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LONG ABSTRACTS

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EXTENDED ABSTRACT

THE EMPLACEMENT OF CLASS 1 KIMBERLITES – PART 1, EVIDENCE OF GEOLOGICAL FEATURES

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INTRODUCTION

This paper has been prepared specifically for the September 2006, Kimberlite Emplacement Workshop, Saskatoon, Canada. To this end, emphasis is placed on a big bang/ bottom-up model for the emplacement of Class 1 kimberlite pipes first presented by Clement and Reid (1989) and reinforced by Skinner and Marsh (2004). In this part (Part 1) the evidence of various geological features is presented. Note that as far as is known specific geological features such as diatreme-zones and subvolcanic contact breccias do not exist in Class 2 and Class 3 pipes and crater-facies kimberlites present in these pipes are quite different. Because of this it should be obvious that the processes responsible for the emplacement of Class 1 kimberlites are altogether different from those responsible for the emplacement of Class 2 and Class 3 kimberlites. The model presented here is in contrast to the episodic/ up-down model for the emplacement of all kimberlites as postulated by Sparks et al., in press.

Class 1 kimberlite bodies are pipes that typically consist of three separate zones. From the bottom up these zones include; (a) root zones, where the margins tend to be highly irregular, (b) diatreme zones, where the margins are consistently at a slope of about 82° and (c) crater zones, which in most cases consist of an upper, larger, flared part and a lower, smaller, narrow part. The root zones are filled with many (tens) different intrusions of magmatic-facies kimberlites (MFKs), mostly of macrocrystic, calcite-serpentine-monticellite/phlogopite kimberlite. The diatreme zones are mainly filled with relatively few (<4) diatreme-facies kimberlites (DFKs), mostly of massive volcaniclastic kimberlite that is restricted to the subsurface vent or diatreme. In some cases, such as at the Premier Mine, South Africa, columns of MFK can co-exist side by side with DFK and the separation of root and diatreme zone is not obvious. MFKs in association with DFKs may have contact zones of transitional-facies kimberlites (TFKs), but extended columns of TFKs without associated MFKs and DFKs also exist. Crater zones are filled with a variety of crater-facies kimberlites (CFKs) consisting mostly of early, bedded, eruptive pyroclastic kimberlite in the lower part and later bedded, resedimented volcaniclastic kimberlites, presumably derived mostly from an earlier tuff ring, in the upper part.

ROOT ZONES

The root zones of Class 1 pipes extend from >3km from the original surface (maximum depth of exposure on Class 1 kimberlite mines) up to about 2 km from surface. On the Kimberley mines (Group I, Cretaceous kimberlites) the root zones, having pronounced morphological irregularity, and the diatreme zones having pronounced morphological regularity, have a transition at between 700 and 900 m from the present day surface (Clement 1982). But if about 1400m have been removed by erosion (Hawthorne, 1975) the transition from root zone to diatreme zone occurs at about 2,2 km from the original surface. MFKs with typical Class 1 character do reach much higher levels in other places (e.g. in the Orapa cluster, Botswana and at Premier Mine). Some of these kimberlites penetrate the diatreme zone but do not reach the crater zone. In their model of kimberlite emplacement Clement and Reid (1989) infer an upward migration of intermittent embryonic columns of magmatic kimberlite to within 500m of the surface. In no cases do Class 1 MFKs, reach the surface and Class 1 kimberlite lavas do not exist. This may be explained by water-rich, Class 1 kimberlites having a solvus different to that of dry magmas like basalt. Experimental work on water-rich and CO_2-rich peridotite (Wyllie, 1987) shows that the solvus of water-rich peridotite is deflected towards lower temperatures at low pressure while that of CO_2-rich peridotite (like dry basalt) is deflected to higher temperatures at low pressure. Although no such experimental work has been conducted on kimberlite it is quite likely that kimberlites will behave in a similar way. The implications of this are that the intrusion path of a relatively water-rich kimberlite will cross the solvus well below the surface, whereas the intrusion path of a CO_2-rich kimberlite will not. Calcite-rich, Class 2 kimberlites clearly survive up to the surface as hot magmas, whereas relatively water-rich, Class 1 kimberlites do not.

