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Canadian Kimberlite Pipe Morphology: Insights from Analogue Experiments

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Introduction

Hundreds of kimberlites have been discovered in Canada in the last three plus decades. The first ~100 pipes were found in two new provinces in 1988-1989 (Fig. 1). It was apparent that the infills of these pipes, now termed Fort à la Corne-type Pyroclastic Kimberlites (FPK), are distinct from the well-characterized pipes of southern Africa now termed Kimberley-type Pyroclastic Kimberlites (KPK). The 1991 discovery of the Lac de Gras province led to the Canadian Diamond Rush and to the opening of seven diamond mines. The first province containing KPK-type pipes was found in 1995. By the end of 2010 there were >900 known kimberlites in Canada. The KPK-type pipes are broadly like those of southern Africa: steep-sided pipes infilled with HK-KPK. In contrast, the shape, infill and implied emplacement models of the FPK-type pipes are quite different. Figures 1 and 2 summarize observations establishing a correlation between the physical properties of the host rocks (i.e. competence) and the type of kimberlite pipe, differences likely resulting from fundamentally distinct styles of eruption. Newton et al. (2017) used a series of analogue experiments to test and inform on the hypothesis that: *host rock competence determines the morphology of kimberlite pipes (e.g. width, depth, shape)*. The experimental results reproduce a range of "pipe" properties similar to those observed in Canadian kimberlite bodies and support the hypothesis. As the 12th International Kimberlite Conference is celebrating '30 Years of Diamonds in Canada' it is warranted to revisit Newton et al. (2017) to highlight certain aspects of the experimental results and expand on the discussion. This is especially significant given the importance of more accurately predicting pipe morphology from exploration to resource development and mining.

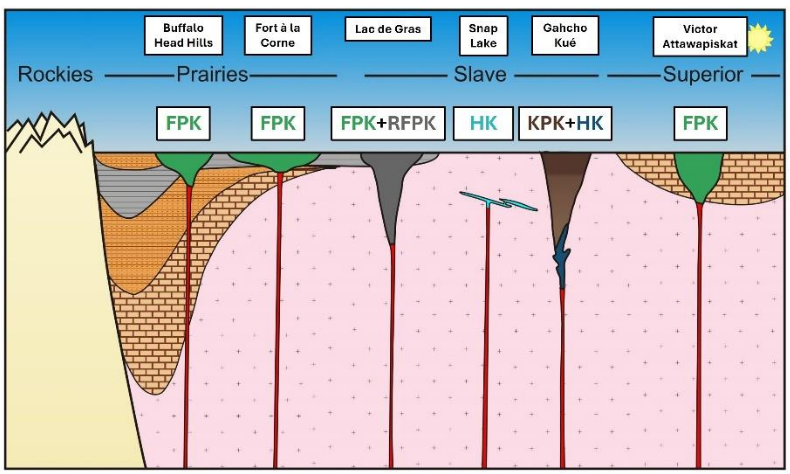
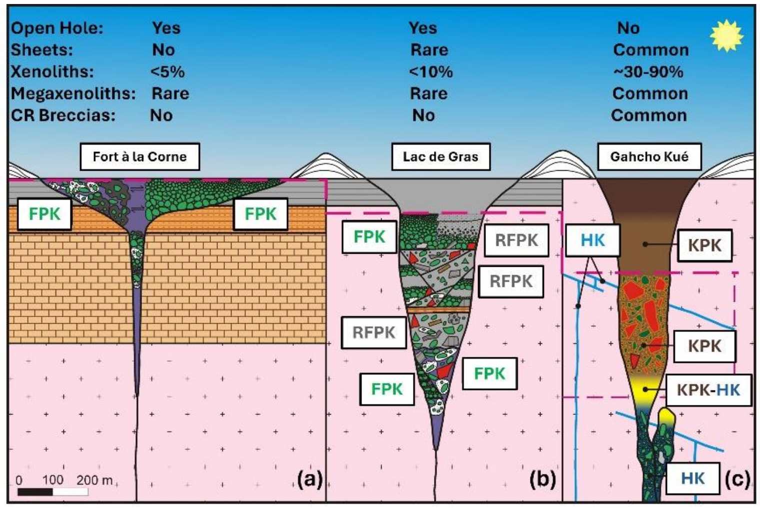


Figure 1: Schematic cross-section across Canada showing the contrasting pipe shapes and infills and correlation with geological setting (after Field and Scott Smith 1999; Scott Smith 2006). Geology: Basement - pink. Sediments: lithified carbonates – pale brown; siltstone – orange; poorly consolidated shale – grey.

