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Thomas M. Gernon[*] Mark A. Gilbertson[†]
R. Stephen J. Sparks[‡] Matthew Field[**]

[*]Department of Earth Sciences, University of Bristol, U.K., Thomas.Gernon@bristol.ac.uk

[†]Department of Mechanical Engineering, University of Bristol, U.K., m.gilbertson@bristol.ac.uk

[‡]Department of Earth Sciences, University of Bristol, U.K., Steve.Sparks@bristol.ac.uk

[**]De Beers MRM R&D Group, Wells, U.K., Matthew.Field@DTC.com

TAPERED FLUIDIZED BEDS AND THE ROLE OF FLUIDIZATION IN MINERAL EMPLACEMENT

Thomas M. Gernon[1]*, Mark A. Gilbertson[2], R. Stephen J. Sparks[1] and Matthew Field[1,3]
[1]Department of Earth Sciences; [2]Department of Mechanical Engineering;
University of Bristol, Bristol, BS8 1RJ, United Kingdom
[3]De Beers MRM R&D Group, Mendip Court, Bath Road, Wells, BA5 3DG, United Kingdom
* T: +44-117-954-5244; F: +44-117-925-3385; E: Thomas.Gernon@bristol.ac.uk

ABSTRACT

One of the most prominent features of fluidized beds is their ability to mix and segregate. This is of great importance for many industrial processes, but takes on a particular significance for mineral extraction where a small amount of valuable matter is mixed with a large amount of waste. In this study we consider the occurrence of diamonds in the volcanic rock called "kimberlite". These are often emplaced (erupted and deposited) in large volcanic pipes commonly referred to as "diatremes" (length scale of the order of a kilometre) with a vent at the bottom through which the minerals were introduced along with other fragmental particulate matter and a gas flow. The purpose of this study is to gain an understanding of the processes that led to the dispersal of minerals before their emplacement to allow efficient extraction. The paper describes experimental observations of a tapered fluidized bed. The objective was to identify the physical behaviour of gas and particles; so, of particular interest are the extent to which fluidization takes place within the bed, and the arrangements of particles seen. Gas flow-rate, particle size, and degree of taper were all varied. These observations can be used to identify the structures and processes that can take place; it is then possible to understand field data in terms of the physics that led to the emplacement of material. This will be shown using new data taken from southern Africa. Scale-up of evidence is of obvious difficulty in this system and this is discussed in terms of the possible behaviour of the bubbles that have generated mixing of material before emplacement.

INTRODUCTION

One of the most prominent features of bubbling fluidized beds is the degree of mixing they allow. The main agent of the mixing is the gas bubbles that form in the bed (Baeyens and Geldart (1); Shen *et al*. (2, 3); Lim *et al.* (4)). They drive circulation by entraining particles laterally into their vortex region and dragging particles vertically upwards in their wake, and through the action of drift (the kinematic distortion of material surfaces through the passage of an object such as a bubble) (Eames and Gilbertson (5)). This upward axial movement of particles is

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compensated by a downward movement of particles along the margins, known as "gulf streaming" (Rowe *et al.* (6)). This return flow is a result of mass conservation: the bubbles move up the centre of the bed, so the return flow must be at the edge. Furthermore, many practical fluidized beds contain mixtures of different particles and the degree of segregation or mixing of the different types of particle is also dependent on the local gas velocity and the bubble distribution (Gibilaro and Rowe (7); Wu and Baeyens (8); Gilbertson and Eames (9)).

Mixing is determined by the distribution of bubbles within a fluidized bed, which is affected by the shape of the bed. Studies of bubble distribution have been dominated by planar and cylindrical beds and it is not clear how it is affected by the presence of tapered walls. Furthermore, the gas velocity within a bed that does not have parallel walls will vary, affecting both fluidization and segregation behaviour within the bed. A further important consideration is the effect of scale on the bubble distribution and hence mixing within the bed.

