Institution: University of Bristol

Unit of Assessment: 7 – Earth Systems and Environmental Sciences

Title of case study: Kimberlite Diamonds: Advances in kimberlite volcanology research leads to the reduction of financial risk and alteration of strategy and policies within the diamond mining industry

1. Summary of the impact

Kimberlite research at Bristol has been a collaborative enterprise with De Beers over the past 10 years. The research investigating the geology of kimberlites, and understanding the processes that form them and their associated diamond deposits, has clarified their importance to the diamond mining industry, ensuring high quality geological information informs their commercial activities. The success of this initiative has led to procedures and strategies being changed within De Beers, and led to the mitigation of potential future losses in the form of a decreased risk of failure of a resource model. Typically, such resource models can be valued at between tens and hundreds of millions of pounds.

2. Underpinning research

Kimberlites are of great commercial interest because they are the primary source of diamonds. The origin of kimberlites has been a long-standing issue invoking some controversy **[a]**. Various factors have contributed to this controversy, such as (i) the lack of direct observations of kimberlite eruptions, (ii) the scarcity of preserved extrusive kimberlites, (iii) the unique environment of emplacement within deep volcanic conduits, and (iv) extensive alteration and lithification, which have either modified or eradicated the primary structures and textures. Despite these problems, it is of economic and commercial interest for the diamond mining industry to have a sufficient understanding of the formation and associated processes. Only small proportions are likely to be diamondiferous, many of which are considered subeconomic because the quality or quantity of diamonds is insufficient. Research at Bristol has addressed these issues as described below.

Prior to the collaboration described here (< 2003), the typical approach to kimberlites within the diamond mining industry was dominated by microscopy, with very limited understanding of the volcanology and outdated ideas that were focused on the petrological aspects of these rocks only; "*one of the major short-comings of the existing knowledge applied to diamond-hosting ore-bodies (mainly kimberlites) was that these rocks were not treated as volcanic rocks, but as igneous rocks. This meant that volcanological principles had never been applied to these rocks, and that the sub-division of the ore bodies for economic purposes were based on subjective, largely irrelevant criteria that did not correlate well with diamond grades or diamond values*" **[b]**.

Kimberlite eruptions were thought to be caused either by short-lived catastrophic explosions or by interactions with external groundwater. It was also assumed that the contents of the kimberlite pipes came from eruptions of that pipe with reconstructed magmas rich in silica and magnesia **[1]**. The paradigm was also that the alteration of kimberlites was largely caused by magmatic fluids. Much of the terminology was esoteric and hard to relate to the mainstream volcanological literature **[1]**. This led to various problems and incorrect interpretations with advancing projects. As such, a paradigm shift was required. De Beers, one of the largest diamond mining companies in the world, *"was tasked with significantly improving the technical processes required to evaluate diamond-bearing deposits more efficiently, i.e. reduce the time taken and costs expended to transform a new discovery to the point where a decision could be taken to develop it further or abandon, and in those being chosen for development to improve the time it would take to bring the project into production"* **[b]**.

This paradigm shift required considerable academic support to bring about significant changes to the way diamond mineral resources are evaluated. However, the lack of specialist expertise in volcanic geology meant that diamond mining companies (such as De Beers) were unable to conduct the necessary volcanological research internally and "*members of the mining community felt that a significant improvement could be achieved if we engaged a world leader in volcanology to help guide our search"* **[b]**. In 2003, Matthew Field (De Beers, Wells) contacted Professor Steve Sparks (a Channing Wills Professor of Geology at the time, 2004-2010), based purely on his reputation for academic excellence, with a proposal to conduct research into the volcanism of kimberlites. By 2004, De Beers (Wells) had begun to fund research at Bristol via a bottom-up approach with later input from De Beers Canada, in total supporting four Fourth Year

Undergraduate theses, seven joint Natural Environment Research Council (NERC) and Co-operative Award in Science & Engineering (CASE) PhD studentships, and three postdoctoral researchers. By 2006, conference presentations had already been given and the first publication related to this research was produced **[2]**. This was quickly followed by further scientific publications **[1,3-6]**, many of which have seen impressive citation numbers (e.g. **[2]** which has seen 163 Google Scholar citations). The swiftness and agility of the progress made by this collaboration can be attributed largely to (i) the facilities available (electron microprobe, fluidisation beds, geophysical fluid dynamics laboratory, experimental facilities), (ii) the pre-existing expertise within the UoA (several other members of staff were brought into the Kimberlite team, for instance, Dr John Schumacher, Dr Jeremy Philips, Dr Richard Brooker and Dr Mark Gilbertson (Department of Mechanical Engineering, UoB)), and (iii) the wealth of international volcanology expertise provided by the Bristol researchers.

