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Mantle depletion and metasomatism recorded in orthopyroxene in highly depleted peridotites

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ABSTRACT

Although trace element concentrations in clinopyroxene serve as a useful tool for assessing the depletion and enrichment history of mantle peridotites, this is not applicable for peridotites in which the clinopyroxene component has been consumed (~25% partial melting). Orthopyroxene persists in mantle residues until ~40% melting and it is therefore this mineral that offers petrological insights into the evolution of refractory peridotites. Major and trace element concentrations in orthopyroxene ± clinopyroxene from two spinel facies harzburgitic xenolith suites from New Zealand are examined. Samples from Cape L'Evique (CLEV) on Chatham Island contain traces of clinopyroxene (<2 modal %) but a suite from Lake Moana (MOA) in the South Island is devoid of this mineral. When compared with modelled orthopyroxene trace element budgets, which are constructed from a review of published source modes, melting modes and element/melt partition co-efficients, the measured orthopyroxene rare earth element data in both suites generally indicate minimums of 25–30% partial melting. These results are consistent with co-existing elevated Mg# in olivine (mostly 91.4 to 93.0) and orthopyroxene (mostly 91.3 to 93.6), high spinel Cr# (commonly >45) and low orthopyroxene Al_2O_3 (generally <3.1 wt%). However, comparison of modelled and measured orthopyroxene compositions shows that all samples, even the most refractory, have undergone metasomatism by small volume light rare earth element-bearing agents. Measured orthopyroxene Ti concentrations show that the metasomatic agent that affected the CLEV suite carried Ti, but that the MOA suite metasomatiser was Ti-poor. Orthopyroxene trace elements in the inspected rocks are therefore partly decoupled from the major element abundances, with the results demonstrating that even highly refractory peridotites can record evidence for mantle metasomatism.

1. Introduction

Trace elements in peridotite minerals are useful for determining the degree of depletion and the nature of enrichment that has occurred in the upper mantle. Based on partition coefficients and mass balance calculations, clinopyroxene is the principal trace element host in shallow mantle four-phase (olivine, orthopyroxene, spinel, clinopyroxene) peridotite (e.g., Stosch, 1982; Eggins et al., 1998; Witt-Eickschen and O'Neill, 2005) and consequently is the most common analytical target for spinel facies peridotite studies. However, for a number of important mantle trace elements, such as Ti and rare earth elements (REE), it is essential to consider the budget held by orthopyroxene if the geochemistry of these elements is to be fully understood (e.g., Rampone et al., 1991; McDonough et al., 1992).

Orthopyroxene plays a particularly important role in partitioning trace elements in highly depleted peridotites. At >25% partial melting, the clinopyroxene component is completely consumed and leaves an orthopyroxene-olivine-spinel residue (Walter, 2003), with orthopyroxene now being the main trace element receptor. Some highly depleted peridotites also appear to record metasomatic enrichment and yet lack secondary clinopyroxene (e.g., Boyd, 1989; Kelemen et al., 1993). In these cases, orthopyroxene trace element concentrations should reveal insights into the metasomatic history. Trace element budgets of orthopyroxene are easily obtained, but systematic inspection of the resulting data remains sparse.

This paper reports an examination into the major and trace element composition of orthopyroxene in two highly depleted peridotite suites from New Zealand (Fig. 1) with the goal of using this information to establish their depletion and possible enrichment histories. One suite contains minor (<2%) clinopyroxene, whereas the second suite is devoid of this mineral. The orthopyroxene laser ablation measurements in both suites are compared with orthopyroxene trace element budgets

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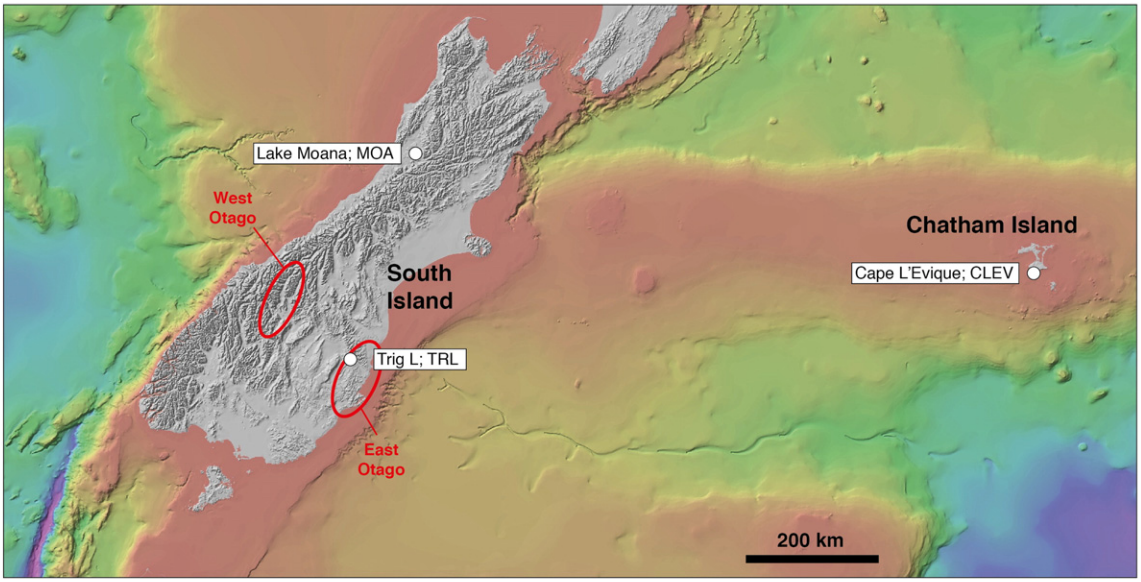