Methods

Analogue experiments conducted by Newton et al. (2017) were designed to test the influence of host rock properties on pipe formation processes in 3 different host rock settings. The experiments use a clear acrylic tank, connected at its base to an 8 mm inner diameter hose supplying compressed air at a regulated pressure of 90 psi (0.6 MPa) which simulates the explosive eruption of kimberlitic volatiles. The tank is layered with variably wetted sand to serve as an analogue for the near-surface rocks through which the gas jet travels.

Figure 2: Geology of three kimberlite provinces from Figure 1 reconstructed to the time of emplacement (pink dashed lines indicate current levels of exposure; after Scott Smith 2008). The two FPK-type pipes illustrate end member pipe shapes: (a) large shallow bowl-shaped pipes as found at Fort à la Corne, Saskatchewan; (b) steep-sided pipes from Lac de Gras containing significant RFPK. (c) steep-sided KPK-type pipes. Country rock geology as in Figure 1. The text above the pipes highlights observed contrasting features in each pipe that are important to pipe formation processes.



Three materials were used to represent poorly consolidated sediments, lithified sediments, and basement, respectively (Fig. 3). Each analogue material uses the same subangular silica sand as the starting material. Unconsolidated sediments are represented using only dry sand. Wetting the dry sand with 8–10 wt.% ethanol forms an intermediate strength analogue material representing lithified sediment and wetting with 8–10 wt.% water forms a competent analogue material representing crystalline basement rocks. The relative thicknesses of the analogue materials are comparable to those of host rock sequences in the type localities of the three pipe classes as shown in Figure 2. Compressed air was released in pulses lasting 4 seconds followed by 2 second breaks. Experiment trials were recorded each using a Nikon digital camera and analyzed using ImageJ to measure the final pipe geometry.

Results

The experiments of Newton et al. (2017) showed that the configuration of analogue materials governs the pipe formation processes and final morphology of the resultant analogue pipes (Fig. 3). Final pipe morphologies compare well with the corresponding pipes shown in Figure 2 and are controlled by the angle of repose of the relevant material. The excavation process in Fort à la Corne (FPK) experiments was extremely fast (~3 seconds). The gas pressure cleared an open crater within the first gas-pressure pulse, subsequent pulses passed through the vent without further modification to the crater shape (i.e. diameter and depth). The model pipes, resulting from the FPK analogue experimental set-up, consist of wide, shallow angled craters (Fig. 3a). The excavation process observed in Lac de Gras analogue experiments was slightly longer (15 seconds), requiring 3-4 gas pulses

