DEVELOPMENTS IN KIMBERLITE EMPLACEMENT THEORY

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Abstract

Various models of near-surface kimberlite pipe emplacement have been proposed over the years. These include a top-down, phreatomagmatic model, a bottom-up, embryonic pipe model and three top-down explosive dyke models. All of these models consider kimberlites as essentially the same rock type. However, different kimberlites have different pipe shapes and contain different rock types with very specific mineral assemblages and textures and therefore are likely to have been emplaced by different processes. Some authors have considered local geological differences as the principal reason for the contrasting geology but others argue that, while geological differences might contribute locally the petrographic peculiarities of particular kimberlites may be due mainly to inherent compositional differences specifically in the ratios of juvenile CO_2 and H_2O.

Keywords: Kimberlite, emplacement, juvenile volatiles.

1. Introduction

Various models of kimberlite pipe emplacement have been proposed over the years. These include the phreatomagmatic model of Lorenz, 1975, the bottom-up, embryonic model of Clement & Reid 1989 and the downward explosive dyke model of Sparks et al., 2006. Recently Cas et al., 2008 have gotten into the act with a model similar to that of Sparks et al., 2006. Wilson & Head 2007 introduced an integrated model of ascent and eruption involving rapid propagation of a dyke tip from the mantle to the surface driven essentially by the exsolution of CO_2. All of these models consider kimberlites as essentially the same rock type. However, it has now been realized that not all kimberlites are the same. Field & Scott Smith, 1999 and Scott Smith, 2008, b show that various kimberlite pipes in southern Africa and Canada exhibit contrasting geology, pipe shapes and near surface emplacement processes. These authors consider local geological differences as the principal reason for the contrasting geology. But Skinner & Marsh 2004 augue that differences in the juvenile CO_2 vs H_2O contents in different kimberlites, even in the same geological environment, could account for the different modes of emplacement which in turn would deliver different rock types within the distinctive pipes classes.

2. **Phereatomagmatic Pipe Model**

Since 1973 Volker Lorenz and co-workers have presented a variety of papers relating to phreatomagmatism and kimberlite eruption but the model as presented in Lorenz, 1975 has seen little change over the years. The model (Fig.2, Lorenz, 1975) envisages essentially five stages:

Stage 1. Magma rises near to the surface along a fissure and intersects groundwater. The water is heated to boiling point at the base of the water column. If the temperature at any level surpasses the pressure controlled boiling point, the water flashes to steam. The steam rises rapidly to surface and water plus any pyroclastic debris is ejected and a small crater forms.

Stage 2. As a function of under-pressurisation, deeper in the crater, the fissure/crater is enlarged through spalling and slumping of wall-rocks. The enlarged crater becomes choked with wall-rock debris and is re-filled with water initiating another cycle of phreatomagmatic eruption. Pyroclastic material continues to be ejected to the surface and a rim of pyroclastic debris forms.

Stage 3. Instability of the walls of the increasingly enlarged eruption channel causes large-scale spalling and under-mining and a ring-fault forms. The wall-rocks contained by the ring-fault and the overlying bedded pyroclastics subside into the crater and become fractured. The cycle of debris and water build-up plus eruption continues.

Stage4. Subsidence, fragmentation and eruption continues and the subsided material, including slumped country rocks and pyroclastic rocks, become intermixed with ejected material. Bedding is largely eliminated.

Stage 5. Tuffisite intrudes the faulted and fractured rocks as well as overlying tuffs. Shifting of the ejection vent could produce several columns of pyroclastic rocks with cross-cutting relationships. Over time the central column of ejecting material becomes intermixed with the subsided material and evidence of the ejection column is lost.

If hot kimberlite magma can get up to the surface, as in Class 2 kimberlites, and mix with groundwater phreatomagmatic eruption is highly likely. But the availability of groundwater is not always guaranteed and there must be some cases where water is not available. Kimberlite clusters are not characterized by scoria cones as is the case in the Eiffel. In no kimberlite pipes is there any evidence for wholesale downfaulting by ring faults. There is some evidence for undermining and collapse of large blocks of earlier kimberlite deposits (e.g. as at Jwaneng, Botswana) but this only applies to a segment of the pipe and not the entire pipe and the collapse could be due to some other process such as deeper magma withdrawal rather than phreatomagmatic eruption. Although the effects of limited phreatomagmatism are evident in special cases such, as the early cratering in Class 2 kimberlite pipes, there is very little geological evidence to support the specific phreatomagmatism model of Lorenz, 1975.

