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GEOLOGY OF THE K1 AND K2 KIMBERLITE PIPES AT MUROWA, ZIMBABWE

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INTRODUCTION

The Murowa kimberlite field includes three main kimberlite pipes and multiple kimberlite dykes that have been emplaced into the Archaen Chibi granite batholith north of the Limpopo Belt in south-central Zimbabwe. Here we describe the geology of the two largest kimberlite pipes: K1 and K2 (Figure 1). Observations of drill core, thin section petrography and mapping of exposed rocks at the Murowa Diamond Mine are used to describe the internal geology and these data form the basis for three-dimensional geological models of each body. The modeled pipe geometries are combined with observed cross-cutting relationships and textural variations among deposits to interpret the style and history of emplacement. Lastly, the observations are used to interpret the relative stage of volcanic development, or 'maturity', of the kimberlite pipes at Murowa.

METHODS

Geological data for K1 and K2 were collected through mapping of exposed rocks in the open pits at different stages of mine development, detailed logging of selected drillcores (43 for K1; 17 for K2), and petrographic analysis of representative thin sections (83 for K1; 46 for K2). These datasets were integrated and used to define distinct geology domains within each pipe. The morphology and spatial distribution of the geology domains were then modeled in Gemcom GEMS ® 3-D modeling software.

GEOLOGY OF K1

K1 is an irregular-shaped, elongate and multi-lobed kimberlite pipe which is 250 m long in a north-south direction, a maximum of 108 m wide in an east-west direction, and lies ~800 m to the north of K2 (Figure 1).

The K1 pipe infill is internally complex: five main kimberlite types (KIMB1 to KIMB5) have been identified to date and these have been modeled in three-dimensions as four geology domains (Figure 2A). Multiple kimberlite dykes cross-cut the K1 pipe and surrounding country rock, and a thick (5-120 m) "marginal" zone of granite breccias

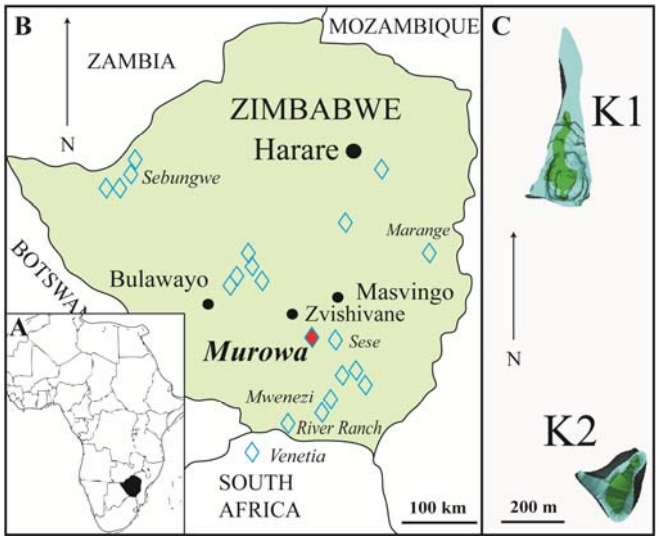

Figure 1: Maps showing the location of Murowa and the K1 and K2 pipes: (A-B) Murowa is located in south-central Zimbabwe, 60 km southeast of Zvishivane. Known diamond deposits in the region are indicated by blue diamonds. (C) Plan view map showing the geometries, sizes and relative positions of K1 and K2 (green) and the surrounding marginal pipe zones (MPZ, blue).

with minor amounts of kimberlite surrounds the pipe. The rock types comprising the K1 pipe infill and marginal pipe zone (MPZ) are described below and their modeled distribution is shown in Figure 2A.

K1 pipe infill

KIMB1

KIMB1 is a massive, friable to moderately competent, mottled brown and grey rock with sharp to diffuse contacts with adjacent rock types, and appears to be restricted to a narrow zone in the southern portion of the pipe. KIMB1 displays a distinctly coherent rock texture consisting of abundant, unbroken, coarse olivine (0.03 - 25 mm in size; 45 - 60 % of rock) and angular to rounded, bleach-white and grey country rock xenoliths (5 - 10 mm in size; 8 - 25 % of rock) uniformly distributed in a brown-grey-black

