BEHAVIOUR OF KIMBERLITE MAGMA IN THE UPPER CRUST AND AT SURFACE

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INTRODUCTION

A polarized debate on the near-surface emplacement of kimberlite magma has emerged over the past 30 years. One model favors volcanic processes and products resulting from the degassing of magmatic CO_2 and H_2O (e.g. Clement, 1982), and the other model invokes the interaction of kimberlite magma with groundwater, resulting in phreatomagmatic processes and products (e.g. Lorenz, 1975). Recent discoveries in Canada (and elsewhere) the past 12 years indicate a much wider variation in kimberlite body morphology and geometry exists than previously thought. Extensive exploration drilling, and subsequent mining of some of these new kimberlite pipes indicates many do not resemble the 'idealized model of a kimberlite magmatic system', which was developed during the interval 1956 – 1996 (based on observations in South Africa, Tanzania, and Botswana e.g. Tremblay, 1956; Dawson, 1967; Hawthorne, 1975). In order to reconcile these new observations with the old, a re-examination of the near surface kimberlite emplacement process is warranted.

VOLATILE SOLUBILITY

The solubility of H_2O in e.g. basalt, andesite and rhyolite at low pressure (<500 MPa) is quite well understood, a result of a number of experimental studies undertaken from the early 1960's to the present. Experimental studies commencing in the mid-70's to the present on CO_2 and/or H_2O solubility on a wide range of silicate melts at higher pressure (0.5 – 5.0 GPa) is also well understood. However, relatively few studies have been undertaken on CO_2 solubility at low pressure conditions (< 500 MPa; Figure 1), and it is these lower pressure studies which are of direct relevance to kimberlite magma degassing and near-surface volcanism. Three basic observations can be made about CO_2 solubility, based on the data presented in Figure 1. First, solubility decreases with decreasing pressure (at fixed T), regardless of melt composition. Second, melts with lower silica content (i.e. those melts which are more depolymerized) have higher CO_2 solubility than melts with higher silica content (and are more polymerized). Alkali contents also exert a strong

influence on CO_2 solubility, but alkalis are generally low in kimberlite, compared to other magma types. Thus, at fixed P-T conditions, CO_2 solubility increases in the sequence rhyolite, basalt, olivine leucitite, kimberlite (Figure 1). Note also in Figure 1 that olivine melilitite and melilitite melts have higher CO_2 solubility than the two kimberlite melts shown, a result of the higher alkali content of these two compositions in comparison to the kimberlites. The third, and final observation to be made from Figure 1 is that at pressure below 2.0 GPa, for all melt types (e.g. olivine leucitite, basalt, rhyolite) were there is enough data points, relatively smooth CO_2 solubility curves can be drawn with changing pressure at fixed T.
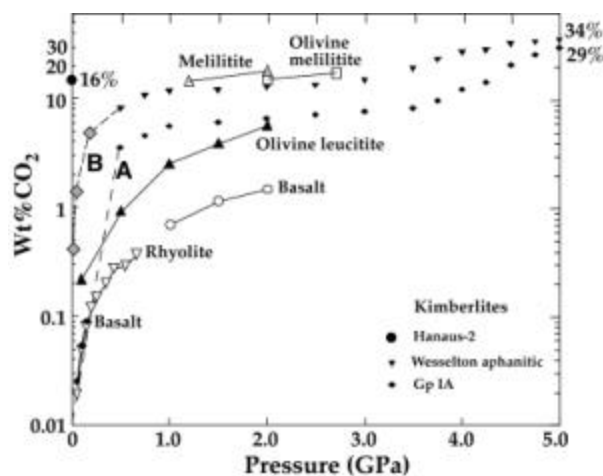

Figure 1. CO_2 solubility as a function of pressure for a variety of melt types at fixed temperature. Data from Blank and Brooker (1994), Brey and Ryabchikov (1994) and Kurszlaukis et al. (1998).

This last observation provides an important starting point for any discussion on the relative merits of the phreatomagmatic versus magmatic volatile degassing models. In Figure 1, there is a single datum-point (Kurszlaukis et al., 1998) based on an experimental study of the Hanaus-2 (Namibia) kimberlite, at atmospheric pressure (0.01 GPa). This study suggests that 16.4 wt% volatiles (combined CO_2 and H_2O) is soluble, which is notable because this is an exceptionally high solubility level for 0.01 GPa conditions. Further, this datum point is totally discordant with all other data presented on Figure 1 (kimberlite or otherwise), in that the reported solubility is higher at 0.01 GPa than for the other two kimberlite

melts shown at pressures up to 3.0 GPa. This single datum point, if taken on its own, indicates that kimberlite magmas will probably not exsolve magmatic volatiles at near-surface conditions, and hence thus never erupt violently. The corollary of this observation is that the only viable mechanism to explain violent near-surface kimberlite eruption is the interaction of hot kimberlite magma with groundwater (phreatomagmatism). Based on the discordance of this single observation with all the other data, this is suggested to be unlikely. Thus the primary magmatic CO_2 and H_2O degassing model is favored and needs to be examined in more detail, but within the context that addition of external water (phreatomagmatism) cannot be completely discounted.

