Pyroclastic kimberlite deposits from the Victor Northwest pipe (Ontario, Canada): the transition from phreatomagmatic to magmatic explosivity

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Abstract: Magmas of all compositions, including kimberlites, may undergo both magmatic and phreatomagmatic fragmentation during emplacement. In this contribution we assess the extent of phreatomagmatism at different stages of the pipe formation for the Victor Northwest kimberlite (northern Ontario, Canada). Detailed drill core and petrographic observations of all volcanic facies within the pipe suggest emplacement in two volcanic cycles, each consisting of three repeated eruptive phases. Pyroclastic kimberlite formed at the start of both cycles is characterized by the presence of fine-grained, poorly sorted deposits containing broken olivine crystals, angular country rock fragments, accretionary lapilli, and variably vesicular irregular-shaped juvenile pyroclasts. All observations indicate these deposits formed by phreatomagmatism. Subsequent clastogenic coherent kimberlite deposits were formed as a result of Hawaiian fire-fountaining during the second phase of both cycles. These phases were followed by mass wasting into the partly filled crater. The evolution from phreatomagmatic to magmatic fragmentation is commonplace in volcanic systems, and our study provides the first indication that the evolution from a phreatomagmatic to magmatic eruption style is also present in Kimberlite volcanoes, suggesting Kimberlite volcanism is not significantly different from more common basaltic to rhyolitic systems. In addition, this research indicates that high fragmentation intensities recorded by the presence of broken olivines, accretionary lapilli, abundant (angular) country rock clasts, and retention of ash are important textural criteria for recognition of phreatomagmatic kimberlite deposits.

Résumé : Des magmas de toutes compositions, incluant les kimberlites, peuvent être sujets à une fragmentation magmatique et phréatomagmatique durant leur mise en place. Dans le présent article, nous évaluons l’étendue du phréatomagmatisme à différentes étapes de la formation de la cheminée pour la kimberlite Victor Nord-Ouest (nord de l’Ontario, Canada). Des observations détaillées pétrographiques et de carottes de forage de tous les faciès volcaniques à l’intérieur de la cheminée suggèrent une mise en place durant deux cycles volcaniques, chacun comprenant trois phases éruptives répétitives. La kimberlite pyroclastique formée au début des deux cycles est caractérisée par la présence de dépôts à grains fins, mal triés, et elle contient des cristaux brisés d’olivine, des fragments angulaires de la roche encaissante, des lapillis accroîtés et des roches pyroclastiques juvéniles de forme irrégulière comportant des vésicules de tailles variables. Toutes les observations indiquent que ces dépôts se sont formés par phréatomagmatisme. Des gisements subséquents de kimberlite cohérente clastogène ont été formés depuis des fontaines de lave de type hawaïen au cours de la seconde phase des deux cycles. Ces phases ont été suivies de mouvements de masse dans le cratère partiellement rempli. Une évolution de fragmentation phréatomagmatique à magmatique est assez fréquente dans les systèmes volcaniques et notre étude fournit la première indication que l’évolution d’un style d’éruption phréatomagmatique à magmatique se retrouve aussi dans les volcans kimberlitiques, suggérant que le volcanisme kimberlitique ne diffère pas de manière significative des systèmes plus communs d’évolution basaltique à rhyolitique. De plus, la présente recherche indique que les intensités élevées de fragmentation, enregistrées par les olivines brisées, les lapillis accroîtés, les abondants clastes (angulaires) de roche encaissante et la rétention des cendres, constituent des critères de texture importants pour reconnaître les gisements de kimberlite phréatomagmatique. [Traduit par la Rédaction]

