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Spatio-temporal evolution of kimberlite magmas at Diavik, NWT

S. Moss (1,2), J.K. Russell (1,2), H. McLean (3), G. Fomradas (3), D. Eichenberg (3)

(1) Volcanology and Petrology Laboratory (VPL) at University of British Columbia, British Columbia, Canada, (2) Mineral Deposit Research Unit, University of British Columbia, British Columbia, Canada, (3) Diavik Diamond Mines Incorporated (DDMI)

1. Introduction:

Studies of modern volcanic systems have shown that variations in eruption style relate to the composition and physical properties of the magma, the degree of magma overpressure, and magma volume (e.g. Parfitt et al., 1995). Similar linking of magma properties to eruption style has not been made for kimberlite eruptions for several reasons. First, kimberlite eruptions have not been observed. Second, quenched kimberlite melt in volcanic deposits is often poorly-preserved due to their susceptibility to post-emplacement alteration and textural modification. Third, these volatile-rich magmas are likely to have transient properties during transport and eruption. For example, the volumetric proportions of melt:solids:gas could evolve from melt dominated systems at mantle conditions to gas dominated systems at the point of eruption. Such variations would have profound impact on the physical properties of kimberlite magmas and, hence, the mechanisms and styles of eruption.

The Diavik kimberlite cluster in the Canadian Northwest Territories (Figure 1a) provides a unique opportunity to document a sequence and style of eruptive and intrusive events. First, we show results of field mapping in the A154 pit and logging of drillcore which reveals unit contacts, cross-cutting relationships between rock units, and overall intrusion and deposit geometries. These observations allow for the relative spatio-temporal organization of kimberlite emplacement events at Diavik. Next, we use petrographic data from drill core samples to characterize differences between emplaced units.

Our analysis suggests that separated three-phase flow involving kimberlite melt, crystals and an exsolved CO_2-H_2O fluid is an important aspect of kimberlite emplacement. Specifically, we expect the volumetric proportions of the fluid phase to increase with ascent, but decrease with time during the eruption due to separation of flow between the gas and the silicate melt. This process can account for a diversity of textures and compositions recorded by pyroclasts within individual volcaniclastic kimberlite deposits or by crystallized dykes of coherent kimberlite.

2. Field mapping:

We have identified a minimum of 4 discrete volcanic (e.g., explosive and subvolcanic intrusion) events in the A154N pipe, including: 1.) a pre-cursor dyke (D) exposed at the present-day surface during mining; 2.) massive pyroclastic deposits within the A154N pipe (PK1); 3.) subvolcanic intrusions of coherent kimberlite (CK) hosted by volcaniclastic deposits of A154N; and 4.) a pyroclastic kimberlite deposit (PK2) captured by and preserved within the vent to the A154N volcano (Moss et al., 2008)

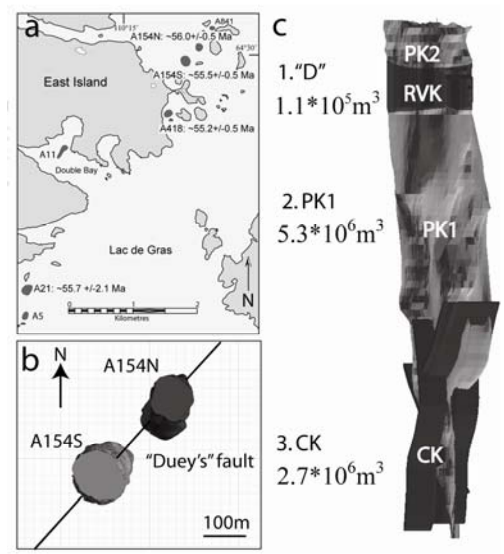

Figure 1: Diavik Diamond Mines Inc. (DDMI) and A154N. (a) East Island of Lac de Gras, NWT, Canada showing known pipes and ages (Amelin, 1996). (b) Map view of A154N and A154S pipes cross-cutting "Dewey's" early fissure dyke. (c) 3-D model of A154N showing relative timing of events (1,2,3) and unit volumes for D, PK, and CK.