Through the collaboration between the UoA and De Beers, previously unsolved mysteries have been systematically revealed, and ideas changed significantly. This has contributed to major advances in kimberlite research, effectively bringing to an end more than a decade of relatively confined scientific growth **[1]**. These changes have been brought about by applying the understanding of physical principles and empirical knowledge of volcanic processes established over the last three decades (also largely developed under the leadership of Sparks), and observations and interpretations of the geology, to develop a model of kimberlite volcanism and to place constraints on kimberlite-forming eruptions **[1-6]**. This underpinning geological and petrological research has developed novel ideas about fluidisation in deep volcanic vents, including processes previously unrecognised in mainstream volcanology **[1-6]**.

Findings of this underpinning research have resulted in (i) the recognition of the diversity and complexity of the lithofacies that infill kimberlite pipes **[1-6]**, and (ii) the demonstration that most kimberlite eruptions were long-lived multistage events, including low to moderate intensity phases as well as some high intensity, rather than single catastrophic explosions **[3,4]**. It has also been revealed that (iii) kimberlites have mostly been altered by external water in hydrothermal systems, with this alteration subsequently shown to strongly affect the reconstruction of original magmas **[3,4]**. This, together with new high Pressure and Temperature lab experiments **[3],** have shown that (iv) kimberlite magmas were much lower in silica and magnesia than had been previously supposed **[1]**. (v) Cases where an eruption of a young kimberlite infilled the conduit of an older kimberlite volcano have also been demonstrated, with implications for estimating the diamond grade **[5,6]**. Consequently, this underpinning research has led to the conclusion that most kimberlitic volcaniclastic rocks can be related to reasonably well understood processes that occur in modern active volcanoes involving other kinds of magmas **[1,2]**.

3. References to the research

[1] Sparks, R.S.J. (2013) Kimberlite Volcanism. *Annual Review of Earth and Planetary Sciences* 41: 497-528. DOI: 10.1146/annurev-earth-042711-105252.

[2] Sparks, R.S.J., **Baker, L.**, **Brown, R.J.**, Field, M., **Schumacher, J.**, **Stripp, G.** and **Walters, A.** (2006), Dynamical constraints on kimberlite volcanism*. Journal of Volcanology and Geothermal Research* 155: 18-48. DOI: 10.1016/j.jvolgeores.2006.02.010.*****

[3] Stripp, G.R., Field, M., **Schumacher, J.**, **Sparks, R.S.J.** and Cressey, G. (2006), Post emplacement serpentinization and related hydrothermal metamorphism in a kimberlite from Venetia, South Africa. *Journal of Metamorphic Geology* 24: 515–534. DOI: 10.1111/j.1525-1314.2006.00652.x.*****

[4] Brown, R.J., Tait, M., Field, M. and **Sparks, R.S.J.** (2009), Geology of a complex kimberlite pipe (K2 pipe, South Africa): insights into conduit processes during explosive ultrabasic eruptions. *Bulletin of Volcanology* 71 (1): 95-112. DOI: 10.1007/s00445-008-0211-4.*

[5] Field, M., **Gernon, T.M.**, Mock, A., **Walters, V.A.**, **Sparks, R.S.J.** and Jerram, D. (2009), Variations of olivine abundance and grain size in the Snap Lake kimberlite intrusion, Northwest Territories, Canada: A possible proxy for diamonds. *Lithos* 112: 23-35. DOI: 10.1016/j.lithos.2009.04.019.

[6] **Gernon, T.M.**, Field, M. and **Sparks, R.S.J.** (2009), Depositional processes in a kimberlite crater: the Upper Cretaceous Orapa South Pipe (Botswana). *Sedimentology* 56 (3): 623–643. DOI: 10.1111/j.1365-3091.2008.00989.x.

4. Details of the impact

Advances in kimberlite volcanology and research findings (in particular **[1]; [c]**) have been taken on board by internationally renowned diamond mining and consultancy companies, such as De Beers and SRK Consulting, to directly inform internal decisions. This has resulted in (i) the reduction of financial risk, and (ii) the alteration of sampling strategies and policies **[b,c,d].** Consequently, the diamond industry has benefited economically, commercially and strategically from the wealth of expertise provided by Bristol **[b-e],** which has also brought about a much needed and fundamental relook at kimberlite volcanology **[d]**.

<u>Local impact within De Beers:</u>

The general success of the Bristol-De Beers initiative (2004) has led to direct interventions to alter project plans and objectives within the De Beers group of Companies **[b]**: *"The fact that volcanological data are now collected on a routine basis across the Group and all the REP's is testimony to the success of this interaction and the incorporation of this philosophy"* **[c]**. In addition, "*A further area of significant impact was with regards to training offered by Sparks to De Beers geologists in the form of a volcanic masterclass and participation on an annual Santorini field trip. Prior to this, the skill levels on some De Beers operations were not very high, but since being involved with Bristol there has been some improvement in this regard"* **[c].** De Beers have further acknowledged that these interactions significantly raised the levels of geological work conducted at their operations and the overall quality of the geologists who now work at those operations **[b].** Consequently, this provision of training and consultancy has led to new and improved processes being adopted on projects. De Beers has witnessed the impact of the Bristol research in (i) the improvement of geological models; *"The introduction of quantitative data collection techniques have also had significant impact on the construction of geological models by the Company's geologists, which also benefitted greatly from interactions with the Bristol team. This benefit is difficult to quantify in financial terms, but again can be treated as a significant risk mitigation initiative"* **[e]**, and (ii) changes in diamond sampling methods; *"our understanding of the geological complexities of many of the kimberlites we were mining and evaluating improved considerably…this lent considerable support to a change in the way in which we sample kimberlites for grade estimation"* **[e].** Both of these factors have led to the mitigation of potential future losses in the form of a decreased risk of failure of a resource model; *"Typically such commercial resource models can be valued at between £10s to 100's of millions of pounds, and the result of the Bristol-De Beers initiative has reduced the risk of such failures through the adoption of new strategies and protocols. These previously occurred due to an incorrect interpretation arising from a poor understanding of the geology"* **[c]**.