Introduction

Despite abundant research on kimberlite pipes, their actual formation mechanisms are intensely debated. Many authors suggest that kimberlite pipes are formed by magmatic processes, with a lesser proportion of pipes formed and filled by phreatomagmatic eruptions (Field and Scott-Smith 1999; Sparks et al. 2006; Cas et al. 2008b). This pattern mimics observations on more common basaltic to rhyolitic volcanoes that can erupt either magmatically or phreatomagmatically depending on a variety of factors such as the availability of water, volatile content and chemistry of the magma, and general eruption dynamics (Lorenz 1986; Cas and Wright 1987; Houghton and Schmincke 1989; Houghton et al. 1996; Carey et al. 2009; Di Traglia et al. 2009). In contrast, some authors contend that all kimberlite pipes and their fragmental deposits are formed by phreatomagmatic processes (Lorenz 1986; Lorenz et al. 1999; Kurszlaukis and Lorenz 2008). These authors argue that magmatic kimberlite eruptions, similar to many modern intra-plate basaltic volcanic systems, only formed scoria cones without underlying pipes, and as a result of limited preservation potential were simply removed from the geological record by millions of years of erosion.

The magmatic versus phreatomagmatic debate predominantly concerns steep-sided, carrot-shaped pipes first described in Southern Africa. These so-called Southern African – type pipes (Field and Scott-Smith 1999; Skinner and Marsh 2004) are generally filled by texturally destructively altered (Stripp et al. 2006; Porritt et al. 2006).
massive volcanioclastic kimberlite (VK), variably interpreted as fluidized pyroclastic material resulting from explosive magmatic eruptions (Clement and Reid 1989; Sparks et al. 2006), magmatic eruption column collapse deposits (Cas et al. 2008b), or well-mixed tephra formed by repeated phreatomagmatic explosions (Kurszlaukis and Lorenz 2008). Studies on predominantly Canadian kimberlites over the last 15 years have described several smaller-volume pipes, generally containing less altered volcanic facies containing more convincing volcanic textures interpreted to be phreatomagmatic in origin (e.g., Graham et al. 1999; Boyer 2005; Lefebvre and Kurszlaukis 2008; Pittari et al. 2008; Porritt and Cas 2009). Thus far, no single eruptive centre has been described to host the transition from phreatomagmatically to magmatically formed deposits, which is so common in many basaltic to rhyolitic volcanic systems worldwide (e.g., Fisher and Schmincke 1984; Cas and Wright 1987). To improve our understanding of the relative contribution of phreatomagmatic and magmatic fragmentation to the formation of kimberlite deposits, more studies involving detailed volcanological facies analysis, specifically those focusing on relatively well-preserved textures indicative of fragmentation style, are needed.

The goal of this study is to assess the contribution of phreatomagmatic and magmatic fragmentation to the different eruptive stages of the Victor Northwest (VNW) kimberlite pipe (northern Ontario, Canada). The study is based on drill core and petrographic observations of all volcanic units within the VNW kimberlite pipe. This particular pipe provides an excellent opportunity to further our understanding of phreatomagmatic versus magmatic fragmentation of kimberlites, as it consists of relatively unaltered volcanic facies that record highly variable fragmentation intensities and volcanic textures that we interpret to reflect the transition from phreatomagmatic to magmatic explosivity within one volcanic eruption. Our study provides the first indication that the evolution from phreatomagmatic to magmatic eruption styles is present within one kimberlite volcano, similar to transitions observed within more common basaltic to rhyolitic volcanic systems.