A field where these considerations are critical is mineral emplacement and extraction. Fluidization is thought to be an important process during the transport and deposition of buoyancy-driven density currents (e.g. pyroclastic flows), giving rise to mixing and segregation (Sparks (10); Wilson (11, 12); Roche *et al.* (13)). The deposits of these flows contain rock inclusions of different sizes and densities that are often randomly scattered within the deposits. Segregation is also evidenced in the deposits, usually by a dense-particle rich basal layer and vertically inclined gas-escape pipes.

Minerals are often emplaced as a result of volcanic activity where they are carried from within the Earth and dispersed within a large amount of non-valuable material. An important example of this is the emplacement of diamonds within a granular material called kimberlite. Kimberlite represents a mantle-derived ultra-basic type of rock. At near-surface levels, gas-rich kimberlite magmas become highly over-pressured and undergo explosive fragmentation, generating a gas-particulate system. Kimberlite is a fine- to very coarse-grained material, but can have a large amount of inclusions with sizes ranging from <1 mm to >1 m. It is emplaced in tapered pipes or diatremes, 0.5 – 1 km wide, with a volcanic vent at the bottom. Gas-fluidization is a favoured mechanism for accounting for the structure, geometry and degree of homogeneity observed in volcaniclastic kimberlites within diverging volcanic pipes or "diatremes" (Dawson (14, 15); Woolsey *et al.* (16), Clement (17), Sparks *et al.* (18), Walters *et al.* (19)). A photograph of a diatreme and the material found within it is shown in Figure 1. Often a very small amount of diamond is emplaced in a large amount of waste, from which it has to be separated. It is then very beneficial for a mining company to understand where diamonds are likely to be located within the diatreme. Understanding the volcanic processes that led to the emplacement of these rocks in tapered pipes is of importance for predicting the distribution of diamonds incorporated therein.

A good starting point is to gain an understanding of the dynamics of fluidization in confined tapered beds. In this study, a series of experiments have been undertaken to determine the gas-fluidization behaviour of single-sized particles in a confined tapered bed with rigid walls. The understanding of the behaviour in such a system will contribute to the understanding of deposits infilling a kimberlite pipe in the presence of a gas flow, however, in such a situation scaling of these observations up to the complex natural system is obviously important.

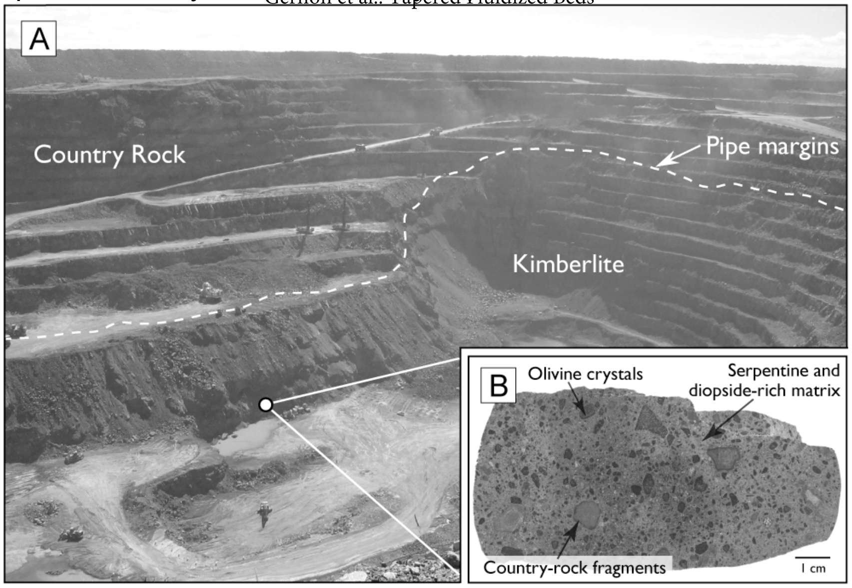

Figure 1: *(A) Photo of a diatreme currently being excavated, and (B) the kimberlite that is found within it.*

