2519 Ma. Proterozoic granitoids intrude the gneisses and show a narrow emplacement time span between 1974 and 1963 Ma, with inheritance between 2873 and 2515 Ma indicating reworking of Archaean basement. Crosscutting gneisses and intrusive varieties yield ages that are within error, constraining the age of Eburnean deformation at ~1967 Ma.

Paleozoic (Pre-Emplacement) Sediments

The basement is unconformably overlain to the northeast by flat-lying, cyclic red bed sediments of the Inkisi Subgroup (West Congolian Supergroup), which host the majority of the kimberlites (Fig. 1b). The rocks are competent, jointed and close to contacts with kimberlites commonly indurated with presence of vugs, veins and alteration spots. Two arkose samples show discrete detrital zircon populations, the youngest of which (with growth zoning) of ~540 Ma provides a maximum constraint on the age of deposition. The Inkisi sediments are overlain to the E of the area by Karoo-age Carboniferous-Triassic sediments of the NW trending Cassange Graben (Fig. 1a).

Cenozoic (Post-Emplacement) Sediments

The western highlands show remnant silcretized sandstones, which are overlain by a veneer of Kalahari sands. Ferricrete deposits are common throughout the concession area and formed during Miocene-Pleistocene planation events. The laterites are 1-7 m thick and are well developed on the plateau west of the Lubia catchment. They have been reworked in laterite gravels and pebble/cobble palaeo-conglomerate lags. The latter are up to 1 m thick and show rounded pebbles of vein quartz and quartzite in a silty sand matrix - the top of the unit is commonly ferruginised. These gravels may have caused redistribution of indicator minerals and diamonds. Recent sediments include alluvium and colluvial deposits. Two mineralized alluvial deposit types occur: (1) Lenticular, overlapping, ~30cm thick immature gravels consisting mostly of angular, pebble-sized locally-derived sandstone clasts. These immature gravels are suspended within sandy alluvium and were deposited in a mobile, slow-flowing meandering fluvial environment. (2) Within the modern day stream, coarse boulder gravels up to 2m thick consist of locally sourced angular sandstone bedrock material as well as rounded quartzite and quartz pebbles. These gravels are a younger deposit, resulting from incision during recent uplift. The lateral extent of these gravels reaches a maximum width of ~10m.

STRUCTURE

Brittle structural elements were mapped from AM, ground gravity mega-blocks, EM, SRTM and Landsat TM imagery. Faults are characterized by magnetic contrasts and magnetic disruptions as well as by scarps and displaced landforms. The faults have vertically displaced and in places tilted the Inkisi sediments and underlying basement surface.

Prominent faults include NE-trending bounding faults of the Machado horst (Fig. 1b and c) - the western fault is a pronounced topographic linear with a marked fault scarp, and can be traced from Andulo town northeastward over a distance of over 100 km. The horst itself is about 8 km wide and 25 km long. A NW-trending fault occurs within the southwestern part of the area, near the headwaters of the Nduluma and Cambei rivers and shows a fault scarp step of ~100 m. A NW-trending fault controls the lower reaches of the Lubia River and stretches of the Kwanza River and hosts a number of kimberlite occurrences. To the north, the Nhama hills represent a tilted and uplifted block bound by NE- and NW-trending faults, with a preserved Tertiary planation surface, slightly tilted to the northeast. (d) A NW-trending fault passes through the Mbueto kimberlite sub-cluster and dissects the horst structure to the northwest.

The kimberlites occur in spatial association with the NE-trending Quilenges-Andulo Fracture Zone that is manifested in the area by the Machado horst and associated faults (Fig. 1b). Mesozoic alkaline complexes, including carbonatites and kimberlites, occur along its 400 km length, and in the concession area kimberlites are preferentially found at the intersections of orthogonal NE and NW trending faults (Fig. 1c). The 6 Mbueto kimberlites within the headwaters of the Lubia River form part of a large crater system at the intersection of two orthogonal faults. NW-trending faults may be linked to the development of the Cassange Graben.