3. **Bottom-up embryonic Pipe Model**

Clement & Reid, 1989 were the first authors to propose a 'bottom-up, embryonic pipe model' based on a comprehensive study of selected southern African kimberlites (Clement, 1982). The occurrence of relatively substantial and complex root zones, including 'blind' pipes, provide evidence to show that some kimberlite pipes were initiated by intermittently active, upward-migrating, subsurface processes (see Fig. 8, Field & Scott Smith, 1999). These processes are fundamental and relate to crystallization and exsolution (second or retrograde boiling) that are bound to occur within water-rich rocks at depths of 2-3 km from surface. Second boiling (Burnham,1985) is considered to lead to petrographic changes, within the kimberlite column (Skinner & Marsh, 2004) and to the development of vapour-phase related subvolcanic fracturing and brecciation in the side-walls adjacent to the kimberlite (Clement, 1982 and Clement & Reid, 1989). The model envisages a step-wise series of events that in some cases, as in blind pipes, could be aborted.

Step 1, intrusion of coherent/hypabyssal kimberlite: Kimberlites intrude as dykes, sills and in some cases as vertically extended small embryonic pipes or columns of up to >1.5 km in height and up to 3-5 ha in cross-section. Clement & Reid, 1989 characterize the root zones of Class 1 kimberlite pipes by pronounced morphological irregularity associated to structures within the wall rocks and reflected by: erratic changes in area with depth; by rapid changes in dip and strike of pipe contacts; by blocky or serrated contacts; by splitting of root zones into discrete columns and by the occurrence of subsurface "blind" dome-like structures or less regular appendages.

Step 2, subvolcanic embryonic activity: This includes gradual changes to the petrographic character of kimberlite in the embryonic vertical columns and the development of subvolcanic contact breccias in the adjacent wall rocks. Changes to typical hypabyssal kimberlite referred to as transitional kimberlite (Skinner & Marsh, 2004 and Hetman et al., 2004), include the late stage crystallization of ducteric, microlitic diopside, loss of calcite, whole-sale serpentinization of olivine and the development of globular structures (or 'nucleated autoliths', Danchin et al., 1975) mistakenly identified as pyroclasts by other authors (e.g. Brown et al., 2008, a). These changes in the kimberlite petrography are considered to occur as a consequence of crystallization and exsolution of juvenile volatiles leading to a physical separation of relict kimberlite melt and exsolved volatiles. Within the relict kimberlite melt, late stage, tiny primary groundmass crystals including monticellite, phlogopite, opaque spinels and perovskite nucleate around larger sized components including xenoliths if present and 'earlier' minerals such as olivine macrocrysts and olivine phenocrysts to form globular or pelletal structures. In some cases these structures may be set in an inter-globular matrix containing calcite plus serpentine +/- apatite. In other cases this process is aborted and the globular structures exhibit incipient or poorly formed incomplete globules. However in most cases the system develops further with the loss of calcite and the crystallization of microlitic diopside. Contemporaneously to the changes within the kimberlite, contact breccias are formed in the side walls of the kimberlite column. The contact breccias are thought to form as a consequence of the considerable mechanical PΔV energy resulting from the volume increase provided by the phase change from water in the kimberlite melt to exsolved water as a super-critical fluid, based on the fact that 1gm of water at $1cm^3$ as a liquid expands to $4500\ cm^3$ as a gas at 1000°C (Holmes, 1965).