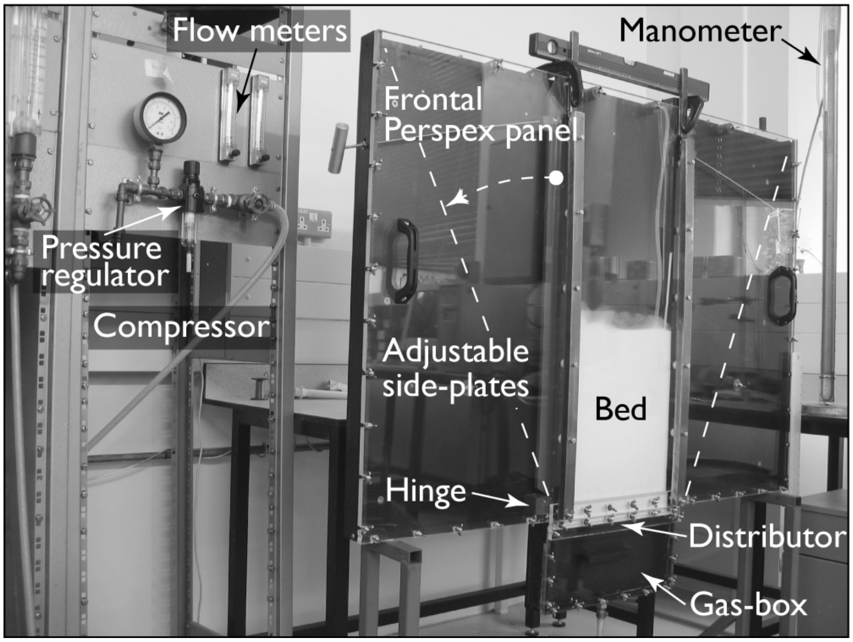

Figure 2: *Photograph of the experimental apparatus; apparatus is 1 meter in height.*

EXPERIMENTS IN TAPERED BEDS

The experimental apparatus is illustrated in Figure 2. Pressurized air is supplied to the gas box from a compressor and enters the bed through a porous distributor plate. The manometer records the point when the frictional drag of gas equals the bed weight (i.e. the fluidised condition, U_{mf} is reached). Particles used were approximately spherical ballotini (d = 45—90 μm [A-type] and 220μm [B-type]). In a set of experiments, gas flow-rate (Q), bed depth (h), particle size (d), and degree of taper (Θ) were all varied and observations of the bed regimes were made.

Experimental observations

Straight-sided fluidized beds are usually considered to be homogeneously fluidized, regardless of depth and particle size. However, in a tapered geometry this is not true, and the bed breaks down into different regions. Figure 3 is a schematic diagram of the structure of a tapered bed. Only a central region (A) is fluidized and the marginal regions remain non-fluidized (D) and the particles are generally immobile. These marginal regions overhang the fluidized zone and become narrower as the flow-rate increases and more particles become fluidized.

