REDOX STATUS OF FE IN SERPENTINITES OF THE COAST RANGE AND ZAMBALES OPHIOLITES

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REDOX STATUS OF FE IN SERPENTINITES OF THE COAST RANGE AND 
ZAMBALES OPHIOLITES

BY

AMY STANDER

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WITH A SPECIALIZATION IN ENVIRONMENTAL AND EARTH SCIENCES

THESIS
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ABSTRACT

Although, the reduced status of the Earth’s upper mantle is a possible controller of the deep, rock-hosted biosphere, knowledge of the redox state of the mantle is incomplete. Peridotites (mantle rocks) are composed of ultramafic (Fe, Mg-rich) minerals such as olivine and pyroxene. During serpentinization, water and ultramafic minerals react, generating a package of secondary minerals dominated by serpentine. This releases hydrogen gas in amounts dependent on system geochemistry and largely controlled by the Fe(II) budget in the protolith, as well as other products. Microbial life can be fueled by the hydrogen produced by serpentinization in environments that are generally not regarded as hospitable to life—cool, dark, low energy, subseafloor settings. Peridotite-hosted vents in the seabed and springs in continental ophiolites reveal active microbial communities at work in these distinctive serpentinization-associated waters.

In this study, 16 variably serpentinized peridotite samples from the Coast Range Ophiolite (CRO) (11 core samples and one hand sample) and Zambales Ophiolite (ZO) (four hand samples) were selected for study based on mineralogy. The objective of this study was to understand better the redox status of Fe in these rocks and produce possible H₂ generation values for the CRO and ZO. Each sample was analyzed using X-ray diffraction and thin sections (when available) to identify possible Fe bearing minerals (olivine, spinel, serpentine, pyroxene, magnetite, other Fe-oxides). X-ray fluorescence was used to obtain the bulk concentration of Fe in each sample (~28,000 to 51,000 ppm (~3.7 to 6.5 wt% FeO)). Mössbauer spectroscopy was used to determine the percentage of total Fe that is Fe²⁺ (~23 to 70%), Fe³⁺ (~14 to
65%), and magnetite (~0 to 63%), which is a combination of Fe$^{2+}$ and Fe$^{3+}$. The data sets were integrated into a hydrogen generation model. I assumed that each sample was representative of the peridotite units of the corresponding ophiolite. This permitted computation of a range of total hydrogen production possible by the peridotite considered, until serpentinization is complete (~900 to 4800 Tmol H$_2$ or ~2000 to 12,735 Tmol H$_2$ if density is factored into the calculation). The CRO can produce less H$_2$ per rock volume than the ZO because the CRO samples generally have a lower Fe concentration, but the CRO has a greater volume and can produce a larger total amount of H$_2$.

Variability in bulk rock Fe concentration and Fe valence states in samples taken in close proximity indicate diverse serpentinization reaction paths even in a single ultramafic unit. Tectonics, emplacement history, age, climate, composition, and hydrology of the ophiolite all influence the redox status in the modern, ophiolite-hosted ultramafics.
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PREFACE

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LIST OF ACRONYMS

BSE ................................................................. Backscattered electron (image)
CRO ................................................................. Coast Range Ophiolite
CROMO ......................................................... Coast Range Ophiolite Microbial Observatory
DSDP ............................................................. Deep Sea Drilling Project
GSA ............................................................... Geologic Society of America
IS ................................................................. Isomer shift
ODP ............................................................... Ocean Drilling Project
PPL ................................................................. Plane-polarized light
MOSS ............................................................. Mössbauer spectroscopy
QS ................................................................. Quadrupole splitting
SEM-EDS ....................................................... Scanning Electron Microscope with an energy-dispersive detector
SSZ ............................................................... Supra-subduction zone
TS ................................................................. Thin section microscopy
USGS ............................................................. United States Geological Survey
XPL ............................................................... Cross-polarized light
XRD ............................................................... X-ray diffraction
XRF ............................................................... X-ray fluorescence
ZO ............................................................... Zambales Ophiolite
This manuscript is prepared for submission to the American Geophysical Union’s (AGU) peer-reviewed journal *Geochemistry, Geophysics, Geosystems* (G³).
1. Introduction

As the search for the deep extent of life on Earth and other planets progresses, it fuels the need to better understand life on Earth and the extreme environments in which life is found. Water-rock chemical reactions often provide the energy source(s) these extremophile microbes need. As peridotite is serpentinized, Fe can be oxidized by water, releasing hydrogen gas, which can be used by microorganisms as an energy source.

The objective of this study was to determine the redox status of the Coast Range Ophiolite (CRO) and Zambales Ophiolite (ZO), based on iron speciation in selected mineral phases. Serpentinized peridotite samples were collected from the CRO and ZO, their general mineralogy was identified, Fe concentration data were obtained, and Mössbauer spectroscopy was utilized. Fe was used as the redox status indicator because of its general abundance in the rocks, its multiple valence states, and its participation in energy production during serpentinization. Possible energy yield in the form of hydrogen released during serpentinization was also calculated.

1.1 Deep life can be fueled by serpentinization

Hydrogen is an energy source for various forms of life from man to microbes. It can be produced naturally through water-rock reactions by rusting or oxidizing the Fe within ultramafic (Mg, Fe-rich) rocks. Serpentinization at its most fundamental level is the hydration of Fe\(^{2+}\) minerals in ultramafic rocks in an overall reducing, anoxic environment. This process can be represented by a redox transformation of mineral-hosted Fe from Fe\(^{2+}\) to Fe\(^{3+}\):
(1) \(2(\text{Fe}^{2+}\text{O})_{\text{rock}} + \text{H}_2\text{O} \rightarrow (\text{Fe}^{3+}_2\text{O}_3)_{\text{rock}} + \text{H}_2\)

The hydrogen so generated can be utilized by microbes as hydrogen gas (H\(_2\)), often with metabolic reactions coupled to cycling of methane (CH\(_4\)) other hydrocarbons, and/or complex organic compounds that are also produced in this environment [Ophan and Hoehler, 2011; Charlou et al., 2010; McCollom and Seewald, 2013; Schrenk et al., 2013].

Chemosynthetic ecosystems that are fueled at least in part from hydrogen produced by serpentinization have been discovered in/around sites where there is active serpentinization occurring, including submarine seeps from fault-bounded peridotite blocks like the Lost City hydrothermal field on the Atlantis Massif near the Mid-Atlantic Ridge [Kelley et al., 2005]; within ophiolite groundwater and/or groundwater springs including the Cedars [Morrill et al., 2013] and CROMO wells [Cardace et al., 2013] in California, USA, various locations within the Oman ophiolite [Neal and Stranger, 1983; Paukert et al. 2012; Sano et al., 1993], the Tablelands ophiolite in Newfoundland [Szponar et al., 2013], the Leka Ophiolite complex in Norway [Okland et al., 2012], and Gruppo di Voltri in Italy [Cipolli et al., 2003] to name a few. Serpentinization tied to plate convergence and aqueous alteration of mantle wedge material also fosters submarine mud volcanoes such as the Kumano Mud Volcano, Nankai Trough, Japan [Case et al., 2013] and the South Chamorro Seamount near the Marianas Trench, and mud diapirs. See appendix for a brief overview of microbiological diversity of serpentinization-related fluids.

Because the oxidation of available Fe and attendant H\(_2\) production is expected in serpentinization, the redox status of the upper mantle can be considered an indicator
of a deep rock-biosphere, at least until temperatures of 121°C, and perhaps 150°C, are reached [Kashefi and Lovley, 2003]. Serpentinites are thus one promising environment for studying endolithic extremophiles [Schrenk et al., 2013; McCollom and Seewald, 2013; Takai et al., 2006;] (microbes that live in rocks and off the energy released as the rocks weather). Subsurface lithoautotrophic microbial ecosystems (SLiMES) [Nealson et al., 2005; Takai et al., 2006] can be fueled by the hydrogen produced during serpentization in an environment that is generally not regarded as hospitable to life—cold, dark, possibly high pressure (compared to surface pressure), anaerobic, and extremely alkaline with high pH (8-12) formation fluids and potentially high levels of metals like Fe, Ni, As and Cr.

1.2 Serpentinization as a geologic process

Mantle rocks of the subseafloor can be sampled where exposed by fault action or tectonics; diverse dredged peridotite samples from oceanographic expeditions and many seafloor drilling projects have also sampled peridotite. However, drilling through stratigraphically complete lithosphere to mantle peridotite is exceedingly difficult due to the depths (generally 5+ km) of rock that would need to be drilled, generally submarine, where there are additional complications and pressure and temperature constraints. Geoscientists often rely also on specimens delivered from great depth by magma streams as xenoliths [e.g., Pearson et al., 2014]. In this study, variably serpentinized (hydrated and altered) peridotite samples from two ophiolites—Coast Range Ophiolite (CRO) in Northern California, USA, and the Zambales Ophiolite (ZO) in the Philippines (Figure 1)—are characterized and compared. The peridotite units in ophiolite bodies are mantle rocks that have been uplifted by
tectonics. In a naturally reducing environment, ultramafic minerals can react with water, a process that often starts on the ocean floor, and alter to serpentine assemblages that are stable at the lower temperatures and pressures of Earth’s surface.

Serpentinization is the process in which hydrous fluids react with ultramafic rocks to produce serpentine and other alteration minerals, and is a volume increasing (which can further fracture rocks and expose fresh surfaces), exothermic (adds heat energy back into the system to further catalyze the reaction), and, therefore, can be a self-sustaining (positive feedback) reaction. For equation 1 to be viable, the environment needs to be oxygen-depleted and reducing so that Fe is oxidized by oxygen from water while the hydrogen is released. Ultramafic minerals formed at high temperatures and pressures undergo chemical weathering (serpentinization) to re-equilibrate with lower temperatures and pressures. Having a heat source (such as magma) nearby, can expedite the serpentinization process, but serpentinization itself is exothermic, thus heating and priming regionally associated rocks for further serpentinization.

Serpentinization is coupled to plate tectonics. Ophiolites that are or were on plate boundaries (Figure 2) can record subduction-related plate flexure or regions of tension that yield fractured areas with deep faults that allow sea water access to ultramafic rocks. For example, ophiolites may result from obduction near the trench of oceanic lithosphere formed at a mid-ocean ridge (MOR) [Dickinson et al., 1996]. Ophiolites may also form in supra-subduction zone(s) (SSZ) in environments similar to nascent spreading centers in backarc or fore-arc settings, which have distinct oceanic lithosphere geochemical signatures [McLaughlin et al., 1988; Coleman, 2000;
Dickinson et al., 1996; Shervais and Kimbrough, 1985]. All formation mechanisms allow for complete or partial ophiolite sequences to be exposed at Earth’s surface.

According to the 1972 GSA Penrose Conference, an ophiolite consists of a partial or complete sequence consisting of, from bottom to top, an ultramafic complex (variably serpentinized mantle peridotite), a gabbroic complex, mafic sheeted dike complex, and mafic volcanic complex dominated by pillow basalt overlain by various sedimentary rocks (see Figure 3) [Dilek, 2003]. This definition holds true, whatever the tectono-magmatic origin may be. Seawater is also mineral-bound within the ophiolite when it is uplifted, and continues to serpentinize the ultramafic units, slowly exiting through vents/springs, and variably mixing with meteoric surface and groundwater.

1.3 Means of inferring serpentinite redox status and relevance to H₂ yield

The redox status of Fe in variably serpentinized peridotite can give clues to the possible hydrogen yield that has occurred and still has the potential to occur because Fe is oxidized by the oxygen in water (equation 1) and the hydrogen is released. Mössbauer spectroscopy (MOSS) of Fe is one way to determine the redox status of multivalent elements in minerals. MOSS determines the proportions of Fe²⁺, Fe³⁺, and mixed valence states like magnetite (with both Fe²⁺, Fe³⁺ present in the mineral, see Table 1). A stoichiometric conversion can be calculated from concentration of Fe³⁺ to quantify possible hydrogen yield over the lifetime of the rock. The larger the quantity of Fe²⁺ in the ultramafic protolith, the greater the chance of hydrogen production when ultramafic minerals react with water.
The Earth’s mantle is solid and composed primarily of olivine group, pyroxene group, spinel, and/or garnet, accompanied by diamond and other minerals that are stable at high temperatures and pressures. In the anhydrous upper mantle, Fe$^{2+}$ is expected to be found in ultramafic minerals, like olivine, pyroxene, and spinel, because it will substitute for Mg in mineral structures (see Table 1). Molecular water in the mantle is possibly located mostly in the transition zone between the upper and lower mantle [Hirschmann et al., 2005; Pearson, 2014] and the mantle wedge in subduction zones where the subducting oceanic slab is releasing water into the mantle.

1.4 Importance of Al-rich phases, spinels, in H$_2$ production

Serpentinization can be catalyzed by spinels and is a complicated and highly variable process that depends on the starting composition of the rock and primary minerals, fluid composition, substitutions between Fe, Mg, and other elements [Evans, 2008], if and how much Al is present in the system [Andreani et al., 2013; Mayhew et al., 2013], system pressure and/or temperature [Mayhew et al., 2013], and even the presence of microbes could encourage one mineral to form over another [Nealson et al., 2005; Takai et al., 2006]. For example, serpentinization needs olivine and water, and responds to additional mineral phases such as spinel and pyroxene. Different forms of serpentine can be created along with magnetite, hydrogen, spinel, and other minerals. Equation 2 and 3 below provide examples of possible parent and alteration mineral combinations. Equation 3 is provided in both mineral names and general chemical formulas (Table 1), which help illustrate the complex chemistry observed in some serpentinization systems.
(2) Olivine + hydrous fluids ± spinel ± pyroxene ↔ serpentine ± brucite ± magnetite ± free hydrogen ± other spinel(s) ± quartz ± albite

Or

(3) Olivine ± pyroxene + hydrous fluids = serpentine ± magnetite ± other clays ± free hydrogen

and in chemical formulas:

\[
\begin{align*}
(Mg, Fe)_2SiO_4 \pm (Mg, Fe, Al, Mn, Ti, Cr, Ca)_2Si_2O_8 \pm (H_2O + dissolved ions) &= \\
(Mg,Fe)_2Si_2O_5(OH) \pm Fe_3O_4 \pm [Ca_{0.17}(Al,Mg,Fe)_2(Si,Al)_3O_{10}(OH)_2 \cdot nH_2O \pm (Mg,Fe,Al)_{1.5}(Si,Al)_3O_{10}(OH)_2 \cdot (Mg,Fe,Al)_{1.5}(OH)_b \pm (Mg,Fe)_{0.3}(Mg,Fe^{2+},Fe^{3+},Al)_3(Si,Al)_3O_{10}(OH)_b] \pm H_2
\end{align*}
\]

[Bach et al., 2006; Sleep et al., 2004].

Spinel group minerals, especially Al-bearing spinels, can act as catalysts for hydrogen production. Mayhew et al. [2013] saw a correlation between the quantity and surface area of spinel phases (mainly magnetite, chromite, and gahnite) and the amount of hydrogen generated, especially at lower temperatures (100 and 55°C) where microbes can live. Spinels are metal oxide minerals \((M^{2+}M^{3+}O_4)\); see Table 1), and Mayhew et al. [2013] suspect that they encourage \(H_2\) generation by acting as an electron transfer shuttle surface for aqueous \(Fe^{2+}\) and hydrogen/protons.

Spinels can include aluminum in their structures. When Andreani et al. [2013] conducted diamond-anvil experiments with olivine, saline water, and aluminum, the rate of olivine alteration increased 1-2 orders of magnitude when Al was included at natural hydrothermal environment temperatures (200 and 300°C) and pressures (200 MPa). Al seemed to enhance the solubility of the olivine in their experiments allowing serpentine to form within ~2 hours of beginning the experiment. The rate of \(H_2\) production could also increase with the increased rate of serpentinization, which may allow for economic gain from serpentinization [Andreani et al., 2013].
The minerals in this study include olivine, pyroxene (cpx and opx), serpentine, brucite, spinel, and magnetite (Table 1) in altering peridotites of the Coast Range Ophiolite and Zambales Ophiolite. A general serpentinization reaction including these minerals is below:

\[(4) \text{olivine} \pm \text{pyroxene} \pm \text{spinel} \pm \text{hydrous fluids} \leftrightarrow \text{serpentine} \pm \text{brucite} \pm \text{spinel} \pm \text{magnetite} \pm \text{hydrogen gas}\]

1.5 Geologic Setting

Ophiolites are generally structurally intact blocks of the oceanic lithosphere (ocean crust and upper mantle, see Figure 3) that are uplifted and deposited on continental crust, or form (essentially in situ) in extensional environments in the back arc. Partial, segmented, and/or mélange ophiolite sequences are common because the emplacement can be complex. The Coast Range Ophiolite is located on modern tectonic plate boundaries as illustrated by Figure 2.