Step 3, formation of later explosively erupted pipes to surface: Side-wall brecciation leads to the development of subvolcanic breccias at greater depth but eventually at higher levels (< 1 km), with the lithostatic load reduced, break-though, to surface is achieved. Clement & Reid, 1989, suggest that downward development of the diatreme zone is considered to result from post-breakthrough top-down modification of the basal parts of the crater zones and a considerable part of the underlying embryonic pipe in a series of explosions. However, the view of Skinner, 2008 is that on breakthrough the pressure in the system is instantly reduced from >300 bars to 1 bar and any remaining juveniles in the embryonic kimberlite column/s would immediately degas all the way down to the base of the column/s at ~2 km below the original surface. One large decompression explosion would result and the extent of this explosion would cover the entire magma column/s all the way from the base of the column/s to the breakthrough point. Considerable PΔV is generated. The explosivity of the system is enormous. The explosion is expected to generate shock waves (Skinner, 2008), which rebound from the surface thereby creating a cone of brecciation from the point of the explosion at ~2 km (at the base of the diatreme zone) expanding outwards and upwards towards the surface at an angle of 82° (Rice, 1989). Immediately thereafter the effect of the decompression is to convert most remaining volatiles in the kimberlite column to gas and this gas armed with included juvenile material erupts upwards into the cone of brecciated rocks creating a short-lived, gas-solid, lean-phase fluidized system (McCallum, 1985). Much of this system is overturned and thoroughly mixed by spouting. As eruption subsides, very small, microlitic diopside and later serpentine crystallize out of the gas cloud as vapour condensates at relatively low temperatures (<500 °C) and the generation of fluidization breccias or tuffisitic kimberlites are formed within the conduit (Skinner, 2008). With the seismic rebound some of the cap rock spalls off into the atmosphere, some smaller fragments become entrained in the fluidized degassing but some large blocks may remain in tact and sink downwards as "floating-reef" into the fluidized system.

This model is based on many detailed petrographic investigations of the actual rocks present in all the zones of many Class 1 kimberlites. It is not model driven. It is very specific to kimberlites and no other volcanic processes appear to be similar but this could be so due to the unique water-rich character of Class 1 kimberlites.

4. Downward Explosive Dyke Model 1

This model is that proposed by Sparks et al., 2006 (see Sparks et al.,2006, Figs. 15 & 16) and is separated into four stages:

Stage I, initial cratering: Exsolved juvenile volatiles released in advance of the rising kimberlite magma are thought to "corrode and weaken crustal rocks and thus create zones of weakness that can then be exploited by kimberlite magma near the surface". It is proposed "that kimberlite magma reaches near the surface along narrow fissures and starts disintergrating into explosive flows within a few hundred metres of the surface". While the fissure exit remains narrow, choked flow conditions prevail and exit pressures will be high. This will very quickly lead to explosive surface cratering. Heating and pressurization of ground water if available can cause phreatomagmatic explosions. Pipe development from the top-down is envisaged.

Stage II, pipe formation: Intense sub-Plinian explosive activity, driven by major degassing of juvenile volatiles, is able to eject juvenile kimberlite and lithic clasts derived by wall-rock failure and crater wall slumping. The deeper parts of the initial crater become under-pressurized resulting in rock-bursting as a consequence of conduit widening.

Stage III, pipe filling: When the exit conditions are such that the erupting mixture can reach one atmosphere, gas velocities decline rapidly with increasing cross-sectional area and further pipe-widening and deepening declines. "Crater walls and pipe margins collapse but large blocks can no longer be removed unless they are broken down". As coarse clasts become trapped in the conduit a fluidized bed fills up the pipe. This process further suppresses explosive activity from input of new magma from below. "Ultimately magma supply rates become so low that rising magma loses its gas passively by bubbling and so late stage dykes and sills can be intruded into pipe fill. Late-stage welding processes at the base of the pipe can also form massive and irregular facies". The transition between stage II and II is not envisaged as a simple two stage sequence but rather as alternating and overlapping episodes of pipe enlargement, emptying and filling.

Stage IV, post-emplacement metamorphism and alteration: After emplacement, "bodies of tens to hundreds of metres in size are expected to take decades to many centuries to cool down by conduction. Circulation of meteoric water through the hot pipe fill results in hydrothermal metamorphism with serpentinization being the principal consequence". Serpentinisation involves large volume changes and as a consequence original primary pore space in the volcaniclastic deposits is infilled with products of hydrothermal metamorphism, principally serpentinization.

This model requires hot, volatile-rich magma at the surface, which is only likely to occur in the case of Class 2 kimberlites. The failure to recognize the importance, significance and existence of the extensive embryonic root zones in Class 1 kimberlites is a limiting feature of this model. The fact that the diatreme shapes of Class 1 pipes are consistently at an angle of 82° and that the sidewalls are clean and sharp and without side wall brecciation is also a limiting issue for this model particularly with respect to proposed undermining by rock-bursting.