**Review of magmatic and phreatomagmatic fragmentation**

Most terrestrial volcanic eruptions are driven by magmatic fragmentation, whereas a smaller proportion of eruptions are driven by phreatomagmatic fragmentation. Deposits formed by the latter process commonly feature high abundances of blocky to irregular ash-sized pyroclasts, fewer bubble-wall vitric shards, and pyroclasts showing more variable and lower vesicularity than their magmatic counterparts, and they commonly have a fine grain size, indicating higher degrees of explosivity (Morissey et al. 2000). Introduction of external water necessary for phreatomagmatic fragmentation dramatically increases explosivity, leading to higher degrees of fragmentation; to more efficient cooling of pyroclasts, leading to less post-fragmentation recovery time and more angular juvenile pyroclasts; and to localized explosivity along conduit walls producing higher abundances of wall rock–derived country rock fragments (CRFs) (Morissey et al. 2000). Accretionary lapilli can also be associated with phreatomagmatic deposits, indicating the presence of water vapour during deposition (e.g., Sheridan and Wohletz 1981; Fisher and Schmincke 1984; Cas and Wright 1987; Schumacher and Schmincke 1991). Phreatomagmatic deposits derived from explosive eruption of conventional basaltic volcanoes typically are preserved as extra-crater thinly bedded planar to low-angle cross-bedded pyroclastic deposits resulting from high-energy pyroclastic surges (Wohletz and Sheridan 1983).

We expect some important textural differences between kimberlitic phreatomagmatic deposits and their basaltic counterparts. The viscosity of kimberlite melt may be one to two orders of magnitude lower than typical basaltic melts (Sparks et al. 2006; Kopylova et al. 2007). There are several possible consequences of this ultra-low viscosity. Firstly, efficient bubble escape may reduce the volume of bubbles during magma ascent, dampen the effects of effective viscosity increase during volatile exsolution, and reduce magmatic explosivity. External water offers a simple means to maintain a high degree of explosivity despite the low viscosity of the melt. Secondly, kimberlite melts are likely to have a low glass-transition temperature, which reduces the potential for glass formation and increases the time window for post-fragmentation relaxation of pyroclasts and crystallization (Porritt and Russell 2012). In summary, the low-melt viscosity, fast relaxation timescale (Dingwell 1996; Porritt and Russell 2012), and efficient escape of the fluid phase from the melt (Cas et al. 2008b) will likely suppress magmatic explosivity, reduce glass formation, and explain the absence of vitric bubble wall shards in kimberlite pyroclastic deposits. In contrast, magmatic fragmentation of kimberlite magmas is likely to produce surface tension–modified, spherical, crystallized juvenile ash particles (Moss et al. 2008) as found in other low-viscosity magmas such as carbonatites (Keller 1989).

There are several complicating factors when identifying possible phreatomagmatic kimberlite deposits. Most kimberlite deposits are found within pipes or craters. These intra-crater settings are different from the extra-crater settings studied in more common basaltic-rhyolitic volcanic systems. Whereas extra-crater phreatomagmatic deposits dominantly consist of tractional base surge bed forms, these deposit types are only rarely found in intra-crater settings (Boxer et al. 1989; Smith and Lorenz 1989; White 1991). Hence, for intra-crater kimberlite systems we are generally left with looking at textural evidence for phreatomagmatic fragmentation within the vent and conduit of kimberlite volcanoes (Field and Scott-Smith 1999; Sparks et al. 2006), rather than interpreting relatively straightforward extra-crater base surge phreatomagmatic deposits.

**Geological setting**

The Victor kimberlite complex is located in the James Bay Lowlands (northern Ontario, Canada, Fig. 1) and is currently being mined for diamonds by De Beers Canada Inc. The Victor complex is the largest kimberlite pipe cluster in the Middle–Late Jurassic Attawapiskat kimberlite province (Kong et al. 1999) and consists of two adjacent kimberlite bodies: Victor North and Victor South. The former, in turn, consists of two crosscutting pipes: Victor Northwest and Victor Main (Fig. 2; see also Webb et al. 2004; van Straaten et al. 2008, 2009, 2011). In this contribution we will focus on the Victor Northwest (VNW) pipe. The kimberlite pipes have been emplaced within an Ordovician to Silurian sedimentary sequence atop Precambrian basement. The interface between the sedimentary country rock and basement rocks is found at 272 m below the present surface (mbs). The kimberlites are overlain by approximately 8–30 m of unconsolidated Quaternary overburden.