In order for a kimberlite magma to erupt, it must undergo fragmentation, which occurs when the volume of exsolved volatiles (fluid or gas, depending upon the P-T conditions) occupies 70 – 80% of the total volume of the magma -volatile system (Sparks, 1978). Put simply, if the volume of volatiles is three times the volume of the magma, the magma will fragment. Thus, it is critical to understand volatile (CO_2 and H_2O) volumes at low pressure. The most important observation which can be made about the volumetric properties of CO_2 or H_2O (Figure 2) is that for a decrease in pressure (at fixed T) from 100 MPa (3.3 km load pressure from overlying rocks) to 10 MPa (330 m load pressure), there is a one order of magnitude increase in volume.
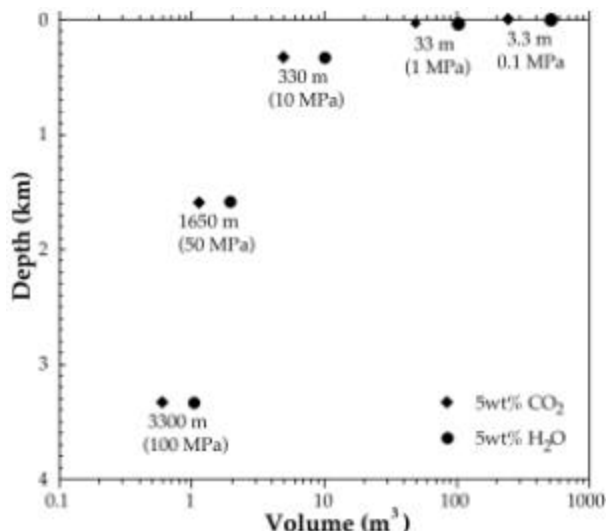

Figure 2. Volume of 5 wt% CO_2 or H_2O completely exsolved from 1 m^3 of magma at 1200 ^{o}C at low pressure conditions. Adapted from Kjarsgaard (2003).

Similarly, a pressure decrease (at fixed T) from 10 MPa to 1 MPa (33 m depth) results in a further one order of magnitude increase in volume.

In the example shown in Figure 2, for 5wt% H_2O at 1200 ^{o}C completely exsolved from 1m^3 of magma, decreasing pressure from 100 MPa to 1 MPa results in the volume of H_2O increasing from approximately 1 m^3 to 100 m^3. For CO_2, the increase is from approximately 0.6 m^3 to 50 m^3 with pressure decrease from 100 to 1 MPa (Figure 1). For either CO_2 or H_2O, this is a spectacular volume increase.

This knowledge of volatile volume, however, needs to be combined with an understanding of the amount of volatiles which have been exsolved by the kimberlite magma at low pressure. Returning to Figure 1, note that there is no experimentally measured CO_2 solubility data for kimberlite melts at low pressure (<0.5 GPa). The two sets of kimberlite CO_2 solubility data shown in Figure 2 are theoretical best-fit curves, based upon measured data from experiments on kimberlite melts (Brey and Ryabchikov, 1994). Two possible scenarios for kimberlite CO_2 solubility at P <0.5 GPa are shown in Figure 1 by dashed lines. Brey and Ryabchikov (1994) suggested a linear decrease in solubility at pressures below 0.5 GPa (straight line 'A', Figure 1). Alternately, I suggest the CO_2 solubility decreases in a regular fashion below 0.5 GPa such that the solubility curve is smooth (Figure 2, dashed line 'B' with inferred data points shown as diamonds). This latter model will be used for the following discussion, on the basis that CO_2 solubility curves known for all other melt types in fact form smooth solubility curves at low pressure.

Based on the known low P high T volumetric properties of CO_2 and H_2O (Figure 2), and the exsolution of CO_2 and H_2O from kimberlite magma (inferred from solubility studies, see above, Figure 1), fragmentation of kimberlite magma should only occur at within 500 m the surface. This is illustrated in Figure 3, utilizing as an example a 1 m^3 volume of kimberlite magma at 1200 ^{o}C with 5 wt% initial volatiles.
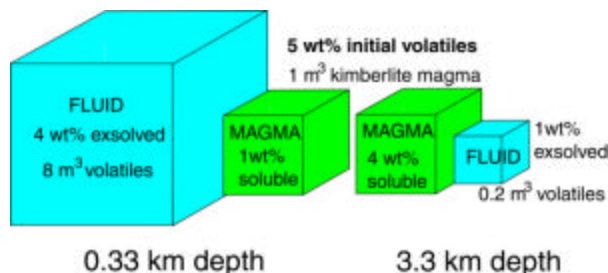

Figure 3. Volume proportions of exsolved fluid and host magma for 5 wt% initial volatiles in 1 m^3 of magma at 1200 ^{o}C at 3.3 km and at 0.33 km depths.