1.5.1 Coast Range Ophiolite (CRO)

The Coast Range Ophiolite (CRO) is exposed at various locations in the mid-western portion of California, USA (Figure 1). The CRO exposures and sampling locations in this study are near Lower Lake (junction of Lake, Napa, and Yolo Counties) on the University of California-Davis, McLaughlin Natural Reserve, and near Stonyford (Colusa County) in the confluence of the Hyphus Creek and Little Stony Creek. See the appendix Figure A1 for a geologic map of the CRO. The CRO formed in a supra-subduction zone (SSZ) setting [Shervais, 2001]. SSZ tectonic
settings may include backarc and forearc basins, and arc volcanism in an intra-oceanic plate convergent margin [Hawkins, 2003]. The CRO formation (rock age and emplacement) is ~163-170 Ma [Coleman, 2000; Shervais et al., 2005; McLaughlin, 1988] and was associated with an oceanic plate back-arc basin and continent collision in a convergent margin. The CRO units are often found between the Franciscan Complex (Middle Jurassic or older peridotite wedges [Coleman, 2000]) to the west and the Great Valley Sequence (Middle Jurassic calc-alkalic and mafic pillow lava, sheeted dikes, and gabbro [Coleman, 2000] to the east. The CRO sequence includes mafic rocks, pyroclastic rocks, gabbro, and peridotite [Coleman, 2000]. It is often found as mélange.

The McLaughlin Natural Reserve is now a research and education-focused space, administered by the UC-Davis and supported by a joint initiative between the Homestake Mining Inc. Co. (currently engaged in closure of a gold mining operation at the site) and local conservation groups.

1.5.2 Zambales Ophiolite (ZO)

The Philippine Islands are a mixture of island arcs and continental fragments [Hall et al., 1995]. They are bordered by oppositely-dipping subduction trenches (Manila Trench to the west and Philippines Trench to the east) and have a complicated history of uplift and faulting. The Zambales Ophiolite (ZO), Zambales Range, Luzon, Philippines (Figure 1) is a SSZ ophiolite and was derived from interactions of an island arc system and back-arc basin [Yumul, 2007; Hawkins and Evans, 1983] during the Cenozoic era [Karig et al., 1986], Eocene epoch (33-56Ma) [Yumul, 2007]), which implies that the rock and emplacement age are roughly the same.
The ZO is broadly composed of two blocks of uplifted, tilted, and strike-slip fault shifted lithosphere that have complete Penrose ophiolite sequences [Yumul, 2007] and vary in geochemistry and thickness of the crustal section [Hawkins and Evans, 1983]. The (1) Acoje block to the north is accreted tholeiitic intraoceanic island arc material, while the (2) Coto block to the south is a typical back-arc basin rock series [Hawkins and Evans, 1983]. See the appendix Figure A2 for a geologic map of the ZO.
2. Methods

2.1 Sample descriptions

Samples include serpentinite cores and hand samples from the Coast Range Ophiolite (CRO) in Northern CA and hand samples obtained from serpentinites from the Zambales (ZO) Ophiolite in the Philippines. Table 2 gives a summary of sample locations, depths, and approximate elevations. Figure 4 presents pictures of each sample following collection. Samples collected ranged in mineralogy, depth (surface and core samples), and locations within the sampling area. X-ray diffraction analysis was performed first on each sample to indentify the main component minerals. Many samples of the CRO and ZO were analyzed; however, only variably serpentinized peridotite samples’ data are reported here. Chlorite-rich samples are not reported as they were interpreted as being from weathered basalt units and not peridotite units [Wetzel and Shock, 2000]. Additional data and sample information are reported in the appendix.

2.1.1 Coast Range Ophiolite Samples

Coast Range Ophiolite Microbial Observatory (CROMO) wells were drilled and cores dominated by serpentinite were collected in 2011 [Cardace, et al., 2013]. The CROMO 2 well located in the Quarry Valley area of the McLaughlin Reserve bottoms out at ~45.7 m (~152 ft) depth from surface in a serpentinized peridotite layer [Cardace, et al., 2013]. CROMO 2 core samples were taken from ~44.5 m (~148 ft) to ~45.7 m (bottom of hole). CROMO samples were vibrated in distilled/DI water. The water and suspended clay minerals were poured into an Al-foil boat. The bulk of the samples (not suspended in the water), were also placed on an Al-foil boat. Both parts
of the samples were dried at 60°C over night and were analyzed with XRD, XRF, and MOSS. See appendix for data on the suspended clays.

Additionally, the McLaughlin Natural Reserve has archived cores from when Homestake Mining Company was surveying the area. Some of the boreholes passed through hundreds of feet of variably-serpentinized peridotite, some of which were found to contain relict olivine grains. Samples were collected from 3 cores: M81-167, M81-309, and M81-313 at various depths (see Table 2).

Hand samples from the Stonyford Volcanic Complex [Shervais, et al., 2005] were collected as float (cobbles in the creek and not collected in situ) located in the Hyphus-Little Stony Creek confluence near Stonyford, California.

### 2.1.2 Zambales Ophiolite Samples

Serpentinized peridotite hand samples were collected in September 2012 from the Poon Bato region of the ZO and were analyzed. See Table 2 for latitude and longitude data, and Figure 4 for pictures of the samples before being powdered for analysis.

### 2.2 XRD

X-ray Diffraction (XRD) analysis determined the bulk mineralogy of the samples. A portable Olympus (formerly InXitu) Terra field XRD instrument, with the specifications equivalent to the CheMin tool developed for Mars exploration as described in Blake et al., [2012], was used for all XRD analyses. The Terra engages a Co X-ray source and a cooled charge-coupled device (CCD) detector arranged in
transmission geometry with the sample, with angular range of 5° to 50° 2θ with < 0.35° 2θ resolution [Blake et al., 2012]. X-ray tube voltage is typically 30 kV, with a power of 10 W, a step size of 0.05°, and an exposure time of 10 s per step. Default settings were used except the number of exposures was 1000 (total run time is about 70 min) and the piezo volume was 70.

Samples were powdered using a percussion mortar and/or agate mortar and pestle; when necessary a Dremel manual drill was used to subsample grains of interest. A total of ~9 g of the focus samples were powdered. Powders were passed through a standard 150 μm sieve (100-mesh) prior to analysis. The portions of each sample selected for analysis were not always completely powdered to ≥150 μm, so some of the harder minerals may be under represented in all experiments that required a powdered sample. About 15 mg of powdered material was transferred with a spatula to the inlet hopper of the standard sample vibration chamber, which continuously mixes the powdered sample for the duration of the analysis. Rotation disks (sample is rotated instead of vibrated) were also used for some samples and all the standards.

The resulting diffractograms were interpreted using XPowder software, which is a commercially available peak search-and-match program that queries the PDF2 database for reference mineral peak information. XPowder allows for identification only (not quantification) of major minerals and trace minerals can be easily missed and/or masked by peaks of other minerals. Diffractograms have °2θ on the x-axis and intensity on the y-axis. An intensity peak is the result of constructive interference when Bragg’s law \( n\lambda=2d \sin \theta \), where n is the "order" of reflection, \( \lambda \) is the incident
X-rays wavelength, d is spacing between atomic planes in a crystal structure, and \( \theta \) is the incidence angle) is fulfilled by the incoming X-rays.

### 2.3 Thin section microscopy

Thin section (TS) petrography was used to identify relic, accessory, and trace minerals, confirm XRD analysis, and observe relationships between minerals at the micro-scale. Thin sections (30 μm-thick, standard slides) available of select samples were viewed at various magnifications (2-10X) in both plane-polarized (ppl) and cross-polarized (xpl) light and photographed (Figures 9-12, 14-21, and 23) using an Olympus BH-2 polarizing light microscope, an Olympus DP73 digital color microscope camera, and Stream Essentials 1.8 image analysis software.

### 2.4 XRF

X-ray fluorescence (XRF) and scanning electron microscopy (SEM) were used to constrain elemental, especially Fe, concentrations in bulk rock and individual grains, respectively. Fe concentrations (see Appendix for additional element concentrations) were obtained from selected bulk samples (see section 2.1 for sampling bias).

A Thermo Scientific Niton XL3t portable XRF analyzer desktop laboratory unit was used for element analysis. Because the Niton XL3t is a handheld device and was used without vacuum conditions, elements lighter than Mg were not detected [Rollinson, 1993; Wirth and Barth, 2012; EPA Method 6200, 2007]. An adapted EPA Method 6200 was used. Samples were analyzed using soils mode, which is tuned for
quantification of elements common in soils and is biased toward those of specific interest to the lab analyzing soils. There are other modes (metal, mining, consumer goods) generally used with the hand held XRF, but they were not available at time of analysis.

Samples were sieved to 150 μm (#100 sieve) and ~2 mL of bulk sample was analyzed. Samples were run for 200 s and analyzed three times with the sample being shaken/agitated between each run. The three values were averaged and the mean was normalized using USGS standards described below.

Fe precision and accuracy were estimated from replicate sample runs and utilizing USGS standards Dunite, Twin Sisters (DTS-1), Dunite, Twin Sisters Mountain DTS-2B (DTS-2), and Peridotite, Cedars CA Ultramafic Mass (PCC-1) which indicate accuracy within ~24-64% and precision with a standard deviation between 170-770 ppm.

To obtain the normalization factor (Table 5), each standard’s reference value was divided by the average observed value (REF/OBS). When REF/OBS was calculated, DTS-1 was 0.6133, DTS-2 was 0.8045, and PCC-1 was 0.6096. See calculations below used to obtain the normalization factor:

\[
\frac{\text{Reference}}{\text{Observed}} = \frac{DTS - 1 \text{ published average}}{\text{average of 4 sample runs}} = \frac{\sim 60710 \text{ ppm}}{\sim 98979 \text{ ppm}} = \sim 0.61
\]

\[
\frac{DTS - 2 \text{ published average}}{\text{average of 4 sample runs}} = \frac{\sim 54300 \text{ ppm}}{\sim 67489 \text{ ppm}} = \sim 0.80
\]

\[
\frac{PCC - 1 \text{ published average}}{\text{average of 4 sample runs}} = \frac{\sim 58402 \text{ ppm}}{\sim 95798 \text{ ppm}} = \sim 0.61
\]

16
Sample values were normalized to DTS-1 because it had a similar percentage difference between the observed value and the published value of PCC-1 which is a serpentinized peridotite similar to the samples. See calculations below used to obtain general accuracy error:

\[
\text{Observed} \quad \text{Reference} = \frac{DTS - 1 \text{ average of 4 sample runs}}{\text{published average}} = \frac{\sim98979 \text{ ppm}}{\sim60710 \text{ ppm}} = \sim1.63 \rightarrow \sim63\% \text{ error}
\]

\[
\frac{DTS - 2 \text{ average of 4 sample runs}}{\text{published average}} = \frac{\sim67489 \text{ ppm}}{\sim54300 \text{ ppm}} = \sim1.24 \rightarrow \sim24\% \text{ error}
\]

\[
\frac{PCC - 1 \text{ average of 4 sample runs}}{\text{published average}} = \frac{\sim95798 \text{ ppm}}{\sim58402 \text{ ppm}} = \sim1.64 \rightarrow \sim64\% \text{ error}
\]

The error for XRF is ±24% based on the discrepancy of DTS-2 after normalizing to DTS-1 (Table 5). Additional error could come from samples not being homogeneous, so the Fe is not equally distributed resulting in over or under exaggerating the concentrations. Standards were run four times and samples were run three times. The samples and standards were shaken/agitated between each run to try and get a more accurate account of the Fe present.

Additional error between reference and observed could occur if the average used for the reference data incorporated values that oven dried the samples prior to analysis and, therefore, has loss on ignition (LOI). The USGS certificate of analysis for DTS-1 and DTS-2 does not include LOI values. The GeoReM database [Jochum et al., 2005] reports that the LOI for DTS-1 is 0.2%m/m, DTS-2 is 0.36%m/m, and PCC-1 is 4.91%m/m. There are more than 100 data sets for PCC-1; however, only two
report LOI (4.91 and 5.12% m/m). DTS-1 has more than 80 data sets and only one reports LOI (0.2% m/m). DTS-2 only has 22 data sets with only one reporting LOI (0.36% m/m). The data sets that report LOI do not always report Fe concentration, so it is difficult to gauge how Fe concentration would vary with less water in the samples; however, it stands to reason that if concentration data are normalized to 100%, then low water contents could result in relatively higher reported concentrations of FeO. For instance, the observed Fe concentrations in this case were higher than the reference values. The main source of error was probably instrumental.

The CROMO 1, CROMO 2, and PHL samples in this study were dried in an incubator oven set at 60°C (140°F). Other CRO samples were air dried at generally less than 37°F (95°F). Standards were transferred directly from original container to sample holders. They were not dried in an oven before analysis.

Most of the samples were powdered using a steel percussion mortar, so it is possible that the samples were contaminated resulting in higher Fe concentrations. This would not account for the higher values of the USGS standards as they were already powdered.

2.5 SEM-EDS

SEM-EDS was used to measure the concentration of most major elements in weight percent (wt%) in specific mineral grains from the thin section of sample 313_329. A JEOL 5900 scanning electron microscope (SEM) with Energy Dispersive X-ray Spectroscopy (SEM-EDS) was used on thin sections to obtain high resolution imagery (Figures 13, 18, 20, 22, and 25-29) and spot analysis compositions of major
elements in wt% oxides (Tables 7-11) in individual mineral grains and within the groundmass.

The detection limit for SEM-EDS is 0.5wt%, so the elements with lower concentrations have lower accuracy. The SEM-EDS also has limited sensitivity for elements with atomic numbers below 11 (Na) [Goldstein, 2003], so the oxygen present is not accounted for. The SEM-EDS instrument was set to do a spot analysis for 30 s for each spot. With more time (e.g., 5 min instead of 30 s) dedicated to data analysis for each spot, the accuracy increases for low concentration elements. Wt% are calculated from the area under the curve created from intensity peaks. SEM-EDS data are reported in Tables 7-10 and corresponding area images are in Figures 13, and 25-29.

2.6 Mössbauer spectroscopy (MOSS)

The redox status of a system can be broadly determined from the valence state of Fe—Fe$^{2+}$ is reduced and Fe$^{3+}$ is oxidized—and MOSS data provide Fe$^{2+}$ and Fe$^{3+}$ as percentages of total Fe. There are limitations to MOSS: it can’t distinguish between similar minerals, and results vary as a function of cation substitution and temperature. There is better peak resolution at colder temperatures with a recommended temperature of 40 K and the magnetic properties can change at temperatures below ~24 K [Dyar, et al., 2008]).

Often MOSS is performed on individual minerals, which will only give the redox status of individual mineral types within the sample. In this study, a bulk analysis was done to gauge better the redox status of the whole sample. It is also very
difficult to hand-pick minerals found in a highly serpentinized rock. Bulk rock samples were again powdered and sieved to 150 μm. Samples were prepared, analyzed, and modeled similar to the methods used in Evans, et al. [2012], which are briefly outlined here. About 40-100 mg of sample were mixed with a sucrose filler and mounted in a sample holder confined by Kapton polyimide film tape. Samples were run at room temperature (~295 K) using a source of 100-60μCi $^{57}$Co in Rh on a WEB Research Co. model WT302 spectrometer at Mt. Holyoke College (South Hadley, MA) for periods of time from 2-24 hours. More time is needed for lower Fe concentrations. Spectra were collected over a velocity range of ±4 mm s$^{-1}$ for samples without oxides and/or ±10mm/s if Fe oxides, like magnetite, were present. A ±10 mm s$^{-1}$ velocity scale is needed to show the magnetite peaks resulting from additional quadrupole splitting from the magnetic properties of the Fe.

Spectra were processed using two software packages from the University of Ghent. Simple paramagnetic doublet (Fe$^{2+}$ and Fe$^{3+}$) spectra were modeled using the Dist3e program. More complex spectra with sextets (magnetite) and doublets were modeled using the MEX FielDD program. While modeling, isomer shifts (IS) and quadrupole splitting (QS) were allowed to vary in unison. Peak widths for doublet sets were allowed to vary in unison with IS and QS [Evans, et al. 2012] in most cases. Some widths were fixed to guarantee a ≥0.23mm/s. Dyar et al. [2008] discusses sources of error (low number of recoil-free emissions, temperature and its influence on QS, IS, and resulting Fe valence state percentages, etc.) of MOSS measurements associated with phyllosilicates (clay minerals), which applies to serpentine minerals (and other alteration minerals like chlorite), which are clay minerals. MOSS results are
given as area under the curve corresponding to percentages Fe$^{2+}$ and Fe$^{3+}$ (doublets), and magnetite (sextet), if present, of the total Fe. Table 3 gives general parameters for MOSS data fitting.

Some samples for MOSS do not contain magnetite; however, TS and XRD indicate that magnetite is present in every sample. For samples with MOSS spectra without magnetite, it is assumed that magnetite is less than 1% of the total Fe. It is possible that the XRD and TS splits were more magnetite-rich than the powder analyzed by MOSS and/or the magnetite indicated by the XRD was actually a different spinel.