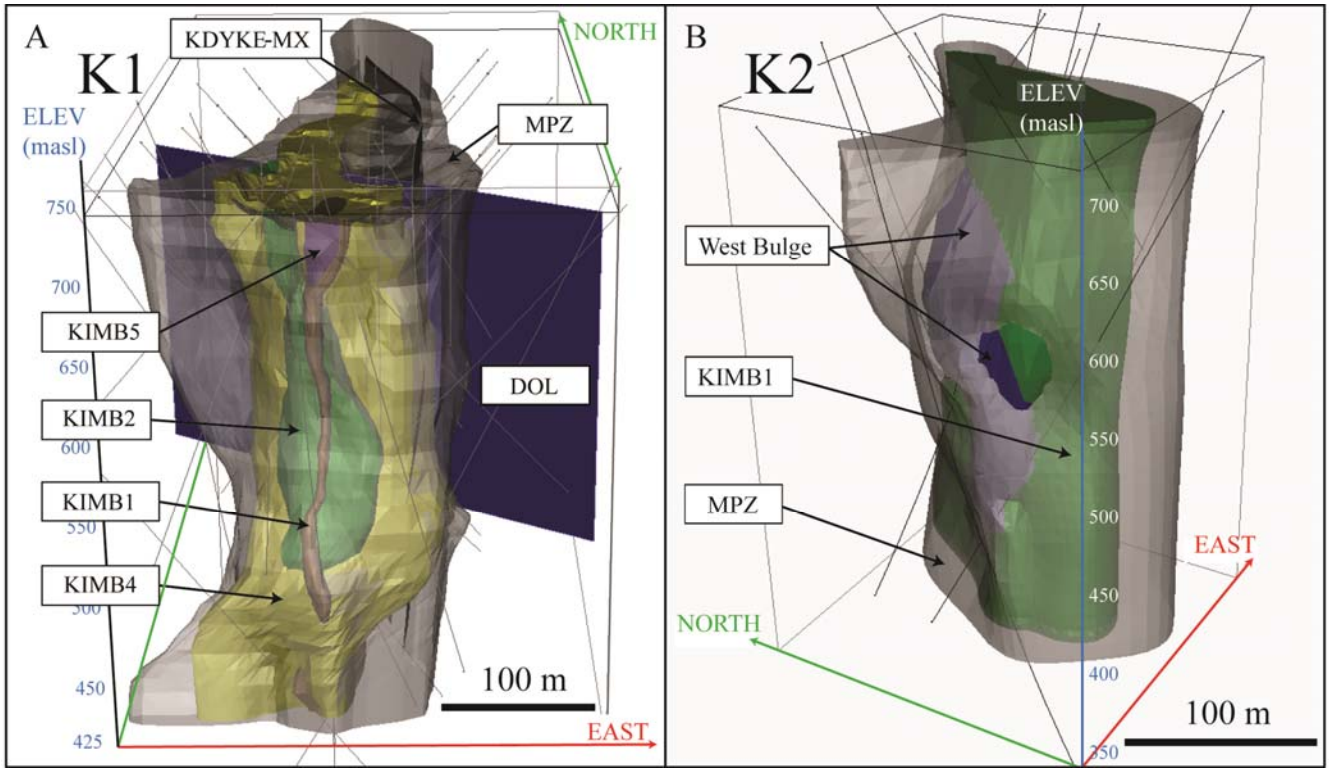

Figure 2: 3-D geological models for K1 and K2 at Murowa: (A) Inclined view from above facing north of K1 geological model comprising KIMB1 (brown), KIMB2 (green), KIMB4 (yellow), KIMB5 (purple), MPZ (transparent grey), KDYKE-MX (black), and a marker dolerite dyke, DOL (dark blue): (B) Inclined view from above facing northeast of K2 geological model comprising KIMB1 (green), West Bulge (blue), and MPZ (transparent grey). Drillholes are shown as grey traces in both (A) and (B).

groundmass. KIMB1 is classified as medium to very coarse grained, massive, country rock xenolith-rich, macrocrystic, monticellite phlogopite coherent kimberlite.