At 3.3 km from the surface, load pressure is high (100 MPa), volatile exsolution is low, and exsolved volatiles occupy a small volume in relation to the magma

volume. At these conditions, the magma will not fragment ("explode"). In contrast, the same kimberlite magma 330 m from the surface experiences much lower load pressure (10 MPa), such that significantly higher amounts of volatiles are exsolved, and these volatiles occupy a large volume in relation to the magma volume. At these conditions, the volume of volatiles is at least three times greater than the magma volume, which leads to fragmentation (i.e. the kimberlite "explodes").

Based on the observations above, it is suggested that kimberlite vent and pipe development must start with kimberlite magma approaching quite close to the surface (300 – 500 m) within a spatially restricted conduit (dyke). At this high level, the kimberlite magma can exsolve enough volatiles such that it can overcome the mechanical or shattering strength of the host rocks, induce magma fragmentation, and breach to the surface. This will immediately result in the foci of explosive fragmentation rapidly migrating downward due to the instantaneous decreased load pressure on the kimberlite magma conduit. This model is similar to that presented by Clement (1982) or Field and Scott-Smith (1999), but differs significantly in that the Clement model proposes fragmentation occurring first at much deeper levels (2 – 3 km depth), and then the magma moving upwards via stoping, spalling and rock bursting, before breaching occurs near the surface.

In order for a kimberlite magma to fragment at greater depths e.g. 2 km from the surface, there are only two possibilities: 1.) the introduction of an external source of H_2O, or, 2.) a higher initial magma volatile content.
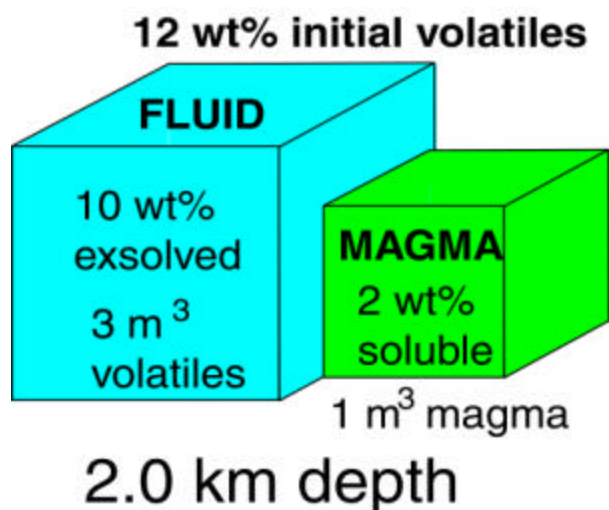

12 wt% initial volatiles

FLUID

10 wt% exsolved

3 m^3 volatiles

MAGMA

2 wt% soluble

1 m^3 magma

2.0 km depth

Figure 4. Volume proportions of exsolved fluid and host magma for 12 wt% initial volatiles in 1 m^3 of magma at 1200 ^{o}C at 2.0 km depth.

The latter possibility is shown in Figure 4, in which a 12 wt% initial volatile content of the magma would be high enough to result in fragmentation. Although this initial volatile level is reasonable, it does not take into consideration the volatile overpressure required to mechanically shatter the confining rocks, which would require an even higher initial volatile content.

PALEODEPOSITIONAL ENVIRONMENT

As was noted earlier, one cannot simply ignore the possible influence of external water sources and phreatomagmatic processes. The influence of paleohydrology, in conjunction with host rock lithology is examined by comparing kimberlite emplacement models developed for which the paleoenvironment at the time of kimberlite magmatism is relatively well constrained (i.e. Fort à la Corne, Saskatchewan; Lac de Gras, NWT). The emplacement models for southern African kimberlites (in which the paleohydrology is less well understood) are re-examined in light of observations from Canada. A few new additional conclusions which can be drawn from this work is the recognition that observed sedimentary features and volumes of resedimented kimberlite (e.g. at Fort à la Corne, Botswana, Lac de Gras), is consistent with pyroclastic eruptions forming positive relief tephra cone deposits of significant size, and not tuff rings. Further, it can be recognized that the 'idealized model of a kimberlite magmatic system' is a composite model, based on high level kimberlite pipe observations from Tanzania and Botswana, and deep level pipe and root zone observations from Kimberley (Kjarsgaard, 2003). However, the main conclusion to be drawn is that the paleodepositional environment (paleohydrology and host rock lithology together) is the most important factor, but is the least well understood. It is not just the host rock lithology alone (Field and Scott-Smith, 1999) which controls near surface emplacement. At low pressure, kimberlite melts are very hot, volatile oversaturated and degassing (regardless of minor bulk chemical variations). This implies that kimberlite melt physical properties are of lesser importance in explaining the observed variation in styles of kimberlite magmatism and near surface volcanism.

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