VICTOR NORTH PYROCLASTIC KIMBERLITE, ONTARIO: RESOURCE VS NON-RESOURCE DISTINGUISHED

Bram van Straaten[1], Maya Kopylova[1], Kelly Russell[1], Kimberley Webb[2], Barbara Scott Smith[3,1]

[1] Department of Earth and Ocean Sciences, University of British Columbia, Canada;
[2] De Beers Canada Inc. Exploration Division.; [3] Scott-Smith Petrology Inc., Canada.

INTRODUCTION

The Victor Kimberlite is located in the James Bay Lowland, Northern Ontario and is scheduled for open pit mining by De Beers Canada in 2008. The kimberlite will be the first diamond mine in Ontario, and the fifth in Canada. The Middle Jurassic Victor kimberlite is a complex of several pipes. The steeply dipping (~70°) pipes occur in an Ordovician to Silurian sedimentary succession, and are unconformably overlying Precambrian granitoid basement. The unconformity occurs at ~275m depth. The kimberlite is overlain by ~10-30m of glacial overburden. The main focus of this abstract will be the Victor North Pyroclastic Kimberlite (VNPK) pipe (Webb *et al.* 2004). The VNPK pipe comprises one of the main resources during mining, but also includes some low-grade areas which appear to be non-economic (Fig. 1). One of the ongoing issues in terms of geological understanding, ore delineation and grade control, is the distinction between the resource and non-resource of the VNPK pipe. Prior to this study, the high- and low-grade kimberlite in this pipe could only be confidently differentiated using thin sections and an optical microscope (Webb *et al.* 2004).

This study reports new methods to distinguish the low- and high-grade kimberlite. In addition, it contributes to an improved understanding of the petrological and volcanological emplacement history of the pipe.

GENERAL GEOLOGY

The main rock type in the Victor North Pyroclastic Kimberlite (VNPK) pipe is a relatively well sorted, loosely packed, crystal lapilli tuff, dominated by discrete or free olivine crystals (crystal without melt selvage) and minor juvenile lapilli (crystal plus melt selvage, generally of lapilli size). There is a general lack of ash-sized particles. However, it should be noted that fine ash particles (<62.5µm) are difficult to recognise, even when using the optical microscope or scanning electron microscope. The inter-clast matrix is usually characterised by serpentine and dolomite showing void-filling textures. The kimberlite comprises the two different generations of olivine found in typical kimberlites: olivine macrocrysts (anhedral, commonly 0.5-10mm large, mantle derived grains) and primary olivine phenocrysts (commonly euhedral and <0.5mm).

A close correlation between the kimberlite petrography and macrodiamond sample grade was found by Webb *et al.* (2004). The macrodiamond sample grade distribution (Fig. 1) in the VNPK pipe can be predicted by the emplacement model (Fig. 2) of nested craters from two phases of eruption: first, a low diamond grade magma erupted. Fragmentation of this magma produced juvenile lapilli with a high olivine phenocryst abundance (Fig. 2A). A second eruption of high diamond grade magma through the same eruptive centre formed a nested crater. The juvenile lapilli of this kimberlite phase have a distinctly lower proportion of olivine phenocrysts (Fig. 2B). A mixed zone with an intermediate moderate diamond grade formed at the interface of the high- and low-grade deposits, and is characterised by a mixture of both juvenile lapillus types (Fig. 2C). An average sample grade of 33 carats per hundred tonnes has been established for the high- plus moderate-grade zones. With an approximate value of 425 US$/ct Victor represents one of the highest value/carat primary diamond deposits in the world.

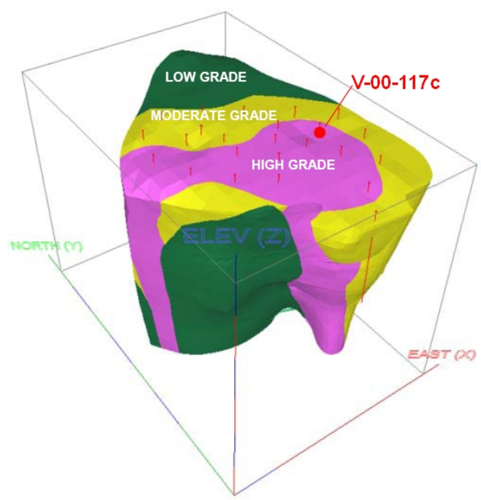

Figure 1: Macrodiamond sample grade distribution (‘01-‘02 bulk sample programme), showing high-, moderate- and low-grade zones in the VNPK pipe. Vertical axis is 300m long. Markers indicate large diameter drill holes. Note the location of the V-00-117c drill core. Figure from Webb *et al.* (2004).