The pre-cursor dyke (D) outcrops as a narrow (~20 – 50cm), near-vertical body of yellow-brown, carbonate-altered kimberlite that strikes ~38° for over 800m in length through the country rock surrounding the A154 open pit (Figure 1b; D). The dyke extends 180m northeast of A154N, is exposed for ~200m between the A154N and A154S pipes, and extends ~150m southwest of A154S. Adjacent kimberlite pipes (A154N and A154S) cross-cut the dyke and contacts are sharp; there is no evidence of D cross-cutting the fragmental kimberlite of either A154N or A154S.

The majority of A154N is filled with massive, poorly-sorted, pyroclastic kimberlite (PK1), and is observed for over 500m vertically in the interior of the pipe. Multiple intrusions of coherent kimberlite cross-cut the fragmental PK1 to a maximum height of 250m below present-day surface. The PK1 is capped by ~100m of re-sedimented volcaniclastic kimberlite (Figure 1c; RVK), representing a pause in the eruption sequence at A154N. Pyroclastic kimberlite (PK2) from an exotic source is deposited on top of the RVK, filling in the uppermost 50m of A154N (Moss et al., 2008). Relative timing between CK and PK2 is unknown, and, thus, PK2 will not be considered further in this present study. These cross-cutting relationships indicate a logical sequence of emplacement events at A154N (Figure 1c), and allow for an evaluation of the physical character of a known sequence of emplaced and erupted magma(s). We suggest that the nature of the

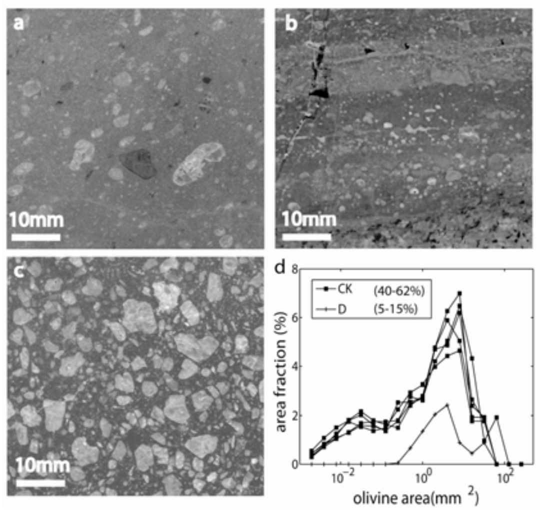

Figure 2: Componentry of coherent kimberlite. (a) polished slab of "Dewey's"; (b) dyke margin of "Dewey's" with abundant carbonate-filled amygdales and flow banding. (c) polished slab of CK (d) area fraction (as %) vs. olivine size (as mm^2) for CK, D.

emplacement style (fissure dyke, pipe excavation, intrusive dykes) is a direct result of varying physical properties of magmas supplied to the A154N context.

3. Image Analysis:

Our characterization of the kimberlite samples involves image analysis of olivine contents and description of the carbonate mineralogy and occurrence. These attributes are sufficient to uniquely characterize the coherent kimberlite samples (D,CK). For the pyroclastic deposit (PK1) we use these techniques to characterize individual juvenile kimberlite pyroclasts. Olivine crystals and pyroclast outlines are manually traced at two scales of observation (slabs and thin sections) using a digitizing pad and Adobe Illustrator™ and analyzed using ImageJ™. for particle areas. Data from slabs and thin sections are subsequently normalized to the largest scale of observation. Thus for juvenile pyroclasts, we are able to report modal olivine content, pyroclast size, vesicularity, overall texture, and carbonate phenocrysts and groundmass.

Olivine abundance and carbonate habits

Macroscopic observation of polished slabs indicates a clear difference in modal olivine from the pre-cursor dyke (D) (Fig. 2a,b) to CK (Figure 2c). Results from image analysis of five representative samples from CK and two from D are expressed as area % olivine (Fig. 2d). Early magmas contain a truncated size range of olivines (D; 0.2-100mm^2), compared to later magmas (CK; 0.03-100mm^2), and overall lower modal abundance (~5-15 % vs. 40-62%). Thin section analysis shows D to have an abundance of primary groundmass carbonate, amygdale-filling carbonate, and subsequent carbonate alteration olivine and groundmass phases (e.g. Fig. 2b). In contrast, late CK magmas contain only minimal pools or discrete domains of serpentine and/or carbonate (Fig. 2c).

