DIATREMES AND KIMBERLITES. 2: INTEGRATED MODEL OF THE ASCENT AND ERUPTION OF KIMBERLITIC MAGMAS AND PRODUCTION OF CRATER, DIATREME, AND HYPABYSSAL FACIES: J. W. Head\(^1\) and L. Wilson\(^2\). \(^1\)Dept. of Geol. Sci., Brown Univ., Providence, RI 02912 USA; \(^2\)Lancaster University, Lancaster, UK, james_head@brown.edu

**Introduction:** We have summarized the definitions and characteristics of kimberlites and diatremes and assessed the major factors that need to be explained in any model for the formation of these features. These include [1,2]:

1. Lack of extensive extrusive deposits.
2. Lack of exposed plutonic complexes.
4. Tripartite division into crater, diatreme and hypabyssal regions and the distinctive facies associated with each of these.
5. The volatile-rich nature, dominantly carbon dioxide.
6. The implied low temperatures of their emplacement.
7. The nature and distribution of country rock inclusions.
8. The nature and distribution of mantle xenoliths.
9. The presence of diamonds.
10. The presence of wide parts of the dikes.
11. The presence of "blows".
12. The configuration of contemporaneous and internal dikes.
13. The general lack of subsequent dikes.
14. Their apparently rapid emplacement.
15. The presence of olivine-cored pelletal lapilli with surrounding usually altered quenched kimberlitic melt or glass.
16. The paucity of thermal metamorphism.
17. The carrot-shaped nature of the diatreme.
19. Vesicles and composite lapilli commonly absent.
20. Presence of glass and rapid quenching.
21. Pronounced sphericity of lapilli and 1-10 mm size.
22. Angular xenoliths from local rocks and smaller amounts of more rounded lower crustal and mantle material.
23. Country rock xenoliths from uppermost part of stratigraphic section exposed deeper within diatreme.

**The model:** On the basis of these constraints and characteristics, we outline a model for the formation of diatremes as a result of eruptions of kimberlite magmas based on the availability of copious carbon dioxide in the mantle source. We suggest that essentially all of the rise to the surface takes place via propagation of a dike, which minimizes thermodynamic problems associated with transporting diamonds from mantle depths. Magma in the tip of the initially propagating dike attempts to reach a low pressure to maximize the flow rate and so a finite region below the tip contains CO\(_2\) fluid, the pressure in which is maintained at the solubility limit of this volatile phase in the magma. Consider a melt starting at a depth of ~100 km, where the pressure is ~3 GPa. This melt could contain as much as 20 weight % of CO\(_2\); the pressure-dependent solubility of this volatile is such that the dike tip pressure would be buffered at ~2 GPa and compressive fracturing of host rocks would occur over most of the vertical extent of the dike. The pressure difference driving the dike magma (source pressure minus tip pressure) would be fixed at 1 GPa, and by the time the tip reached shallow depths the pressure gradient would still be ~10,000 Pa/m, several times larger than the gradients driving basaltic eruptions from shallow magma reservoirs and leading to rise speeds of up to a few tens of m/s. As the dike tip nears the surface, equilibrium volatile release can no longer be maintained and a foam of CO\(_2\) fluid bubbles develops in a vertical zone at least a few km long. When the tip breaks the surface, the pressurized CO\(_2\) fluid escapes rapidly to the atmosphere and a dramatic pressure decrease occurs in the shallow part of the dike, imploding the already fractured dike walls and creating brecciated country rock around the dike. The wave of depressurization propagates into the magma releasing more CO\(_2\), and fragmenting and cooling the magmatic liquid. The expanding gas then accelerates the chilled pyroclasts into the brecciated host rock in an upward wave of fluidization.

**Steps in the Eruption Sequence:** Using this basic concept of generation, ascent and eruption, we outline the stages in the eruption sequence and describe the features that form during each stage.

**Stage 1. Crack tip propagation out of deep source region and CO\(_2\) fluid segregation:** Low pressure region in propagating dike tip produces copious quantities of liquid CO\(_2\) in the mantle source; this segregates and floods the propagating dike tip region. The supply of CO\(_2\) is constantly renewed by streaming of degassed magma to the sides of the dike, exposing fresh magma in the dike center.

**Stage 2: Equilibrium volatile release and wall fracturing:** Magma rise speeds are a few 10s of meters per second. The dike tip pressure is buffered at ~2 GPa during the entire rise to the surface but the external pressure decreases due to decreasing overburden. Wall rock adjacent to the propagating dike is fractured; country rock is torn from the walls to become xenoliths, and quickly sinks through the CO\(_2\) fluid to become engulfed by and incorporated into the magma. The differential increases toward shallower depths and thus the stresses and wall rock damage will be greater, but the geometry of dike emplacement means that there is no place for the fractured wall rock material to go after the dike passes unless it is plucked from walls by ensuing flow of magma. The relative abundance of xenoliths produced by dike tip and wall rock fracturing will be a function of rock strength and position in the crust relative to the evolving differential stress; the most important factor will be the elapsed time that the wall rocks are exposed to dike emplacement, favoring deep xenoliths.