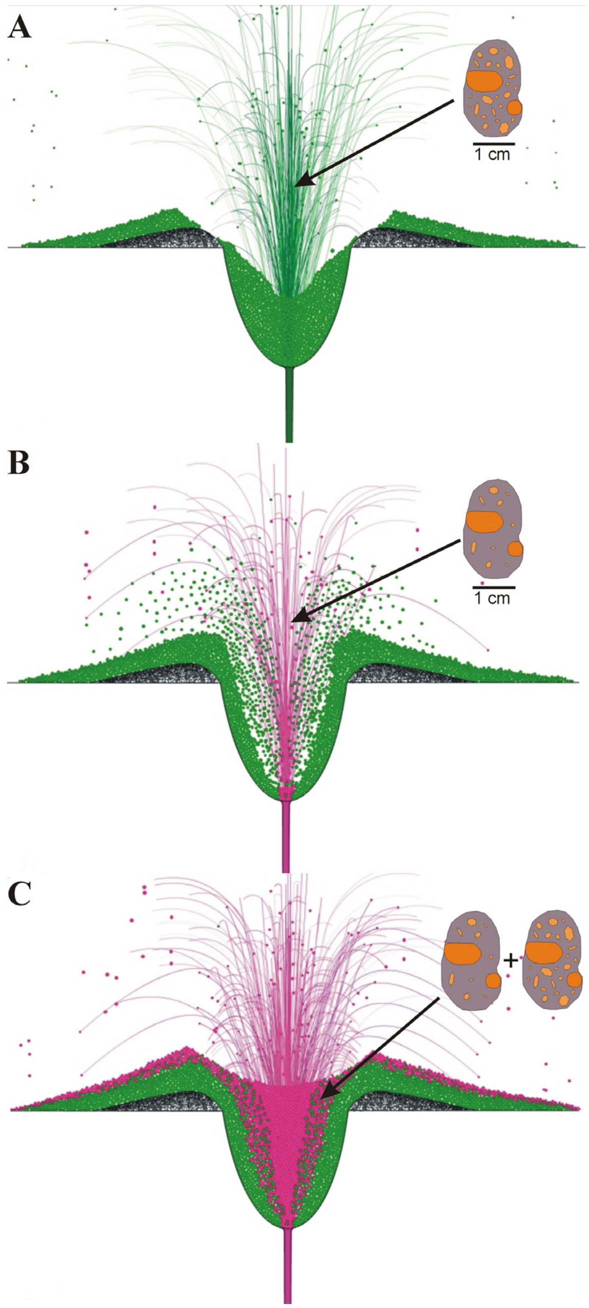

Figure 2: Schematic representation of the emplacement of the low- (green), high- (pink) and moderate- (green, pink) grade pyroclastic kimberlites in the VNPK pipe, with schematic illustrations of typical juvenile lapilli. **A.** Initial crater excavation and subsequent eruption of low-grade magma, forming juvenile lapilli with high olivine phenocryst abundance. **B.** Eruption of high-grade magma forming a nested crater. Juvenile lapilli are poor in olivine phenocrysts. **C.** Sloughing and mixing of the unconsolidated low-grade tephra with the erupting high-grade pyroclastic kimberlite results in an intermediate zone of mixed composition (both juvenile lapillus types) and moderate grade. Figure modified from Webb *et al.* (2004).

MEGASCOPIC FEATURES

Detailed core logging and sampling of one representative drill hole (V-00-117c, see Fig. 1 for location) in the VNPK pipe was undertaken. The selected drill core intersects all three grade zones: high, moderate and low.