Transitional-facies kimberlites are also though to be part of the root zone. In most cases (>50%) they are found in areas restricted to the transition between root zones and diatreme zones but in some cases they may extend as vertical columns on their own from about 2,3km up to <1km from the original surface. At Premier Mine vertical columns of TFK with or without associated MFK coexist with columns of DFK over more than 1km. TFKs are thought to form as a consequence of magmatic volatile exsolution resulting from depressurization (1st boiling) and crystallization (2nd boiling, Skinner and Marsh, 2004).

Clement and Reid (1989) refer to three types of contact breccias associated with the root zones. These are so-called "explosion, fluidization and intrusion breccias". The latter are rare stockwork breccias produced by the slow intrusion of MFK as veinlets and stringers along wall rock joints. The so-called "explosion and fluidization" breccias are similar with the former consisting mostly of angular, non-rotated country rock clasts and the latter consisting mostly of well-rounded, or rotated country rock clasts. In both cases these breccias are clast-supported and are essentially kimberlite free. In situ brecciation is indicated by their monolithic character, their location under undisturbed country rock overhangs, their interlocking nature and by an outward graduation from highly fragmented material to undisturbed wall rock. The fragments in these breccias are in most cases (>50%) closely packed and such breccias have the appearance of country rock which has been intensely shattered. In other breccias the packing is less dense and cavities up to 10cm may occur. But, some (>20%) of these contact breccias have been partly to completely impregnated by MFK. In no cases are these filled or partly filled with DFK. This is the case even when such breccias are cut by later DFK. These contact breccias appear to be entirely subvolcanic and to predate diatreme formation. As most are essentially free of kimberlite it is reasonable to conclude that the brecciation occurred in association with a free gas phase. "Explosion breccias" appear to have formed during the waning stages of kimberlite crystallization at the time of 1^{st} and 2^{nd} boiling accompanying the formation of TFKs (Skinner and Marsh, 2004). This process is considered to generate a state of pressure difference (either over-pressure or preferably under-pressure) between the wall rocks and the intrusive column of magmatic kimberlite leading to subvolcanic fracturing (re. Burnham, 1985). In the circumstances it is felt that the so-called "explosion breccias" of Clement and Reid, 1989) may be better termed "implosion breccias".

DIATREME ZONES

DFKs fill vertical, downward tapering cones of up to 1,7km in height (from around 2,3 km to the base of the crater at about 0,5-0,7km from surface). These cones have slope angles that range between 79° and 84° (average of 82°, Hawthorne, 1975 from measurements on all available Class 1 kimberlites at that time) and are independent of the local geology. Note that the contacts between DFK and wall rock are in most cases sharp (99%) and there is little evidence of faulting, plucking, reaction or alteration. There is no brecciation of wall rock beyond the contacts but, as described above, some diatremes do cut through contact breccia zones formed by earlier MFK processes.

DFKs are thought to represent the end product of a continuing process of 1^{st} and 2^{nd} boiling that initially led to the formation of contact breccias and TFKs. At higher levels (lower confining pressure) of less than 1km (330 bars) the super critical gas overpressures generated by magmatic volatile exsolution, are though to lead to cracking through to surface. As soon as this occurs there is an instantaneous depressurization from about 330 bars to 1 bar (atmospheric pressure). Accompaning this depressurization four things happen; (a) there is instantaneous exsolution of all remaining free volatiles from the rest of the kimberlite column down to depths of about 2,3km from the surface, (b) there is considerable cooling as a direct consequence of depressurization according to the ideal gas law ($PV = nRT$), (c) there is an enormous explosion and (d) the explosion generates a shock wave. This shock wave and the seismic rebound from the surface are consistent with the generation of the cone of shatter, the 82° slope (Rice, 1999) and the sharp wall-rock contacts.