2.7 H$_2$ modeling

For simplicity, in this model, it is assumed that all the Fe is originally Fe$^{2+}$, that the Fe concentration has not changed over time [Adreani et al., 2013B], and that the simplified serpentinization reaction (equation 1) holds true. Peridotite can contain opx, cpx, and/or spinel which can house Fe$^{3+}$ (Table 1), so it is basically assumed that the samples started out as 100% olivine (only Fe$^{2+}$) (dunite peridotite) or that the Fe in other minerals is also only in the 2+ valence state and/or minerals, like spinel, are present in trace amounts which are lost within the error of XRF measurements (see section 2.4).

Using MOSS results, the approximate volume of the CRO or ZO peridotite, the Fe concentration, the simplified serpentinization reaction (Eq. 1), and stoichiometry, the hydrogen yield of the CRO and ZO can be estimated for the life time of the peridotite unit. It was estimated using two different conversion factors: one of which
was density \((g/cm^3)\) and \(mg/kg\) to convert from ppm to \(g\); the other used \(mg/L\) to convert from ppm to \(g\). See section 3.4 for worked-out examples.
3. Results and Discussion

In general, data from XRD, TS, XRF, SEM-EDS, and MOSS analyses confirm there are important differences in the proportions of mineral phases and Fe valence state in those phases, within a geographic region and also across all samples.

3.1 XRD & Thin section petrography

Minerals identified using XRD and/or TS include serpentine, magnetite, other spinel group minerals, pyroxenes, olivine, chlorite, other unidentified clay minerals, brucite, amphibole, and garnet. On XRD diffractograms, brucite and spinels, including magnetite, have overlapping and/or closely spaced intensity peaks that vary in position depending on chemical composition, which can make differentiating these minerals challenging. Spinels (spinel, magnetite, chromite) and brucite look different under a polarizing light microscope. The spinel series in these samples are often reddish-brown or dark brown to black. Spinel is most often in individual, isolated grains that are reddish brown and semi-transparent (Figure 12, 15, 20, among others). Magnetite and chromite are opaque and appear black (Figure 9, 11, 14, 15, etc…). They were not distinguished from each other and assumed to be magnetite in thin sections. Individual mineral elemental analysis would be needed to distinguish them. Brucite is often colorless or yellowish and found intermixed with serpentine and/or in veins (Figure 11, 19). Therefore, thin sections were used to confirm XRD analysis, and identify trace or relict minerals that (1) may not have been included in the ~15 mg of powdered rock used in XRD and/or (2) were present in amounts too small to be detected by the
XRD. Thin sections also allow petrographic study of the spatial distribution of mineral grains and textures.

3.1.1 Diffractograms

The main two serpentine phases available for peak comparisons in reference databases were antigorite and lizardite. While each sample had peaks corresponding to one or both of these phases, it is also highly likely that other phases of serpentine like chrysotile and greenalite were also present. The serpentine peaks (Figures 5-8) generally have the highest intensity in the samples followed by peaks for magnetite, spinel, and olivine near 39 to 44°2θ. The intensity indicates diffraction caused by mineral crystallinity and helps in mineral identification because each mineral has a unique diffraction pattern. Figure 6 is the stacked diffractogram for ZO samples. PHL_3 has the strongest peaks for olivine found in any of the samples. Figure 7 is the stacked diffractogram for CRO CROMO2 samples. CROMO2_3 has an unknown peak with a 2θ of ~31° (i.e., d-spacing of 3.3471 Å). The variation of peaks with a 2θ of ~40-45° is from magnetite and spinel variations.

Overall, XRD data indicate that serpentine, magnetite and/or other spinel are present in all the samples. Pyroxene, olivine, chlorite, brucite, amphibole, garnet, and/or other clay minerals such as smectite are identified in various samples.

3.1.2 Thin section and SEM images

Serpentine is the most abundant mineral based on qualitative assessment of mineral abundance in thin sections. Serpentine often forms a square-like mesh or net-
like texture on the micro- and macro-scale; interlocking veins of serpentine surround fractured relict (or variably serpentinized) olivine and/or pyroxene, as seen especially in Figures 12, 16, 19, 20, and 23. This mesh texture is often more easily visible in xpl with the grey serpentine surrounding the more brightly colored (higher birefringence) olivine/pyroxenes. Serpentine is also found in larger veins that show variations in color, texture, and/or composition (TS Figures 11a, 16a, and 23a, and SEM-EDS Figures 13a & d) from the center to edge of the vein. The dissolution of olivine can also be seen in SEM-EDS images (Figure 22) that show olivine grains with irregular grain boundaries (jagged dendritic wedges on the edges), giving the appearance of micro-scale reaction zone.

### 3.1.3 Mineralogical results summary

Documenting site-specific mineral assemblages is a first step in characterizing the redox status of Fe because Fe occurs in different valence states in different minerals (Table 1). The mineral assemblages in the samples are similar to those predicted [Wetzel and Shock, 2000; Moody, 1976; McCollom and Seewald, 2013; Sleep et al., 2004] and similar to those found in serpentinite cores from Ocean Drilling Project (ODP) sites [Bach et al., 2006; Beard et al., 2009 also found plagioclase; Klein et al., 2014].

All of the target samples contain serpentine (lizardite and/or antigorite, and probably greenalite and/or chrysotile) and spinel group minerals such as magnetite (Fe), chromite (Fe & Cr), gahnite (Zn & Al), and/or galaxite (Mn, Mg, Al, and/or Fe). Different minerals indicate different compositions and temperature and pressure
conditions. Olivine and pyroxenes were identified in samples that appear to be less serpentinized. Olivine was identified in all the ZO samples and three of the four samples from McLaughlin borehole 313, which had hundreds of feet of variably serpentinized peridotite recorded on the core log.

Chlorite was found in small quantities in samples 313_210 and maybe 313_356, indicating that there were, at least locally, variations in composition of the fluid and/or rock, temperature, and/or pressure that encouraged chlorite instead of serpentine to form. From a thermodynamic viewpoint, peridotite alteration modeled in the subseafloor at ~350 to 400°C yields much less chlorite than serpentine, but chlorite is expected, to some extent, in these ophiolite samples (Wetzel and Shock, 2000).

Garnet was found in samples HLSC_1, 313_356, and maybe PHL_3, indicating possible high pressure/temperature conditions, likely in a subduction zone subsurface environment in the mantle wedge [Liou et al., 2007] and/or during emplacement at the continental margin. Andradite garnet (Ca$_3$Fe$_{3+2}$SiO$_4$)$_3$ was identified by XRD in HLSC_1 and 313_356. Andradite garnet can be formed at low pressure and high temperatures [Huckenholz and Yoder, 1971; Gustafson, 1974]. Chemical analysis is needed to confirm the XRD analysis. The garnet grains in 313_356 do not appear to be the well-formed, geometric crystals expected if the garnets were neoformed minerals, instead suggesting that they may have started to undergo dissolution and/or other alteration since their original formation. It is possible that these samples were in a relatively shallow area in a subduction zone but still exposed to high temperatures (prograde metamorphism), and then uplifted (retrograde metamorphism) and emplaced. Sample 313_356 seems to have a more complicated
history than some of the other samples as indicated by the garnet and lack of serpentine veins or classic serpentininite mesh textures.

The brucite group mineral identified by XRD is portlandite, which is a Ca-rich hydroxide instead of the expected Mg-rich \((\text{Mg(OH)}_2)\) brucite, predicted by McCollom and Bach [2009] and references therein. Portlandite was identified in samples also containing pyroxene (cpx—hedenbergite and johannsenite—and opx—enstatite group), which could account for the Ca. However, the Ca could have also come from entrapped seawater and/or the sedimentary rock units of the CRO and ZO. It is also possible that Fe and Mg-rich brucite is present in the samples.

The minerals most likely to contain Fe are magnetite, spinel, olivine, pyroxenes, and serpentine.

### 3. 2 XRF & SEM-EDS

In general, the Fe concentrations found in the samples are similar to those found in other variably serpentinized peridotite (see Table 6, Figure 24, Table A2 for data from literature, and Table A8 for raw XRF data collected). CRO core 313 and the ZO samples have the highest concentrations of Fe (Figure 24). They are also the samples with more abundant relict olivine and, therefore, are less serpentinized (see Figures 10-12, 14, 16-21, 23). This leads to the conclusion that Fe is reapportioned into different host minerals through water-rock reaction, may have left the system in fluid phases \((\text{Fe}^{2+})\) during serpentinization, and/or CRO core 313 and the ZO samples parent rocks had more Fe than the other samples. It is possible that \(\text{Fe}^{2+}\) could have been oxidized, precipitated, and accumulated in areas other than where the samples
were collected, perhaps in the more hydrothermal areas of the ophiolites where Au, Ag, S, and other metals also accumulate. CRO core 313 was located in what was a pit mine, so maybe, it was more Fe-rich because more Fe was being deposited, which may also account for the higher percent of Fe$^{3+}$ reported in MOSS.

Sample 313_210 has the highest bulk concentration of Fe across all samples. It also contains large grains of possible Fe-oxide(s) (and/or hydroxides) (Figure 10), which may account for the larger bulk concentration of Fe.

HLSC_1 has the lowest concentration of Fe and most of the Fe is in magnetite instead of the silicates. The TS for HLSC_1 also shows Fe-oxide zones similar to 313_210 and magnetite scattered throughout (Figure 9). HLSC_1 may be a case of under exaggeration of the bulk sample concentration, or the thin section could be an over exaggeration and just happens to be a Fe-oxide rich section.

SEM-EDS data for sample 313_329 (Tables 7-10, Figures A19-23) indicate that the Fe concentration in the minerals analyzed is ≤0.02wt% (200 ppm) (see section 2.5 for detection limit discussion—0.5 wt%) for olivine (Tables 7, 9, and 10), ≤11.1wt% (111,000 ppm) for an alteration mineral (probably serpentine) (Table 8) next to an olivine grain (Table 7) that had ≤0.02 wt% Fe at its center. The fractured spinel (Table 11) had ≤33.3 wt% Fe (332,500 ppm) with the median being 0.03 wt% (300 ppm) (of the 10 spots analyzed on the spinel, seven had Fe wt % of 0.03, one with 0.02, one with 26.6, and one with 33.3 wt%). According to these numbers and mineral observations, the bulk of the Fe is concentrated in spinel group minerals including magnetite and other Fe-oxides. There is also Fe in serpentine, possibly greenalite, with smaller contributions from olivine.
Spinel also contains large quantities of Al (22.7 to 80.3 wt % or 332,500 to 803,100 ppm). The smallest concentration of Al occurred at the spot where Fe was also the highest. The Al and the spinels could be a catalyst for hydrogen generation [Andreani et al., 2013]. Besides spinels, Al can also be hosted in olivine, serpentine, pyroxene, and other clay minerals. Al was identified in olivine by SEM-EDS as having ≤5.89 wt% (589,000 ppm), which was surprising because olivine is not usually thought of as incorporating elements with a 3+ valence state into a 2+ slot.

3. 3 MOSS

MOSS parameters (IS, QS, W, A, and B_{hf}), chi-squared (X^2), and areas under the curve (Table 12) are similar to those of serpentine and other minerals reported by others (Table 3, Table A2). Within each MOSS plot (Figures 30-45), the best-fit curve (red) can be seen as a combination of Fe^{2+}, Fe^{3+}, and magnetite (Fe_{2}^{3+}Fe_{2}^{2+}O_{4}) curves. In practice, curve fitting parameters determine the % area under the curves that is tied to Fe^{2+}, Fe^{3+}, or magnetite. For samples from CRO and ZO, percentages of total iron found as Fe^{2+}, Fe^{3+}, and magnetite-hosted Fe are stacked in Figure 46. Magnetite has distinct fit, sextet patterns and curves that are distinguishable from other minerals in the sample such as Fe-oxides like hematite. The silicates (serpentine, olivine, pyroxene, chlorite, and amphibole), other clay minerals, hydroxides, and/or other spinel group minerals account for the Fe^{2+} and Fe^{3+} doublet curves. Each the Fe^{2+} and Fe^{3+} doublet curve could account for a different mineral.
3.3.1 MOSS analysis of bulk sample

The amount of magnetite in each sample is just a random chance from sampling and the magnetite peaks are fit so they can be removed and look more directly at the silicates, especially serpentine. Magnetite, however, will be discussed in this section in the attempt to gauge the status of the whole bulk rock and not just the silicates, which will be discussed in the next section (3.3.2). The %Fe\(^{3+}\) and %Fe\(^{2+}\) values that include divided up %magnetite are also utilized in the H\(_2\) generation calculations.

HLSC\_1 has the most Fe attributed to magnetite: ~63%. Samples 309\_105\_A, 313\_210, 313\_318, 313\_329, 313\_356, and PHL\_3 have the least Fe attributed to magnetite (<1%) and generally have the least visible magnetite in TS. When %magnetite is divided up into Fe\(^{2+}\) and Fe\(^{3+}\) (see Figure 47) and added to %Fe\(^{3+}\) and %Fe\(^{2+}\), the average Fe\(^{2+}\) for CRO is 54% Fe\(^{2+}\) (~30% range from 40-70%) and ZO averages less at 37% Fe\(^{2+}\) (~6% range from 34-40%). In other words, ZO averages more Fe\(^{3+}\) (~63%, 6% range from 60-66) than the CRO (~46% Fe\(^{3+}\), 30% range from 30-60%). The wide range for CRO samples may largely be due to the larger number of samples (12 vs. 4 for ZO).

Samples from CRO core 313 had the most variation with ~18% range (~36% Fe\(^{3+}\) in sample 313\_210 to 54% Fe\(^{3+}\) in sample 313\_356). ZO samples had a smaller range (6% from 60-66 %Fe\(^{3+}\)), but also fewer samples to compare. I suspect, however, that even with a similar spread of hand and core samples, the ZO would have closer percentages (i.e., tighter range) than the CRO because the ZO rocks have a less complicated tectonic history; the CRO, however, is often found reworked in m\'élanges.
or mixtures of the classic ophiolite sequence. The ZO hand samples were collected at the surface, so it is possible that less serpentinized and weathered samples could be found deeper below the surface, which would cause more variation in Fe valence state percentages. The CRO was a mix of surface samples, shallow cores, and deep cores (>300ft). When all surface and core samples are compared together, there is not a direct correlation between depth and \%Fe^{3+}, possibly due to the mixing and/or additional oxidation at the surface when exposed to O_2. When cores samples only are compared, especially 309 and 313, there is a slight positive correlation between depth and \%Fe^{3+} (Figure A39).

3.3.2 MOSS analysis of silicates

To better understand the redox state of the system, the magnetite was factored out (Table 12, Figure 48) to get a Fe^{3+}/Fe_{tot} in other minerals, especially silicates like serpentine.

When comparing ZO samples to CRO core 313 samples that still had relict olivine, it seems like the more olivine there is, the more Fe^{3+} there is. In other words, ZO samples have the highest \%Fe^{3+} average (~63%). CRO core 313 samples had ~45% average). Some samples with little to no olivine, such as CROMO2 samples 1A and 4A, and 313_356, actually hover around 50 \% Fe^{3+}. Sample167_238 has the expected higher \%Fe^{3+} (57%), which may have relict olivine and/or pyroxenes similar to ZO and 313 samples. HLSC_1, CROMO2 _2, CROMO2_3A, 309_105_A, and 309_150 have <40 \%Fe^{3+}. 

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Variations in Fe valence states were expected because of the varying degree of serpentinization, the mineral contents, and environments even within a few feet. It was assumed that the Fe would be oxidized during serpentinization, so it was expected that samples with trace amounts of olivine would have a higher percentage of Fe$^{3+}$ than Fe$^{2+}$; however, the general trend where the more olivine-rich or the less serpentinized rocks had higher %Fe$^{3+}$. The Fe$^{3+}$ could be within the pyroxenes, spinel, and serpentine and/or it is possible that when the Fe$^{2+}$ was mobilized, it was carried away in the fluid while the Fe$^{3+}$ was deposited (recall that Fe$^{3+}$ is not soluble in water at high pH, which would apply in this case). As discussed in section 2.7, Adreani et al. [2013B] did not see a change in Fe concentration over time, so the Fe is probably staying within close proximity to its parent mineral.

O’Hanley and Dyar [1993; 1998] (Table A2) analyzed ~35 lizardite and chrysotile specimens from Canada with MOSS and found a range of 22-100% Fe$^{3+}$ (most between 30 and 88 %Fe$^{3+}$ and chrysotile generally had less %Fe$^{3+}$ than lizardite). Klein et al. [2014] analyzed 12 samples from the Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP) of variably serpentinized peridotites (harzburgites and dunites). They found a range from 14-66 %Fe$^{3+}$ and ~54% average without factoring in magnetite. The samples also ranged from magnetite-rich to magnetite-poor. Canil et al. [1994] found <5 %Fe$^{3+}$ in various African peridotites that included garnet harzburgite and iherzolite, and spinel iherzolite.

