OXYGEN FUGACITY OF KIMBERLITE MAGMAS AND THEIR RELATIONSHIP TO THE CHARACTERISTICS OF DIAMOND POPULATIONS, LAC DE GRAS, N.W.T., CANADA

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INTRODUCTION

Surface features of natural diamonds record a number of diamond destroying processes that can lead to partial or complete diamond dissolution. Diamond destructive processes can negatively impact kimberlite grade and diamond value. The most common dissolution processes are resorption of octahedron crystals to tetrahexahedron (THH) and development of etch pits. It is not well understood whether dissolution happens in the mantle source (e.g. Harris, 1987, Taylor et al., 1995) or during ascent in kimberlite magma (e.g. Robinson et al., 1989). Rates of diamond oxidation and dissolution in kimberlite are sensitive to the redox regime and temperature (T) of the melt (e.g Arima, 1998). Comparison of diamond surface features and T and fO_2 values in different kimberlite pipes can provide information on the nature of dissolution processes and help to predict the degree of diamond preservation in a pipe. Towards this end we estimated T and fO_2 values of kimberlite melt and described morphology and dissolution features of diamond population from several Lac de Gras kimberlite pipes.

GEOLOGY AND SAMPLES

The Lac de Gras kimberlite field is located in the east-central part of the Archean Slave Province, Canada. Kimberlites have Eocene and Late Cretaceous emplacement ages (Davis & Kjarsgaard, 1997) and intrude metamorphosed Archean sedimentary, volcanic, and plutonic rocks (Carlson et al, 1998). The majority of these pipes are filled by crater facies kimberlite intruded by hypabyssal facies magma (Kirkley *et al*., 1998; Pell, 1997). Diatreme facies kimberlite is rare in comparison with South African examples. This study examines fresh kimberlite sampled in drill core from six kimberlite pipes: Leslie, Aaron, Grizzly, Misery, Panda and Beartooth and diamond population from the latter three.

The Leslie, Grizzly and a part of the Aaron pipe are filled with extremely fresh macrocrystic hypabyssal monticellite kimberlite. The Panda, Misery, Beartooth and a part of the Aaron pipe are vocaniclastic kimberlites. Hypabyssal kimberlites have fresh olivine phenocrysts (0.2 – 1 mm) with inclusions of magnesiochromite along their margins (Figure 1). Olivine phenocrysts from the more altered volcaniclastic facies kimberlites have preserved fresh cores with magnesiochromite inclusions. The presence of chromite inclusions in olivine allowed us to estimate T and fO_2 of their co-crystallization.

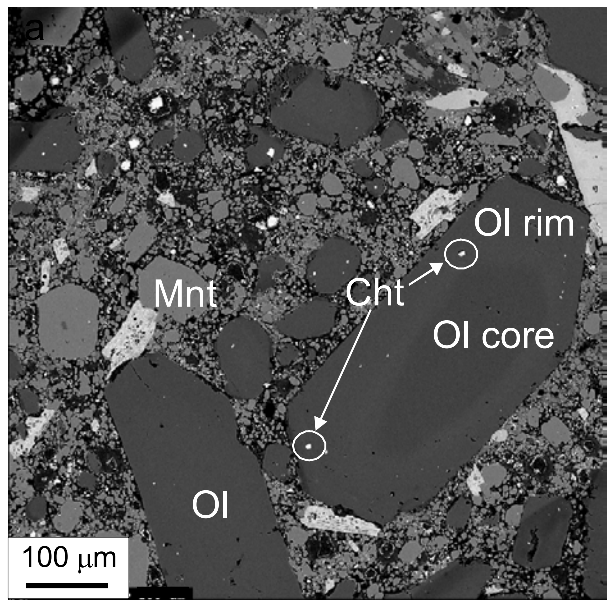

Figure 1: Back scattered electron image of the Leslie kimberlite showing euhedral chromite inclusions in margin zone of olivine phenocrysts with scale bar shown (Ol- olivine, Mnt – monticellite, Cht – chromite).

Ol-Sp GEOTHERMOMETERY AND OXYGEN BAROMETERY

The lack of any significant alteration in olivine phenocrysts and presence of chromite inclusions permit application of Mg-Fe exchange thermometers and oxygen barometers to estimate the crystallization T and fO_2 of kimberlite magma. For olivine - spinel pairs the reaction:

$$\underset{\text{olivine}}{6\,Fe_2SiO_4} + O_2 = \underset{\text{orthopyroxene}}{3\,Fe_2Si_2O_6} + \underset{\text{chromite}}{2\,Fe_3O_4} \quad (1)$$