Overall the kimberlite in the drill core is massive with very gradual fluctuations in grain size. Rare, better defined, 1-2m thick, fining upward beds are present. The upper parts of these beds have abundant components up to 2mm in size. More abundant larger (2-8mm sized) components occur at their bases. Large (5-15cm) country rock xenoliths are usually concentrated at the base of these beds. Both the high- and low-grade kimberlite intersections in this drill core show an increase in country rock xenolith abundance and size with depth. Only very minor other differences were observed between the high- and low-grade kimberlite phases in the drill core, clearly attesting to the indistinct gradational nature of this grade boundary. These features include: slightly higher abundance of country rock basement clasts (granitic and dolerite), more commonly altered olivines, and more abundant Cr-diopside xenocrysts in the low-grade unit. All of these features were already noted by Webb *et al.* (2004). None of these features allows an easy macroscopic distinction between the high- and low-grade kimberlite phases.

MICROSCOPIC FEATURES

Representative polished core samples and thin sections of drill core V-00-117c were studied petrographically. The goal of the microscopic study and analysis was to search for additional differences between the high- and low-grade kimberlite phases. The focus of the analytical work was juvenile lapilli (crystal plus melt selvage), which are representative of the kimberlite magmas. Detailed optical microscope, scanning electron microscope and electron microprobe analyses were performed at the University of British Columbia.

The juvenile lapilli in the high- and low-grade kimberlite phases are remarkably similar in terms of their primary mineralogy. The most reliable discriminator is the olivine phenocryst abundance in the juvenile lapilli. As indicated by Webb *et al.* (2004), the low-grade kimberlite phase juvenile lapilli have higher olivine phenocryst abundances (see Fig. 2). The juvenile lapillus groundmass of both kimberlite phases comprises (in order of abundance): euhedral calcite or dolomite laths, euhedral-subhedral spinel, minor small euhedral apatite and less common other opaque minerals (ilmenite, rutile). These groundmass phases are set in cryptocrystalline dolomite ± serpentine (base; Fig. 3).

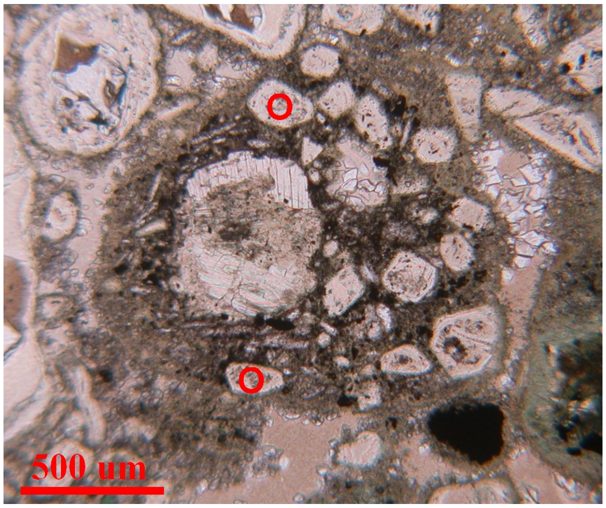

Figure 3: Low-grade kimberlite phase juvenile lapillus with high abundance of serpentine pseudomorphed olivine phenocrysts (O). Additional groundmass phases are carbonate laths and opaque minerals. PPL image.

GROUNDMASS MINERAL COMPOSITIONS

All groundmass phases were studied under the scanning electron microscope (SEM) to examine for the presence of zoning. Subsequent quantitative analyses were done using the electron microprobe (EMP).

The first minerals to crystallise from the kimberlite magma are olivine phenocrysts and/or chromites. The low-grade kimberlite phase olivine phenocrysts are commonly altered, and thus not easy to analyse. The chromites, however, are very resistant to alteration, and are abundantly present in both the high- and low-grade kimberlite phases. The chromite occurs as cores in groundmass spinel crystals (Fig. 4). The spinel crystals are strongly zoned from chromite cores to magnetite rims. This zoning pattern, and the abundant presence of atoll-textured spinel are typical of Group I kimberlites (Mitchell, 1986). The chromite cores are themselves zoned and this zoning trend is observed in almost all larger (≥20µm) cores. They are zoned from an early Al-rich chromite centre to an Al-poor and Cr-rich chromite edge (Fig. 4, 5).