3. 4 $H_2$ modeling

Hydrogen generation was calculated using the normalized average Fe concentrations, the estimated volumes of the ZO and CRO, the valence states of Fe
obtained from MOSS with % magnetite divided into %Fe\(^{3+}\) and %Fe\(^{2+}\) values, and the simplified serpentinization reaction equation (1). For each sample’s hydrogen yield, it is assumed that the Fe concentration for that sample was the same for all of the peridotite units of the CRO or ZO. Table 13 and 14 (utilizes density into conversion from ppm Fe to possible Tmol H\(_2\) (T, Tera=10\(^{12}\)) are summaries of normalized Fe concentration in ppm (see appendix Table A7 for FeO wt%), Fe valence states in percent from MOSS, and possible hydrogen gas yield per 1km\(^3\) of rock and per the total volume of the peridotite units of the corresponding ophiolite. The estimated volume of the peridotite units in the CRO is 7730km\(^3\) [Area (~3865km\(^2\)—Carnevale, 2013; depth (~2km)—Coleman, 2000] and 1455 in the ZO [Area (~485km\(^2\)]—Abrajano and Pasteris, 1989; depth (~3km)—Hawkins and Evans, 1983]. Average density (g/cm\(^3\)) of variably (40-100%) serpentinized hazburgites and dunites taken from Andreani et al. [2013B] and Klein et al. [2013].

Explanations and example calculations starting with CRO sample 167_238 Fe concentration (ppm) to possible H\(_2\) (Tmol) already released (total %Fe\(^{3+}\)) are below.

Calculation using mg/L to convert ppm to g:

\[
\left( \frac{\text{Concentration of Fe in ppm}}{29910 \text{ ppm Fe}} \right) \times \left( \frac{\text{Convert ppm to mass (mg)}}{1 \text{ mg/L}} \right) \times \left( \frac{1 \text{ g}}{1000 \text{ mg}} \right) \times \left( \frac{\text{convert g Fe to mol Fe}}{1 \text{ mol Fe}} \right) \times \left( \frac{1 \text{ mol H}_2}{1 \text{ mol Fe}^{2+}} \right) \times \left( \text{multiply total \% Fe}^{2+} \text{ or Fe}^{3+} \right) \times \left( \frac{2}{3} \times 30 \% \text{Mag} \right)
\]
The same conversion, only using mg/kg and density (g/cm$^3$):

\[
\left( \frac{\text{Concentration of Fe in ppm}}{29910 \text{ppm Fe}} \right) \times \left( \frac{\text{Convert ppm to mass}}{1 \text{ kg}} \right) \times \left( \frac{1 \text{ mol Fe}}{55.85 g \text{ Fe}} \right) \times \left( \frac{1 \text{ mol H}_2}{1 \text{ mol Fe}^{2+}} \right) \times \left( \text{multiply total } % \text{ Fe}^{2+} \text{ or Fe}^{3+} + \left( \frac{2}{3} \times 30 \text{% Mag} \right) \right) \times \left( \text{Multiply by average density and convert it to kg/m}^3 \right) \times \left( \text{multiply the volume of the ophiolite} \right) = \left( \frac{7730 km^3}{1} \right) \times \left( \frac{2.68 g}{cm^3} \right) \times \left( \frac{100 cm}{1 m} \right) \times \left( \frac{1000 m}{1 km} \right) \times \left( \frac{1 kg}{1000 g} \right) = \left( 6.65 \times 10^{15} \text{ mol H}_2 \right) \left( 6650 \text{ Tmol} \right)
\]

The total possible hydrogen production (Tmol) normalized to a volume of one 1km$^3$ (Figure 49 and 51) illustrates that even though the overall volume of the ZO is smaller, it can produce more hydrogen per unit volume than the CRO due to the generally higher concentration of Fe (Figure 24). The average total hydrogen that could be produced-per 1km$^3$, given the present Fe valence status of the bulk rock, is 0.46 Tmol H$_2$(g) for the CRO and 0.64 Tmol H$_2$(g) for the ZO. Core 313 samples had the highest average for a CRO location at 0.53 Tmol H$_2$(g), followed by 167_238 and
CROMO2 (0.43 Tmol H$_{2}(g)$), and HLSC_1 and core 309 (0.40 Tmol H$_{2}(g)$). When density is used in the calculation, the averages in Tmol are ZO-1.70, CRO-1.22, 313 core-1.41, and CROMO 1.15.

Figure 50 and 51 show hydrogen generation in Tmol using the estimated volumes of the ZO and CRO peridotite, as reported in the literature. Due to its total smaller volume, the ZO is estimated to produce less hydrogen than the CRO. The average hydrogen production for the CRO is 3511 Tmol and 923 Tmol for the ZO. The highest CRO site average is 4058 Tmol for core 313 samples, followed by CROMO1 (3327 Tmol), 167_328 (3310 Tmol), HLSC_1 (3107 Tmol), and core 309 (3086 Tmol). When density is used in the calculation, the averages in Tmol are ZO-2475, CRO-9410, core 313-10,877, and CROMO 8918.

3.5 Implications of rock data and modeling outputs

Possible hydrogen yield over the lifetime of the ultramafic peridotite blocks considered range from ~2848 Tmol to ~4752 Tmol for the CRO and ~908 Tmol to 1029 Tmol for the ZO (when density is use it is ~2028 to 2758 for ZO and ~7634 to 12735 for CRO), and is modeled here as largely controlled by Fe concentration and the volume of the ophiolite. The likelihood of water causing oxidization of Fe$^{2+}$ to Fe$^{3+}$ and releasing hydrogen is also a factor, but not directly tied into the calculations. The range of samples with their different Fe concentrations may give an upper and a lower limit of the total hydrogen generation possible from the peridotite units. It is also possible to have hydrogen produced from other mafic and ultramafic layers such as basalt and gabbros, so the actual hydrogen generation from the entire ophiolite could be higher than the simplified model predicts.
Fe is not uniformly distributed and sample concentrations (normalized) range from ~28741 to 50673 ppm in the CRO and ~58364 to 78265 in the ZO. The valence states of the Fe also vary with each sample; the % magnetite ranges from ~0-63%, Fe\(^{3+}\) from ~14 to 65%, and Fe\(^{2+}\) from ~23 to 70%. When magnetite is separated into its Fe\(^{2+}\) and Fe\(^{3+}\) components, total Fe\(^{2+}\) ranges from ~34 to 70% and Fe\(^{3+}\) ranges from ~30 to 66%. The range for silicates and factoring out magnetite ranges from 24 to 66% Fe\(^{3+}\). Variation in concentration and valence states indicates different reaction histories. On the other hand, if we assume that the olivine had similar starting Fe compositions, then the variation in observed concentrations shows that the Fe is not constant in the system(s).

The more Al-rich a sample is the more hydrogen can be yielded via serpentinization [Andreani et al., 2013]. Additional analysis of the bulk samples considered in this work and separated mineral grains is required to constrain where and how much Al is in the system at the time, to constrain the relative volumes of minerals (% serpentine, olivine, chlorite, magnetite, spinel, etc…) to help gage the extent of serpentinization (parent vs. alteration minerals), to better identify minerals including trace minerals to understand better the chemistry of the system, and to analyze fluid data, if possible, of current fluids in the system including dissolved gases like hydrogen.

Based on TS, XRD, and MOSS, the CRO and ZO are still reactive as both ophiolites still have budgets of Fe\(^{2+}\) and serpentinization is not complete. However, in areas that are mostly serpentinized, the remaining Fe\(^{2+}\) budget has been partitioned into minerals like spinel, serpentine, and magnetite that are generally chemically stable.
at surface conditions and based on the sample set, $\%$Fe$^{2+}$ could stay near 50% of the total Fe.
4. Conclusion

Serpentinites evolve complexly in the natural environment. Tectonics, emplacement history, age, climate, composition, unit hydrology, etc…all influence the redox status of a given ophiolite. The samples presented here give a glimpse into the variability of the redox status of ophiolite-hosted ultramafic peridotites, at ZO and CRO localities.

In general, the ZO has higher Fe concentrations and greater modern Fe\(^{3+}\), thus could produce more hydrogen per unit volume than the CRO because of the higher Fe content in the system. The larger area and volume extent (though poorly constrained) of the CRO does mean that the lower hydrogen productivity per unit volume might yet yield greater hydrogen in total, if integrated over the entire ultramafic volume, over the alteration lifetime of the ultramafic block. Taken together, this work indicates that geologically long term support of a H\(_2\)-fueled deep biosphere by serpentinization is feasible, and shows that the ultramafic subsurfaces of the CRO and ZO are not yet depleted in Fe\(^{2+}\).

Serpentinizing systems on Earth can be used as an analog for other terrestrial planets as we continue to search for the limits of life both on Earth and in the universe.
5. Implications for future research

A more thorough and accurate chemical (XRF, Mg concentration data for both bulk sample and individual minerals) and mineralogical analysis of the samples presented here, along with additional samples, are needed to better (1) constrain the possible hydrogen generation of the CRO and ZO, (2) understand the Fe and Mg concentration, their relationship within the contexts of peridotites, serpentinized or not, and which minerals they are partitioned into, (3) differentiate between spinel group minerals such as spinel, magnetite, and chromite, (4) obtain mineral specific redox status and possible zoning as a marker of the changes the mineral(s) has undergone as the rock and ophiolite unit were formed, and (5) provide markers to look for as we continue the search for life on Earth and other terrestrial planets.
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Table 1: Some of the possible minerals involved/created during serpentinization [Winter, 2010; Nesse, 2000; Sleep et al., 2004; Mindat.org; webmineral.com].

| Mineral Group       | Mineral name       | Chemical Formula                                      | Fe valence state |
|---------------------|--------------------|-------------------------------------------------------|------------------|
| **Olivine**         |                    |                                                       |                  |
|                     | Olivine            | (Mg, Fe)$_2$SiO$_4$                                    | 2+               |
|                     | Forsterite (Fo)    | Mg$_2$SiO$_4$                                         | 2+               |
|                     | Fayalite (Fa)      | Fe$_2$SiO$_4$                                         | 2+               |
| **Orthopyroxene (opx)** |                |                                                       |                  |
|                     | Orthopyroxene      | (Mg, Fe)$_2$Si$_2$O$_6$                               | 2+               |
|                     | ferrosilite        | FeSiO$_3$, (Fe$_2$Si$_2$O$_6$)                         | 2+               |
| **Clinopyroxene (cpx)** |                |                                                       |                  |
|                     | Pigeonite          | (Mg, Fe$^{2+}$, Ca)Si$_2$O$_6$                         | 2+               |
|                     | Hedenbergite       | (CaFeSi$_2$O$_3$)                                     | 2+               |
|                     | Augite             | (Ca, Mg, Fe$^{2+}$, Fe$^{3+}$, Al)$_2$(Si,Al)$_2$O$_6$ | Both             |
|                     | Aegirine-augite    | (Na, Ca)(Fe$^{2+}$, Fe$^{3+}$, Mg)Si$_2$O$_6$         | Both             |
|                     | Omphacite          | (Ca, Na)(Mg, Fe$^{2+}$, Fe$^{3+}$, Al) Si$_2$O$_6$     | Both             |
| **Amphibole**       | Tremolite to ferro-actinolite | Ca$_2$(Mg, Fe)$_3$Si$_6$O$_{22}$(OH)$_2$ | 2+ |
|                     | Richterite         | NaCa$_2$(Mg, Fe)$_3$Si$_6$O$_{22}$(OH)$_2$             | 2+               |
|                     | Hornblende          | (Na,K)$_0$.Ca$_2$(Mg, Fe$^{2+}$, Fe$^{3+}$, Al)$_3$(Si,Al)$_6$O$_{22}$(OH)$_2$ | Both |
|                     | Pargasite-hornblend| NaCa$_2$(Mg, Fe$^{2+}$)$_4$Al$_6$Si$_2$O$_{22}$(OH)$_2$ | 2+               |
| **Spinel**          | Spinel             | MgAl$_2$O$_4$                                         |                  |
|                     | Spinel group       | (Mg, Fe$^{2+}$, Zn, Mn)(Fe$^{3+}$, Al)$_2$O$_4$       | Both             |
|                     | Magnetite          | Fe$_3$O$_4$, (Fe$^{2+}$Fe$^{3+}$)$_2$O$_3$             | Both             |
|                     | Chromite           | FeCr$_2$O$_4$                                         | Both             |
|                     | Gahnite            | ZnAl$_2$O$_4$                                         |                  |
|                     | Galaxite           | (Mn,Mg)(Al,Fe$^{3+}$)$_2$O$_4$                        | 3+               |
| **Serpentine**      | Antigorite         | Mg$_3$Si$_2$O$_4$(OH)$_4$                              | 2+               |
|                     | Chrysotile         | (Fe, Mg)$_3$Si$_2$O$_4$(OH)$_4$                        | 2+               |
|                     | Lizardite          |                                                        | 2+               |
|                     | Greenalite         | (Fe$^{2+}$, Fe$^{3+}$)$_2$.(Si,Al)$_2$O$_4$(OH)$_4$    | Both             |
| **Other clay minerals** |               |                                                       |                  |
|                     | Smectite           | ~Ca$_0$.16(Mg,Fe)$_2$Si$_2$Al$_2$O$_{10}$(OH)$_2$.nH$_2$O | 2+ |
|                     | Chlorite           | (Mg,Fe,Al)$_3$(Si,Al)$_2$O$_{10}$(OH)$_2$. (Mg,Fe,Al)$_3$(OH)$_6$ | 2+ |
|                     | Vermiculite        | ~2(Mg,Fe)$_2$.Fe$^{2+}$Si$^{2+}$.Fe$^{3+}$,Al$_2$(Si,Al)$_2$O$_{10}$(OH)$_6$ | Both |
|                     | Talc               | Mg$_3$Si$_2$O$_{10}$(OH)$_2$, also (Mg,Fe)$_3$Si$_2$O$_{10}$(OH)$_2$ | 2+                 |
| **Hydroxides**      | Brucite            | Mg(OH)$_2$, also (Mg,Fe,Ca)(OH)$_2$                    | 2+               |
|                     | Portlandite        | Ca(OH)$_2$                                            |                  |
| **Fe Oxides**       | Wüstite            | FeO                                                   | 2+               |
|                     | Magnetite          | Fe$_3$O$_4$, (FeFe$_2$O$_4$)                           | Both             |
|                     | Hematite           | Fe$_2$O$_3$                                            | 3+               |
| **Limonite/ Fe oxyhydroxides** |            |                                                       |                  |
|                     | Goethite           | FeO(OH)                                               | 2+               |
|                     | Lepidocrocite      | FeO(OH)                                               | 2+               |
| **Metals**          | awaruite           | Ni$_2$Fe                                               | Both             |
Table 2: Approximate locations, elevations, and depths of samples collected from Hyphus-Little Stoney Creek confluence in northern CA, CROMO2 well in Lower Lake, CA, and Zambales Ophiolite sites, Philippines. Homestake Mining Co. drill core sample locations, depths, and elevations.

| Sample       | Approx. Depth (ft above sea level) | Collar Elevation (ft above sea level) | Drill Hole | Total depth of well (ft) | Total depth of well (m) | Coordinates | Grid Coordinates |
|--------------|-----------------------------------|---------------------------------------|------------|-------------------------|-------------------------|-------------|-------------------|
|              | ft                                | m                                     |            |                         |                         | North       | East              |
|              |                                   |                                       |            |                         |                         | N.W.        | N.E/S.W.         |
| 167_238      | 238-BOH                           | 73                                    | 2019.5     | 249                     | -75.9                   | 107458.91’  | 104156.78’       | 125+96.7’ 9+34.6’ NW |
| 309_105_A    | 105                               | 32                                    | 1890.3     | 330                     | -100.6                  | 104118.95’  | 104022.53’       | 101+24.4’ 13+15.1’ SW |
| 309_150      | 150                               | 32                                    |            |                         |                         |             |                   |                     |
| 309_84       | 84                                | 46                                    |            |                         |                         |             |                   |                     |
| 313_210      | 210                               | 64                                    | 1776.2     | 370                     | -112.8                  | 103533.86’  | 105296.39’       | 88+57.4’ 7+15.4’ SW |
| 313_318      | 318                               | 97                                    |            |                         |                         |             |                   |                     |
| 313_329      | 329                               | 100                                   |            |                         |                         |             |                   |                     |
| 313_356      | 356                               | 109                                   |            |                         |                         |             |                   |                     |

| Sample       | Approx. Depth (ft above sea level) | Collar Elevation (ft above sea level) | Drill Hole | Total depth of well (ft) | Total depth of well (m) | Latitude       | Longitude       |
|--------------|-----------------------------------|---------------------------------------|------------|-------------------------|-------------------------|----------------|------------------|
|              | ft                                | m                                     |            |                         |                         |                |                  |
| HLSC_1       | 0                                 | 0                                     | ~1230      | na                      | 0                       | 0              | N 39.32401°      | W 122.52460°    |
| CROMO2_1A    | 144-BOH                           | 44-45.7                               | ~2120      | QV 2, 1                 | 150                     | 45.7           | N 38°51.724’     | W 122°25.827’   |
| CROMO2_2A    |                                   |                                       |            |                         |                         |                |                  |
| CROMO2_3A    |                                   |                                       |            |                         |                         |                |                  |
| CROMO2_4A    |                                   |                                       |            |                         |                         |                |                  |
| PHL_1        | 0                                 | 0                                     | -590       | na                      | 0                       | 0              | N 15°19.333’     | E 120°04.306’   |
| PHL_2B       | 0                                 | 0                                     |            | na                      | 0                       | 0              |                  |                  |
| PHL_3        | 0                                 | 0                                     |            | na                      | 0                       | 0              |                  |                  |
| PHL_5        | 0                                 | 0                                     |            | na                      | 0                       | 0              |                  |                  |