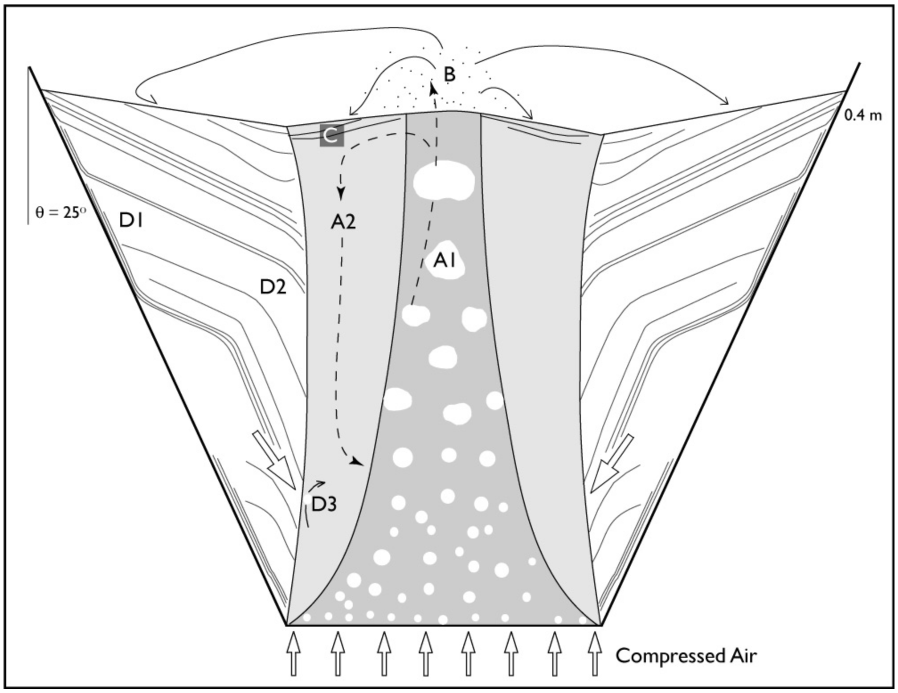

Figure 3: *Schematic diagram of the tapered bed regimes. See text for details.*

The central region can be split into two, with a central region (A1) where there are bubbles and a net upward movement of particles, and a marginal region (A2) where the particles are fluidized, but form a return flow. Upon reaching the surface, bubbles in zone A1 burst causing elutriation of fines (B), which deposit forming outward-dipping laminations (C) and inward-dipping laminations (C) nearer the margins at the top of zone D. At critically high gas velocities, marginal non-fluidized wedges become unstable and slip downwards into the fluidized region accounting for a “conveyor-belt”-type mechanism of particle transport. The generation of internal deformation structures such as marginal frictional drag fabrics (D1) and shear and splay faults (D2) was observed at this point. Decreasing the bed taper angle causes this failure and deformation to occur at lower flow-rates but does not significantly affect flow regimes. The behaviour is identical for both particle types, though fine particles exhibit anomalous channelling patterns in shallower beds (> 0.3 m).

The contrast between a straight-sided and a tapered bed is shown in Figure 4, along with the effects of bed depth and gas flow-rate. It can be seen that increasing the gas flow-rate increases the extent of the fluidized region of the bed, but this has a smaller effect as the gas speed is increased further. This is also shown in Figure 5, which shows the proportion of particle weight supported by the gas flow as the gas flow is increased. Figures 4 and 5 also demonstrate that, at a constant gas flow-rate, increasing the height of a tapered bed results in the central fluidized zone to move inwards to generate successively narrower fluidized chimney-like structures. These are similar to the nested "pipes-within-pipes" described in Walters *et al.* (19).