**Stage 3: Dike tip nears surface, disequilibrium produces magmatic CO\(_2\) foam:** As the dike tip nears the surface, there is continued compression and fracturing of the walls, and the possibility of intrusion of small dikelets due to the decreasing overburden pressure. Decompression and rapid vertical growth of the CO\(_2\)-
Stage 4: Dike tip breaks surface, vents gas, implodes walls: The propagating dike tip is convex upward and first reaches the surface in the highest central point, immediately venting the upper CO₂ gas slug in the dike; upon being exposed to the surface, the gas velocity increases from the ~20 m/s rise speed of the dike to ~300 m/s, producing a classic Prandtl jet into the atmosphere. The dike will immediately centralize along the widest portion (almost certainly the central part that reaches the surface first) and the remainder of the upper part of the gas filled dike will immediately close, leaving a linear fractured and crushed zone with little to no evidence of associated magma. In the central vent itself, the break-through and the ensuing gas jet will rip wall rock from the uppermost country rock, and the proportion of shallow country rock should be high in the initial rim deposits. Some of the magmatic foam must also vent at this time. At the same time, the sharp decrease in pressure caused by the gas venting implodes the walls of the upper part of the dike.

Stage 5a: Depressurization wave propagates into magma: At this point, the depressurization wave caused by the gas venting propagates back down into the magma and more CO₂ is released in the magma portion of the dike, forming additional foam during gas expansion. This expansion causes fragmentation of the magma while at the same time cooling it considerably. CO₂ gas expansion under these pressure and temperature conditions would create the following conditions: 1) gas expansion would be dramatic, creating a foam with much greater than half the available space being gas; 2) the intervening magma would form into spheres to optimize surface area to volume; 3) spheres would tend to nucleate around any solid particles in the rising magma (olivine phenocrysts, xenolithic grains); 4) abrupt and very rapid adiabatic cooling of these particles would occur to produce glassy or microcrystalline spherules, cored by phenocrysts and xenoliths; 5) cooling would be so rapid (going from magmatic to room temperature in seconds) that welding of particles and agglutinization would be uncommon.

Stage 5b: Gas expansion creates upward fluidization wave, accelerates chilled pyroclasts: The gas expansion in the dike created by the gas venting produces an upward wave of fluidization in the shattered country rock that is the major cause of the formation of the diatreme itself. The combination of foam disintegration in the upper part of the dike below the gas phase, and the further foam formation and disintegration in the magma below the initial magmatic foam zone, is together responsible for the upward fluidization wave. This produces a cold stream of gas through the upper part of the zone, which contains cooled spherules and fine-grained particles which migrate thorough the upper fractured zone and vent to the surface. The gas stream should preferentially carry fine-grained cooled magmatic material to the surface, along with cooled spherules. Variations in pressure will cause instabilities in the gas exsolution and flow and this will introduce waves of gas release, pressure changes and venting. This will create a series of fluidization waves (a ‘ringing’) that will last several tens of minutes. During this time, continual readjustments in the diatreme will be taking place as waves propagate back and forth, and particle-containing cool gas flow permeates the diatreme zone and vents to the surface. This fluidization will also cause sorting in the brecciated diatreme zone and settling of some of the country rock from the upper part of the column down into deeper parts of the diatreme. This disruption phase will also serve to modify, distort and destroy evidence of earlier stages of dike emplacement. During this time, the magma deeper in the dike itself will quickly undergo catastrophic chilling and thus will cease to rise into the diatreme. The deposits on the surface should be characterized by a basal coarse breccia from the initial venting, followed by coarse fragments, xenoliths and lapilli from the initial magmatic foam phase, followed by deposits dominated by products from the second magmatic foam phase (chilled glass lapilli and ash). Rise of magma into the vent and subsequent ponding or flows are not predicted.

Stage 6: Event Aftermath: Following the event, the deposits will be characterized by a porous cone-shaped diatreme surrounded by a crater rim of breccia and pyroclastic deposits. If the diatreme forms in an active groundwater area, a crater lake is likely to form and groundwater will permeate the diatreme, quickly altering the primary mineralogy. Although the surface deposits are similar in some ways to tuff cones and maars formed by hydrovolcanic processes, no part of this model requires interaction of the rising dike with groundwater. Although this could happen, the very rapid chilling of the magmatic foams minimizes the likelihood of prolonged and repetitive hydrovolcanic eruptions occurring during formation of these features.

Conclusions: This model for the ascent and eruption of kimberlitic magma accounts for the major observational characteristics of kimberlites and diatremes as outlined in [2] and summarized in the introduction. Lack of abundant CO₂ could result in kimberlite dike intrusions and eruptions without diatreme formation, more similar to traditional basaltic pyroclastic eruptions.