Bottom of hole (BOH).
Table 3: Typical 295K Mössbauer spectroscopy (MOSS) data fitting parameters for some minerals found in Coast Range Ophiolite and Zambales Ophiolite taken from Dyar et al., [2006].

| Valence state or mineral | Doublet/sextet | IS (mm/s) | QS (mm/s) | Site occupancy or B\(_{hf}\) (tesla) |
|--------------------------|----------------|-----------|-----------|-------------------------------------|
| Ferric [Fe\(^{3+}\)]    | Doublet       | 0.2-0.5   | 0.3-1.3   |                                     |
| Ferrous [Fe\(^{2+}\)]   | Doublet       | 1.0-1.5   | 1.5-4.0   |                                     |
| Magnetite                | Sextet        | 0.26      | -0.02     | ~ 490                               |
|                           | Sextet        | 0.67      | 0.0       | ~ 460                               |
| Hematite                 | Sextet        | 0.37      | -0.02     | 518                                 |
| Spinel                   | Doublet       | 1.11      | 1.75      | M                                   |
|                          | Doublet       | 0.90      | 0.96      | T                                   |
|                          | Doublet       | 0.86      | 1.63      | T                                   |
|                          | Doublet       | 0.31      | 0.79      | M                                   |
| Chromite                 | Doublet       | 0.32      | 0.44      |                                     |
|                          | Doublet       | 0.22      | 0.91      |                                     |
|                          | Doublet       | 0.96      | 0.50      |                                     |
|                          | Doublet       | 0.90      | 1.15      |                                     |
| Olivine (Fa)             | Doublet       | 1.14      | 3.10      | M                                   |
| Olivine (Fo)             | Doublet       | 1.14      | 2.93      | M                                   |
| Ferrosilite (opx)        | Doublet       | 1.18      | 2.49      | M1                                  |
| Hedenbergite (opx)       | Doublet       | 1.18      | 2.21      | M1                                  |
|                          | Doublet       | 0.34      | 0.68      | M1                                  |
| Diopside (cpx)           | Doublet       | 1.16      | 1.87      | M1                                  |
| Amphibole:               | Doublet       | 1.15      | 2.14      | M2                                  |
| Tremolite-actinolite     | Doublet       | 1.11      | 2.85      | M1                                  |
| Serpentine: Lizardite    | Doublet       | 1.12      | 1.80      | M2                                  |
| Serpentine: Chrysotile   | Doublet       | 1.11      | 2.40      | M3                                  |
|                          | Doublet       | 1.14      | 2.70      | M                                   |
|                          | Doublet       | 0.40      | 0.70      | M                                   |
|                          | Doublet       | 0.24      | 0.39      | T                                   |
|                          | Doublet       | 0.13      | 2.75      | M                                   |
|                          | Doublet       | 0.31      | 0.86      | M                                   |
|                          | Doublet       | 0.18      | 0.33      | T                                   |

Isomer shift (IS) is the shift up or down of nuclear levels that results from the overlap of nuclear and s-electron charge distributions, [Dyar et al., 2006]. Quadrupole splitting (QS) is the separation between two component peaks or the difference between two transition energies [Dyar et al., 2006]. The magnetic hyperfine field (B\(_{hf}\)) accounts for the magnetic field created by the Fe. All peaks had a width ≥0.23 mm/s. Tetrahedral site (T) and octahedral site (M) for molecular structure site occupancies.
Table 4: Minerals identified using XRD and TS spectroscopy. Bold uppercase X indicates mineral identified in both XRD and TS; small x, XRD only; small italicized x, TS only.

| Sample   | Serpentine | Magnetite | Spinel Group | Cpx | Opx | Olivine | Chlorite | Other Clays (d-spacing 14-16 Å) | Brucite | Amphibole | Garnet |
|----------|------------|-----------|--------------|-----|-----|---------|----------|---------------------------------|---------|-----------|--------|
| HLSC_1   | X          | X         | x            |     |     |         |          |                                 | X       | x         |        |
| 167_238* | x          | x         | x            |     |     |         |          |                                 |         |           |        |
| 309_105_A*‡| x          | x         | x            |     |     |         |          |                                 |         |           |        |
| 309_150* | x          | x         | x            |     |     |         | x        |                                 | x       | x?        |        |
| 313_210‡ | X          | X         | X            | x?  | X   |         | x        |                                 |         |           | X?     |
| 313_318‡ | X          | X         | X            | x   |     | X       | x        |                                 |         |           |        |
| 313_329‡ | X          | X         | X            | x   |     | X       | x        |                                 |         |           | X?     |
| 313_356‡ | X          | X         | x            | x?  | X   |         | x        |                                 |         |           |        |
| CROMO2_1A**| x          | x         | x            |     |     |         |          |                                 |         |           | x?     |
| CROMO2_2**| x          | x         | x            |     |     |         |          |                                 |         |           |        |
| CROMO2_3A**| x          | x         | x            |     |     |         |          |                                 |         |           | x?     |
| CROMO2_4A**| x          | x         | x            |     |     |         |          |                                 |         |           |        |
| PHL_1    | X          | x         | x            | x?  | x   |         | X        |                                 |         |           |        |
| PHL_2B   | X          | x         | X            | x   |     | X       | x        |                                 |         |           | X?     |
| PHL_3‡   | X          | X         | X            | x   |     | X       | x        |                                 |         |           | x?     |
| PHL_5‡   | X          | X         | X            | x?  | x   |         | X        |                                 |         |           |        |

Shading used to group drill holes and localities; (?) indicates minerals may be present; cpx is clinopyroxene; opx is orthopyroxene; the most common form of brucite identified by XRD was portlandite, which substitutes Ca for Mg.

*No thin section for comparison.

**No thin section for direct comparison. Thin section from shallower depths (~2-3m) confirms serpentine, magnetite, and other spinel group minerals.

‡‡MOSS indicates that the Fe is contained in magnetite <1%, which means that in the portion of sample analyzed by MOSS, there was little to no magnetite and the magnetite indicated by XRD could actually be another spinel group mineral.
Table 5: USGS standards DTS-1, DTS-2, and PCC-1 were used to determine accuracy and precision of the Thermo Scientific Niton XL3t and to normalize the Fe concentrations.

| SAMPLE | Published Std value | Total Fe as Fe₂O₃ Wt% | Fe₂O₃ ± | Fe ppm | ± ppm |
|--------|---------------------|------------------------|---------|--------|-------|
| Dunite, Twin Sisters, DTS-1* | 8.68 | 0.24 | 60710 | 1679 |
| | Run 1 | 102595 | 857 |
| | Run 2 | 91366 | 758 |
| | Run 3 | 107423 | 886 |
| | Run 4 | 94530 | 785 |
| | Run 5 | 94878 | 786 |
| | Run 6 | 94693 | 786 |
| | Precision | Accuracy |
| | MEAN | 94701 | 98979 |
| | STDEV | 174 | 7351 |
| | RSD% | 0.18 | 7.43 |
| | OBS/REF | 1.63 |
| | normalizing factor (normalized to DTS-1) | 0.613 |
| | normalized result | 60710 |
| | normalized OBS/REF | 1.00 |

| SAMPLE | Published Std value | Total Fe as Fe₂O₃ Wt% | Fe ± | Fe ppm | ± ppm |
|--------|---------------------|------------------------|------|--------|-------|
| Dunite, Twin Sisters Mountain DTS-2* | 7.76 | 0.21 | 54275 | 1469 |
| | Run 1 | 61917 | 560 |
| | Run 2 | 71788 | 641 |
| | Run 3 | 63397 | 575 |
| | Run 4 | 72856 | 658 |
| | Run 5 | 72427 | 619 |
| | Run 6 | 73922 | 660 |
| | Precision | Accuracy |
| | MEAN | 73069 | 67489 |
| | STDEV | 770 | 5629 |
| | RSD% | 1.05 | 8.34 |
| | OBS/REF | 1.24 |
| | normalizing factor (normalized to DTS-1) | 0.613 |
| | normalized result | 41396 |
| | normalized OBS/REF | 0.76 |

| SAMPLE | Published Std value | Total Fe as Fe₂O₃ Wt% | Fe₂O₃ ± | Fe ppm | ± ppm |
|--------|---------------------|------------------------|---------|--------|-------|
| Peridotite, Cedars CA Ultramafic Mass, PCC-1 ‡ | 8.35 | 5 | 58402 | 34971 |
| | Run 1 | 74439 | 627 |
| | Run 2 | 126579 | 1084 |
| | Run 3 | 73596 | 618 |
| | Run 4 | 108576 | 916 |
| | Run 5 | 108790 | 913 |
| | Run 6 | 108119 | 916 |
| | Precision | Accuracy |
| | MEAN | 108495 | 95798 |
| | STDEV | 343 | 26203 |
| | RSD% | 0.32 | 27.35 |
| | OBS/REF | 1.64 |
| | normalizing factor (normalized to DTS-1) | 0.613 |
| | normalized result | 58759 |
| | normalized OBS/REF | 1.01 |

Precision mean is calculated using runs 4-5 because the sample containers were not moved between runs. Accuracy mean was based on runs 1-4 because the sample containers were shaken between each run. *Values taken from published USGS powdered standard reference values. ‡Flanagan [1976] mean values did not include error values, so an overestimated ±5% error was assigned.
Table 6: XRF Fe concentrations and normalized averages in ppm.

| Sample name | Run | Fe (ppm) | Fe Error (ppm) | Avg. Conc. (ppm) | Std Dev | Avg Error (ppm) | Normalized Avg. (ppm) |
|-------------|-----|---------|----------------|-----------------|---------|----------------|----------------------|
| HLSC_1      | 1   | 46779   | 442            | 46885           | 1600    | 445            | 28741                |
|             | 2   | 45341   | 439            |                 |         |                |                      |
|             | 3   | 48536   | 454            |                 |         |                |                      |
| 167_238     | 1   | 47496   | 422            | 48793           | 2599    | 430            | 29910                |
|             | 2   | 51786   | 455            |                 |         |                |                      |
|             | 3   | 47099   | 414            |                 |         |                |                      |
| 309_105_A   | 1   | 52935   | 456            | 51721           | 1626    | 463            | 31705                |
|             | 2   | 52355   | 477            |                 |         |                |                      |
|             | 3   | 49874   | 455            |                 |         |                |                      |
| 309_105_B   | 1   | 48973   | 463            | 59039           | 8827    | 552            | 36191                |
|             | 2   | 62686   | 583            |                 |         |                |                      |
|             | 3   | 65458   | 612            |                 |         |                |                      |
| 309_150     | 1   | 54727   | 498            | 56527           | 4022    | 513            | 34651                |
|             | 2   | 61135   | 553            |                 |         |                |                      |
|             | 3   | 53719   | 488            |                 |         |                |                      |
| 313_210     | 1   | 93367   | 729            | 82664           | 12004   | 664            | 50673                |
|             | 2   | 69685   | 574            |                 |         |                |                      |
|             | 3   | 84939   | 687            |                 |         |                |                      |
| 313_318     | 1   | 51081   | 486            | 53564           | 3735    | 507            | 32835                |
|             | 2   | 57860   | 543            |                 |         |                |                      |
|             | 3   | 51752   | 493            |                 |         |                |                      |
| 313_329     | 1   | 73110   | 666            | 68497           | 3851    | 838            | 41989                |
|             | 2   | 73426   | 676            |                 |         |                |                      |
|             | 3   | 66604   | 611            |                 |         |                |                      |
|             | 4   | 60849   | 1398           |                 |         |                |                      |
| 313_356     | 1   | 75456   | 687            | 60906           | 13442   | 570            | 37335                |
|             | 2   | 58312   | 551            |                 |         |                |                      |
|             | 3   | 48949   | 472            |                 |         |                |                      |
Table 6 continued

| Sample name | Run | Fe (ppm) | Fe Error (ppm) | Avg. Conc. (ppm) | Std Dev | Avg Error (ppm) | Normalized Avg. (ppm) |
|-------------|-----|----------|----------------|------------------|---------|-----------------|----------------------|
| CROMO2_1A   | 1   | 51628    | 509            | 50250            | 1560    | 498             | 30803                |
|             | 2   | 48557    | 478            |                  |         |                 |                      |
|             | 3   | 50565    | 507            |                  |         |                 |                      |
| CROMO2_2    | 1   | 46999    | 443            | 50515            | 3292    | 473             | 30966                |
|             | 2   | 53526    | 497            |                  |         |                 |                      |
|             | 3   | 51020    | 480            |                  |         |                 |                      |
| CROMO2_3A   | 1   | 75864    | 653            | 61810            | 12459   | 535             | 37889                |
|             | 2   | 52121    | 453            |                  |         |                 |                      |
|             | 3   | 57444    | 498            |                  |         |                 |                      |
| CROMO2_4A   | 1   | 50800    | 483            | 49412            | 1288    | 463             | 30290                |
|             | 2   | 49182    | 455            |                  |         |                 |                      |
|             | 3   | 48255    | 450            |                  |         |                 |                      |
| PHL_1       | 1   | 80763    | 614            | 78265            | 2566    | 585             | 47976                |
|             | 2   | 78395    | 597            |                  |         |                 |                      |
|             | 3   | 75637    | 545            |                  |         |                 |                      |
| PHL_2B      | 1   | 58751    | 519            | 58364            | 1006    | 517             | 35777                |
|             | 2   | 57222    | 509            |                  |         |                 |                      |
|             | 3   | 59120    | 523            |                  |         |                 |                      |
| PHL_3       | 1   | 77208    | 637            | 77887            | 5112    | 638             | 47745                |
|             | 2   | 73148    | 597            |                  |         |                 |                      |
|             | 3   | 83305    | 680            |                  |         |                 |                      |
| PHL_5       | 1   | 68477    | 540            | 68465            | 2298    | 538             | 41969                |
|             | 2   | 66161    | 523            |                  |         |                 |                      |
|             | 3   | 70757    | 550            |                  |         |                 |                      |
Table 7: SEM-EDS elemental concentrations for interior of olivine grains (1) in 313_329. See Figure 25 for larger image.

| Spot | Element | Wt% | $\chi^2$ | Z Corr | A Corr | F Corr | Calculated ppm* | *Element present? |
|------|---------|-----|----------|--------|--------|--------|-----------------|-------------------|
| 1    | Si      | 63.06 | 2.41     | 1.01   | 1.426  | 1      | 630600         | yes               |
|      | Mg      | 36.93 | 0.67     | 0.984  | 1.096  | 0.982  | 369300         | yes               |
|      | Fe      | 0.01  | 1.05     | 1.136  | 1.016  | 1      | 100            | yes               |
| Total|         | 100   | 1.17     |        |        |        |                 |                   |
| 2    | Si      | 61.81 | 2.81     | 1.01   | 1.441  | 1      | 618100         | yes               |
|      | Mg      | 38.18 | 1.44     | 0.984  | 1.097  | 0.982  | 381800         | yes               |
|      | Fe      | 0.01  | 1.06     | 1.137  | 1.016  | 1      | 100            | yes               |
| Total|         | 100   | 0.98     |        |        |        |                 |                   |
| 3    | Si      | 63.58 | 1.26     | 1.01   | 1.419  | 1      | 635800         | yes               |
|      | Mg      | 36.4  | 0.4      | 0.984  | 1.097  | 0.982  | 364000         | yes               |
|      | Fe      | 0.01  | 0.34     | 1.136  | 1.016  | 1      | 100            | yes               |
| Total|         | 100   | 0.84     |        |        |        |                 |                   |
| 4    | Mg      | 36.01 | 1.02     | 0.983  | 1.097  | 0.981  | 360100         | yes               |
|      | Fe      | 0.01  | 0.05     | 1.136  | 1.016  | 1      | 100            | yes               |
|      | Si      | 63.98 | 1.89     | 1.009  | 1.414  | 1      | 639800         | yes               |
| Total|         | 100   | 1.02     |        |        |        |                 |                   |
| 5    | Si      | 71.95 | 1.1      | 1.007  | 1.329  | 1      | 719500         | yes               |
|      | Mg      | 23.12 | 1.04     | 0.981  | 1.112  | 0.975  | 231200         | yes               |
|      | Al      | 4.92  | 0.25     | 0.994  | 1.443  | 0.964  | 49200          | yes               |
|      | Fe      | 0.01  | 0.77     | 1.133  | 1.018  | 1      | 100            | yes               |
| Total|         | 100   | 1.09     |        |        |        |                 |                   |
| 6    | Mg      | 22.64 | 0.37     | 0.981  | 1.112  | 0.975  | 226400         | yes               |
|      | Fe      | 0.01  | 0.39     | 1.133  | 1.018  | 1      | 100            | yes               |
|      | Si      | 71.46 | 3.76     | 1.007  | 1.337  | 1      | 714600         | yes               |
|      | Al      | 5.89  | 0.46     | 0.994  | 1.434  | 0.964  | 58900          | yes               |
| Total|         | 100   | 1        |        |        |        |                 |                   |
| 7    | Mg      | 23.89 | 0.58     | 0.98   | 1.115  | 0.974  | 238900         | yes               |
|      | Si      | 76.1  | 2.97     | 1.006  | 1.27   | 1      | 761000         | yes               |
|      | Fe      | 0.01  | 2.25     | 1.133  | 1.019  | 1      | 100            | yes               |
|      | Al      | Not included in sum but present similar intensity peaks to other spots (5-9) in this grain. |
| Total|         | 100   | 1.87     |        |        |        |                 |                   |
Table 7 continued.