KIMBERLITES

The kimberlites occur as pipes, some with multiple lobes, and are between 0.25 and 16.7 ha in size. The average size estimate is 4.2 ha, based on magnetics, gravity and drilling. The kimberlites include resedimented volcaniclastic (RVK), pyroclastic (PK) and coherent magmatic (MK) varieties.

Kimberlite Facies Types

RVK-A kimberlites (Fig. 2a-c) are reddish brown, diluted, matrix- to clast-supported, lithic-bearing and bedded kimberlites that show, on average, very low juvenile components. Bedding angles are sub-horizontal to steeply inclined, and primary sedimentary structures are common. Samples typically contain abundant quartz grains, as well as country-rock xenoliths, with juvenile compound clasts and olivine macrocrysts, set in a fine-grained matrix of mud, silt or sand. Some beds display soft-sediment deformation structures and distorted and folded layering can be observed. Interbedded are thin beds that show dense packing of juvenile components with good clast-size sorting (Fig. 2a). Most quartz grains are angular in shape (broken) and show moderate to good sorting. The magnetic susceptibility is low between 0.1 and 1.3 x 10^{-3} S.I. units and pipes dominated by RVK facies types generally show good gravity responses.

Interbedded or intermingled are coarse-grained, juvenile-rich RVK-B sequences that are massive in appearance, with inclined cryptic layering, poor sorting, macrocryst or clast alignment, and broken compound clasts (lapilli and magmaclasts) observed. These features may be indicative of mass flow processes, or proximal primary pyroclastic flows.

RVK facies types are related to successive infill of a kimberlite crater through wall rock and tuff ring collapse. Periodicity of eruption is indicated by inter-stratification of different kimberlite types, sharp contacts between juvenile-rich and diluted kimberlite types, as well as presence of autolith clast material. Soft sediment deformation and intermingling of kimberlite types suggests deposition into partially water-laden, poorly consolidated sediments.

PK kimberlites (Fig. 2d-f) are fine- to coarse-grained, fragmental and juvenile-rich, volcaniclastic micaceous kimberlites. The rocks show variable sorting and grading and have a massive appearance on the scale of meters to decameters (in the case of pyroclastic flows and surges) or show well-developed horizontal bedding and clast size sorting and grading (pyroclastic falls). Olivine occurs as macrocrysts and phenocrysts, is commonly pseudomorphed by serpentine and often displays selvages. Crustal xenoliths include basement and Inkisi clasts, many of which show hydrothermally altered rims. Autoliths, cored and non-cored magmaclasts are present and garnet xenocrysts in places show kelyphitic rims. Pelletal ash grains, accretionary lapilli and bombs in pyroclastic fall deposits commonly comprise serpentinized olivine cores, mantled by a segregationary textured spherical selvage. The magnetic susceptibility of these kimberlites is high between 5.5 and 29.5 x 10^{-3} S.I. units.

MK-A kimberlites are poorly sorted and massive, coherent micaceous kimberlites that have been interpreted as hypabyssal feeders. The rocks show high mantle component abundance, with relatively low proportions of crustal xenoliths that invariably show selvages. Macrocrystic olivines are common and have been altered to serpentine. Mantle xenoliths include sheared and garnet-bearing peridotites. Contacts with other facies types are sharp. Of note is coarse crystalline carbonate growth around some of the xenoliths. The magnetic susceptibility of these kimberlites is high between 10.4 and 41.4 x 10^{-3} S.I. units.

MK-B kimberlites (Fig. 2g) are aphanitic coherent and extremely competent kimberlites that are free of macrocrysts. The rocks contain 1-5 cm-sized carbonate-filled patches (amygdales or resorbed crustal xenoliths?).

Olivine phenocrysts are fresh, fine-grained and abundant. The groundmass is uniformly textured and consists of calcite and apatite micro-phenocrysts and atoll spinel set in a serpentine mesostasis. MK-B was encountered during follow-up of a 6 ha magnetic target on a hill top at 1720 m elevation and has a vertical extent of at least 50 m. It has been interpreted as a volcanic plug or, preferably, a lava lake deposit and is at least 50m thick in outcrop. Based on whole-rock geochemistry, the MK-A and MK-B kimberlites have been classified as Group 1 kimberlites.