There are clear differences between the spinels occurring in the high- and low-grade kimberlite phases. The first difference is the development of atoll-textured rims. The low-grade kimberlite phase spinels have thicker and more obvious atoll-textured rims, and the magnetite in the atoll-rim is usually not in contact with the chromite core. The high-grade kimberlite phase spinels commonly have thinner atoll-textured rims, and the magnetite rim is usually in contact with the chromite core (Fig. 4). The major difference between the high- and low-grade kimberlite phase spinels is the distinct contrast in the chromite core compositions (Fig. 5). Both the centres and the edges of the chromite cores of spinel crystals in the low-grade kimberlite phase have lower Mg-numbers at a similar Cr-number to those in the high-grade phase.

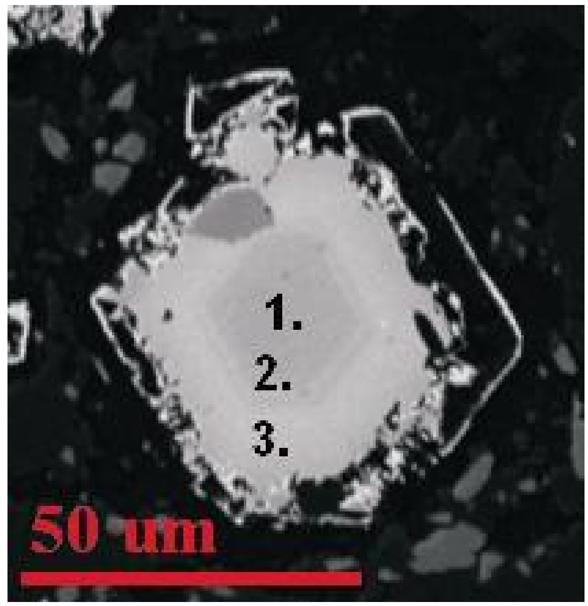

Figure 4: Typical high-grade kimberlite phase spinel: (1.) Al-rich chromite centre of core, (2.) Al-poor, Cr-rich chromite edge of core, and (3.) thick magnetite rim (in contact with chromite core). BSE-image.

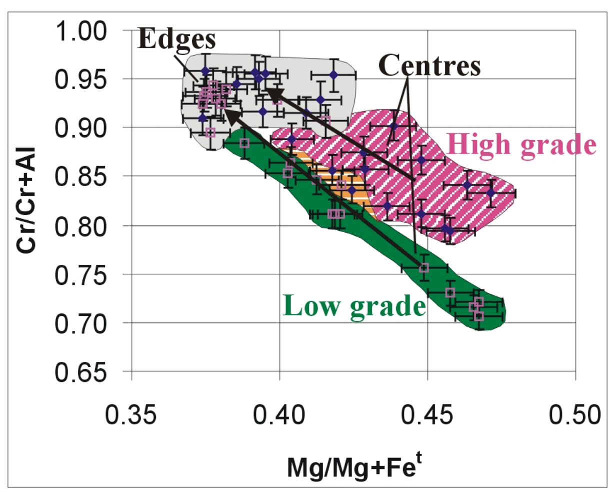

Figure 5: Mg-number vs. Cr-number plot of chromite centres and edges of cores. The low-grade kimberlite phase chromites show distinctly lower Mg# at similar Cr# than their low-grade equivalents. Error bars indicate 2 SD precision of the EMP analysis. Oblique striped (pink) field: high-grade; solid (green): low-grade; horizontally striped (orange): overlap.

SEM-analyses and reflective light optical microscopy show that a minor part of the groundmass opaque minerals are ilmenite and rutile. Common oxide intergrowths give important information about the timing of crystallisation of the various oxide mineral phases. Al-poor chromites in contact with Mg-rich ilmenite and rutile indicate coeval crystallisation of these phases. The mineral composition of the groundmass ilmenites shows a similar pattern as the chromites (Fig. 6). The low-grade kimberlite phase ilmenites have a slightly lower Mg# than their high-grade counterparts. The difference in Mg# is less pronounced than that for the chromites.

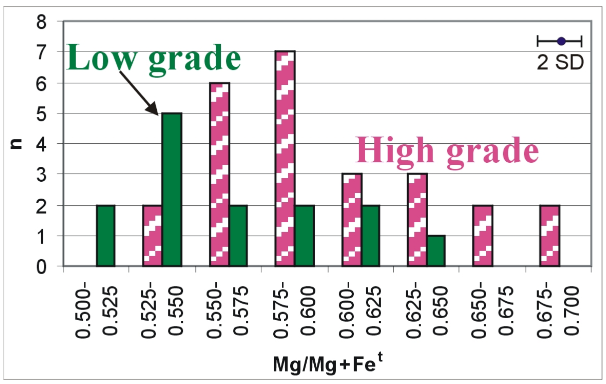

Figure 6: Groundmass ilmenite mineral compositions. Low-grade kimberlite phase ilmenites have a slightly lower Mg# than their high-grade counterparts. 2 SD indicates precision.