5. **Downward explosive dyke model 2.**

This model is that proposed by Cas et al., 2008 (see Cas et al.,2008, Fig. 6) and is separated into six stages:

Stage 1, conduit formation: The model calls for rising (presumably hot) magma and gas which produce a network of dykes and sills that are the conduits to the surface. This process is expected to produce increasing degrees of fracturing (presumably of the side walls) in the zone of fluid propagation.

Stage 2, vent opening: "When fractures reach the surface, the sudden decompression of the magma-gas system to atmospheric pressure will generate a very large gas overpressure". It is speculated that this gas overpressure will trigger "a high-energy ballistic gas explosion that will break through and open a roughly shaped vent". Material will be excavated and violently ejected. "The morphology of the vent will be controlled largely by the mechanical competency of the country rock, the volatile content of the magma, the depth of volatile exsolution and the depth of the fragmentation surface during the eruption". The records of this stage will be obliterated by succeeding stages.

Stage 3, vent clearing, reaming and sculpting: "The sudden decompression of the rising magma on opening of the vent should lead to acceleration of volatile exsolution and explosive fragmentation of the magma. This would produce an accelerating gas jet carrying both juvenile and lithic clasts feeding a buoyant eruption column". The levels at which "vesiculation and explosive fragmentation occur in the magma column will migrate downwards into the magma column as it decompresses, so allowing deeper excavation of the vent". "There is a sustained period of gas jet driven erosion, abrasion, ablation and smoothing of the vent walls".

Stage 4, pyroclastic vent infilling: "During the waning stage of the eruption the gas-particulate eruption column rising above the vent will become too dense to remain buoyant" and "the column will collapse into the vent".

Stage5, late-stage filling of the pipe: More or less layered deposits including resedimented volcaniclastic kimberlites, air-fall pyroclastic kimberlites and other crater deposits overlying the diatreme filled massive volcaniclastic kimberlite or TK are derived by reworking of extra crater tuff-ring deposits back into the crater or by post TK late stage eruptions.

Stage 6, post emplacement alteration: On-going diagenetic alteration mainly from a reaction with permeating meteoric water.

This model suffers from the same limiting features as affected by the previous model.

6. Downward exploding dyke model 3.

Wilson & Head, 2007 present an integrated model of kimberlite ascent and explosive eruption all the way from the mantle to the surface (see Wilson & Head, 2007, Fig. 2). They believe that kimberlite magmas are initiated in a dyke in a "deep CO_2-rich source region in the mantle", leading" to rapid propagation of a dyke tip, below which CO_2 fluid collects, with a zone of magmatic foam beneath". The veracity of this model can be debated but this is beyond the scope of this paper, which refers only to near surface emplacement processes. In this respect, Wilson and Head 2007 maintain that when the dyke tip breaks the surface, "gas release (presumably from a hot kimberlite magma) causes a depressurization wave to travel downward into the magma below. This wave implodes the side walls (presumably of the dyke), fragments the magma and creates a 'ringing' fluidization wave". Together these processes are thought to form the diatreme. After reaching the surface five stages are envisaged.

Stage 1, gas venting: " The dyke tip breaks the surface, vents CO_2 gas and implodes the walls" through depressurisation. The gas "velocity increases from ~20m/s to 1.4km/s if a pure gas (that will cool adiabatically to 27°C) or 600m/s (327°C) if loaded with small magma droplets or 300m/s (227°C) if loaded with droplets plus an equal amount of country rock fragments". An expansion wave (due to volume increase) causing the violent acceleration of the dyke fluid will propagate downward at about half the speed of sound.

Stage 2, depressurisation: A "depressurization wave initiated by the gas venting propagates down through the layer of magmatic foam", "expanding existing bubbles and disrupting the foam into magma droplets and released gas". Surface tension will form the magma droplets into spheres incorporating solid particles, e.g. olivine that act as nuclei for the volatile bubbles. Rapid cooling produces glassy spherules.