**Methods**

In this paper we reconstruct the eruption history of the entire VNW pipe, specifically focusing on the fragmentation style and eruption mechanisms. Detailed non-genetic descriptions of all volcanic facies within the VNW pipe are provided in van Straaten et al. (2009) and are only summarized here. A subsequent publication (van Straaten et al. 2011) focused on a unique unit within the upper (U) stratigraphy of the VNW pipe (DCK-U, where DCK is dark and competent kimberlite), which represents clastogenic extrusive coherent kimberlite. All studies are based on logging ~4.2 km of drill core and studying about 200 representative polished core samples and thin sections. For this particular paper, we re-evaluated all the data, paying particular attention to textures.
such as olivine angularity, pyroclast type, CRF abundance, angularity and size, and fine-grained opaque mineral abundance.

We established the average proportion of angular olivine for each lithology by counting the number of olivines with one or more sharp angle (<80°) out of >25–50 olivine macrocrysts in one thin section. In units VK-U$_1$, DCK-U, and VK-U$_3$ (see van Straaten et al. 2011 for all data) >25 grains per thin section were counted, with a total of 550–1500 grains counted for each lithology. The error bars represent one standard deviation of the data. In units BK-L$_1$, DCK-L, and VK-U$_2$ (where L refers to the lower stratigraphy) more than 50 grains were counted per thin section, with a total of 150–350 grains for each lithology in at least three different thin sections. Error bars represent the minimum and maximum value for each lithology. For each lithology, the average value is interpreted to represent the proportion of angular broken olivine crystals. The proportion of angular olivines in typical macrocrysty intrusive coherent kimberlite was estimated by counting olivines in a thin section of the Snap Lake dyke (Kopylova et al. 2010), Diavik lower A154N pipe (Moss 2009), and a large juvenile pyroclast within the Victor Main kimberlite pipe (van Straaten 2010). The broken olivine content in these samples ranges from 0% to 9%.

In addition to the detailed description of the VNW pipe geology, we also reconstructed the local country rock stratigraphy using three 280–310 m deep vertical drill cores in the vicinity of the Victor kimberlite complex (V-03-337c, V03-270ah, V-97-00).

## Results

### Country rock stratigraphy

As part of this study we evaluated the local country rock stratigraphy and integrated this data with available hydrological studies. The country rock stratigraphy around the Victor kimberlite complex is fairly uniform laterally and consists of from bottom to top (Fig. 2):

(A) Granitoid basement with the occasional dolerite dyke intersected in one deep drill hole, V-00-117c. The granitoid is variably deformed, is commonly compositionally banded, and can best be described as a quartz + plagioclase + K-feldspar + biotite ± amphibole ± rare garnet bearing gneiss (deepest drill hole indicates a minimum thickness of 33 m)

(B) A fining-upward sequence of grit to sandstone to siltstone (~1.7 m thick)

(C) Burrowed silt/mudstones and dolomitic mudstones/dolostones (12 m thick)

(D) Grey evaporitic mudstone (13 m thick)

(E) Clastic red beds surrounding a laminated-massive chalky mud/dolostone (30 m thick)

(F) Dolostone to bioturbated limestone to dolostone; the limestone unit in the centre often contains shelly beds and corals (27 m thick)

(G) Numerous complete–incomplete cycles from bioturbated limestone (with common vugs and gypsum casts) to cream-coloured chalky laminated–massive non-biobturated non-fossiliferous mud/dolostone to grey mudstone, siltstone, and (or) sandstone (59 m thick)

(H) Burrowed to massive grey-yellow limestone (~100 m thick, depending on overburden thickness)