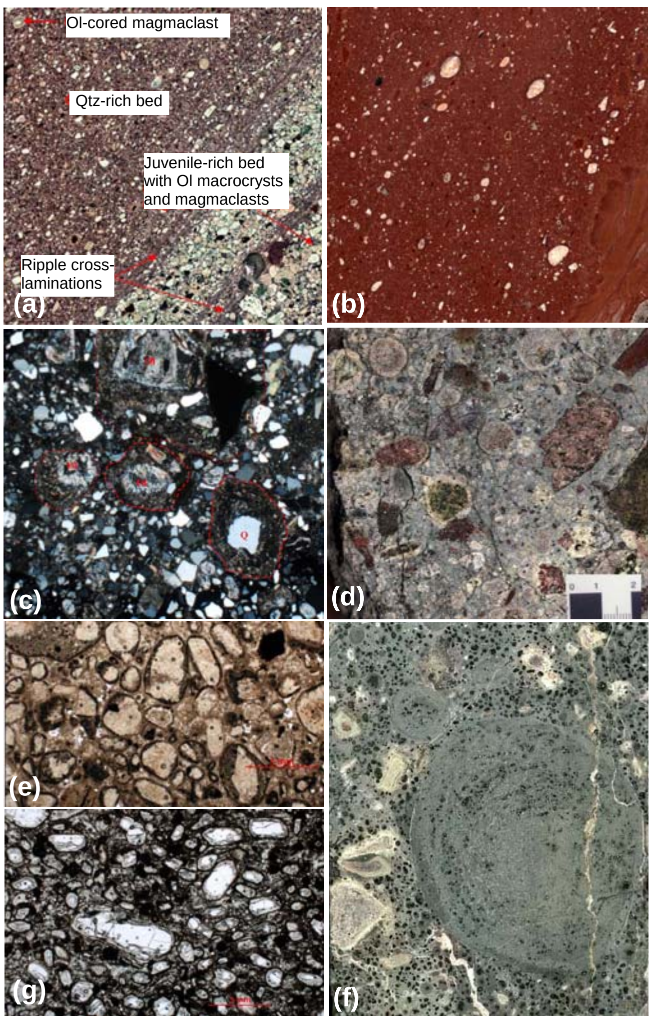

Figure 2: (a, b) Scanned polished slab images of RVK-A showing inclined bedding angle in (a) and paucity of juvenile components and fine-grained nature in (b). (c) Photomicrograph (XPL) showing cored magmaclasts. Note the shapes and abundance of quartz grains. (d, e) Scanned image and photomicrograph of PK. The rock is a massive, coarse-grained, poorly-sorted, clast-supported heterolithic lapilli tuff. Both cored and un-cored accretionary lapilli are common and are closely-packed. The olivine macrocrysts are rounded to elongate in shape and occur as both discrete crystals and as cores in accretionary lapilli. The olivine phenocrysts are euhedral in shape and occur as discrete crystals and within the lapilli. (f) Scanned image showing spherical accretionary lapilli and bombs and hydrothermally altered accessory lithics. The image is 10 cm across. (g) Photomicrograph of aphanitic coherent kimberlite (MK-B).

Facies Distribution

The Lubia kimberlites show a spatial correlation of facies distribution and pipe sizes with surface elevation. Kimberlites within the headwaters of the Lubia catchment (Mbueto) on the +1600 m laterite plateau are dominated by RVK types, with large surface areas (based on gravity responses, drilling) and represent the upper parts of crater systems that have seen limited erosion. In contrast, kimberlites encountered in the incised valley of the Lubia River at ~1300 m elevation have smaller surface areas (based on magnetics and gravity), and are dominated by PK and MK facies types. It is estimated that an additional ~250 m has been eroded from these pipes, with current erosion level showing lower crater and feeder systems, respectively.