Stage 3, upward fluidisation: "Gas expansion causes an upward fluidization wave". Variations in pressure will cause instabilities in the gas exsolution process and this will introduce cyclic waves of gas release and venting causing a series of fluidization waves (a 'ringing') to propagate through the system. The fluidization waves will cause sorting in the brecciated diatreme zone and will allow settling of large blocks of country rock from higher levels into deeper parts of the diatreme. During this time, the magma deeper in the dyke will undergo catastrophic adiabatic chilling.

Stage 4, post eruption alteration: If the diatreme forms in an active groundwater area, a crater lake is likely and groundwater will permeate the diatreme, quickly altering the primary mineralogy.

The major objection to this model is that it is too theoretical and is not supported by the rock types present in kimberlites. For example there is no evidence for the CO_2 foam layer nor for the glassy or quenched spherulitic structures. Evidence suggests that although CO_2 degassing is probably responsible for emplacement of kimberlite from the mantle to the surface, CO_2 it is virtually completely degassed prior to explosive eruption particularly in the case of Class 1 kimberlites.

7. Discussion

CO_2 vs H_2O: A feature of kimberlites, perhaps not fully appreciated by many kimberlite geologists, is that the differences in the availablility of juvenile CO_2 and H_2O can have a

major influence of the capabilities of most kimberlites to reach the surface as hot kimberlite magmas. The scarcity of genuine kimberlite lavas supports this allegation.

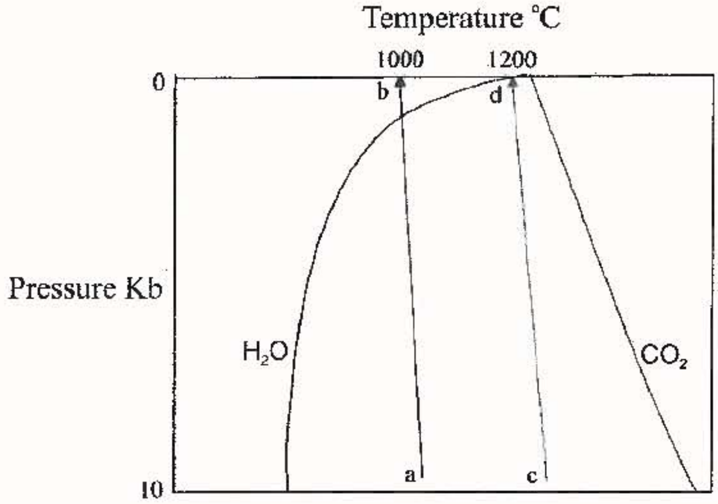

Figure 1. A schematic illustration of the differences between possible water-saturated and CO_2-saturated kimberlite solidi (after peridotite solidi, Wyllie,1987). Arrow ab shows an adiabatic trajectory within water-rich magma whereas arrow cd is within a magma richer in CO_2.

Experimental work carried out by Wyllie, 1987 on CO_2 and H_2O enriched peridotite shows that at low pressures, as the surface is approached, the intrusion path of H_2O-rich peridotite (Fig.1 ab) will cross the solidus and crystallize, whereas CO_2-rich peridotite (Fig. 1. cd) will remain above the solidus and will not completely crystallize. Although experimental work has yet to be conducted on kimberlites, it is likely that similar situations will apply because kimberlite is essentially a volatile enriched peridotite.

Application of this scenario to various models: All the models presented, apart from the bottom-up model of Clement & Reid 1989, require that hot magmatic kimberlite is delivered via dykes to the surface. If the above scenario is applicable to kimberlites only carbonatitic kimberlites could reach the surface as hot magmas and only the Clement & Reid, 1989 model can work with regard to water saturated kimberlites.