KIMB2

KIMB2 is a massive, competent, pale green and pink rock with sharp to diffuse contacts with adjacent rock types, and appears to occur in two separate zones in the south-southwestern portion of the pipe. KIMB2 displays a volcaniclastic rock texture and is distinct because of a) poorly sorted fine to medium-sized olivine (0.03 - 8 mm; 15 - 20 %) replaced by coarse clinopyroxene and serpentine; b) ultrathin rims consisting of phlogopite microphenocrysts around some olivine and granite fragments, interpreted to be relict kimberlite selvages of cored melt-bearing pyroclasts; and c) high modal abundance of small country rock xenoliths (0.5 - 120 mm; 25 - 55 %) that are uniformly to heterogeneously distributed in a green and brown matrix. KIMB2 is thus classified as a fine to medium-grained volcaniclastic kimberlite.

KIMB3

KIMB3 is a massive, competent, brown-green rock observed as minor, small (1-2 m), discontinuous and intermittent occurrences that overlap spatially and share diffuse contacts with adjacent rock types. KIMB3 displays an apparent coherent rock texture and is distinguished by its spatially-limited and discontinuous occurrence, a moderate modal abundance of olivine (0.03 - 20 mm; 25 - 35 %) and abundant country rock xenoliths (2 - 200 mm; 20 - 70 %) uniformly to heterogeneously distributed in a purple and brown groundmass. KIMB3 is classified as a fine to coarse grained, country rock xenolith-rich coherent kimberlite.

KIMB4

KIMB4 is a massive, friable to moderately competent, pale green and brown rock with both sharp and diffuse contacts with adjacent rock types, and is the main pipe-filling rock type observed at K1. KIMB4 displays a volcaniclastic rock texture and is distinguished by a low to moderate modal abundance and patchy distribution of olivine (0.03 - 30 mm; 5 - 20 %), as well as the presence of ubiquitous large, irregular to sub-round brown clasts ('blobs') of coherent kimberlite in a pale green and blue matrix. KIMB4 also contains garnet harzburgite and garnet lherzolite xenoliths, melt-bearing pyroclasts, and abundant, heterogeneously distributed country rock xenoliths (0.5 mm - 1.0 m; 30 - 70 %) including: a) angular to rounded granite; b) fragments of granite breccia with kimberlitic matrix (serpentine/carbonate) but no olivine; and c) very minor

dolerite. KIMB4 is thus classified as a fine to coarse grained volcaniclastic kimberlite.

KIMB5

KIMB5 is a massive, competent, black rock with sharp contacts with adjacent rock types, and occurs only in a small area in the southern part of K1 (Figure 2). KIMB5 displays an overall coherent rock texture and is distinguished by dark green-black olivine (0.03 - 25 mm; 45 - 55 %), rare bleach-white and green country rock xenoliths (2 - 30 mm; < 2%), and apparent enigmatic spherical clasts of kimberlite that are uniformly distributed in a black-grey-green groundmass, with an abundance of carbonate and serpentine 'pools'. KIMB5 is thus classified as fine to medium grained, massive, macrocrystic, spherical clast-bearing phlogopite coherent kimberlite.

KDYKE

KDYKEs at K1 are massive, competent, grey and black rocks with generally sharp contacts with adjacent rock types. KDYKEs occur within the pipe as subhorizontal sheets and irregular, poorly-constrained intrusions, with either cross-cutting or coeval relationships with all other kimberlite types. Outside the pipe, KDYKEs occur as vertical sheets or dykes striking at both north-south and east-west orientations. Two main types of KDYKE are distinguished petrographically and are classified as a) macrocrystic monticellite phlogopite coherent kimberlite, and b) poorly macrocrystic phlogopite coherent kimberlite. Type b) dykes can be distinguished from Type a) dykes based on the lower abundance of olivine, the absence of monticellite, and the habits of groundmass and phenocrystic phlogopite. A third type of dyke is distinct due to a high modal abundance (20 - 30 %) and coarse size distribution of a variety of mantle xenoliths (hence, KDYKE-MX), and is observed at multiple locations in the open pit and drillcore as a near vertical, ~0.5 - 1.0 m sheet striking north-south (Figure 2a).