| Spot | Element | Wt%   | $X^2$ | Z Corr | A Corr | F Corr | Calculated ppm | *Element present? |
|------|---------|-------|-------|--------|--------|--------|----------------|-------------------|
| 8    | Mg      | 22.54 | 0.22  | 0.98   | 1.114  | 0.974  | 225400         | yes              |
|      | Si      | 73.48 | 0.93  | 1.006  | 1.309  | 1      | 734800         | yes              |
|      | Fe      | 0.01  | 1.48  | 1.133  | 1.018  | 1      | 100            | yes              |
|      | Al      | 3.97  | 0.32  | 0.994  | 1.433  | 0.962  | 39700          | yes              |
|      | Total   | 100   | 1.06  |        |        |        |                |                  |
| 9    | Mg      | 22.73 | 0.74  | 0.981  | 1.113  | 0.975  | 227300         | yes              |
|      | Si      | 72.22 | 3.96  | 1.007  | 1.326  | 1      | 722200         | yes              |
|      | Fe      | 0.01  | 0.24  | 1.133  | 1.018  | 1      | 100            | yes              |
|      | Al      | 5.05  | 0.31  | 0.994  | 1.436  | 0.964  | 50500          | yes              |
|      | Total   | 100   | 1.13  |        |        |        |                |                  |
| 10   | Mg      | 37.95 | 1.08  | 0.984  | 1.094  | 0.982  | 379500         | yes              |
|      | Si      | 62.04 | 1.34  | 1.01   | 1.438  | 1      | 620400         | yes              |
|      | Fe      | 0.02  | 0.89  | 1.137  | 1.016  | 1      | 200            | yes              |
|      | Total   | 100   | 1.13  |        |        |        |                |                  |

*Element present is based on a second look at the intensity peaks. Elements labeled as no, did not actually have a peak and the values reported are often zero. Those labeled as “not likely” or “maybe” may have a presence, but the peaks could be counted as noise between other peaks. Those labeled as yes have distinguished intensity peaks. See appendix Figure A19 for peak images.
Table 8: SEM-EDS elemental concentrations for the alteration mineral along the exterior of the olivine grains in Table 7 in 313_329. See Figure 26 for larger image.

| Spot | Element | Wt%   | X²     | Z Corr | A Corr | F Corr | Calculated ppm | *Element present? |
|------|---------|-------|--------|--------|--------|--------|----------------|--------------------|
| 1    | Mg      | 32.3  | 0.63   | 0.983  | 1.103  | 0.979  | 323300         | yes                |
|      | Fe      | 0.01  | 1.97   | 1.135  | 1.017  | 1      | 100            | yes                |
|      | Si      | 67.7  | 1.15   | 1.009  | 1.37   | 1      | 676700         | yes                |
|      | Total   | 100   | 0.99   |        |        |        |                |                    |
| 2    | Mg      | 33.8  | 0.01   | 0.983  | 1.099  | 0.98   | 337700         | yes                |
|      | Fe      | 0     | 0.97   | 1.136  | 1.017  | 1      | 0              | yes                |
|      | Si      | 64.9  | 3.16   | 1.009  | 1.406  | 1      | 648800         | yes                |
|      | Al      | 1.35  | 1.3    | 0.996  | 1.636  | 0.971  | 13500          | not likely         |
|      | Total   | 100   | 1.15   |        |        |        |                |                    |
| 3    | Mg      | 33.3  | 0.22   | 0.983  | 1.1    | 0.98   | 332700         | yes                |
|      | Fe      | 0.01  | 0.31   | 1.136  | 1.017  | 1      | 100            | yes                |
|      | Al      | 1.79  | 0.58   | 0.996  | 1.627  | 0.971  | 17900          | not likely         |
|      | Si      | 64.9  | 3.22   | 1.009  | 1.407  | 1      | 649300         | yes                |
|      | Total   | 100   | 0.96   |        |        |        |                |                    |
| 4    | Mg      | 97.2  | 0.08   | 1      | 1.002  | 0.999  | 971700         | yes                |
|      | Fe      | 0.01  | 1.51   | 1.154  | 1.005  | 1      | 100            | yes                |
|      | Al      | 2.81  | 3.66   | 1.013  | 2.973  | 1      | 28100          | not likely         |
|      | Si      | Not included in wt%, but present similar to other spots (1-3 & 5-7) |          |  |  | | |  |
|      | Total   | 100   | 10.72  |        |        |        |                |                    |
| 5    | Mg      | 34    | 0.36   | 0.983  | 1.1    | 0.98   | 339600         | yes                |
|      | Fe      | 0     | 1      | 1.136  | 1.017  | 1      | 0              | yes                |
|      | Al      | 0     | 0.3    | 0.996  | 1.641  | 0.97   | 0              | not likely         |
|      | Si      | 66    | 4.99   | 1.009  | 1.389  | 1      | 660300         | yes                |
|      | Total   | 100   | 0.75   |        |        |        |                |                    |
| 6    | Mg      | 33    | 1.16   | 0.983  | 1.101  | 0.98   | 329500         | yes                |
|      | Fe      | 0     | 2.46   | 1.135  | 1.017  | 1      | 0              | yes                |
|      | Al      | 0.59  | 2.64   | 0.996  | 1.622  | 0.97   | 5900           | not likely         |
|      | Si      | 66.5  | 2.89   | 1.009  | 1.386  | 1      | 664600         | yes                |
|      | Total   | 100   | 0.86   |        |        |        |                |                    |
**Table 8 continued.**

| Spot | Element | Wt% | X$^2$ | Z Corr | A Corr | F Corr | Calculated ppm | *Element present? |
|------|---------|-----|-------|--------|--------|--------|----------------|------------------|
| 7    | Mg      | 34.3| 1.33  | 0.983  | 1.1    | 0.98   | 342600         | yes              |
|      | Fe      | 0   | 0.83  | 1.136  | 1.017  | 1      | 0              | yes              |
|      | Al      | 0.19| 0.68  | 0.996  | 1.646  | 0.971  | 1900           | not likely       |
|      | Si      | 65.5| 4.73  | 1.009  | 1.396  | 1      | 655400         | yes              |
| Total|         | 100 | 1.01  |        |        |        |                |                  |
| 8    | Si      | 54.8| 3.62  | 0.999  | 1.498  | 1      | 548400         | yes              |
|      | Mg      | 35.6| 1.57  | 0.973  | 1.286  | 0.986  | 356000         | yes              |
|      | Fe      | 9.56| 0.34  | 1.124  | 1.014  | 1      | 95600          | yes              |
| Total|         | 100 | 1.24  |        |        |        |                |                  |
| 9    | Fe      | 11.1| 0.9   | 1.122  | 1.014  | 1      | 111000         | yes              |
|      | Si      | 54.2| 0.29  | 0.996  | 1.507  | 1      | 541700         | yes              |
|      | Mg      | 34.7| 0.4   | 0.97   | 1.326  | 0.987  | 347200         | yes              |
| Total|         | 100 | 1.01  |        |        |        |                |                  |
| 10   | Si      | 66.7| 1.25  | 1.009  | 1.381  | 1      | 667200         | yes              |
|      | Mg      | 33.3| 0.92  | 0.983  | 1.101  | 0.98   | 332700         | yes              |
|      | Fe      | 0.01| 0.91  | 1.135  | 1.017  | 1      | 100            | yes              |
| Total|         | 100 | 1.11  |        |        |        |                |                  |

*Element present is based on a second look at the intensity peaks. Elements labeled as no, did not actually have a peak and the values reported are often zero. Those labeled as “not likely” or “maybe” may have a presence, but the peaks could be counted as noise between other peaks. Those labeled as yes have distinguished intensity peaks. See appendix Figure A20 for peak images.
Table 9: SEM-EDS elemental concentrations for olivine in 313_329. Image is at 250x shows serpentine and magnetite in veins and olivine grains. Pit is from ICPMS laser ablation (data in appendix). See Figure 27 for larger image.

| Spot | Element | Wt% | X² | Z Corr | A Corr | F Corr | Calculated ppm | *Element present? |
|------|---------|-----|----|--------|--------|--------|----------------|-------------------|
| 1    | Mg      | 37.5| 0.24| 0.984  | 1.094  | 0.982  | 374500         | yes               |
|      | Ca      | 0   | 1.079| 1.165  | 1      | 0      | 0              | no                |
|      | Cr      | 0   | 1.119| 1.039  | 1      | 0      | 0              | no                |
|      | Mn      | 0   | 1.128| 1.026  | 1      | 0      | 0              | no                |
|      | Fe      | 0.01| 0.43 | 1.137  | 1.016  | 1      | 100            | yes               |
|      | Si      | 61.1| 0.2  | 1.01   | 1.453  | 1      | 610700         | yes               |
|      | Al      | 1.48| 3.12 | 0.997  | 1.705  | 0.974  | 14800          | yes               |
| Total|         | 100 | 0.85 |        |        |        |                |                   |
| 2    | Mg      | 37.8| 0.43 | 0.984  | 1.097  | 0.983  | 378200         | yes               |
|      | Ca      | 0.42| 1.079| 1.164  | 1      | 0      | 4200           | no                |
|      | Cr      | 0   | 1.118| 1.039  | 1      | 0      | 0              | no                |
|      | Mn      | 0   | 1.128| 1.026  | 1      | 0      | 0              | no                |
|      | Fe      | 0.01| 1.94 | 1.136  | 1.016  | 1      | 100            | yes               |
|      | Si      | 60.6| 1.2  | 1.01   | 1.455  | 1      | 605900         | yes               |
|      | Al      | 1.16| 0.32 | 0.997  | 1.714  | 0.975  | 11600          | yes               |
| Total|         | 100 | 0.81 |        |        |        |                |                   |
| 3    | Mg      | 40.3| 1.7  | 0.985  | 1.091  | 0.983  | 403400         | yes               |
|      | Ca      | 0   | 1.08 | 1.164  | 1      | 0      | 0              | no                |
|      | Cr      | 0   | 1.119| 1.038  | 1      | 0      | 0              | no                |
|      | Mn      | 0   | 1.128| 1.025  | 1      | 0      | 0              | no                |
|      | Fe      | 0.01| 0.51 | 1.137  | 1.016  | 1      | 100            | yes               |
|      | Si      | 59.7| 3.63 | 1.011  | 1.467  | 1      | 596600         | yes               |
|      | Al      | 0   | 6.1  | 0.998  | 1.76   | 0.976  | 0              | not likely        |
| Total|         | 100 | 0.97 |        |        |        |                |                   |
| 4    | Mg      | 39.6| 0.48 | 0.984  | 1.093  | 0.983  | 395800         | yes               |
|      | Ca      | 0.26| 1.08 | 1.163  | 1      | 0      | 2600           | no                |
|      | Cr      | 0   | 1.119| 1.038  | 1      | 0      | 0              | no                |
|      | Mn      | 0   | 1.128| 1.026  | 1      | 0      | 0              | no                |
|      | Fe      | 0.01| 1.17 | 1.137  | 1.016  | 1      | 100            | yes               |
|      | Si      | 59  | 0.5  | 1.01   | 1.476  | 1      | 589500         | yes               |
|      | Al      | 1.21| 1.56 | 0.998  | 1.746  | 0.976  | 12100          | not likely        |
| Total|         | 100 | 0.79 |        |        |        |                |                   |
### Table 9 continued

| Spot | Element | Wt% | $X^2$ | Z Corr | A Corr | F Corr | Calculated ppm | *Element present? |
|------|---------|-----|-------|--------|--------|--------|-----------------|-------------------|
| 5    | Mg      | 39.1| 0.18  | 0.984 | 1.092  | 0.983  | 391300         | yes               |
|      | Ca      | 0   | 1.08  | 1.165 | 1      | 0      | 0               | no                |
|      | Cr      | 0   | 1.119 | 1.038 | 1      | 0      | 0               | no                |
|      | Mn      | 0   | 1.128 | 1.026 | 1      | 0      | 0               | no                |
|      | Fe      | 0.01| 1.43  | 1.137 | 1.016  | 1      | 100            | yes               |
|      | Si      | 60.5| 0.21  | 1.01  | 1.458  | 1      | 604900         | yes               |
|      | Al      | 0.37| 0.8   | 0.998 | 1.737  | 0.975  | 3700           | not likely        |
| **Total** |       | 100 | 0.63  |        |        |        |                 |                   |
| 6    | Mg      | 37.8| 0.84  | 0.984 | 1.098  | 0.983  | 377900         | yes               |
|      | Ca      | 0.55| 1.079 | 1.164 | 1      | 1      | 5500           | no                |
|      | Cr      | 0   | 1.118 | 1.039 | 1      | 0      | 0               | no                |
|      | Mn      | 0   | 1.127 | 1.026 | 1      | 0      | 0               | no                |
|      | Fe      | 0.01| 1.37  | 1.136 | 1.016  | 1      | 100            | yes               |
|      | Si      | 60.8| 0.25  | 1.01  | 1.451  | 1      | 607900         | yes               |
|      | Al      | 0.86| 0.6   | 0.997 | 1.715  | 0.975  | 8600           | yes               |
| **Total** |       | 100 | 0.95  |        |        |        |                 |                   |
| 7    | Mg      | 38.7| 0.22  | 0.984 | 1.093  | 0.983  | 387400         | yes               |
|      | Ca      | 0.1 | 1.079 | 1.164 | 1      | 1      | 1000           | no                |
|      | Cr      | 0.02| 1.14  | 1.119 | 1.038  | 1      | 200            | no                |
|      | Mn      | 0   | 1.128 | 1.026 | 1      | 0      | 0               | no                |
|      | Fe      | 0.01| 0.71  | 1.137 | 1.016  | 1      | 100            | yes               |
|      | Si      | 59.8| 3.99  | 1.01  | 1.468  | 1      | 597700         | yes               |
|      | Al      | 1.37| 1.76  | 0.997 | 1.73   | 0.975  | 13700          | not likely        |
| **Total** |       | 100 | 1.08  |        |        |        |                 |                   |

*Element present is based on a second look at the intensity peaks. Elements labeled as no, did not actually have a peak and the values reported are often zero. Those labeled as “not likely” or “maybe” may have a presence, but the peaks could be counted as noise between other peaks. Those labeled as yes have distinguished intensity peaks. See appendix Figure A21 for peak images.
Table 10: SEM-EDS elemental concentrations of pyroxene grains in 313_329. See Figure 28 for large image.

| Spot | Element | Wt% | $X^2$ | Z Corr | A Corr | F Corr | Calculated ppm | *Element present? |
|------|---------|-----|-------|--------|--------|--------|----------------|-------------------|
| 1    | Si      | 60.2| 0.18  | 1.01   | 1.462  | 1      | 602100         | yes               |
|      | Al      | 0.62| 0.25  | 0.998  | 1.737  | 0.975  | 6200           | not likely        |
|      | Ca      | 0   | 1.08  | 1.164  | 1      | 0      | 0              | no                |
|      | Mg      | 39.2| 1.51  | 0.984  | 1.092  | 0.983  | 391600         | yes               |
|      | Cr      | 0   | 1.119 | 1.038  | 1      | 0      | 0              | no                |
|      | Mn      | 0   | 1.128 | 1.026  | 1      | 0      | 0              | no                |
|      | Fe      | 0.01| 0.49  | 1.137  | 1.016  | 1      | 100            | yes               |
|      | Total   | 100 | 0.6   | 1.01   | 1.462  | 1      | 602100         | yes               |
| 2    | Mg      | 38.6| 0.62  | 0.984  | 1.094  | 0.983  | 385800         | yes               |
|      | Ca      | 0.02| 1.079 | 1.165  | 1      | 0      | 200            | no                |
|      | Cr      | 0   | 1.119 | 1.038  | 1      | 0      | 0              | no                |
|      | Mn      | 0   | 1.128 | 1.026  | 1      | 0      | 0              | no                |
|      | Fe      | 0.01| 0.41  | 1.137  | 1.016  | 1      | 100            | yes               |
|      | Si      | 61.4| 0.34  | 1.01   | 1.446  | 1      | 613900         | yes               |
|      | Al      | 0   | 1.3   | 0.997  | 1.727  | 0.974  | 0              | not likely        |
|      | Total   | 100 | 0.62  | 1.01   | 1.462  | 1      | 385800         | yes               |
| 3    | Mg      | 38.6| 0.83  | 0.984  | 1.094  | 0.983  | 385900         | yes               |
|      | Ca      | 0.2 | 1.079 | 1.165  | 1      | 0      | 200            | no                |
|      | Cr      | 0   | 1.119 | 1.039  | 1      | 0      | 0              | no                |
|      | Mn      | 0   | 1.128 | 1.026  | 1      | 0      | 0              | no                |
|      | Fe      | 0.01| 0.41  | 1.137  | 1.016  | 1      | 100            | yes               |
|      | Si      | 60.2| 4.29  | 1.01   | 1.461  | 1      | 602400         | yes               |
|      | Al      | 0.62| 1.75  | 0.997  | 1.728  | 0.975  | 9600           | not likely        |
|      | Total   | 100 | 0.66  | 1.01   | 1.462  | 1      | 385900         | yes               |
| 4    | Mg      | 36.2| 0.47  | 0.984  | 1.097  | 0.982  | 362400         | yes               |
|      | Ca      | 0.09| 1.079 | 1.167  | 1      | 0      | 900            | no                |
|      | Cr      | 0   | 1.118 | 1.039  | 1      | 0      | 0              | no                |
|      | Mn      | 0   | 1.127 | 1.026  | 1      | 0      | 0              | no                |
|      | Fe      | 0.01| 1.23  | 1.136  | 1.016  | 1      | 100            | yes               |
|      | Si      | 63.1| 5.64  | 1.01   | 1.426  | 1      | 630600         | yes               |
|      | Al      | 0.6 | 0.5   | 0.997  | 1.683  | 0.973  | 6000           | not likely        |
|      | Total   | 100 | 0.96  | 1.01   | 1.462  | 1      | 362400         | yes               |
Table 10 continued.

