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Spatial and temporal evolution of kimberlite magma at A154N, Diavik, Northwest Territories, Canada ☆

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ABSTRACT

The A154N kimberlite pipe is part of the Diavik kimberlite cluster in the Northwest Territories, Canada. The pipe is filled by deposits that record a sequence of eruptive and intrusive events for which we have established relative times and modes of emplacement. As such, this sequence of kimberlite deposits provides a unique opportunity to explore the connections between magma properties, pipe or conduit geometry and eruption style.

Deposits within the A154N pipe represent four discrete volcanic events including: (1) an array of pre-cursor dykes of coherent kimberlite that intrude the adjoining country rock (CK_1); (2) pyroclastic deposits recording the explosive eruption of A154N (PK_1); (3) late dykes of coherent kimberlite intruding the main infill of the pipe (CK_2); and (4) a sequence of water-laid pyroclastic deposits that sourced from another kimberlite volcano (PK_2). We use observations on polished slabs and thin sections to characterize the magma that erupted to produce each deposit. Image analysis techniques are used to quantify olivine content (abundance and size distributions) and abundances of vesicles within deposits and within individual juvenile pyroclasts. Our analysis shows that during the eruption cycle (CK_1 to PK_1 to CK_2), olivine content increased and volatile content decreased.

Lastly, we estimate physical properties for the magmas that produced each deposit. The magma properties are combined with 3-D models for the geometry of the conduit at the time of eruption to constrain the mass flux and duration of each eruptive event. Steady-state assumptions for velocity and magma flux yield total eruption durations of minutes to hours. The diversity of textures and compositions recorded in pyroclastic kimberlite (PK_1) and dykes of coherent kimberlite (CK_1 and CK_2) are a possible manifestation of separated three-phase flow involving kimberlite melt and crystals, and an ever-increasing proportion of exsolved CO_2–H_2O fluid. Specifically, we suggest that the early dykes (CK_1), pyroclastic kimberlite (PK_1), and late-stage dykes (CK_2) are representative of three separate regimes of kimberlite magma created by the ascent of a vigorously degassing magma. We envisage this being composed of: (a) the gas-charged front of the magma created by decoupling the more buoyant gas phase from the silicate melt; (b) a transient, gas-rich body of magma in which later-stage exsolved fluids/gases are essentially coupled to the melt; and (c) a fluid-depleted tail of magma which remains buoyant within the lithosphere but ascends more slowly than the fluid and exsolving gas phases.

1. Introduction

Studies of modern volcanic systems have shown that variations in eruption style typically relate to the composition and physical properties of the magma, the degree of magma overpressure, the total volume of magma, and vent geometry. For example, solid, liquid and gas ratios in erupting magmas have been shown to modulate the style (i.e. effusive vs. explosive) and intensity (e.g. fountain height) of basaltic eruptions (e.g. Parfitt et al., 1995; Houghton and Gonnermann, 2008). Moreover, low viscosity magmas can outgas efficiently and allow for a concomitant reduction of magma overpressure and eruption intensity (e.g. Stasiuk et al., 1996; Namiki and Manga, 2008). Vent geometry can also be a significant factor in determining eruption style and intensity (e.g. Wilson et al., 1980; Scandone and Malone, 1985; Bower and Woods, 1998).

Similar linkages between magma properties, vent geometry, and eruption style have not been made for kimberlite eruptions for several reasons: (1) kimberlite eruptions have not been observed, and surface features and extra-crater deposits of even the youngest kimberlite volcanoes are usually highly eroded or completely removed; (2)

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pristine samples of kimberlite melt are rarely preserved because kimberlitic volcanic deposits are highly susceptibility to post-emplacement alteration and textural modification; and (3) kimberlite magmas are volatile-rich and likely to have highly transient physical properties during transport and eruption. For example, due to the high volatile contents estimated and measured for kimberlite magmas (e.g. Eggler, 1978; Price et al., 2000; Sparks et al., 2006, this issue) the volumetric proportions of melt:solid:gas must evolve from melt-dominated systems at mantle conditions to gas-dominated systems at the point of eruption (Gernon et al., this issue). Such variations will have profound impacts on the physical properties of kimberlite magmas and, hence, the mechanisms and styles of eruption.

Though conduit geometries of active volcanoes are difficult to measure, it is accepted that conduit morphologies are dynamic and subject to change (Scandone, 1996). In conventional volcanological studies, the data used to constrain unknown conduit geometries are measured heights of eruption columns from active systems or particle size distributions in fallout deposits for unobserved systems. In contrast, mining of diamondiferous kimberlite offers a unique opportunity to characterize conduit and vent geometries of an erupted volcano. For example, drill-core intercepts, downhole geophysical measurements, and open-pit surveys provide direct observations of subsurface contacts and, thus, constrain the 3-D geometry of kimberlite conduits.