can be used as an oxygen barometer. An experimentally-calibrated version of this oxygen barometer developed by Ballhaus *et al*., (1991) requires electron microprobe data only for olivine and spinel and T of equilibration. Reaction (1) implies silica activity has to be buffered by the presence of both olivine and orthopyroxene. For orthopyroxene-undersaturated rocks the oxygen barometer gives the maximum fO_2 and the required correction for such a system is approximately –0.2 log unit (Ballhaus *et al.*, 1991). Temperatures were determined by olivine-spinel $FeMg_{-1}$ exchange thermometer of O'Neill & Wall, (1987) corrected and simplified by Ballhaus *et al.*, (1991). The $Fe^{3+}/\Sigma Fe$ of chromites were calculated by stoichiometry using method of Droop (1987) and tested against spinels standards with Fe^{3+} known from Mössbauer spectroscopy (Canil and O'Neill, 1996; Canil et al., 1990). The calculated crystallization temperatures are 1000˚ - 1100˚C +/- 50˚ (at 1 GPa) for margins of phenocryst olivine in samples from the Leslie, Aaron, Grizzly, Panda, Beartooth and Misery pipes. Higher temperature of 1350˚C was recorded by olivine in the Leslie pipe. At these temperatures the fO_2 recorded by coexisting olivine and chromite in the phenocrysts are 0 to 1 (+/- 0.4) log units more oxidized than the nickel-nickel oxide (NNO) buffer (Figure 2).

Differences in T- fO_2 values between the pipes are within uncertainties, but the data for each pipe cluster and may represent real differences in the emplacement conditions for each pipe. For example, the Misery pipe shows the lowest fO_2 and the Panda and Beartooth pipes the lowest temperatures. Values for Grizzly and Aaron are very similar. We thus cannot estimate absolute T – fO_2 values for each kimberlite, but we believe that our data describes the relative difference between pipes.

The T – fO_2 dependence at a given P obtained in the present study allows us to evaluate the T – P – fO_2 path of the Lac de Gras kimberlites. Ogasawara *et al.* (1997) showed that the direct oxidation of diamond into CO_2

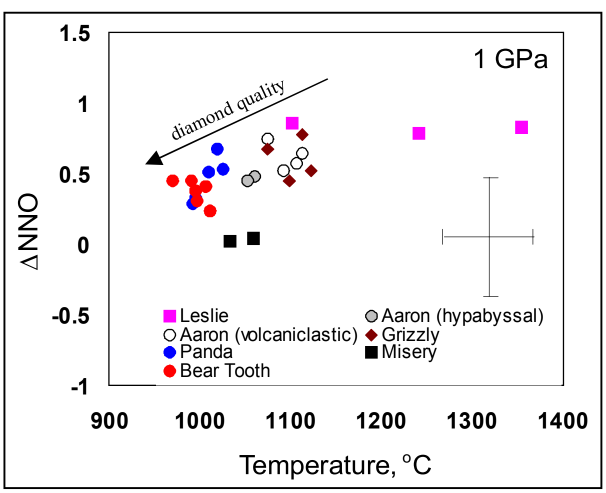

Figure 2: Oxigen fugacity and crystallization temperatures for olivine – spinel assemblages in the six kimberlite pipes. fO_2 is shown in ΔNNO units (=log fO_2 sample – fO_2 NNO buffer at P and T). The error bars are shown.

favors better preservation of diamonds than graphitization. Figure 3 shows that over a range of pressures from 3.5 to 5 GPa, the fO_2 of the kimberlite melt would be ~1 log unit above the diamond /graphite-CO (D/GCO) buffer. During entrainment, diamonds or diamond-bearing mantle xenoliths in these kimberlites were moved into the CO_2 stability field without graphitization. This path may have aided in promoting both the generally good diamond grade and quality in some of the Lac de Gras kimberlite pipes.