Rutile-ilmenite intergrowths are very common throughout the juvenile lapillus groundmass of both phases, and allowed for estimation of the oxygen fugacity of the magma. The oxygen barometer of Zhao *et al.* (1999) was used, assuming similar spinel-olivine crystallisation temperatures as for other kimberlites in Canada (1080°C at 10 kbar, Fedortchouk & Canil 2004). Similar oxygen fugacities were obtained for the high- and low-grade kimberlite phases (Fig. 7), and the results are about 3.2-3.8 log units above the diamond/graphite – CO_2 (D/GCO) buffer, and 0.9-0.3 log unit below the nickel – nickel oxide (NNO) buffer. These results are ~1.3 log units less oxidised than estimates by Fedortchouk & Canil (2004) for Lac de Gras kimberlites.

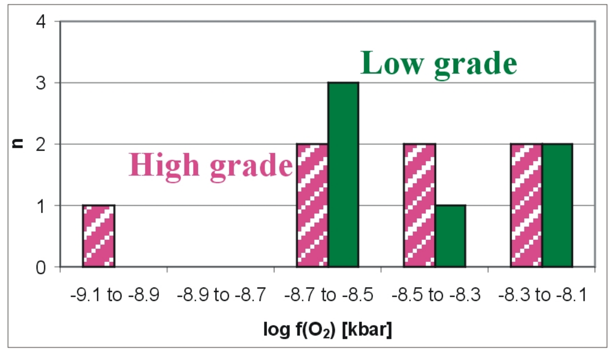

Figure 7: Oxygen fugacity values for the high- and low-grade kimberlite phases, indicating similar oxidation states for both magmas during rutile and ilmenite crystallisation.

Late stage groundmass crystallisation included precipitation of various carbonate phases. Euhedral calcite and dolomite laths are a common feature, and are set in a cryptocrystalline dolomite base with minor serpentine. There is a difference in composition of the groundmass dolomite laths between the high- and low-grade kimberlite phases. The low-grade kimberlite phase dolomite laths have slightly lower Mg# (higher Fe content, see Fig. 8), similar to observations on oxide groundmass minerals. The preservation of variable Mg# between the two phases of kimberlite suggests that the dolomite laths are primary. The calcite laths contain moderate amounts of Sr (Fig. 9) with respect to secondary calcites (found in veins and replacing olivine), which presents additional evidence that these carbonates are primary (e.g. Armstrong *et al.* 2004).

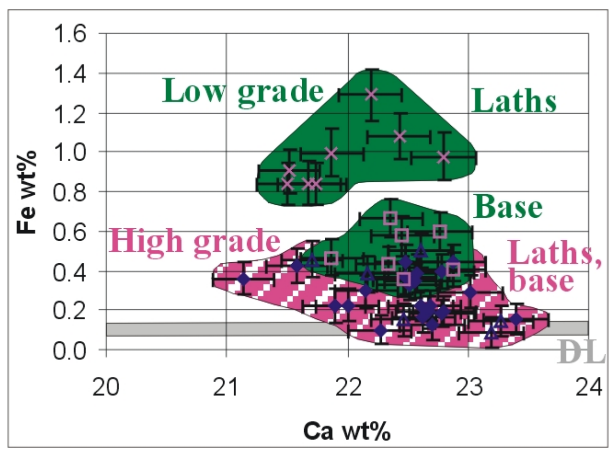

Figure 8: Groundmass dolomite compositions, showing a higher Fe content for the low-grade laths, compared to the high-grade laths. DL: upper and lower detection limit; error bars indicate 2 SD precision.