The VNW pipe extends to at least 90 m (likely ~295 m, see Fig. 2) below the basement – Palaeozoic country rock interface. At these levels hydraulic conductivities are low and predominantly confined to faults, dolerite dyke contacts, and joint surfaces in the granitoid (Fig. 2). Several faults of Silurian, or younger, age occur in the immediate area surrounding the Victor kimberlite complex (Suchy and Stearn 1993; Hydrological Consultants Inc. 2004). Two inferred steeply dipping faults that are crosscut by the kimberlite bodies have been included in the hydrogeological model for open-pit mine dewatering (Fig. 2 and Hydrological Consultants Inc. 2004). There is an artesian aquifer within the sandstone layer overlying the basement (unit B in Fig. 2; Webb et al. 2004). The modelled water flow into the mine ($8.7 \times 10^4$ m$^3$/day, Hydrological Consultants Inc. 2004) is expected to concentrate along hydraulically active fault zones in the sedimentary rock succession, the pipe contact damage zone, and permeable limestones (Fig. 2).

### VNW pipe geology

The detailed geology of the VNW pipe has been reported in van Straaten et al. (2009, 2011). A summary of the intra-crater geology and observations relevant to the reconstruction of phreatomagmatic and magmatic eruption mechanisms are presented below.

The VNW pipe consists of a large variety of rock types, ranging from pyroclastic kimberlite with variable CRF abundance, CRF-poor pyroclastic kimberlite, clastogenic extrusive coherent kimberlite to sedimentary country rock breccias (CRBs; van Straaten et al. 2009, 2011). The stratigraphic units within the VNW pipe can be subdivided into two sequences, upper (U) and lower (L), each of which can be shown to correspond to a separate, but similar, explosive eruption cycle (van Straaten et al. 2009). The lower stratigraphy contains the bedded kimberlite (BK-L$_1$) and DCK-L units, whereas the upper stratigraphy includes the VK-U$_2$, DCK-U, VK-U$_2$, and VK-U$_3$ units.
Each eruptive cycle consists of an early explosive phase (BK-L and VK-U) that produces pyroclastic deposits containing abundant angular broken olivine grains. The olivine shapes and sizes in these deposits are very different from sub-round olivine grains that dominate the crystal component in typical pre-eruption kimberlite magmas preserved in dykes and large juvenile pyroclasts. The early pyroclastic deposits are overlain by DCK, which is massive, featureless, and characterized by mostly unbroken (sub-round) olivine grains. Each eruptive cycle is capped by minor resedimented VK (not shown on Fig. 2) and a thick blanket of sedimentary CRBs. The two cycles show a consistent decrease in explosivity and begin with high-intensity explosive activity (cycle 1: BK-L; cycle 2: VK-U), followed by less explosive eruptive activity (cycle 1: DCK-L; cycle 2: DCK-U, VK-U, VK-U) and subsequent post-eruption pipe-wall collapse producing CRBs (cycle 1: CRB-L, CRB-L; cycle 2: CRB-U; van Straaten et al. 2009).

The volcanic origin of the volcaniclastic units, and their mode of fragmentation, have not been reported previously and are discussed in detail in this paper. The less explosive activity in the second cycle formed extrusive coherent rock DCK-U, interpreted to be clastogenic deposits formed by intra-crater lava fountaining and coalescence (van Straaten et al. 2011). Until recently, clastogenic deposits had not been recognized within kimberlite pipes.

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despite the fact that such deposits are commonplace in basaltic volcanoes (e.g., Sumner et al. 2005).

**Textural analysis of units within the VNW pipe**

The BK-L₁ unit, the oldest unit in the lower stratigraphy within the VNW pipe, contains abundant broken olivines (Figs. 3, 4). This unit is dominated by ash-armoured pyroclasts (Fig. 5) featuring 0.5–2 mm selvages on 0.5–3 cm olivine grains or CRFs; unaltered examples of these pyroclasts contain abundant splintery broken olivines in the rim, confirming their clastic nature. In rare instances juvenile pyroclasts (i.e., pyroclasts composed of crystallised kimberlite melt) might be present in VK beds. Some juvenile pyroclasts are complex in that they are, themselves, rimmed or coated by finer-grained, likely clastic material. DCK-L, the younger unit of the lower stratigraphy, shows an upward decreasing abundance of angular broken olivine (Figs. 3, 4). The unit contains only rare diffuse selvages around olivine crystals; this type of selvage is more commonly observed in DCK-U (see below). The DCK-L₁ unit is overlain by country rock breccias (CRB-L₁).