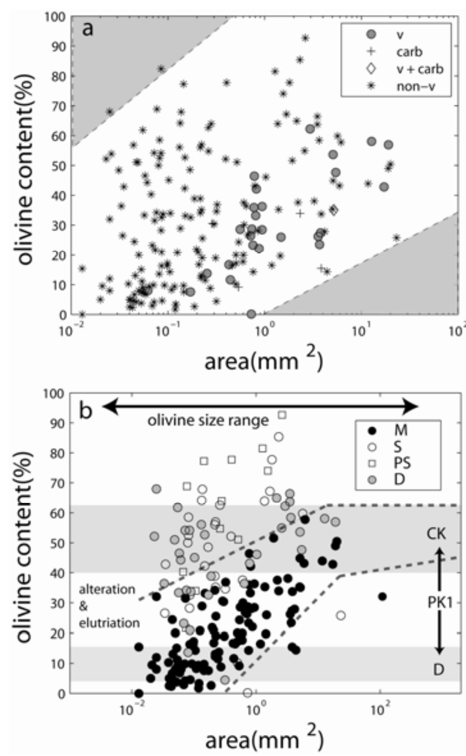

Figure 3: Juvenile pyroclasts from PK1 of A154N: (a) olivine content (%) vs. size (mm^2) of juvenile pyroclasts showing vesiculated (v), groundmass carbonate (carb), and non-vesiculated (non-v) sub-types. Shaded regions highlight un-observed olivine : melt relationships; (b) textural sub-types of juvenile pyroclasts comprised of: multiple olivine crystals (M), selvage coating 1 or 2 olivine crystals (S), partial selvage (PS), and cored (C) clasts. Shaded bands indicate measured modal olivine (%) for CK and D.

Juvenile pyroclasts of PK1 of A154N

To assess the solids content of magma that produced PK1 within A154N, we examine juvenile pyroclasts comprising crystallized kimberlite magma +/- olivine crystals in the PK1. Twenty samples were collected at ~10m intervals throughout a 200m vertical section of the PK1 of A154N. Ten or more juvenile pyroclasts from each thin sections were chosen for analysis based on observable groundmass mineralogy and a lack of alteration. Pyroclast area and the percentage of olivine were calculated by analyzing the traced images for total area and the area % occupied by olivine in each clast. Size vs. olivine content with textural sub-types are shown in Figure 3a,b. Juvenile pyroclast data observable at the thin section scale cover a range of sizes (0.01-20mm^2) and olivine contents (0 – 90%) and reveal lower limits (0.01mm^2) in size. Approximately 14% (29 of 211) of analyzed juvenile pyroclasts contain vesicles or amygdales, in juvenile pyroclasts ranging from .06mm^2 to 20mm^2 (Figure 3a). Vesicle contents range from 1 – 20% by area. Small juvenile pyroclasts with high crystal:melt ratios or large juvenile pyroclasts with low crystal:melt ratios are not observed (Figure 3a). Combined modal % olivine for all juvenile pyroclasts is 43.7 %.

4. Discussion:

Modal estimates (area %) of olivine contents vary widely in measured juvenile pyroclasts of PK1. A possible explanation is that single batches of magma have intrinsically heterogeneous olivine contents. Variations could also result from the crystal size distribution of olivine in the pre-eruptive magma. A third possibility is that PK1 has captured juvenile pyroclasts derived from multiple eruptions. The PK1 shows little evidence of cross-cutting eruptive events; PK1 is internally massive, contains minor, sparsely distributed clasts of mud-rich, fragmental kimberlite with small (0.1-1mm) olivine fragments and crystals and no juvenile pyroclasts. Juvenile pyroclasts of variable olivine content are observed in the same thin section, and possess broadly similar groundmass mineralogy (e.g. spinel, serpentine). It is therefore unlikely that the juvenile pyroclasts in the PK1 derive from multiple eruptions.