<u>International Impact on Diamond Mining:</u>

Whilst it is difficult to quantify precisely how the kimberlite research initiative has contributed in monetary terms to the international diamond industry, *"there are a number of important changes that have happened in the industry because of the contribution of Bristol University"* **[d]**. One example is *"the sampling programme for the world class Orapa kimberlite mine was changed because of the geological mapping and interpretation conducted by Bristol researchers (see the papers by Gernon et al., 2009a,b) [sic **[6]**]. In the strictest confidence I can confirm that this change in sampling strategy has had a major positive influence on the life of this mine. This mine contributes roughly 10% of the world's annual diamond supply. This change will significantly increase that proportion"* **[b].** Furthermore, "*Research conducted at Orapa mine by the Bristol team showed the current reserve being mined may not continue below a certain depth level, and therefore the sampling programme to evaluate the deeper levels was tailored to ensure that significant diamonds are recovered from the deeper regions to test whether the diamond grades and qualities may have changed"* **[e]**. A second example is that *"Mapping at Jwaneng Mine provided a clearer understanding of the geological continuity of facies in this mine, and this provided confidence that allowed management to approve changing the sampling methodology for grade determination*" **[e]**.

Other contributions of Bristol research to the diamond mining industry include; firstly, the reevaluation of kimberlite terminology; "*We have since seen the nomenclature and data collection standards been progressively updated and developed…to a much improved and better communicated standard throughout the industry internationally. The new standards have been adopted by most kimberlite exploration and mining companies…such as De Beers, BHP, Rio Tinto, Stornoway, Shore Gold and Peregrine Diamonds"* **[d]**. Secondly, a modern re-interpretation of the volcanology processes that could form kimberlites; *"new or better understood processes have allowed kimberlite geologists to improve the understanding and prediction of diamond size and abundance variations within a deposit. The new ideas are being applied by the most knowledgeable kimberlite geologists who develop diamond estimation models, such as SRK, Mineral Services and other independent specialists"* **[d]**. Lastly, the provision of an updated emplacement model for kimberlites; *"To a geologist estimating the diamond distribution, these big-picture models improve the prediction of the spatial compartmentalization of diamonds…Very importantly, the models influence diamond sampling programs by guiding the location and frequency of samples required…the improved kimberlite models are therefore improving the quality of the classification of diamond resource estimates internationally"* **[d].**

As well as improving diamond sampling and increasing confidence in grade estimations, research conducted by Bristol since 2004 has also highlighted that *"the local oversimplification of the geology and assumptions of homogeneity in the estimation of diamond content may be causing an over-estimation of the diamond content. The correct understanding of the pipe forming processes…forced SRK to reduce the confidence classification for the deposit, and caused us to treat the samples differently and raise the awareness that the diamond content may be as much as 10-20 % less. This caused the investing company to decide to protect itself and not invest in the project"* **[d]**.

Conference presentations and published papers in leading journals **[1-6]** have brought the Bristol group's work on kimberlites to the attention of other workers in the field, which has led *"immediately to similar research initiatives sponsored by De Beers' main competitors in the diamond market, BHP Billiton and Rio Tinto, being initiated. As a consequence knowledge of kimberlite geology went through a period of rapid growth. It is difficult to quantify how this may have affected the industry as a whole, but in my opinion it probably has had a significant improvement on how kimberlite ore bodies are now defined"* **[b]**. This is further supported by **[e]**: *"De Beers and its associated companies benefitted greatly from this research collaboration. I have no doubt that other diamond exploration and mining companies would also have benefitted from this as the methodologies and techniques introduced by this research programme inevitably spread across the industry"*.

5. Sources to corroborate the impact

[a] Cas, R.A.F., Hayman, P. and Porritt, L. (2008) Some major problems with existing models and terminology associated with kimberlite pipes from a volcanological perspective, and some suggestions. *Journal of Volcanology and Geothermal Research* 174: 209–225. DOI: 10.1016/j.jvolgeores.2007.12.031.

[b] De Beers (Wells). Factual Statement.

[c] De Beers Global Mining Division (South Africa). Factual Statement.

[d] SRK Consulting (Canada). Factual Statement.

[e] De Beers (Wells). Factual Statement.