The VK-U₁, the oldest unit from the upper stratigraphy within the VNW pipe, consists of abundant broken olivines (Figs. 3, 4), abundant heterolithic small (<1 cm) angular CRFs, and small (50 μm–5 mm) irregular shaped variably vesicular juvenile pyroclasts (Fig. 5; see also fig. 5C of Webb et al. 2004). Uncored juvenile pyroclasts dominate over cored examples, and the vesicularity varies from 0 to 10 vol.%. In addition to juvenile pyroclasts, VK-U₁ also contains 1–4 mm rim-type accretionary pyroclasts (sensu Schumacher and Schmincke 1991) featuring a core of coarse to fine ash (<100–200 μm) and a 100–400 μm thick fine ash (<25–50 μm) rim (Fig. 5C). The coherent DCK-U, the next unit of the upper stratigraphy, contains non-vesicular spherical 1–8 mm diffuse fine-grained selvages surrounding olivine crystals in the upper outer portions of the deposit, as well as the central and deeper levels of the deposit (Fig. 5). The selvages are interpreted as partly coalesced juvenile pyroclasts (van Straaten et al. 2011). The unit contains minor angular broken olivines in the lower part and negligible proportions of angular broken olivines in the upper part (Figs. 3, 4). The volumetrically small and centrally located VK-U₂, another unit in the upper stratigraphy, contains no significant angular broken olivines (Figs. 3, 4), and the pyroclasts are generally 1–15 mm in size and spherical and cored in shape. Only the rare larger (>5 cm) juvenile pyroclasts contain some vesicles (~0–5 vol.%). The overlying VK-U₃ does not contain significant angular broken olivine either (Figs. 3, 4) and consists mainly of 3–10 mm non-vesicular cored pyroclasts (Fig. 5). The VK-U₃ unit is overlain by country rock breccias (CRB-U).

An important difference between lower volcaniclastic units in each eruption cycle (BK-L₁ and VK-U₁) and later more voluminous clastogenic coherent (DCK-L₁, DCK-U) and volcaniclastic (VK-U₂, VK-U₃) kimberlite units is the large difference in the abundance of CRFs. It decreases from 20%–80% in the volcaniclastic units to 5%–10% in the coherent units (fig. 3 of van Straaten et al. 2009). We also studied abundances of fine-grained opaque minerals in all units. Our observation on modes of 10–50 μm spinel and perovskite in the VNW pipe indicate more abundant opaques in the upper volcaniclastic units (3–4 vol.%; BK-L₁, VK-U₁; Fig. 6A), as well as in the clastogenic coherent lithologies (4–5 vol.%; DCK-L, DCK-U; Fig. 6B). The remaining volcaniclastic units (VK-U₂, VK-U₃)
The lower volcaniclastic units in each eruption cycle (BK-L1 and VK-U1) are typical of an early voluminous pipe infill, removed by later exploitation (van Straaten et al. 2011). Along the same lines of evidence, we observe pervasively shattered olivines (Fig. 3), abundant small (<1 cm) angular CRFs, and ash-armoured crystals/lithic clasts. In addition, the deposit is generally CRF-rich, with metre-scale bedding defined by varying abundances of CRFs (fig. 3 of van Straaten et al. 2009). Because the BK-L1 unit occurs as a thin veneer onto the steep-sided pipe walls, we did not sample the BK-L1 unit with the same frequency as described above, but, in addition, variably vesicular, uncored, small, irregularly shaped pyroclasts as well as rim-type accretionary pyroclasts are present. The irregular shape and the variably vesicular nature of the juvenile pyroclasts in unit VK-U1 could be explained by quenching of variably vesicular magma due to interaction with water.