| Spot | Element | Wt% | $X^2$ | Z Corr | A Corr | F Corr | Calculated ppm | *Element present? |
|------|---------|-----|-------|--------|--------|--------|-----------------|-------------------|
| 5    | Mg      | 37.8| 0.13  | 0.984  | 1.097  | 0.983  | 378100         | yes               |
| Ca   | 0.49    |     |       | 1.079  | 1.164  | 1      | 4900           | no                |
| Cr   | 0       |     |       | 1.118  | 1.039  | 1      | 0               | no                |
| Mn   | 0       |     |       | 1.128  | 1.026  | 1      | 0               | no                |
| Fe   | 0.01    | 1.46|       | 1.136  | 1.016  | 1      | 100            | yes               |
| Si   | 60.1    | 0.11| 1.01  | 1.461  | 1      | 601400 |                | yes               |
| Al   | 1.55    | 1.15| 0.997 | 1.714  | 0.975  | 15500  |                | maybe             |
| Total| 100     | 0.69|       |        |        |        | 378900         |                   |

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| Mg   | 37.9   | 0.11| 0.984 | 1.094 | 0.982 | 378900 | yes            |
| Ca   | 0      |     | 1.079 | 1.165 | 1     | 0      | no             |
| Cr   | 0      |     | 1.119 | 1.038 | 1     | 0      | no             |
| Mn   | 0      |     | 1.128 | 1.026 | 1     | 0      | no             |
| Fe   | 0.01   | 0.29| 1.137 | 1.016 | 1     | 100    | yes            |
| Si   | 61.2   | 0.18| 1.01  | 1.451 | 1     | 611600 | yes            |
| Al   | 0.93   | 0   | 0.997 | 1.713 | 0.974 | 9300   | not likely     |
| Total| 100    | 0.52|       |        |        |        |                |

6
| Mg   | 37.9   | 0.45| 0.984 | 1.097 | 0.983 | 379200 | yes            |
| Ca   | 0.57   |     | 1.079 | 1.164 | 1     | 5700   | no             |
| Cr   | 0      |     | 1.119 | 1.039 | 1     | 0      | no             |
| Mn   | 0      |     | 1.128 | 1.026 | 1     | 0      | no             |
| Fe   | 0.01   | 0.6 | 1.137 | 1.016 | 1     | 100    | yes            |
| Si   | 59.3   | 0.28| 1.01  | 1.471 | 1     | 593300 | yes            |
| Al   | 2.17   | 4.36| 0.997 | 1.717 | 0.976 | 21700  | not likely     |
| Total| 100    | 0.65|       |        |        |        |                |

7
| Mg   | 37.2   | 0.31| 0.984 | 1.096 | 0.982 | 372000 | yes            |
| Ca   | 0.09   |     | 1.079 | 1.166 | 1     | 900    | no             |
| Cr   | 0      |     | 1.118 | 1.039 | 1     | 0      | no             |
| Mn   | 0      |     | 1.128 | 1.026 | 1     | 0      | no             |
| Fe   | 0.01   | 2.49| 1.136 | 1.016 | 1     | 100    | yes            |
| Si   | 62.7   | 0.55| 1.01  | 1.429 | 1     | 627100 | yes            |
| Al   | 0      | 1.2 | 0.997 | 1.701 | 0.973 | 0      | no             |
| Total| 100    | 0.69|       |        |        |        |                |

*Element present is based on a second look at the intensity peaks. Elements labeled as no, did not actually have a peak and the values reported are often zero. Those labeled as “not likely” or “maybe” may have a presence, but the peaks could be counted as noise between other peaks. Those labeled as yes have distinguished intensity peaks. See appendix Figure A22 for peak images.
Table 11: SEM-EDS major element concentrations for a spinel grain in 313_329. Image is at 150x shows a spinel grain surrounded by serpentine and olivine grains. Pit is from ICPMS laser ablation (data in appendix). See Figure 29 for larger image.

| Spot | Element | Wt% | X²  | Z Corr | A Corr | F Corr | Calculated ppm | *Element present? |
|------|---------|-----|-----|--------|--------|--------|-----------------|-------------------|
| 1    | Mg      | 15.8| 0.78| 0.988  | 1.058  | 0.957  | 158400         | yes               |
|      | Fe      | 0.03| 1.09| 1.141  | 1.012  | 1      | 300            | yes               |
|      | Si      | 5.1 | 1.55| 1.014  | 2.395  | 1      | 51000          | yes               |
|      | Al      | 78.9| 2.38| 1.001  | 1.275  | 0.999  | 789400         | yes               |
|      | Cr      | 0.05| 2.7 | 1.123  | 1.031  | 1      | 500            | yes               |
|      | Mn      | 0   | 2.57| 1.132  | 1.02   | 1      | 0              | not likely        |
|      | Ca      | 0.03|     | 1.084  | 1.144  | 1      | 300            | no                |
| Total|         | 100 | 0.75| 0.96   | 1.058  | 1      | 170900         | yes               |
| 2    | Mg      | 17.1| 0.16| 0.988  | 1.058  | 1      | 160800         | yes               |
|      | Cr      | 0.06| 1.63| 1.123  | 1.031  | 1      | 600            | yes               |
|      | Fe      | 0.03| 1.81| 1.141  | 1.012  | 1      | 300            | yes               |
|      | Si      | 6   | 3.95| 1.014  | 2.377  | 1      | 60000          | yes               |
|      | Al      | 76.8| 3.6 | 1.001  | 1.298  | 0.998  | 768200         | yes               |
|      | Mn      | 0   | 2.86| 1.132  | 1.02   | 1      | 0              | not likely        |
|      | Ca      | 0   |     | 1.084  | 1.144  | 1      | 0              | no                |
| Total|         | 100 | 1.09| 0.96   | 1.056  | 1      | 160800         | yes               |
| 3    | Mg      | 16.1| 0.52| 0.988  | 1.056  | 0.957  | 160800         | yes               |
|      | Cr      | 0.07| 1.71| 1.123  | 1.031  | 1      | 700            | no                |
|      | Mn      | 0   | 1.37| 1.133  | 1.02   | 1      | 0              | not likely        |
|      | Fe      | 0.03| 3.33| 1.141  | 1.012  | 1      | 300            | yes               |
|      | Si      | 3.52| 0.1 | 1.014  | 2.423  | 1      | 35200          | yes               |
|      | Al      | 80.3| 1.02| 1.002  | 1.279  | 0.999  | 803100         | yes               |
|      | Ca      | 0   |     | 1.084  | 1.143  | 1      | 0              | no                |
| Total|         | 100 | 0.62| 0.957  | 1.02   | 1      | 174200         | yes               |
| 4    | Cr      | 17.4| 2.97| 1.065  | 1.02   | 0.943  | 174200         | yes               |
|      | Al      | 43.1| 2.23| 0.947  | 1.776  | 0.999  | 431200         | yes               |
|      | Mg      | 10.9| 0.14| 0.934  | 1.944  | 0.988  | 109000         | yes               |
|      | Si      | 1.95| 1.59| 0.959  | 2.134  | 0.999  | 19500          | yes               |
|      | Fe      | 26.6| 1.29| 1.082  | 1.033  | 1      | 266000         | yes               |
| Total|         | 100 | 1.07| 1.02   | 1.02   | 1      | 174200         | yes               |
| Spot | Element | Wt% | $\chi^2$ | Z Corr | A Corr | F Corr | Calculated ppm | *Element present? |
|------|---------|-----|--------|--------|--------|--------|----------------|-------------------|
| 5    | Mg      | 14.5| 0.99   | 0.988  | 1.061  | 0.957  | 145400         | yes               |
|      | Ca      | 0   |        |        |        |        | 0              | no                |
|      | Cr      | 0.05| 4.9    | 1.123  | 1.032  | 1      | 500            | yes               |
|      | Mn      | 0   | 1.54   | 1.132  | 1.021  | 1      | 0              | not likely        |
|      | Fe      | 0.03| 0.92   | 1.141  | 1.012  | 1      | 300            | yes               |
|      | Si      | 8.16| 2.25   | 1.014  | 2.346  | 1      | 81600          | yes               |
|      | Al      | 77.2| 3.24   | 1.001  | 1.254  | 1      | 0.998          | 772200            |
|      | Total   | 100 | 0.64   |        |        |        |                |                   |
| 6    | Mg      | 16.5| 0.19   | 0.988  | 1.061  | 0.959  | 164900         | yes               |
|      | Ca      | 0.4 |        |        | 1.083  | 1.143  | 4000           | no                |
|      | Cr      | 0.07| 1.84   | 1.123  | 1.032  | 1      | 700            | yes               |
|      | Mn      | 0   | 3.79   | 1.132  | 1.021  | 1      | 0              | not likely        |
|      | Fe      | 0.03| 1.15   | 1.141  | 1.012  | 1      | 300            | yes               |
|      | Si      | 5.3 | 6.95   | 1.014  | 2.385  | 1      | 53000          | yes               |
|      | Al      | 77.7| 4.1    | 1.001  | 1.289  | 1      | 0.999          | 777200            |
|      | Total   | 100 | 1.05   |        |        |        |                |                   |
| 7    | Mg      | 15.8| 0.14   | 0.988  | 1.059  | 0.957  | 158100         | yes               |
|      | Ca      | 0   |        |        | 1.084  | 1.144  | 1              | no                |
|      | Cr      | 0.19| 129.5  | 1.123  | 1.031  | 1      | 1900           | yes               |
|      | Mn      | 0.01| 10.3   | 1.132  | 1.02   | 1      | 100            | not likely        |
|      | Fe      | 0.02| 3.92   | 1.141  | 1.012  | 1      | 200            | yes               |
|      | Si      | 4.38| 0.7    | 1.014  | 2.407  | 1      | 43800          | yes               |
|      | Al      | 79.6| 4.76   | 1.001  | 1.276  | 1      | 0.999          | 795900            |
|      | Total   | 100 | 2.99   |        |        |        |                |                   |
| 8    | Mg      | 17.4| 0.03   | 0.988  | 1.061  | 0.96   | 173700         | yes               |
|      | Ca      | 0.44|        |        | 1.083  | 1.143  | 1              | 4400             |
|      | Cr      | 0.06| 1.73   | 1.123  | 1.032  | 1      | 600            | yes               |
|      | Mn      | 0   | 5.73   | 1.132  | 1.021  | 1      | 0              | not likely        |
|      | Fe      | 0.03| 0.86   | 1.141  | 1.012  | 1      | 300            | yes               |
|      | Si      | 4.69| 0.05   | 1.014  | 2.393  | 1      | 46900          | yes               |
|      | Al      | 77.4| 3.03   | 1.001  | 1.305  | 1      | 0.999          | 774100            |
|      | Total   | 100 | 0.54   |        |        |        |                |                   |
| 9    | Mg      | 18.2| 0.59   | 0.988  | 1.063  | 0.961  | 181600         | yes               |
|      | Ca      | 0.67|        |        | 1.083  | 1.142  | 1              | 6700             |
|      | Cr      | 0.06| 1.78   | 1.123  | 1.032  | 1      | 600            | yes               |
|      | Mn      | 0   | 2.14   | 1.132  | 1.021  | 1      | 0              | not likely        |
|      | Fe      | 0.03| 0.55   | 1.141  | 1.012  | 1      | 300            | yes               |
|      | Si      | 5.42| 1.3    | 1.014  | 2.375  | 1      | 54200          | yes               |
|      | Al      | 75.7| 3.29   | 1.001  | 1.321  | 1      | 0.999          | 756700            |
|      | Total   | 100 | 0.52   |        |        |        |                |                   |
**Table 11 continued**

| Spot | Element | Wt%  | $X^2$ | Z Corr | A Corr | F Corr | Calculated ppm | *Element present? |
|------|---------|------|-------|--------|--------|--------|----------------|-------------------|
| 10   | Cr      | 17.4 | 2.17  | 1.045  | 1.036  | 0.939  | 173700         | yes               |
|      | Fe      | 33.3 | 0.08  | 1.062  | 1.043  | 1      | 332500         | yes               |
|      | Al      | 22.7 | 1.46  | 0.928  | 1.882  | 0.997  | 227200         | yes               |
|      | Si      | 7.57 | 0.31  | 0.941  | 1.88   | 0.998  | 75700          | yes               |
|      | Mg      | 7.46 | 0.09  | 0.916  | 2.209  | 0.993  | 74600          | yes               |
|      | Ca      | 11.6 | 2.59  | 1.007  | 1.088  | 0.975  | 116300         | yes               |
|      | **Total** | **100** | **1.02** |        |        |        |                |                   |

*Element present is based on a second look at the intensity peaks. Elements labeled as no, did not actually have a peak and the values reported are often zero. Those labeled as “not likely” or “maybe” may have a presence, but the peaks could be counted as noise between other peaks. Those labeled as yes have distinguished intensity peaks. See appendix Figure A23 for peak images.
Table 12: Mössbauer parameters for Coast Range Ophiolite and Zambales Ophiolite samples.

| Sample          | HLSC_1# | 167_238# | 309_105_A | 309_150 | 313_210 |
|-----------------|---------|----------|-----------|---------|---------|
| Sextet 1 Magnetite | IS      | 0.27     | 0.27      | 0.26    |         |
|                 | QS      | -0.04    | -0.01     | -0.01   |         |
|                 | W       | 0.24     | 0.230*    | 0.23    |         |
|                 | A       | 25       | 12        | 12      |         |
|                 | B$_{hf}$| 490.1    | 490.3     | 489.6   |         |
| Sextet 2 Magnetite | IS      | 0.67     | 0.67      | 0.67    |         |
|                 | QS      | -0.01    | -0.03     | -0.02   |         |
|                 | W       | 0.28     | 0.26      | 0.30    |         |
|                 | A       | 38       | 18        | 22      |         |
|                 | B$_{hf}$| 459.2    | 459.7     | 459.7   |         |
| Ferric 1 Silicate | IS      | 0.33     | 0.25      | 0.38    | 0.37    |
|                 | QS      | 0.69     | 0.47      | 0.71    | 0.64    |
|                 | W       | 0.72     | 0.51      | 0.41    | 0.56    |
|                 | A       | 14       | 40        | 18      | 16      |
| Ferric 2 Silicate | IS      | 1.16     | 1.14      | 1.14    | 1.14    |
|                 | QS      | 2.67     | 2.72      | 2.73    | 2.71    |
|                 | W       | 0.37     | 0.31      | 0.25    | 0.33    |
|                 | A       | 23       | 9         | 70      | 50      |
| Ferrous 1 Silicate | IS      | 1.45     | 1.45      | 1.15    | 1.14    |
|                 | QS      | 2.67     | 2.72      | 2.73    | 2.70    |
|                 | W       | 0.37     | 0.31      | 0.25    | 0.33    |
|                 | A       | 23       | 9         | 70      | 50      |
| Ferrous 2 Silicate | IS      | 1.45     | 1.45      | 1.15    | 1.14    |
|                 | QS      | 2.67     | 2.72      | 2.73    | 2.70    |
|                 | W       | 0.37     | 0.31      | 0.25    | 0.33    |
|                 | A       | 23       | 9         | 70      | 50      |
| X$^2$           | 849.88  | 1690.49  | 484.52    | 2096.67 | 1228.27 |
| $[X^2]$         | 1.6593  | 3.3028   | 0.9456    | 4.0934  | 2.3749  |
| Sum areas       | 100     | 100      | 100       | 100     | 100     |
| Magnetite       | 63      | 30       | 0         | 34      | 0       |
| %Fe $^{3+}$     | 14      | 40       | 30        | 16      | 36      |
| %Fe $^{2+}$     | 23      | 30       | 70        | 50      | 65      |
| %Fe $^{3+}$ excluding magnetite | 39 | 57 | 30 | 24 | 36 |
Table 12 continued