The rebounding shock wave is thought to result in considerable upward and outward spalling of shattered cap rock material. The relative scarcity of cap rock xenoliths (down to < 5 volume % in some kimberlites such as those in Arkhangelsk, Russia) in the volcaniclastic kimberlites is evidence of this. Much of this blast also generates a tuff cone, which must have formed as shown by the resedimented volcaniclastic kimberlite that is later re-deposited back into the crater. Some large blocks of cap rock material fall back into the diatreme vent and are caught up in the maelstrom of a violently fluidized mixture of solids (olivine + kimberlite magma clasts + country rock xenoliths) and gas. Some of the blocks sink to the base of the fluidized system at about 2,3km from the surface but many are buoyed-up in the system. Spouting or overturning results in homogenization of most of the fluidized product. This is shown by the homogeneous diamond distributions and by the remarkable petrographic similarity both horizontally and vertically of over up to 1 km depth as is the case at Premier Mine with respect to the Brown, Grey and Black kimberlites. The product of the fluidized system is essentially a homogeneous, massive volcaniclastic kimberlite but in some (<-5%) cases, discernable layers are evident in parts of the diatreme vent at limited depth locations close to the side walls. These layers do not extend all the way across the vent and the layering is evident only on a macro scale (indicated by layers of mixed larger country rock clasts) but is not evident on a micro scale. This material has a clear matrix of DFK plus the xenoliths and must initially have been subjected to some mixing. The layers are thought to form as a consequence of the variance in the extent of fluidization between the side walls and the centre of the diatreme.

It could be argued that both contact breccias and diatreme-zones are produced by phreatomagmatic explosions (e.g. Lorenz, 1975). But in the first place these kimberlites are amongst the most volatile rich of all igneous rocks (e.g. Le Roex et al., 2003) so there is no need to call on meteoric water when juvenile water is abundant. Secondly petrographic evidence from MFK, TFK and DFK indicates that volatile exsolution from the magma at this time is excessive. Thirdly contact breccias form at depths of between 3 and 1km from surface and diatreme zones extend from depths of about 2,3 km from surface. At such depths and pressures, water is supercritical and the phase change from water as a liquid to water as a gas, needed to drive the phreatomagmatic explosion, is not possible.

CRATER ZONES

Crater zones typically include; (a) lower, smaller, steep-sided (82°) portions, filled mainly by coarsely bedded, pyroclastic flow material with minor intercalated beds of air-fall tuff kimberlite and (b) upper, commonly larger, flared portions that contain sectors of steeply-dipping debris flow, side-wall collapse breccias and grain flow deposits overlain by flatter, well-bedded sediments ranging from kimberlitic conglomerates to sandstones and mudstones (e.g. Stiefenhofer and Farrow, 2004). The nature of the CFKs indicate initial relatively rapid deposition of PK within the original crater (500 – 700m deep "hole in the ground") emptied by the earlier explosive eruption. This is then followed by later side-wall collapse, crater enlargement and flaring and deposition of debris flow deposits. Then, over a longer time, the remaining crater is filled with conglomerates, grits and sandstones derived essentially from presumable relict tuff ring deposits. Finally the remaining crater is filled by much finer-grained, crater-lake deposits consisting mostly of quartz grains and mud derived from afar. The important issues here are; (a) that there is a considerable hole in the ground above the diatreme-facies kimberlites that must have been created by a very large single explosion, (b) that there is little evidence for extended episodes of eruption and (c) because of this sequence of deposition there can be no intertplay between crater formation and deposition and diatreme formation. PKs are not intercalated with RVKs unless there is contamination from adjacent kimberlite/s. In rare instances RVKs may be cut by limited amounts of much later magmatic kimberlite (e.g. at Orapa) but this kimberlite exhibits many features of hot, extrusive Class 2 type kimberlite lava (e.g. amoeboid lapilli, vesicles and glass).

CONCLUSION

Routine magmatic processes 1^{st} and 2^{nd} boiling, developed in volatile-rich kimberlite, are thought lead to the transition from MFK, through TFK to DFK as described in Part 2. These processes are also thought to lead to the production of contact breccias at depth and later, at shallower levels, to a combination of cracking through to surface, extensive depressurization, wholesale further exsolution, a concomitant drop in temperature and explosive degassing and fluidization. A diatreme (characterized by consistent 82° slopes) and a significant crater is formed by these processes.

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