Fig. 1. Location map of samples selected for analysis. Grey areas represent continental crust above sea level. CLEV comes from the main island (Chatham Island) in the Chatham Islands group. West Otago and East Otago represent Miocene xenolith occurrences (Scott et al., 2014b).

concentrations calculated from batch melting models. In spite of very low concentrations, orthopyroxene trace elements provide very useful insights into the depletion and enrichment processes in the mantle lithosphere. The Data Supplementary contains a review of partition coefficients, source modes and melt models used for constructing theoretical orthopyroxene compositions in spinel facies peridotites.

2. Geological setting

New Zealand and offshore islands represent a small exposed fraction of a large undersea continent known as Zealandia. This continent was, together with Australia and Antarctica, located on the paleo-Pacific margin of the Gondwana supercontinent until 85 Ma when this margin began to fragment and form the Tasman Sea and Southern Ocean. The exposed crustal portion of Zealandia comprises a variety of Cretaceous to Cambrian accretionary fore-arc, arc and back-arc terranes (Mortimer, 2004) and there is no evidence for Proterozoic or older crust. The underlying mantle lithosphere, at least under southern Zealandia where it has been most studied, is composed of variably depleted regional-scale blocks (Scott et al., 2014b). Whole rock Os isotopes (McCoy-West et al., 2013; Liu et al., 2015) and clinopyroxene Hf isotopes (Scott et al., 2014b) indicate that portions of the lithospheric mantle are >2 Ga, but that these old fragments may represent ancient lithosphere incorporated into younger lithosphere during Phanerozoic continent formation (Liu et al., 2015). Many xenoliths show the geochemical hallmarks of having reacted with carbonatite or CO_2-bearing silicate melts in the upper mantle (Scott et al., 2014a, 2014b; McCoy-West et al., 2015).

Samples inspected in the present study are depleted peridotite suites from two different settings in Zealandia. Peridotite xenoliths with the prefix CLEV come from an intraplate Eocene basaltic lava flow at Cape L'Evique on Chatham Island, ~800 km east of the South Island (Fig. 1). The Chatham Islands group is located near the edge of continental crust and composed of numerous temporally spaced (Cretaceous to Miocene) but spatially restricted intraplate volcanoes (Panter et al., 2006). Continental crust exposed at the surface in this area represents exhumed Cenozoic fore-arc metasedimentary rocks that experienced lower greenschist facies conditions in the Jurassic (Adams et al., 2008). Two peridotite xenoliths from the CLEV site were analysed by McCoy-West et al. (2013) and found to have undergone moderate degrees of mantle depletion and to have Os model ages of ~1.1 Ga. Samples with the prefix MOA come from a 86 Ma lamprophyric dike on the flank of Mt. Te Kinga draining into Lake Moana in western South Island (van der Meer et al., 2013, 2016). The underlying continental crust is composed of Early Paleozoic metasediments that had been intruded by Paleozoic and Cretaceous granitoids (Waight et al., 1997). Clinopyroxene-free harzburgite xenoliths were reported from close to MOA location by Tulloch and Nathan (1990), who recognised highly depleted olivine and spinel chemistries. Os isotopic analysis of one sample yielded an Os model age of 0.52 Ga (McCoy-West et al., 2013).

3. Analytical methods

3.1. Electron beam analysis

Mineral major elements were primarily measured at the University of Otago, New Zealand, using wavelength dispersive spectrometry on a JEOL 8600 microprobe. This instrument was equipped with two spectrometers and was operated with a current of 20 nA, an accelerating voltage of 15 kV and a defocused beam diameter of 20 μm. Data were reduced using an inhouse ZAF correction program. After the microprobe was decommissioned in 2015, several samples were analysed at Otago with a Zeiss Sigma Variable Pressure Field Emission scanning electron microscope with an energy dispersive spectrometer attachment. Analyses were conducted with an accelerating voltage of 15 kV and an aperture of 60 μm over 50 s^{-1} live time. Beam stability was controlled by analysing cobalt metal. Line scans used to re-integrate spinel and clinopyroxene exsolution in orthopyroxene were conducted by repeatedly scanning a short profile over a period of about 5 min. The data from both electron microbeam instruments were calibrated against Smithsonian standards: 165905 Cr-augite (Si, Al, Ca, Mg ± Cr), 746 hypersthene (Fe), 143965 hornblende (Na), 85276 fayalite (Mn), chromite (Cr), and 143966 microcline (K). The analytical routines were tested against known Smithsonian mineral compositions to ensure reproducibility.

3.2. Laser ablation inductively coupled plasma mass spectrometry

Trace element analyses of pyroxene grains were measured using in situ laser ablation attached to Agilent 7500 Quadrupole inductively coupled plasma mass spectrometers (ICP-MS) at the University of Otago and/or Thermo Element XR ICP-MS at the University of Alberta, Canada. Analyses were performed on polished thin sections and/or on