Mineral Chemistry

The kimberlites within the Lubia cluster are dominated by lherzolitic (G9) and pyroxenitic (G5) garnets with these signatures similarly expressed in stream sampling results for the Lubia catchment (Fig. 3a). Many of the kimberlites show bimodality in terms of: (a) a high-Ti megacrystic lherzolitic (LHZ) population (G1), extending throughout the Cr range for LHZ garnets and indicative of high-T melt-related metasomatism, and (b) a low-Ti, and low- to high-Cr LHZ population trend. In a number of cases this extends to higher Ca concentrations at moderate Cr, suggesting the presence of a wehrlitic (G12) component. A clear splay in the low-Cr portion of the array indicates shallow depth of sampling of LHZ garnets, consistent with the chromite-clinopyroxene-garnet equilibrium (CCGE) trend of Kopylova *et al.* (2000). The proportion of depleted harzburgitic (HRZ) and eclogitic (ECL) diamond proxy compositions is generally low (< 3%) and some of the HRZ garnets are enriched in Ti, suggesting that pre-existing HRZ may have been perturbed by high-T melt-related processes. The spinel dataset (Fig. 3c) displays a characteristic mantle-derived xenocryst trend and a more diffuse phenocrysts trend. The xenocryst trend shows a low proportion of high-Cr (low-Ti) grains, which is significant in terms of diamond potential, but the prevalence of low-Cr spinel xenocrysts indicates entrainment of shallow mantle material, consistent with low-Cr LHZ garnets of the CCGE trend.

The kimberlites within the S part of the area are dominated by G5 garnets (stream sampling results for the Nduluma catchment shown in Fig. 3b). A low-Ti, low- to (at best) moderate-Cr LHZ garnet component with elevated Ca concentration indicates shallow depth of sampling. High-pressure, depleted HRZ garnets are almost completely absent and no high interest ECL diamond-inclusion garnets were recovered. The spinel dataset (Fig. 3d) shows a combination of low-Ti xenocrysts of upper mantle origin and kimberlite-derived phenocrysts at variable Cr-Ti contents. The xenocryst trend is well defined but terminates at lower Cr contents compared to the Lubia catchment and diamond-inclusion type compositions are absent, which is in agreement with the garnet data.