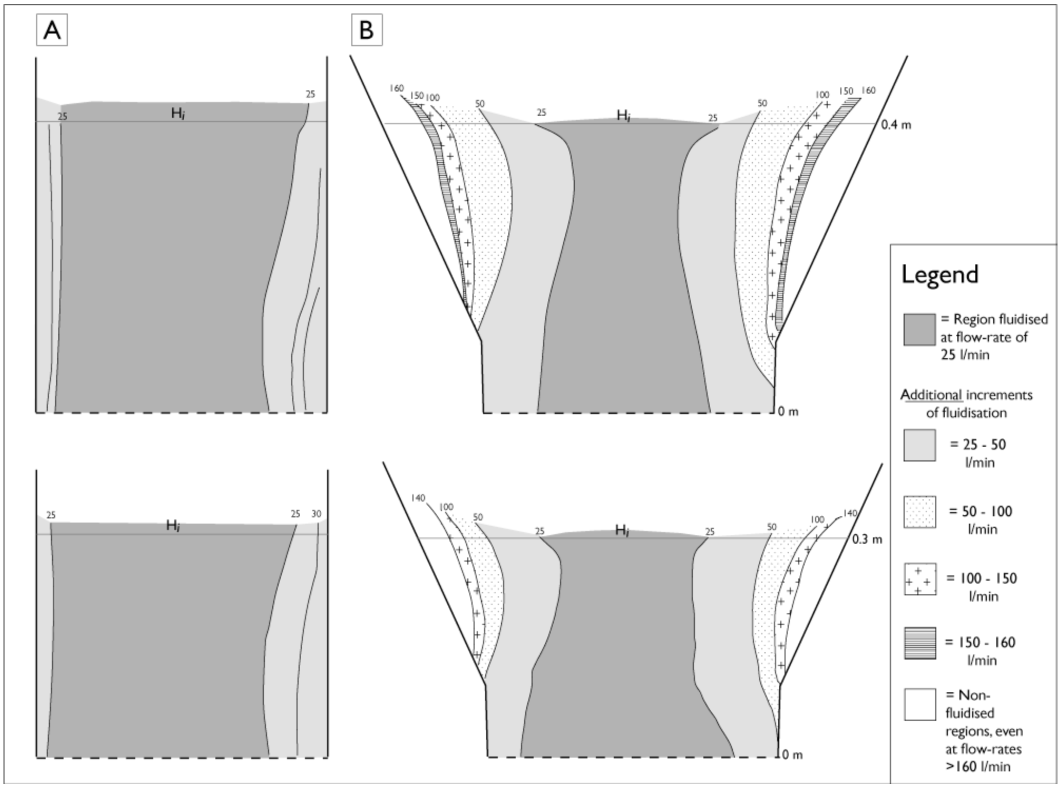

Figure 4: *Visually determined fluidized–de-fluidized profile: growth of the fluidized region of B-type particles with changing gas flow-rates (see legend for details), bed height (0.3 and 0.4 m) and taper angles (A) = 0°°, (B) = 25°.* H_i *marks the initial bed height. See text for full explanation.*

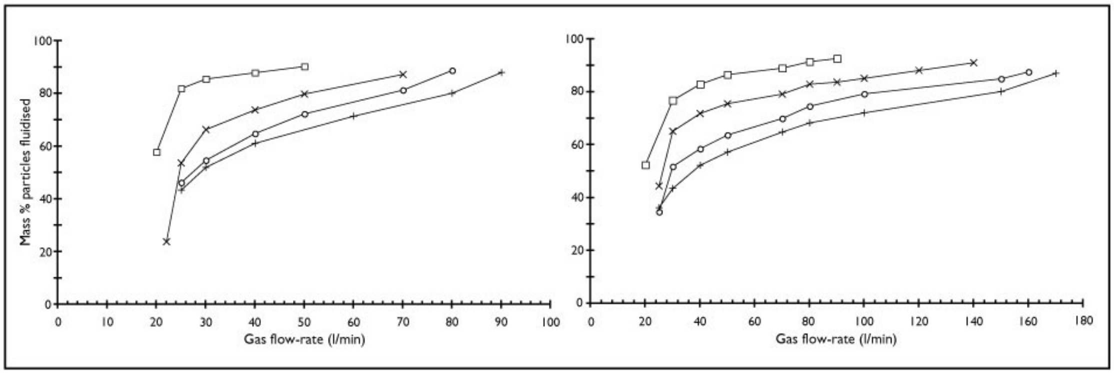

Figure 5: *Fluidization curves for the tapered beds for 15° on the left and 25° on the right. The pressure drop has been normalised with respect to the weight of powder in the bed. The different lines are for different depths of the bed:* ☐: *0.2 m;* ×: *0.3 m;* O: *0.4 m and* +: *0.5 m.*

DISCUSSION

The nature of tapered fluidized beds is inherently different from straight-sided ones because they become heterogeneous with large areas becoming de-fluidized. This will have large effects on the structure of the bed as the mobile particles and their mixing will be confined to the central region of the bed. If new material is introduced to the bed then it will be confined to the central region of the bed and the top surface.