K1 marginal pipe zone (MPZ)

A variety of clastic and in situ granite breccias and volcaniclastic rocks with distinctly less kimberlite than the rock types described above were observed in drillcores and in the current open pit. These rocks collectively form a distinct, thick "marginal zone" or envelope surrounding and cross-cut by all of the pipe infill, and are thus collectively referred to as the "marginal pipe zone" (MPZ; Figure 3). All rock types in the MPZ contain < 20 % kimberlitic components (matrix minerals, solid mantle, solidified kimberlite melt), and < 3 % olivine > 1 mm in size. Some rock types are characterised by a very fine grained green "rock flour" matrix comprised of fragments and shards of granite and granitic xenocrysts. Distinct attributes of MPZ rock types are described below:

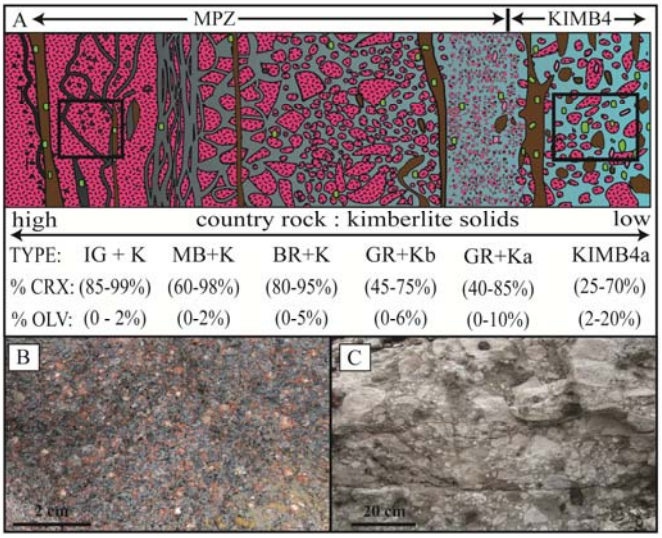

Figure 3: Rock textures observed in the marginal pipe zone (MPZ) of K1: (A) schematic illustration of the continuum of textural varieties observed in the MPZ surrounding K1. Estimated modal abundances of country rock (%CRX) and olivine (%OLV) are shown at the bottom; (B) fenitized and altered IG+K; (C) KIMB4 volcaniclastic kimberlite with abundant 15-25 cm long clasts of coherent kimberlite.

IG+K: An in situ granitic rock with minor amounts of veining and fenitization by fluid phase minerals associated with kimberlite emplacement (Smith et al., 2004). Minor small localised zones of in situ brecciation and slight clast-rotation are present.

***BR+K*:** A clast-rotated granite breccia comprising poorly sorted, angular to sub-rounded granite clasts (80 -95% of total rock) in a matrix of blue-green fluid phase minerals associated with kimberlite emplacement (i.e., serpentine, carbonate). Small (<1 cm) olivine-poor, melt-bearing clasts (< 1 %) of kimberlite are locally present. Olivine pseudomorphs make up < 2 % of the rock.

***MB+K*:** A variety of BR + K with angular, elongate and parallel or sub-parallel shards of granite (60 -98 % of total rock) and minor to absent olivine pseudomorphs in a green to black matrix.

***GR + Kb*:** A clast-rotated, poorly sorted granite breccia with minor, small (0.03 - 4 mm) olivine and minor (<2 %), locally-present, olivine-poor, melt-bearing clasts of kimberlite in a blue-green to pale green matrix. Country rock comprises 45 - 75% of the total rock.