Another important indicator of the eruption mechanism is the presence of surface water at the VNW pipe emplacement, and the likelihood of fully charged aquifers. We suggest that the remaining kimberlite deposits (DCK-L, DCK-U, VK-U2, VK-U3) are formed by magmatic eruptions. The DCK-U unit is unequivocally formed by magmatic eruptions (van Straaten et al. 2011), based on an origin as a coalesced firefountain deposit. Coalesced (or reconstituted rocks, van Straaten et al. 2011) can only form during magmatic eruptions. We assume DCK-L is a completely new kimberlite deposit, based on similar textures and relative position within the pipe. The relatively high proportion of broken olivine in the lower DCK-L indicates that crystals are still actively breaking, while at the same time coalescence processes are taking place. We infer that the olivine crystals break as a result of tensile failure due to the shock waves accompanying high-energy phreatomagmatic eruptions (e.g., Wohletz 1986) rather than by massive decompression accompanying gas exsolution associated with magmatic eruptions. As such, the presence of broken olivine crystals in the lower parts of the DCK-L and DCK-U might indicate a phreatomagmatic component during the early stages of DCK formation. Such simultaneous phreatomagmatic and magmatic eruptions are not uncommon in basaltic systems (Kienle et al. 1980).

The remaining units in the upper stratigraphy of the VNW pipe (VK-U1 and VK-U2) are most likely formed by the same magmatic eruption that formed the DCK-U. Evidence for this includes the fact that the VK-U1 is enveloped by the DCK-U, contains identical juvenile pyroclasts, has similarly low angular olivine abundance, and likely contains gradational contacts with DCK-U (Fig. 3 of van Straaten et al. 2011). Along the same lines of evidence, we
suggest that VK-U3 is formed by magmatic fragmentation; it has similar textural characteristics and likely gradational contacts to VK-U2 and DCK-U. As discussed in van Straaten et al. (2009), some or all of VK-U3 could have been derived from redistribution of tephra ring material.

Evolution of emplacement styles

The emplacement history for the VNW pipe can be subdivided into two volcanic cycles, each consisting of three eruptive phases. Each cycle starts with phreatomagmatic crater excavation and infill, followed by magmatic eruptions and concluding with mass wasting (Fig. 7).

Phase A of cycles 1 and 2 is characterized by high fragmentation intensities accompanying phreatomagmatic crater excavation. The magma–water interaction resulted in abundant broken olivines, a high abundance of CRFs, an insignificant loss of fine ash, and the presence of accretionary pyroclasts. Magmatic Phase B fills the VNW pipe with clastogenic extrusive rocks formed by lava fountaining. Magmatic eruptions at this phase gradually decrease in explosivity and fragmentation intensity, as recorded by the decreasing abundance of broken olivines. The first and second eruption cycles left partially open holes, filled at Phase C with pipe wall collapse breccias and resedimented kimberlite deposited in standing water as a result of mass wasting of tephra ring material.

Our study provides the first indication that the evolution from phreatomagmatic to magmatic eruption style is present in kimberlite volcanoes. Transitions from phreatomagmatic to magmatic eruptions, like those recorded at the VNW pipe, are commonplace in basaltic volcanic systems around the world and are typically achieved by an increase in magma flux, depletion of water within the local aquifers, destruction or sealing of porosity within the in situ country rocks, or changes in the volatile content of the magma (e.g., Lorenz 1986; Cas and Wright 1987; Houghton and Schmincke 1989; Houghton et al. 1996; Carey et al. 2009; Di Traglia et al. 2009). The fact that kimberlites share this eruption pattern with non-kimberlitic volcanoes testifies to the volcanological similarities of these systems. Until recently, kimberlites have generally been interpreted as erupting in a single, non-evolving style, and authors have been strongly divided on whether kimberlites erupt magmatically or phreatomagmatically (Field and Scott-Smith 1999; Sparks et al. 2006; Lorenz et al. 1999; Kurszlaukis and Lorenz 2008). To date, only one kimberlite pipe has been shown to include both magmatic and phreatomagmatic eruption processes; at the Fox kimberlite pipe, Porritt and Cas (2009) provided evidence for a progression from magmatic to phreatomagmatic emplacement. Importantly, transitions from magmatic to phreatomagmatic fragmentation within one eruption are much less common within the geological record (e.g., Fisher and Schmincke 1984; Cas and Wright 1987).

