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Olivine and clinopyroxene mantle xenocryst geochemistry from the Kirkland Lake kimberlite field, Ontario

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Introduction

The Targeted Geoscience Initiative (TGI) is a collaborative federal geoscience program that provides industry with the next generation of geoscience knowledge and innovative techniques to better detect buried mineral deposits, thereby reducing some of the risks of exploration. This study reports results from the Mantle Metal Mobility research activity included within the TGI-5 program. Mantle xenoliths and xenocrysts entrained within kimberlites provide a rare window to study the composition and petrogenesis of the lithospheric mantle underlying the Canadian Shield (Hunt et al., 2012; Scully et al., 2004; Smit et al., 2014). Five kimberlites, the B30 and Buffonta dykes and the A4, C-14, Diamond Lake pipes, were targeted for this study. Each of these kimberlites cut Archean mafic to felsic volcanic rocks of the Abitibi greenstone belt and are included within the Jurassic Kirkland Lake kimberlite field (Heaman and Kjarsgaard, 2000). The geology and setting of these multi-phase kimberlite volcanic rocks (e.g., hypabyssal and massive volcaniclastic kimberlite, kimberlite breccia) have been described previously (Meyer et al., 1994; Scully et al., 2004; Vicker, 1997). Herein we report new Electron Probe Microanalysis (EPMA) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) datasets for olivine and clinopyroxene crystals recovered from the Kirkland Lake kimberlites. This data release (Appendix 1–4) accompanies a full interpretation of the data and a discussion of its significance in an accompanying journal article (Lawley et al., 2018).

Methods

Sample preparation and imaging

Mineral separates were prepared from five kimberlite samples (NAD83, Latitude, Longitude; A4: 48.2200, -79.8800; B30: 48.2843, -79.9176; C-14: 48.2818, -79.8011; Diamond

Lake: 48.1203, -79.7591; and Buffonta: 48.4771, -79.9512) using electric pulse disaggregation at Overburden Drilling Management, Ottawa. Olivine and clinopyroxene crystals (0.5–1.0 mm) were hand-picked from the nonmagnetic, >3.3 and 3.2–3.3 specific gravity fractions, respectively. Representative mineral separates for each mineral were then mounted in epoxy, polished to approximately half their thickness and imaged using a Tescan Mira-3 field-emission scanning electron microscope (SEM) at the Geological Survey of Canada prior to analysis. Imaging was used to identify core and rim relationships for the mounted olivine and clinopyroxene crystals. Further discussion on mantle xenocryst petrography is presented in Lawley et al. (2018).

Electron Probe Micronalysis (EPMA)

EPMA analysis was completed on polished clinopyroxene and olivine epoxy mounts at the University of Alberta using a JEOL JXA-8900R equipped with 5 tunable wavelength dispersive spectrometers. Analyses were completed using a 2 µm beam diameter and a beam energy and current of 20 keV and 20 nA, respectively. Reported signal intensities and concentrations are corrected for deadtime, drift, element interference (Donovan et al., 1993) and matrix-effects using a combination of ZAF and PhiRho-Z algorithms (Armstrong, 1988). Most elements were acquired with peak measurement times of 30 s and each analysis is reported as the average of 3 points. Standard-sample bracketing to quantify major to minor element concentrations used a combination of silicate, oxide and metal standards (Alfa nickel, Alfa chromium oxide, Rockport fayalite, MTI Rutile, Wakefield diopside, Frank Smith pyrope garnet, albite VA 131705, Itrongay sanidine, Wilberforce apatite, Navegadora Mine spessartine). Matrix-matched clinopyroxene (Cr diopside) and olivine (forsterite 90) standards were used to monitor analytical performance. EPMA and LA-ICP-MS olivine and clinopyroxene results are reported in Appendix 2–3, respectively.

LA-ICP-MS spot analysis

LA-ICP-MS spot analysis were completed at the Geological Survey of Canada using an Agilent Technologies 7700 x ICP-MS coupled to a Photon Machines Analyte 193-nm excimer laser ablation system (Cabri and Jackson, 2011; Lawley et al., 2015). Data were acquired using a fast, time-resolved analysis data acquisition protocol (peak hoping, one point per peak for a total sweep time of 541 and 555 ms for clinopyroxene and olivine, respectively) and fixed laser operating conditions during standard-sample bracketing (Appendix 1). LA-ICP-MS sample

ablation pits re-targeted EPMA analysis spots wherever possible.

Primary calibration standards included the United States Geological Survey (USGS) doped synthetic basalt glass standard GSD-1G (Guillong et al., 2005) and the doped synthetic pyrrhotite standard PO726 (prepared by L. Cabri and G. Laflamme at CANMET), which was used to calibrate chalcophile and siderophile elements such as Au, Pt, Pd and S. USGS basalt glass standard BCR-2G (Jochum et al., 2005b) was used as a quality control standard to monitor instrument performance during sample (n = 10–12)-standard (2 × GSD-1G; 1 × PO726) bracketing for olivine and clinopyroxene analyses. Reference concentrations for these primary and secondary standards are taken from the online geological and environmental reference materials database (GeoReM)(Jochum et al., 2005a). A fragment of a well-characterized San Carlos olivine grain (Bussweiler et al., 2017) was used as a matrix-matched olivine reference monitor for quality-control purposes.