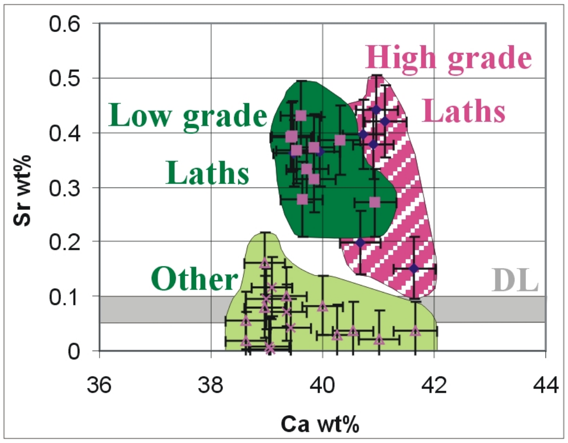

Figure 9: Groundmass calcite laths (upper fields) and calcite in veins and olivine replacements (lower field). This clearly suggests a primary origin for the moderately Sr-bearing calcite laths. DL: upper and lower detection limit; error bars indicate 2 SD precision.

CONCLUSIONS

1. The Victor North Pyroclastic Kimberlite is classified as a spinel-bearing carbonate Group I kimberlite.
2. Groundmass dolomite is more abundant than calcite, and the primary nature of both is suggested by the mineral composition and texture.
3. Earlier formed chromite cores of groundmass spinel crystals show an atypical Cr-Al trend of Al-depletion towards the edges of the cores.
4. The Al-poor edges of the chromite cores formed at the same time as groundmass ilmenite and rutile.
5. Rutile – ilmenite intergrowths record oxidizing conditions, in principle capable of diamond resorption.
6. Similar oxygen fugacities in both the high- and low-grade kimberlite phases suggest that diamond resorption was not responsible for the observed grade difference.
7. The low-grade kimberlite phase chromites, ilmenites and dolomite laths all have lower Mg-numbers than analogous high-grade kimberlite phase groundmass minerals. In addition, the low-grade kimberlite phase is characterised by a higher abundance of olivine phenocrysts. It is proposed that the low- and high-grade primary magmas had a fairly similar bulk Mg#, but because the low-grade magma crystallised more olivine, the Mg# of the residual magma was reduced more than its high-grade counterpart, giving rise to groundmass minerals with lower Mg#.
8. Economic implications: the study confirms the conclusion by Webb *et al.* (2004) that the high- and low-grade phases of kimberlite in the VNPK pipe formed from two distinct magmas which brought contrasting amounts of diamonds towards the surface. This validates the geological and emplacement models (Fig. 2), which in turn, predict the diamond distribution within the pipe (Fig. 1).

ACKNOWLEDGEMENTS

We would like to thank De Beers Canada Inc. for their financial and logistical support, and their permission to publish this long abstract. The help of Mati Raudsepp and Elisabetta Pani with the SEM and EMP analyses is acknowledged. Thanks to Cliff Revering for comments on the abstract.

REFERENCES

Armstrong, J.P., Wilson, M., Barnett, R.L., Nowicki, T. and Kjarsgaard, B.A., 2004. Mineralogy of primary carbonate-bearing hypabyssal kimberlite, Lac de Gras, Slave Province, Northwest Territories, Canada. Lithos, 76(1-4): 415-433.

Fedortchouk, Y. and Canil, D., 2004. Intensive variables in kimberlite magmas, Lac de Gras, Canada and implications for diamond survival. J. Petrology, 45(9): 1725-1745.

Mitchell, R.H., 1986. Kimberlites: mineralogy, geochemistry and petrology. Plenum Press, New York, 442 pp.

Webb, K.J., Scott Smith, B.H., Paul, J.L. and Hetman, C.M., 2004. Geology of the Victor Kimberlite, Attawapiskat, Northern Ontario, Canada: cross-cutting and nested craters. Lithos, 76(1-4): 29-50.

Zhao, D.G., Essene, E.J. and Zhang, Y.X, 1999. An oxygen barometer for rutile-ilmenite assemblages: oxidation state of metasomatic agents in the mantle. Earth and Planetary Science Letters, 166(3-4): 127-137.

Contact: Bram I. van Straaten, Department of Earth and Ocean Sciences, University of British Columbia, 6339 Stores Rd., Vancouver, BC, Canada, V6T 1Z1, E-mail: bvanstraaten@eos.ubc.ca

8th international KIMBERLITE conference

LONG ABSTRACTS

2006 Kimberlite Emplacement Workshop
Saskatoon, Canada September 7-12th, 2006