An interesting feature of the VNW pipe emplacement history is the repetition of the phreatomagmatic to magmatic eruption to quiescence cycle. Detailed volcanic facies analysis of the VNW pipe (van Straaten et al. 2009) identified angular cognate lithic clasts within the VK-U1 unit, likely derived from the lower pipe succession. These observations indicate that the time gap between cycles 1 and 2 was long enough to allow for lithification of at least some of the early deposits. In addition, formation of pipe-wall collapse CRBs and resedimented VK deposited within standing water suggest a significant period of volcanic quiescence, accompanied by recharging of the aquifers and (or) input of surface water into the crater. This allowed for effective magma–water interaction during the onset of cycle 2. Adjacent and overlapping
maars and tephra cones, as well as the development of new vents within earlier-established craters, are commonplace in basaltic volcanic fields (e.g., Cas and Wright 1987). Similarly, the VNW pipe represents a location where two volcanic events followed the same feeder system and formed coincident volcanic craters.

Textural criteria for recognition of phreatomagmatic kimberlites

Our study allows us to formulate textural criteria that distinguish kimberlite deposits formed by phreatomagmatic eruptions from those formed by magmatic eruptions. As in basaltic to rhyolitic systems, phreatomagmatic kimberlite deposits are fine grained, poorly sorted, generally CRF-rich, and contain variably vesicular pyroclasts and accretionary pyroclasts. Characteristic textures resulting from phreatomagmatic fragmentation in kimberlite deposits are a reflection of the relatively low melt viscosity, as well as the crystal-rich nature of kimberlite magma. The low melt viscosity and low glass-transition temperature results in the absence of blocky glassy ash particles, common in non-kimberlitic phreatomagmatic deposits. The crystal-rich nature of the melt, coupled with high fragmentation intensities, causes abundant angular broken olivines. These broken olivines, as well as the relatively low degree of loss of fines and the weak ash elutriation are suggested to be hallmarks of phreatomagmatic kimberlite deposits. In this context we suggest that any kimberlite deposit that contains abundant evidence for high fragmentation intensities (i.e., angular broken olivines, small angular CRFs, small juvenile pyroclasts) combined with a lack of loss of melt (i.e., opaques) should be investigated for a possible phreatomagmatic origin.

Conclusions

- Detailed observations of all volcanic facies within the VNW pipe suggest emplacement in two volcanic cycles, each consisting of three repeated eruptive cycles summarized as follows.
  - Pyroclastic kimberlite formed at the start of both cycles is characterized by the presence of fine-grained, poorly sorted deposits containing broken olivine crystals; angular CRFs; accretionary lapilli; and variably vesicular, irregularly shaped juvenile pyroclasts. All observations indicate that these deposits are formed by phreatomagmatism.
  - Subsequent clastogenic extrusive coherent kimberlite deposits are formed as a result of Hawaiian fire-fountaining during the second phase of both cycles.
  - These phases are followed by mass wasting into the partly filled crater.

- This study provides the first indication that the evolution from a phreatomagmatic to magmatic eruption style is also present in kimberlite volcanoes, suggesting kimberlite volcanism is not significantly different from more common basaltic to rhyolitic systems.
- This research indicates that high fragmentation intensities recorded by the presence of broken olivines, accretionary lapilli, abundant (angular) CRFs, and retention of ash are important textural criteria for recognition of phreatomagmatic kimberlite deposits.

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