***GR+Ka*:** Moderately to well sorted, fine to coarse, volcaniclastic rock consisting of granite rock and crystal

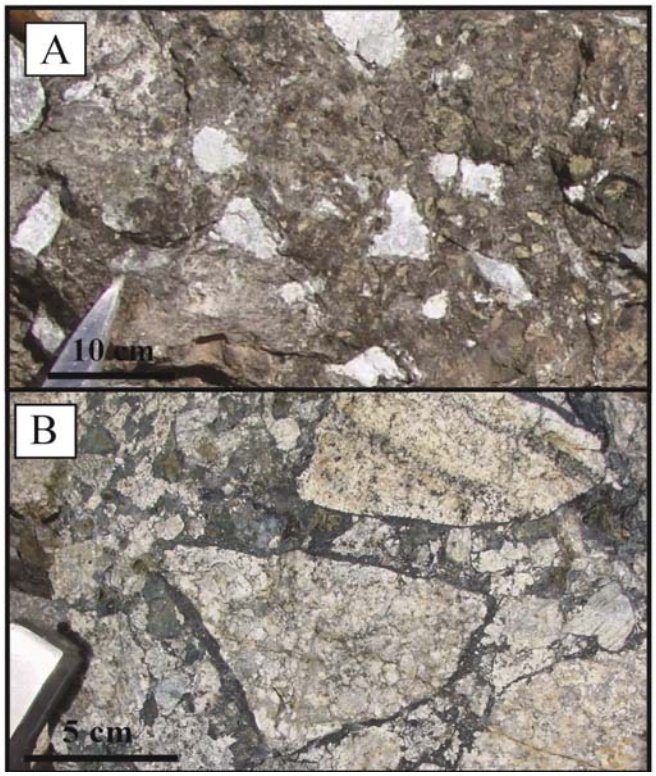

Figure 4: Common rock types at K2: (A) KIMB1, the dominant pipe infill, characterised by distinct bleach-white granite xenoliths and coarse olivine pseudomorphs in a brown phlogopite-rich groundmass; (B) BR+K within the MPZ, comprised of angular, rotated granite clasts and olivine pseudomorphs (brown) in a blue-green serpentine-rich matrix.

fragments (40-85 %), minor to absent small (0.03 - 3 mm; 2 % ≥ 1 mm) olivine pseudomorphs, and minor to absent melt-bearing clasts of kimberlite (< 2 %) in a pale-green matrix.

GEOLOGY OF K2

K2 is a steep-sided, sub-circular and slightly elongate pipe, 200 m long in a northeast-southwest direction, a maximum of 110 m wide in an east-west direction, flares slightly with depth, and lies 800 m to the south of K1 (Figure 1). Current data suggest the K2 pipe infill is internally simple, being comprised of one main kimberlite type (modeled in three-dimensions as two geology domains; Figure 2B). A second volumetrically minor kimberlite type is preserved locally near the pipe margins. The country rocks to K2 are variably brecciated and altered granite and mylonite with minor quantities of kimberlitic components. These rocks form a distinct, thick envelope around the K2 pipe, and are thus collectively referred to as the "marginal pipe zone" (MPZ). Late-stage kimberlite dykes cross-cut the K2 pipe and surrounding country rock. The rock types comprising the K2 pipe infill and MPZ are described below and their distribution is shown in Figure 2B.

K2 pipe infill

KIMB1

KIMB1 is a dark brown to black, generally massive rock that comprises the dominant infill of the K2 pipe. KIMB1 displays an overall coherent rock texture, and is distinct due to the presence of common extensively altered white granite xenoliths (1-5 cm; 5 - 35 % of rock) and conspicuous coarse and very coarse grained olivine. Olivine (0.05 - 25 mm; 45-50 %) is typically unbroken and uniformly distributed in a phlogopite-rich groundmass (Figure 4a). Phlogopite varies in grain size and habit and is typically coarser-grained in the west of the body. KIMB1 is classified as medium to very coarse grained, massive to locally crudely flow aligned macrocrystic monticellite phlogopite coherent kimberlite.

KIMB2

KIMB2 is a dark brown to black, generally massive rock with an overall coherent texture, and is macroscopically similar to KIMB1. However, KIMB2 is distinguished from KIMB1 petrographically based on the presence of strongly pleochroic and/or zoned phlogopite phenocrysts and coarser grained atoll-textured groundmass spinel. KIMB2 is classified as medium to very coarse grained massive macrocrystic monticellite phlogopite coherent kimberlite.

KDYKE

KDYKEs at K2 are competent, grey and black, generally massive coherent rocks with sharp contacts with adjacent rock types, and are interpreted to be hypabyssal sheets or thick intrusions. KDYKEs occur in 13 of the 17 drillcores and intersection thicknesses range 0.1 to 21 m. KYDKEs occur throughout KIMB1, are considerably more common on the west side of the pipe, and also occur within the MPZ. Two types of KDYKE are distinguished petrographically, and are classified as a) macrocrystic monticellite phlogopite coherent kimberlite, and b) macrocrystic phlogopite coherent kimberlite. Type b can be distinguished from Type a based on the absence of monticellite, lower abundance of coarse conspicuous olivine, presence of ultrafine grained groundmass phlogopite, and high abundance of interstitial carbonate and serpentine.

K2 marginal pipe zone (MPZ)

The MPZ at K2 comprises similar rock types as observed at K1. These variably brecciated and altered rocks contain 0 - 30 % kimberlitic components (solid mantle, solidified kimberlite melt, groundmass/matrix minerals) in the form of stringers, sheets and thick intrusions, individual 'free' olivine grains and in rare cases also melt-bearing clasts of kimberlite (Fig. 4b).