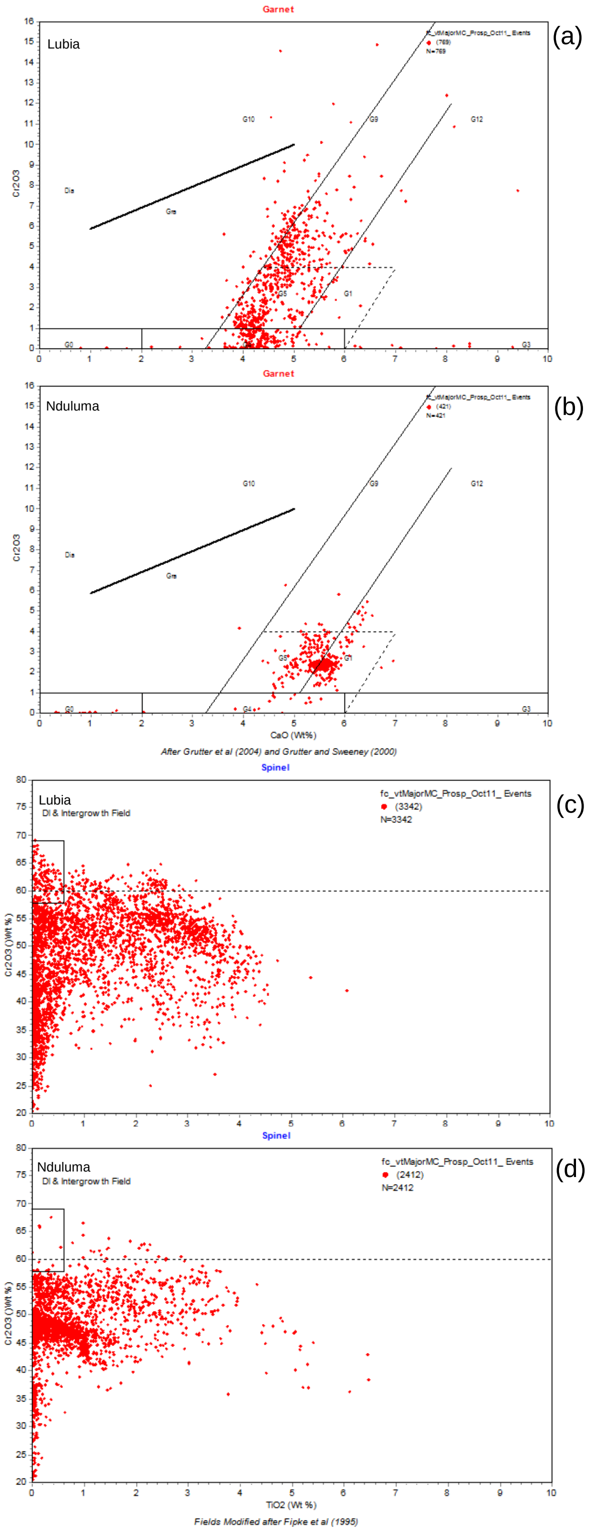

Figure 3. Major element garnet and spinel chemistry for the Lubia and Nduluma catchments (after Grutter et al., 2004 and Grutter and Sweeney, 2000 and Fipke et al., 1995).

Kimberlite Geochronology

The Lubia cluster kimberlites yielded LA-ICPMS U-Pb zircon ages between 252 and 216 Ma (N=14, median age of 235 Ma, 129 grains) as well as an $^{40}Ar/^{39}Ar$ kelyphite plateau age of 239 ± 0.7 Ma (Phillips et al., this volume). The results show a new intra-Karoo age kimberlite population in Angola, which is similar to that of Jwaneng Mine in Botswana. Crustal zircons recovered from 3 of the Lubia kimberlites yielded ~1.9 Ga crystallization ages, indicating Palaeoproterozoic basement beneath the cluster. No suitable minerals were recovered for geochronology from the 6 kimberlites of the southern cluster. The Chilesso carbonatite complex near Andulo town was dated at ~120 Ma, which is more typical of the age of alkaline magmatism in other parts of Angola. It is possible that the kimberlites of the southern cluster are of similar, Cretaceous age.

DISCUSSION

Many of the kimberlites within the Triassic Lubia cluster are diamondiferous, but MiDA sampling of 14 kimberlites returned low grades. Duricrust ferricretes occur as a cap on many of the kimberlites and erosion and redistribution of an enriched eluviated cap may explain the prevalence of alluvial diamonds immediately downstream of the kimberlites. The diamonds recovered from artisinal mining appear to be characterized by a combination of good quality clear stones and large brown stones. This duality in the population may be related to a thermal and perhaps mechanical imprint on the lithospheric mantle during Palaeoproterozoic times, as indicated by the low to moderate interest major element chemistry of garnets and other indicator minerals. This event may be related to Eburnean continental margin processes, which would have caused a disturbed and elevated geotherm, with evidence of thinning of the subcontinental lithospheric mantle.

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REFERENCES

Fipke, C.E., Gurney, J.J., Moore, R.O., 1995. Diamond exploration techniques emphasizing indicator mineral geochemistry and Canadian examples; Geological Survey of Canada Bulletin 423, 86p.

Grütter, H.S., Gurney, J.J., Menzies, A.H., Winter, F., 2004. An updated classification scheme for mantle-derived garnet, for use by diamond explorers, Lithos 77, 841-857.

Grütter, H.S., Sweeney, R.J., 2000. Tests and constraints on single-grain Cr-pyrope barometer models: some initial results (extended abstract); Geological Association of Canada-Mineralogical Association of Canada, Joint Annual Meeting 2000, Calgary, Alberta.

Kopylova, M.G., Russell, J.K., Stanley, C., Cookenboo, H., 2000. Garnet from Cr- and Ca-saturated mantle: implications for diamond exploration. Journal of Geochemical Exploration 68, 183–199.