Application to different kimberlite classes: What this means is that in the case of hot kimberlite magma that is water-rich, it will naturally tend to crystallize at depth and will not reach the surface at all unless some other process becomes affective in getting it there. This appears to be the case with regard to Class 1 kimberlites, which have developed significant early root zones at depth and later, diatreme and crater zones at higher levels. The Clement & Reid, 1989 model is ideally suited to producing the pipe shapes and rock types present in Class 1 kimberlites. In contrast Class 2 kimberlites such as Fort a la Corne (Scott Smith, 2008, a) and Victor (Webb et al., 2004), and Class 3 kimberlites such as some of the Lac de Gras bodies in Canada (Nowicki et al, 2004) and Jwaneng in Botswana (Brown et al., 2008, b) are formed differently. There is no doubt that in the case of Class 2 kimberlites relatively hot kimberlite magma reaches all the way to the surface without crystallizing completely. Many erupted pyroclastic rocks at Forte a la Corne (Scott Smith, 2008, a) are characterized by kimberlite magmaclasts that are commonly amoeboid in shape (indicative of a partially liquid interiors); the groundmass to the magmaclasts are typically very fine-grained to cryptocrystalline (indicative of rapid quenching from a relatively hot magma) and calcite-filled vesicles are common. At Victor much of the kimberlite infill into the craters is described by Webb et al, 2004 as "hypabyssal-like"and all these kimberlites are classified as "spinel-and perovskite bearing, phlogopite carbonate kimberlites". In the case of Class 3 kimberlites, the groundmasses of most kimberlite magmaclasts (mainly within primary volcaniclastic air-fall tuffs and in some cases within resedimented volcaniclastic sediments) have the appearance of fragments of typical finely crystalline hypabyssal kimberlite (as seen in unaltered Class 1 hypabyssal kimberlite). Magmaclasts typically have irregular to sub-spherical shapes and are not amoeboid in shape. Groundmass minerals although quite small (generally < 0.1 mm in maximum dimension) are not cryptocrystalline, as in Class 2 pyroclastic kimberlites and there is no evidence of microlitic diopside crystallization as is the case in Class 1 kimberlites. The Class 3 kimberlites appear to have reached the surface via some process that has largely preserved the original mineralogy and texture of kimberlite similar to that which has crystallized at depth in coherent hypabyssal dykes. There is little evidence to suggest, at least in the case of volcaniclastic kimberlites, that they have reached the surface as hot magmas. However, in the case of the Lac de Gras region there is evidence that some kimberlites (eg. Grizzly, Leslie, Pigeon, Arnie and Mark, Nowicki et al, 2004) that occur as hypabyssal-like pipes have reached the surface as hot magmas. But these bodies may relate more closely to Class 2 kimberlites such as those at Victor. There is some evidence at Lac de Gras for the presence of all three kimberlite classes, e.g. Panda, Koala North and most of Koala appear to be Class 3 bodies (Nowicki et al., 2004) and Fox appears to be a Class 1 kimberlite (Nowicki et al, 2004 and Porritt et al., 2008) whereas parts of other kimberlites may have the appearance of Class 2 kimberlite.

Kimberlites with mixed classes in the same pipe: There are several examples where the pipe infill material indicates that entirely different petrographic types of kimberlites have been emplaced in the same pipe. An example of this is shown by the Letlhakane DK1 pipe in Botswana where separate parts of the pipe appear to have been emplaced by both Class 1 and Class 3 styles of eruption.

Problems with the H_2O vs CO_2 idea: One cannot simply go to whole-rock analyses of early dykes and sills in a particular area in order to ascertain the availability of CO_2 and H_2O in the kimberlite emplacement process or to be able to predict the likely kimberlite Class. Most of the early hypabyssal kimberlites present as dykes and sills in the vicinity of pipes are relatively enriched in CO_2 e.g. in South Africa. (Clement, 1982) and at Ekati (Nowicki et al., 2004). However, whole-rock analyses do show that hypabyssal or hypabyssal-like kimberlites associated with pipes do contain relatively lower CO_2 contents but this is most likely due to higher degrees of degassing within the pipes compared to the dykes/sills. If second boiling occurs in a pipe system, degassing is inevitable. Petrographic work on Class 1 kimberlites world-wide shows that continued production of hypabyssal transitional kimberlites in the embryonic pipes over an extended period leads to a loss of calcite. The scarcity of primary calcite in Class 1 tuffisitic kimberlites must be due to CO_2 degassing. In Class 2 kimberlites that are likely to be relatively anhydrous and carbonatitic, because of the fact that they exist at high levels as hot magmas, CO_2 will be lost by degassing, particularly in highly eruptive pyroclastic variants and it may be difficult to assess the original availability of CO_2. In kimberlites that crystallize abundant phlogopite but little primary serpentine, juvenile water may be tied-up in the phlogopite structure and will not be freely available to participate in the emplacement process and the kimberlite could react as if it were water-poor.