DISCUSSION & INTERPRETATION

In this section, the observations described above and the modeled distribution and geometry of the rock types at K1 and K2 (Figure 2) are combined with observed cross-cutting relationships and textural variations among deposits to interpret the style and history of kimberlite emplacement.

K1 model and emplacement interpretations

The major rock types or domains at K1 described above have been modeled in 3-D: KIMB1, KIMB2, KIMB4, KDYKE-MX, and MPZ (Figure 2a). The continuum of granite breccia and volcaniclastic rock textures at K1 (Figure 3) are interpreted to result from multiple emplacement events involving kimberlite magmas with varying proportions of gas, liquid and solid phases encountering different country rock regimes, and intruding/erupting over contrasting timescales. At one extreme, the fine-grained and well-sorted "rock flour" textures characterizing many of the MPZ rocks (e.g., GR+Ka) are interpreted to result from intrusion of kimberlitic fluids poor in mantle solids, leading to fine-scale fragmentation of country rock and prolonged mechanical mixing. Conversely, the wide size range of country rock fragments, presence of irregular-shaped, large clasts of coherent kimberlite, abundance of melt-bearing pyroclasts, and heterogeneous distribution of olivine observed in KIMB4 are interpreted to reflect incomplete kimberlite magma disruption and heterogeneous mixing with country rock fragments produced by prior emplacement events. Furthermore, the presence of lithic fragments comprising MPZ rock textures (e.g., MB+K) within KIMB4 combined with the size and enclosing nature of the breccia zone relative to the kimberlite pipe are interpreted to suggest that the country rock brecciation and fragmentation by solids-poor kimberlite fluids was an early event relative to the emplacement of pipe-infilling rocks at K1. Within the pipe, KIMB2 is cross-cut by KIMB4, KIMB4 is cross-cut by KIMB1, and KDYKE intrusions cross-cut all other rock types. These relationships are interpreted to suggest that early, more explosive emplacement of volcaniclastic rocks (e.g., KIMB2, KIMB4) was succeeded by passive intrusions of coherent rocks (e.g., KIMB1, KDYKE) at K1.

K2 model and emplacement interpretations

KIMB1 and the MPZ at K2 have been modeled in 3-D (Figure 2). KIMB1 is separated into two domains: the main pipe and 'West Bulge' domains. The latter is defined by a significantly higher frequency of KDYKE intersections. KIMB2 is interpreted to be a volumetrically minor pipe infill and the thin intersections of this rock type have been modeled within KIMB1. The textural characteristics of the main infill preserved in the K2 pipe suggest a less explosive emplacement style relative to K1. The even distribution and generally limited size of country rock xenoliths (<20 cm), overall homogeneous size distribution of olivine grains, lack of pyroclastic textures and lack of significant internal organization are interpreted to indicate rapid but passive emplacement of kimberlite magma following extensive excavation of variably brecciated and altered granite and mylonite.

Kimberlite pipe 'maturity'

Every kimberlite volcano is a unique occurrence, and not all kimberlites can be easily or completely described by any single model or class of pipe size, shape, or emplacement. Alternatively, attributes observed in a given kimberlite pipe may be placed into broad spectrums interpreted to reflect a relative stage of pipe development, or 'maturity'. For example, a symmetrical, generally smooth-walled, steep-sided and downward-tapering kimberlite body that is infilled by texturally-homogeneous volcaniclastic kimberlite with ~10% country rock xenoliths and minor amounts of solidified kimberlite melt preserved in melt-bearing pyroclasts could be interpreted as 'mature'. These features imply that kimberlite magma has breached the surface, and that a cylindrical pipe has been developed by one or more explosive fragmentation processes sustained over time. The observed textures and deposit geometries at K1 document end-members of three such maturity spectrums: an irregular, elongate and 'flared'-at-depth pipe shape; diffuse, texturally-variable pipe margins; and incomplete magma fragmentation interpreted from the sizes and shapes of discrete pieces of solidified kimberlite magma. Collectively, these attributes characterize relatively 'immature' volcanism compared to some other kimberlites. In contrast, observations of circular pipes tapering at high angles down to feeder dykes (e.g., Clement, 1982), smooth-walled pipes (e.g., Moss et al., 2008), or pipes bearing pyroclastic deposits with high degrees of sorting, olivine crystal tuffs, and/or minor amounts of country rock (e.g., Scott Smith, 2008) are examples of more 'mature' kimberlite volcanism.

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