There is obviously a very different scale between the laboratory experiments and full-scale industrial equipment, let alone geological systems. However, it is likely that the overall structure will be preserved at larger scales as the spatial extent of fluidization is controlled by the proportion and distribution of bubbles in the bed (Lim (20); Lim *et al.* (4)). Field data taken for this project from rock outcrops at three southern African kimberlite pipes (Jwaneng and Orapa, Botswana; Venetia, South Africa) demonstrates the occurrence of central zones characterised by intense mixing and marginal regions dominated by frictional shear features generated during the late stages of volcanic emplacement. In general, the emplaced solids are homogenous over the width of the bed, which suggests that, at least in the late stages of the eruption, fluidization was not very violent.

It has been shown that it is possible to simulate bubble behaviour using the kinematic model of Clift and Grace for the interaction between bubbles (Lim (20); Croxford (21)). We are currently adapting the simulated bubbling fluidized bed developed by Lim (20) to account for spatial and temporal bubble distributions in beds at different taper angles, bed heights, and scales. If the bubble distribution can be determined then the mixing within the bed may be inferred. Simulations involving the bubble phase represent the most powerful technique in predicting flow profiles in deep tapered beds. They will allow us to constrain the extent of the fluidization and degree of mixing in a deep volcanic pipe.

There are a number of other notable differences between the experimental measurements and full-scale situations (particularly in diatremes, which have depths of the order of a kilometre), which will need to be taken into account. One further effect of the large scale is that the gas will be compressible and the pressure at the bottom of the bed will be large. This will affect the gas velocities as gas passes up the bed, and the forms of the gas structures within the bed owing to the increased coupling between the gas and the particles, probably encouraging jetting (22).

A further difference between the experiments and practical situations is the nature of the material within the bed. For example, kimberlite is a material characterized by its high particle density, very large particle size-range and the highly variable particle shapes (which are rarely spherical). All these factors can cause uneven fluidization and the development of fluidized and non-fluidized cells and segregation within a bed. In addition, the large inclusions within kimberlite (size of the order of a metre or more) will locally affect the flow field and interact with one another.

A ROLE FOR FLUIDISATION IN KIMBERLITE EMPLACEMENT?

We have already published field, textural and experimental constraints that provide evidence for the occurrence of fluidization in massive volcaniclastic kimberlites

(Walters *et al.* (19)). These are that: (i) no other natural process could account for the degree of homogeneity observed in most volcaniclastic kimberlite deposits; (ii) the absence of fine ash particles can be explained by elutriation during fluidization, and (iii) steep internal contacts observed between volcaniclastic kimberlite units correspond to geometries produced experimentally by reducing gas flow-rates. We also present evidence for fluidization-induced segregation at several kimberlite pipes, in the form of gas-escape structures developed at a range of scales (Gernon *et al.* (23)).

This experimental study provides further insights into the role of fluidization in kimberlite emplacement. We imposed a mechanically rigid tapered geometry on the system and found that bubbling patterns changed, causing the generation of non-fluidized peripheral regions. The implications of these experiments are that in the waning stages of a kimberlite eruption, decreases in gas flow-rate or the addition of material to the pipe would both have the effect of narrowing the lateral extent of the fluidized chimney. The “conveyor-belt” effect described can account for the marginal sinking of “mega-blocks” of rock without undergoing significant deformation; it also explains marginal frictional drag fabrics and steep inward-dipping bedding – features observed in many kimberlite pipes (e.g. Jwaneng, Botswana).

Our experimental observations can be used to identify the structures and processes that can take place; it is then possible to understand field data in terms of the physics that led to the emplacement of material. Ultimately, an understanding of the processes that led to the dispersal of diamonds before their emplacement may lead to more efficient extraction procedures.

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