Two stage processes in Class 2 and Class 3 pipes: More importantly with regard to emplacement mechanisms is the fact that in the case of both Class 2 and Class 3 kimberlites, they appear, at least in the upper horizons, to have undergone two-stage processes of initial explosive crater excavation followed by later crater infill. In the case of both Forte a la Corne and Victor the craters appear to have flared from bases set within well-known aquifers and the intial explosive cratering could have been due to phreatomagmatism. However, later crater infilling is not phreatomagmatic (Scott Smith, 2008, a). At Forte a la Corne the infill deposits are largely a variety of pyroclastics deposited mainly through air-fall from gas-charged Strombolian-type eruption columns or from Hawaiian-type lava spatter and lava-fountaining (Scott Smith, 2008, a). At Victor the emplacement process is ascribed to multi-stage and variable lava-fountaining (Webb et al., 2004). Note that in the case of Forte al la Corne the shape of the crater is flat and saucer shaped (Scott Smith, 2008, a) whereas it is a bit steeper at Victor (Webb et al., 2004). Note also that in both places the infill kimberlites contain very low proportions of xenolithic material and most of the rocks that previously occupied the crater spaces have gone missing for whatever reason. In the case of Class 3 kimberlites the side walls of craters appear to be a lot steeper (Scott Smith 2008, b). The mechanisms for the cratering process are not as clearly established as is the case in Class 2 pipes but one could call upon either phreatomagmatic processes during times of availability of meteoric water and/or magmatic eruptions as proposed by Sparks et al., 2006 during drier times. What is clear is that in most cases, except possibly at Jwaneng (Brown et al., 2008, b) the complex five-stage eruption model of Lorenz, 1975 is not at all applicable due mainly to the more or less ordered state of the volcaniclastic rocks filling these pipes.

8. Conclusions

The very specific geology and petrography of Class 1 kimberlites world-wide favours the bottom-up, embryonic model first postulated by Clement & Reid, 1989. In this model abundant juvenile water is available to assist the emplacement process but most available CO_2 is apparently used up during the formation of root zone hypabyssal transitional kimberlites (Skinner & Marsh, 2004) and is largely completely depleted by the time the diatreme zone, tuffisitic volcaniclastic kimberlites are formed. In addition most of the kimberlite has almost completely crystallized prior to explosive eruption to surface. In some cases rare, small, late-stage eruptions into pre-existing diatreme- and crater-facies kimberlites could involve carbonatitic kimberlite magmas that could reach the surface as hot magmas e.g. magmatic kimberlites located within the crater zone resedimented volcaniclastic kimberlites at Orapa (now mined away) and the so-called carbonatitic kimberlite dykes intrusive into the Premier Mine Grey tuffisitic kimberlite. Any geologist who has had the opportunity to closely view the complex intrusive root zones of the Kimberley mines will realize that the comment by Sparks et al., 2006, that "models of intrusive mining prior to eruption have severe volume problems" is not appropriate as the intrusive root zones actually exist.

There is little doubt that phreatomagmatic processes have been active in the initial cratering activity of the Class 2 Forte a la Corne and Victor kimberlites in Canada (Scott Smith, 2008,a and Webb et al., 2004). Phreatomagmatic processes could also have been responsible for initial cratering in Class 3 kimberlites but there is little to no evidence to support the complex down faulting phreatomagmatic model of Lorenz, 1975 in any class of kimberlite, except possibly in the case of the emplacement of the Jwaneng Central pipe in Botswana (Brown et al., 2008, b). There is little evidence to support the Clement & Reid , 1989 model in most Class 2 and Class 3 kimberlites but there are examples, e.g. at Voorspoed and Lace (Howarth, MSc. in prep) where at least early bottom-up embryonic activity has occurred but later eruption is similar to Class 3 eruptions characterized by layered volcaniclastic infills of the crater. The geologic evidence supports parts of the Sparks et al., 2006 and/or the Cas et al., 2008 proposals in producing the infill material of Class 2 but there is uncertainty with respect to Class 3 kimberlites, mainly because of the lack of evidence to indicate the presence of relatively hot kimberlite close to the surface. The Wilson & Head, 2007 model is too theoretical and is not supported by actual kimberlite petrography.

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