Internal standards were used to correct for different ablation yield between the sample and calibration standard. Our approach also addresses, to some extent, signal drift and matrix effects in the ICP-MS during analysis. For clinopyroxene and olivine analyses, Ca and Mg concentrations from EPMA analysis were used as the internal standards, respectively. Olivine LA-ICP-MS results were also re-processed using Si as the internal standard to calculate Mg# (atomic Mg/Mg+Fe) for each spot analysis (Lawley et al. 2018). Signal integration of the time-resolved LA-ICP-MS spectra and conversion of these integrated signals to element concentrations was completed in the Glitter software package (Griffin et al., 2008) and following the approach of Longerich et al. (1996).

Quality control (BCR-2G and San Carlos olivine) and sample results are reported as electronic files herein (Appendix 2–3). Replicate analysis of BCR-2G suggest that concentrations are generally within 1–10% of their accepted values (Jochum et al., 2005a). Exceptions include Ag, As, Cd, Sb, Se, and Sb, which deviate by up to 30% of their accepted values. Unfortunately, the accepted values for these elements within BCR-2G are subject to large analytical uncertainties (Jenner and O'Neill, 2012). Measurement repeatability calculated for BCR-2G is typically <5% RSD for most elements, but increases to 20 and 30% RSD for elements with 100s to a few ppb concentrations, respectively. Replicate analysis of the matrix-matched San Carlos olivine quality control standard suggest that the reported concentrations are within 1–10% of expected concentrations for well-calibrated elements even at sub-ppm concentrations (Ca, Mn, Co, Cr, Cu,

Ni, W). Measurement repeatability varied, but was generally below 5% RSD for well-calibrated elements. LA-ICP-MS olivine and clinopyroxene results are reported in Appendix 2–3, respectively. A full discussion on mantle xenocryst geochemistry results is presented in Lawley et al. (2018).

LA-ICP-MS Pb isotope analysis

In situ clinopyroxene Pb isotope analysis was completed at the Geological Survey of Canada using the same analytical system for spot and mapping analyses and is based on the approach of Lawley et al. (2017). Analytical spots were selected as close as possible to previously LA-ICP-MS and EPMA analyses. Standard-sample bracketing used National Institute of Standards and Technology (NIST) 610 to correct for instrumental mass bias and sensitivity drift during each analytical session. Gas blank measurements (30 s) were followed by 120 s of sample ablation. Data quality was monitored and trace element concentrations were calculated with the Glitter software package (Griffin et al., 2008). Reported Pb isotope ratios are corrected for drift, mass bias, and signal channel spikes. Quality control standard USGS basaltic glass GSD-1G was run as an 'unknown' for each standard (2 × NIST 610)-sample (n = 3–4) bracket to monitor analytical performance. Element concentrations were calculated using Glitter (Griffin et al., 2008) by calibrating against NIST 610 and using Ca from EPMA analysis as the internal standard. Accepted values for NIST 610 and GSD-1G were taken from the GeoRem database (Jochum et al., 2005a). All clinopyroxene crystals yield low-ppm to ppb concentrations of Pb, which makes accurate and precise 204Pb-based isotope ratio determinations an analytical challenge using our analytical set-up. As a result, only the more abundant radiogenic Pb isotopes (^{208}Pb, ^{207}Pb, and ^{206}Pb) and the ratios (^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb) are reported. Replicate analysis of quality control standard GSD-1G (accepted values ^{207}Pb/^{206}Pb = 0.8042 and ^{208}Pb/^{206}Pb = 1.9871; Jochum et al., 2005a) yield weighted average ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb ratios at 0.8036 ± 0.0040 (MSWD = 0.1, n = 20) and 1.9797 ± 0.0097 (MSWD = 0.1, n = 20), respectively. All LA-ICP-MS Pb isotope and QAQC (GSD-1G) results are reported in Appendix 4. A full discussion on mantle xenocryst isotope geochemistry is presented in Lawley et al. (2018).

Geothermobarometry

Robust PT data from mantle garnet peridotites, as determined by simultaneously compared

multiple barometers and thermometers (Grütter, 2009), provide input for xenolith-based paleogeotherms calculations (Mather et al., 2011). For this reason, previously published EPMA data for garnet peridotite xenoliths (n = 50) from the Kirkland Lake area (Meyer et al., 1994; Vicker, 1997) were re-calculated using updated geothermobarometers that were not available at the time of the original publications and improved compositional QAQC filters within the Microsoft Excel add-in PTEXL (cf. T. Köhler; T. Stachel). PT for garnet lherzolite samples were calculated using an updated two-pyroxene thermometer (Taylor, 1998) and garnet-orthopyroxene barometer (Nickel and Green, 1985), respectively. An alternative geothermometer, based on Ca in orthopyroxene (Brey and Köhler, 1990), was utilized to calculate T for clinopyroxene-free harzburgitic peridotite. Single-grain olivine thermometry results, calculated in PTEXL, are T intersection fits to this xenolith-based geotherm (i.e., to obtain P) using the chemical classification and Al-in-olivine thermometer presented in Bussweiler et al. (2017). Clinopyroxene crystals were classified based on the EPMA data, following the methodology of Nimis (1998) and Ramsay (1995). New single grain clinopyroxene PT determinations (calculated using enstatite-in-clinopyroxene thermometer and Cr-in-clinopyroxene geobarometer, respectively; Nimis and Taylor, 2000) were calculated in PTEXL. Depth profiles and a complete discussion of results are presented in Lawley et al. (2018).

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