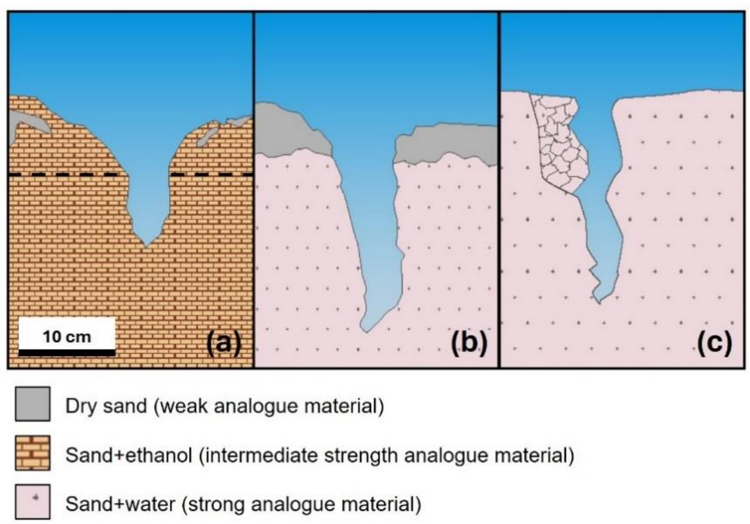


Figure 3: Example final pipe morphology for each of the three experiments for which the analogues represent the pipes (a), (b) and (c) in Figure 2. (a) Fort à la Corne FPK-type pipe analogue experiment. Dashed line indicates initial position of contact before 'eruption'. (b) Lac de Gras FPK-type analogue experiment. (c) Gahcho Kué KPK-type pipe analogue experiment.

to break up the competent analogue material and clear a pipe. Unstable crater rim deposits comprising analogue materials repeatedly slumped into the pipe and required ‘re-clearing’ of the vent. At the end of the experiments, the Lac de Gras (LdG) analogue pipes featured a steep pipe overlain by a shallow angled crater (Fig. 3b). Our KPK-type experiments were an order of magnitude longer in duration than LdG-type, requiring many gas pulses over a period of 3 minutes. The excavation process required formation of vertical and horizontal fractures resembling intrusive sheet locations and subsurface breccia zones to slowly break up the competent material and allow breakthrough to surface. Much of the substrate failed to leave the pipe even after wall stability has been reached. KPK-type analogue pipes are steep and narrow, with ~50% of its volume consisting of remaining competent analogue material that failed to leave the pipe. (Fig. 3c).

Discussion

Experimental results support the hypothesis that the excavation processes and final morphology of kimberlite pipes can be dictated by the characteristics of surface host rocks (Scott Smith 2008) and that variations in infill geology can be attributed to these excavation processes. In our FPK-type pipe (a) experiments, air pressure quickly opens a crater through a weak substrate. In this scenario, later magma would be allowed to exit the vent and be deposited back into a wide crater as primary pyroclastics. In our LdG-type pipe (b) experiments an open pipe again clears rapidly. However, in this scenario the open pipe is narrow and steep-sided. Much of the material leaving the vent would accumulate on the crater rim. Pipe infill in this case could likely include primary pyroclastic deposits and resedimented material that has slumped back into the pipe from the crater rim. Our experiments in the KPK-type pipe setting are markedly different. Pipe excavation here is a longer process that involves subsurface brecciation of more competent substrate before the pipe opens to surface. In this case, magma would not exit the vent but would instead be forced into fractures and breccia zones in the host rock. Pipe infill would likely be characterized by host rock xenoliths and the products of prolonged mixing of host rock and magma. Conceptually, kimberlite eruptions can be initiated by a gas-rich phase that precedes and is decoupled from the main magma (Wilson and Head 2007). It is this gas-charged precursor that does much of the work of pipe excavation and, in both FPK-type pipes, low overburden pressure allows for rapid excavation of an open pipe. Subsequent melt-dominated eruptions are deposited into a largely empty pipe resulting in primary pyroclastic pipe infill. In contrast, the increased overburden pressure in the KPK-type pipe results in the arriving magma being confined subsurface and required to navigate the fracture and breccia zones in the host rock rather than continuing to the surface. This results in the filling of fractures and breccias in the host rock and mingling of magma and host rock xenoliths in a still pressurized subsurface system.

Summary

1) Sandbox experiments were conducted in three distinct analogue host-rock settings (Fig. 3).
2) The classic pipe morphologies observed in these three settings can be reproduced experimentally by altering host rock competence alone.
3) In both FPK-type pipe experiments (Fig. 3a, b) open pipes are cleared within seconds, while KPK pipes (Fig. 3c) require prolonged subsurface brecciation before breakthrough.
4) The nature of pipe infill can be controlled by the strength of the surficial rock into which they are emplaced, and the resulting open (FPK) or closed systems (KPK) that arriving magma will enter.

References

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