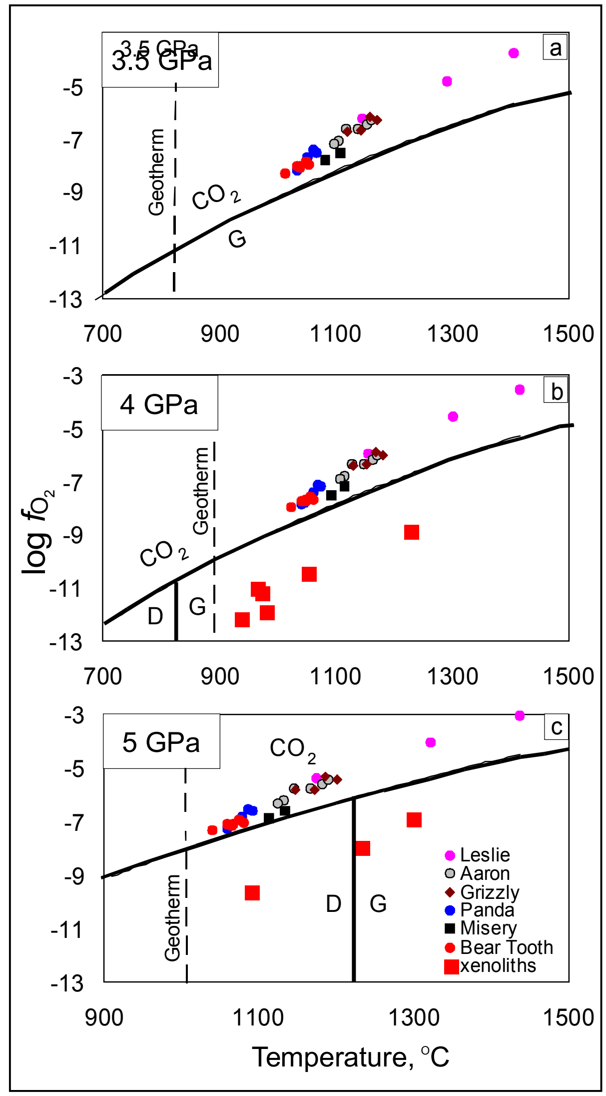

Figure 3: Stability fields of diamond (D), graphite (G) and CO_2 in log fO_2 - T space calculated at (a) 3.5 GPa, (b) 4 GPa, and (C) 5 GPa, compared to T - fO_2 data from six kimberlites recalculated to these pressures. The fO_2 recorded by mantle xenoliths from South Africa (McCammon et al., 2001) are 3 log units below that of kimberlites. Curves for G/DCO buffer were calculated from Frost & Wood (1997). D/G transition is from Kennedy & Kennedy (1976). Lac de Gras geotherm is from MacKenzie & Canil (1999).

FEATURES OF DIAMOND POPULATION

We examined diamond populations recovered from reverse circulation drill holes in the Panda, Misery and Beartooth pipes. The diamonds were sieved into seven classes using Tyler sieves and for each sieve class the proportion of different morphologies have been recorded as octahedrons (O - less than 50% faces resorbed), tetrahexahedrons (THH - more than 50% of faces resorbed), cubes and fragments (Table 1).

Table 1: Percentages of diamonds according to morphology type from the Panda, Misery and Beartooth pipes

	Panda	Misery	Beartooth
octahedron	59.6	25.6	46.3
THH	9.1	59.9	11.3
cube	4.3	4.0	18.4
fragments	27.1	10.5	24.0
O/THH	6.5	0.4	4.1

The degree of resorption was then calculated as the Octahedron/ THH ratio (O/THH). The proportions of stones with etch and growth features were counted (Table 2).

Table 2: Proportion of diamonds with etch and growth features among octahedron and THH stones from the Panda, Misery and Beartooth pipes

Pipe		Panda	Misery	Beartooth
Octahedron	Etch Pits	75	25	71
	Ruts	46	11	31
	Growth features	15	45	17
THH	Etch Pits	25	12	30
	Ruts	51	26	25

In the present study we recorded such etching features as negatively oriented trigons, hexagons, square pits and ruts shown on Figure 4.

Diamond populations from the Panda and Beartooth pipes are very similar in terms of degree of resorption and development of etch and growth surface features but are different from the Misery pipe (Table 1, 2, Figure 5).

T and fO_2 values of the kimberlite melt in the Panda and Beartooth pipes are nearly equivalent but differ from those of the Misery pipe (Figure 2). This may indicate a possible relation between conditions in the kimberlite

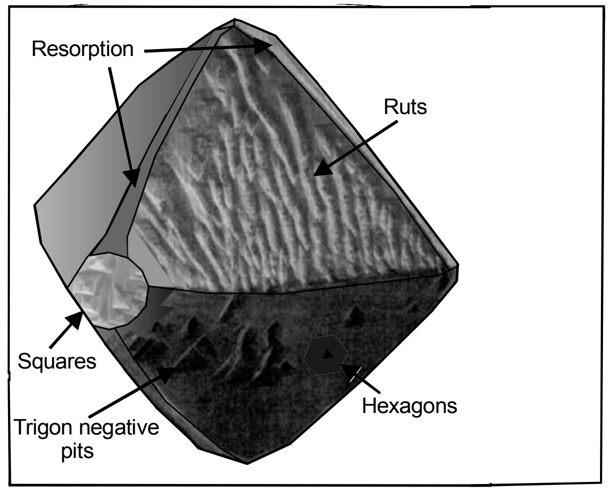

Figure 4: Different diamond destruction processes present on an octahedron diamond: beginning of resorption into THH and etching surface features (negative trigon pits, squares, hexagons and ruts). The picture combines photos from Afanasiev et al., 2000).

melt and characteristics of diamond population. The Misery pipe has diamonds with a much higher degree of resorption than the Panda and Beartooth stones yet the lowest fO_2 values. This correlation is inconsistent with the presence of THH forms resulting from conditions in the kimberlite melt. We cannot resolve this paradox in the present study and more data from different kimberlite pipes are needed. The proportion of octahedrons and THH with etch pits and ruts, and their distribution among sieve sizes in the Panda and Beartooth populations is similar (Table 2, Figure 5). Misery diamonds have fewer etch features but the Misery population has a higher porportion of stones with growth features. Detailed diamond descriptions were not performed for the Grizzly pipe, but overall the quality of stones in this pipe is much poorer. Our preliminary results show that some characteristics of diamond populations (e.g morphology and surface features) may be related to fO_2 conditions in the melt.