The A154N kimberlite pipe in the Eocene Diavik kimberlite cluster (Graham et al., 1999) in the Northwest Territories, Canada, (Fig. 1a) comprises a sequence of extrusive and intrusive events for which the relative timing, vent geometry and mode of emplacement are clearly established. As such, it provides a unique opportunity to explore the connections between magma properties, vent geometry and eruption style.

Our analysis of this sequence of deposits suggests that transient magma properties arising from separated three-phase flow involving kimberlite melt, crystals, and an exsolved CO_2–H_2O fluid provide a fundamental control on the style of kimberlite eruption and emplacement. Specifically, we expect and observe the volumetric proportions of the fluid phase to: (1) increase with ascent; but (2) to decrease with time during the eruption due to decoupling of the gas and the silicate melt within the flow. We also expect the fraction of solids (i.e. crystals and xenoliths) to concentrate at the base of the ascending plug of kimberlite magma during ascent. These processes can account for the diversity of textures and compositions in pyroclasts and within dykes of coherent kimberlite.

2. Field mapping

Field mapping in the open pit at Diavik and logging of drill-core has identified a minimum of 4 discrete volcanic (e.g. 3 eruptive and 1 intrusive) events in the A154N pipe (Fig. 1b and c), including: (1) an array of dykes (CK_1) intruded into country rock exposed at the present-day surface (415 meters above sea level) during mining; (2) massive pyroclastic deposits within the pipe (PK_1); (3) sub-surface intrusions of coherent kimberlite (CK_2) intruded into PK_1. The sequence is capped disconformably by an externally-sourced pyroclastic kimberlite

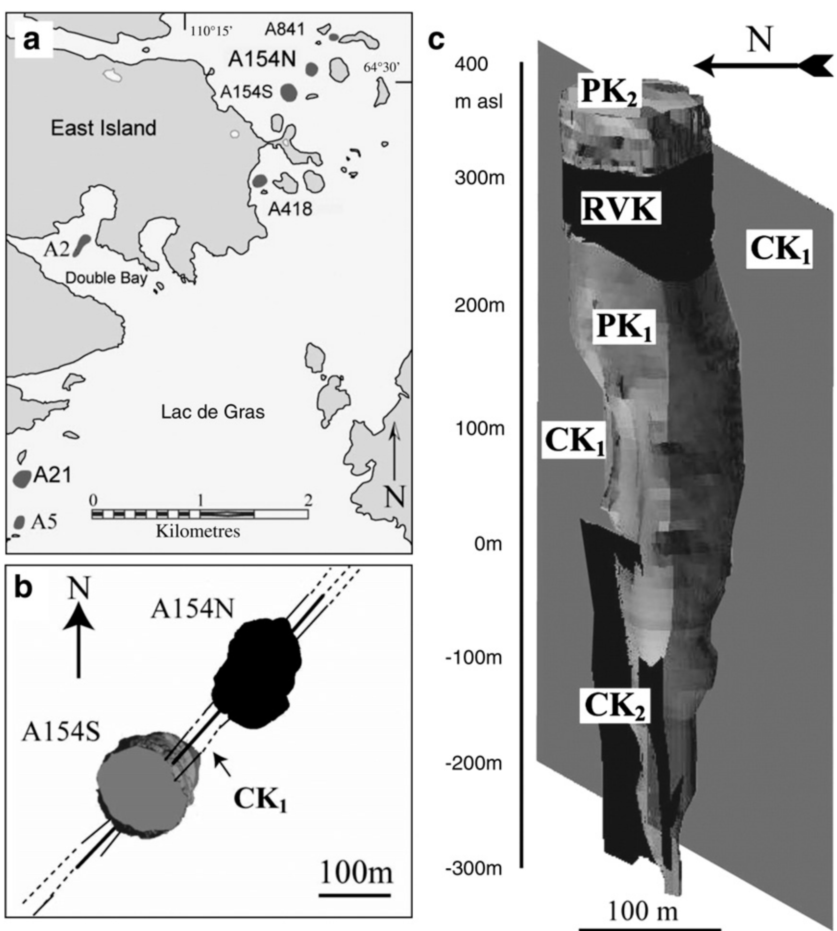

Fig. 1. Location of the Diavik kimberlite field and internal units of A154N: (a) Kimberlite pipes at Diavik, East Island of Lac de Gras, NWT, Canada; (b) Plan view of the A154N and A154S pipes and mapped (solid lines) and inferred (dashed) dykes of CK_1; (c) Inclined 3-D model of A154N looking E, showing five separate units of kimberlite, including: pre-cursor kimberlite dykes (CK_1) (translucent); pyroclastic kimberlite (PK_1); coherent kimberlite dykes (CK_2); re-sedimented volcaniclastic kimberlite (RVK); upper pyroclastic kimberlite (PK_2).