To assess the manner of control exerted by olivine crystals (modal % vs. crystal size distribution) on disruption of kimberlite magma, we have sub-divided juvenile pyroclasts into four textural classes (Figure 3b): (1) pyroclasts containing 'multiple' olivine grains in a groundmass of crystallized kimberlite magma (M); (2) single olivine crystals with a crystallized kimberlite selvage (S); (3) single olivine crystals with a partial selvage of crystallized kimberlite (PS); and (4) pyroclasts containing a core olivine surrounded by other, smaller olivines and crystallized kimberlite magma (C). Each sub-type contains olivine content expected based on texture (e.g., complete selvage $\geq$ 50% olivine). However, for juvenile pyroclasts containing multiple olivine, olivine content show large ranges (30-50%) for pyroclasts of all sizes. Combined modal % in juvenile pyroclasts (43.7%) likely represents a maxima; smaller pyroclasts are unlikely to be preserved due to alteration and elutriation, and therefore preserved juvenile pyroclasts represent a sample bias towards crystal-rich magmas and likely over-estimate the olivine content. Larger pyroclasts (>100mm^2) are rarely observed, but appear similar in modal olivine content to CK. We interpret these data to reflect both a constraint on fragmentation by the original size distribution of olivines in the magma *and* a heterogeneity in modal olivine content in the erupting magma. Combined with observations in preceding and subsequently emplaced magmas, emplaced magmas record variation in modal olivine content with time: % $ol_D \leq$ % $ol_{JP} \leq$ % ol_{CK}. The emplacement events at A154N also record a diminishing presence of both volatile and/or molecular CO_2: an early dyke (D) contains groundmass carbonate and abundant carbonate-serpentine (i.e. CO_2 and H_2O) domains; juvenile pyroclasts from pipe-forming PK1 contain variable modal % vesicles/amygdales over a large size range; late dykes have few to no carbonate-serpentine domains, and do not contain microphenocrysts of calcite and/or dolomite.

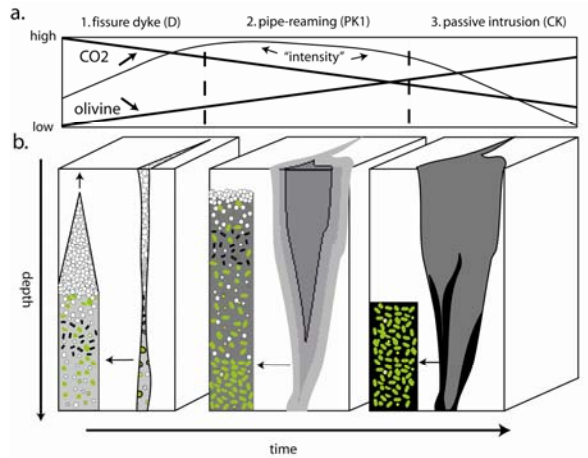

Figure 4: Phase separation and emplacement style at A154N: (a) inferred CO_2, olivine and relative intensity through time for D, PK1, and CK; (b) schematic cartoon showing vesicle, olivine and carbonate content (light grey = high) for D, PK1, and CK.

5. Interpretation

We interpret the three events at A154N (D,PK1,CK) to record emplacement of a separated three-phase flow involving kimberlite melt, crystals and a proportion of exsolved CO_2-H_2O fluid (Figure 4). Emplacement styles (fissure dyke, pipe-excavation, passive intrusion) and relative volumes are reflective of the variable proportions of these three phases observed in the rocks. First, a low-volume, gas-charged (i.e. CO_2, H_2O) fissure eruption of olivine-poor kimberlite magma emplaced D. Second, a sustained (high flux, long duration) eruption of variable gas and olivine content excavated the A154N pipe and deposited the PK1. Third, non-eruptive, olivine-rich and gas-poor coherent kimberlite was passively emplaced into the interior of PK1. Though relative timing between events is well-constrained, ongoing work is directed at determining how much time elapsed between emplacement events.

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Parfitt, E.A., Wilson, L. and Neal, C.A., 1995. Factors influencing the height of Hawaiian lava fountains: implications for the use of fountain height as an indicator of gas content. Bulletin of Volcanology 57, 440-450.