CONCLUSIONS

1. Inclusions of chromites in margin zones of olivine phenocrysts in hypabyssal and volcaniclastic kimberlites from the Leslie, Aaron, Grizzly, Panda, Beartooth and Misery in the Lac de Gras area allowed to use Ol-Sp thermobarometry. The olivine margines crystallized from kimberlite melt at 1000˚ – 1100˚C (calculated at 1 GPa) and 0 to +1 log unit above NNO buffer.

2. The T – fO_2 values obtained for the six Lac de Gras kimberlites show that the diamonds entrained in these kimberlites ascended in the stability field of CO_2 without graphitization. Such a T – fO_2 path favored better preservation of diamond quality and grade.
3. Kimberlite pipes with better quality diamonds have fO2 and T values lower relative to the pipes with poorer stones. This may indicate a relationship between the conditions in kimberlite melt and features of the diamond population.
4. **4.** The Misery pipe with the lowest fO_2 has the highest degree of resorption, but a relatively low proportion of stones with etch pits. Further study is required to better understand which of the diamond dissolution processes is controlled by the redox regime in kimberlite melt during ascent.

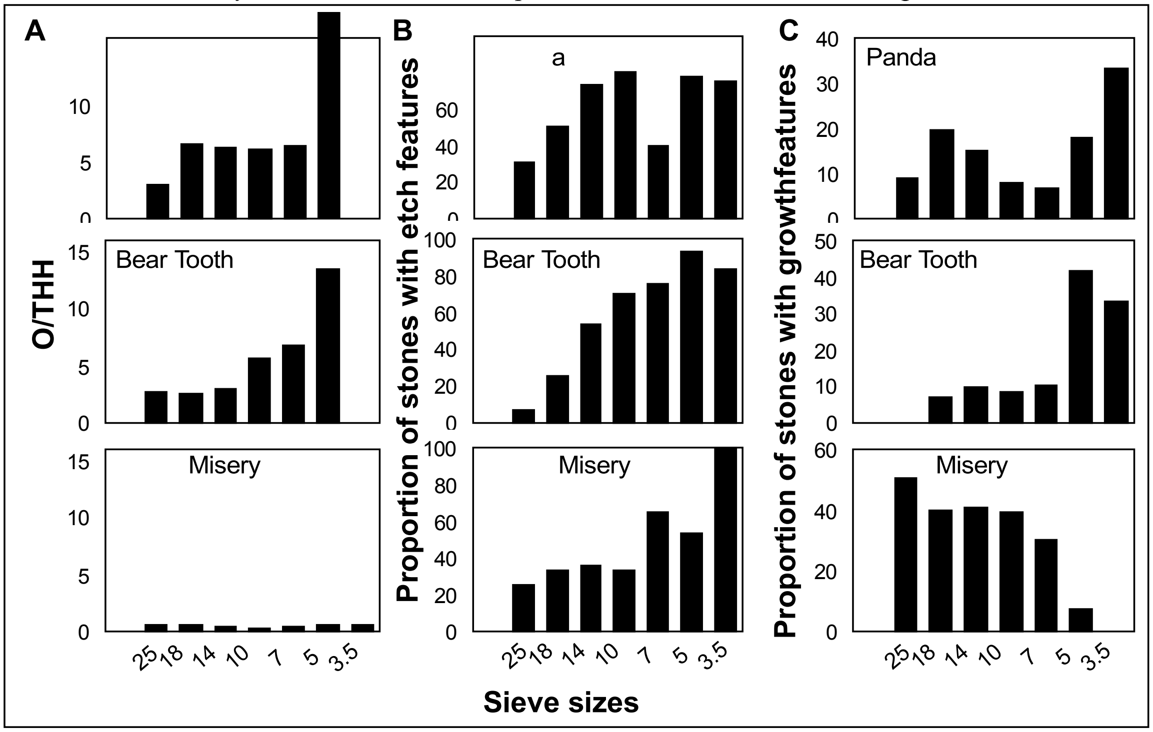

Figure 5: (a) Distribution of O/THH ratio values as measure of degree of resorption and (b) proportion of diamonds with etching and (c) growth features among sieve sizes in the Panda, Misery and Beartooth kimberlites. The plot shows similarities in the characteristics of the Panda and Beartooth diamond populations and differences with the Misery diamonds.

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