|                    | Sample      | 313_318 | 313_329 | 313_356 | CROMO2_1A‡ | CROMO2_2‡ |
|--------------------|-------------|---------|---------|---------|------------|------------|
| Sextet 1 Magnetite |             |         |         |         |            |            |
| IS                 | 0.25        |         |         |         | 0.24       |            |
| QS                 | -0.02       |         |         |         | -0.04      |            |
| W                  | 0.30        |         |         |         | 0.30       |            |
| A                  | 11          |         |         |         | 10         |            |
| Bmf                | 488.9       |         |         |         | 489.3      |            |
| Sextet 2 Magnetite |             |         |         |         |            |            |
| IS                 | 0.69        |         |         |         | 0.67       |            |
| QS                 | -0.01       |         |         |         | -0.02      |            |
| W                  | 0.32        |         |         |         | 0.30       |            |
| A                  | 16          |         |         |         | 12         |            |
| Bmf                | 459.6       |         |         |         | 459.7      |            |
| Ferric 1 Silicate  |             |         |         |         |            |            |
| IS                 | 0.36        |         |         |         | 0.35       | 0.34       |
| QS                 | 0.68        |         |         |         | 0.69       | 0.66       |
| W                  | 0.56        |         |         |         | 0.60       | 0.56       |
| A                  | 49          |         |         |         | 35         | 28         |
| Ferric 2 Silicate  |             |         |         |         |            |            |
| IS                 | 0.36        |         |         |         | 0.47       |            |
| QS                 | 0.52        |         |         |         | 0.64       |            |
| W                  | 0.40        |         |         |         | 0.61       |            |
| A                  | 17          |         |         |         | 13         |            |
| Ferrous 1 Silicate |             |         |         |         |            |            |
| IS                 | 1.14        |         |         |         | 1.14       | 1.14       |
| QS                 | 2.71        |         |         |         | 2.69       | 2.67       |
| W                  | 0.23*       |         |         |         | 0.30       | 0.31       |
| A                  | 51          |         |         |         | 38         | 50         |
| Ferrous 2 Silicate |             |         |         |         |            |            |
| IS                 | 1.13        |         |         |         | 1.14       |            |
| QS                 | 2.78        |         |         |         | 2.69       |            |
| W                  | 0.25        |         |         |         | 0.30       |            |
| A                  | 51          |         |         |         | 38         | 50         |
| X²                  | 512.83      | 483.88  | 1283.09 | 1284.9   | 953.84     |
| [X²]               | 1.0018      | 0.9459  | 2.499   | 2.5003   | 1.8534     |
| Sum areas          | 100         | 100     | 100     | 100      | 100        |
| Magnetite          | 0           | 0       | 0       | 26       | 22         |
| %Fe³⁺              | 49          | 42      | 54      | 35       | 28         |
| %Fe²⁺              | 51          | 58      | 46      | 38       | 50         |
| %Fe³⁺ excluding magnetite | 49 | 42 | 54 | 48 | 36 |
Table 12 continued

| Sample                | CROMO2_3A‡ | CROMO2_4A‡ | PHL_1‡ | PHL_2B‡ | PHL_3 | PHL_5‡ |
|-----------------------|------------|------------|--------|---------|-------|--------|
| Sextet 1 Magnetite    |            |            |        |         |       |        |
| IS                    | 0.28       | 0.27       | 0.30   | 0.33    |       | 0.29   |
| QS                    | 0.00       | -0.01      | -0.02  | -0.01   | -0.02 | -0.02  |
| W                     | 0.30       | 0.23       | 0.35   | 0.35    | 0.35  | 0.35   |
| A                     | 10         | 12         | 19     | 6       | 21    |        |
| Bhf                   | 489.9      | 489.4      | 498.6  | 501.5   | 495.5 |        |
| Sextet 2 Magnetite    |            |            |        |         |       |        |
| IS                    | 0.67       | 0.67       | 0.88   | 1.07    |       | 0.72   |
| QS                    | -0.01      | 0.00       | 0.16   | 0.23    | -0.03 |        |
| W                     | 0.30       | 0.30       | 0.30   | 0.30    | 0.30  |        |
| A                     | 12         | 21         | 8      | 6       |       | 9      |
| Bhf                   | 458.5      | 459.0      | 476.1  | 499.5   | 464.3 |        |
| Ferric 1 Silicate     |            |            |        |         |       |        |
| IS                    | 0.35       | 0.36       | 0.34   | 0.35    | 0.35  | 0.35   |
| QS                    | 0.65       | 0.67       | 0.66   | 0.68    | 0.56  | 0.65   |
| W                     | 0.55       | 0.61       | 0.59   | 0.63    | 0.36  | 0.59   |
| A                     | 29         | 32         | 42     | 54      | 45    | 47     |
| Ferric 2 Silicate     |            |            |        |         |       |        |
| IS                    |            |            |        |         |       |        |
| QS                    |            |            |        |         |       |        |
| W                     |            |            |        |         |       |        |
| A                     |            |            |        |         |       |        |
| Ferrous 1 Silicate    |            |            |        |         |       |        |
| IS                    | 1.14       | 1.13       | 1.15   | 1.14    | 1.14  | 1.14   |
| QS                    | 2.66       | 2.69       | 2.82   | 2.69    | 2.13  | 2.69   |
| W                     | 0.31       | 0.31       | 0.37   | 0.37    | 0.26  | 0.32   |
| A                     | 49         | 35         | 31     | 34      | 10    | 24     |
| Ferrous 2 Silicate    |            |            |        |         |       |        |
| IS                    |            |            |        |         |       |        |
| QS                    |            |            |        |         |       |        |
| W                     |            |            |        |         |       |        |
| A                     |            |            |        |         |       |        |
| X²                    | 1334.05    | 15229.04   | 1218.41| 2457.07 | 577.59| 1395.6 |
| |X²|                  | 2.5859     | 29.1855 | 2.3508  | 0.7119 | 1.1233| 2.6954 |
| Sum areas             | 100        | 100        | 100    | 100     | 100   | 100    |
| Magnetite             | 22         | 33         | 27     | 12      | 0     | 30     |
| %Fe 3⁺                 | 29         | 32         | 42     | 54      | 65    | 47     |
| %Fe 2⁺                | 49         | 35         | 31     | 34      | 35    | 24     |
| %Fe 3⁺ excluding      |            |            |        |         |       |        |
| magnetite             |            |            |        |         |       |        |

Isomer shift (IS) is in mm/s; Quadrupole splitting (QS) is in mm/s; Peak width (W) is in mm/s; magnetic hyperfine field (Bₘₐₜ) is in tesla; % Area (A) under the curve; CHI-squared (X²), and normalized CHI-squared (|X²|). Silicates are serpentine, pyroxene, and/or chlorite. *Indicates restricted (fixed) parameter. ‡Moss curves fit by M.Nelms in Dyar Lab at Mout Holyoke College and rest were fit by A. Stander.
Table 13: Summary table of Fe concentration (ppm), Fe valence states in percent from MOSS, and possible hydrogen gas yield per 1km$^3$ of rock and per the total volume of the peridotite units of the ophiolite.

| Sample     | Normalized Fe average conc (ppm) | Mössbauer results | $H_{\text{gas}}$ (Tmoles) per 1 km$^3$ | Volume ophiolite peridotite (km$^3$)** | $H_{\text{gas}}$ (Tmoles) per volume oph. |
|------------|---------------------------------|-------------------|---------------------------------------|----------------------------------------|---------------------------------|
|            |                                 | % Magnetite 🌐 | % Ferric ($Fe^{3+}$) 🌈 | % Ferrous ($Fe^{2+}$) 🌈 | Released ($†Fe^{3+}$)* 🌟 | To be released ($†Fe^{2+}$)* 🌟 | Released ($‡Fe^{3+}$) 🌟 | To be released ($‡Fe^{2+}$) 🌟 |
| HLSC_1     | 28741                           | 63                | 14                                    | 23                                     | 0.29                           | 0.11                           | 7730                           | 2235                           | 872 |
| 167_238    | 29910                           | 30                | 40                                    | 30                                     | 0.32                           | 0.11                           | 7730                           | 2481                           | 829 |
| 309_105_A  | 31705                           | 0                 | 30                                    | 70                                     | 0.17                           | 0.20                           | 7730                           | 1308                           | 1540 |
| 309_150    | 34651                           | 34                | 16                                    | 50                                     | 0.24                           | 0.19                           | 7730                           | 1850                           | 1473 |
| 313_210    | 50673                           | 0                 | 36                                    | 65                                     | 0.32                           | 0.29                           | 7730                           | 2490                           | 2262 |
| 313_318    | 32835                           | 0                 | 49                                    | 51                                     | 0.29                           | 0.15                           | 7730                           | 2223                           | 1161 |
| 313_329    | 41989                           | 0                 | 42                                    | 58                                     | 0.32                           | 0.22                           | 7730                           | 2450                           | 1681 |
| 313_356    | 37335                           | 0                 | 54                                    | 46                                     | 0.36                           | 0.16                           | 7730                           | 2767                           | 1200 |
| CROMO2_1A  | 30803                           | 26                | 35                                    | 38                                     | 0.29                           | 0.13                           | 7730                           | 2261                           | 1001 |
| CROMO2_2   | 30966                           | 22                | 28                                    | 50                                     | 0.24                           | 0.16                           | 7730                           | 1825                           | 1231 |
| CROMO2_3A  | 37889                           | 22                | 29                                    | 49                                     | 0.30                           | 0.19                           | 7730                           | 2289                           | 1478 |
| CROMO2_4A  | 30290                           | 33                | 32                                    | 35                                     | 0.29                           | 0.13                           | 7730                           | 2258                           | 967 |
| PHL_1      | 47976                           | 27                | 42                                    | 31                                     | 0.51                           | 0.17                           | 1455                           | 747                            | 251 |
| PHL_2B     | 35777                           | 12                | 54                                    | 34                                     | 0.40                           | 0.12                           | 1455                           | 581                            | 175 |
| PHL_3      | 47745                           | 0                 | 65                                    | 35                                     | 0.56                           | 0.15                           | 1455                           | 814                            | 215 |
| PHL_5      | 41969                           | 30                | 47                                    | 24                                     | 0.50                           | 0.13                           | 1455                           | 724                            | 184 |

Hydrogen values are calculated assuming that all of the peridotite units of the ophiolite have the same composition as the sample. Tmoles (10$^{12}$ = tera T) 🌟 To be released values use the total % $Fe^{2+}$ in sample (calculated using MOSS $Fe^{3+}$ + 1/3 of the % magnetite), and it is assumed that the Fe(II) in the system can still react with water to produce hydrogen. 🌟 Released values use the total % $Fe^{3+}$ in sample (calculated using MOSS $Fe^{3+}$ + 2/3 of the % magnetite), and that all of the Fe(III) has reacted with water to produce hydrogen. 🌟 Normalized volume to 1km$^3$ to eliminate volume as a controlling factor of hydrogen production from the ZO and CRO. ** Estimated volume of the peridotite units in the CRO [Area (~3865km$^2$)—Carnevale, 2013; depth (~2km)—Coleman, 2000] and the ZO [Area (~485km$^2$)—Abrajano and Pasteris, 1989; depth (~3km)—Hawkins and Evans, 1983]. Values in FeO wt% are in the appendix, Table A7.
Table 14: Summary table of Fe concentration (ppm), and possible hydrogen gas yield per 1 km$^3$ of rock calculated using an approximate density (2.68 g/cm$^3$), and per the total volume of the peridotite units of the ophiolite.

| Sample          | Normalized Fe average conc (ppm) | moles $H_2$ per 1 kg rock | Density (g/cm$^3$) | $H_2$ (Tmoles) per 1 km$^3$ | Volume peridotite (km$^3$)** | $H_2$ (Tmoles) per volume oph. |
|----------------|----------------------------------|---------------------------|--------------------|-----------------------------|------------------------------|--------------------------------|
|                 |                                  | Released ($\frac{1}{3}$Fe$^{3+}$)* | To be released ($\frac{1}{2}$Fe$^{2+}$)* | Released ($\frac{1}{3}$Fe$^{3+}$)* | To be released ($\frac{1}{2}$Fe$^{2+}$)* | Released ($\frac{1}{3}$Fe$^{3+}$)* | To be released ($\frac{1}{2}$Fe$^{2+}$)* |
| HLSC_1          | 28741                            | 0.29                       | 0.11               | 2.68                        | 0.77                         | 0.30                           | 7730                           | 5989                        | 2336                        |
| 167_238         | 29910                            | 0.32                       | 0.11               | 2.68                        | 0.86                         | 0.29                           | 7730                           | 6650                        | 2222                        |
| 309_105_A       | 31705                            | 0.17                       | 0.20               | 2.68                        | 0.45                         | 0.53                           | 7730                           | 3506                        | 4128                        |
| 309_150         | 34651                            | 0.24                       | 0.19               | 2.68                        | 0.64                         | 0.51                           | 7730                           | 4959                        | 3947                        |
| 313_210         | 50673                            | 0.32                       | 0.29               | 2.68                        | 0.86                         | 0.78                           | 7730                           | 6673                        | 6062                        |
| 313_318         | 32835                            | 0.29                       | 0.15               | 2.68                        | 0.77                         | 0.40                           | 7730                           | 5958                        | 3111                        |
| 313_329         | 41989                            | 0.32                       | 0.22               | 2.68                        | 0.85                         | 0.58                           | 7730                           | 6566                        | 4505                        |
| 313_356         | 37335                            | 0.36                       | 0.16               | 2.68                        | 0.96                         | 0.42                           | 7730                           | 7415                        | 3217                        |
| CROMO2_1A       | 30803                            | 0.29                       | 0.13               | 2.68                        | 0.78                         | 0.35                           | 7730                           | 6059                        | 2684                        |
| CROMO2_2        | 30966                            | 0.24                       | 0.16               | 2.68                        | 0.63                         | 0.43                           | 7730                           | 4891                        | 3298                        |
| CROMO2_3A       | 37889                            | 0.30                       | 0.19               | 2.68                        | 0.79                         | 0.51                           | 7730                           | 6136                        | 3960                        |
| CROMO2_4A       | 30290                            | 0.29                       | 0.13               | 2.68                        | 0.79                         | 0.34                           | 7730                           | 6051                        | 2592                        |
| PHL_1           | 47976                            | 0.51                       | 0.17               | 2.68                        | 1.38                         | 0.46                           | 1455                           | 2003                        | 674                         |
| PHL_2B          | 35777                            | 0.40                       | 0.12               | 2.68                        | 1.07                         | 0.32                           | 1455                           | 1558                        | 470                         |
| PHL_3           | 47745                            | 0.56                       | 0.15               | 2.68                        | 1.50                         | 0.40                           | 1455                           | 2182                        | 576                         |
| PHL_5           | 41969                            | 0.50                       | 0.13               | 2.68                        | 1.33                         | 0.34                           | 1455                           | 1941                        | 494                         |

Hydrogen values are calculated assuming that all of the peridotite units of the ophiolite have the same composition as the sample. Tmoles ($10^{-12}$ = tera T) † To be released values use the total % Fe$^{2+}$ in sample (calculated using MOSS Fe$^{2+}$ + 1/3 of the % magnetite), and it is assumed that the Fe(II) in the system can still react with water to produce hydrogen. ‡ Released values use the total % Fe$^{3+}$ in sample (calculated using MOSS Fe$^{3+}$ + 2/3 of the % magnetite), and that all of the Fe(III) has reacted with water to produce hydrogen. * Normalized volume to 1 km$^3$ to eliminate volume as a controlling factor of hydrogen production from the ZO and CRO. ** Estimated volume of the peridotite units in the CRO [Area (~3865 km$^2$)—Carnevale, 2013; depth (~2 km)—Coleman, 2000] and the ZO [Area (~485 km$^2$)—Abrajano and Pasteris, 1989; depth (~3 km)—Hawkins and Evans, 1983] ***Average density (g/cm$^3$) of variably serpentinized hazburgites and dunites taken from Andreani et al. 2013B and Klein et al., 2013.
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|       | Ocean floor | Ophiolite sequence |
|-------|-------------|--------------------|
| Sediments | Sedimentary rocks |
| Pillow basalt | Mafic volcanic complex |
| Dikes | Mafic sheeted dike complex |
| Massive Gabbro | Gabbroic complex |
| Sheeted Gabbro |

|       | Upper Mantle |
|-------|--------------|
| Peridotite | Ultramafic complex |

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grain (c) as fluids flowed around it; or it could be further oxidation of the magnetite into hematite. The presence of chlorite in small volumes is not unexpected. Wetzel and Shock [2000] conducted theoretical experiments at 500 bars and 350 and 400°C, which predict that serpentinization should yield 10 to 25 vol% of chlorite, considering peridotites of diverse starting compositions.
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Table A1: Short literature review of microbiology of serpentinization sites, H₂, and additional references.

| Location | Water source | Microbiology | Hydrogen in fluids | Source(s) |
|----------|--------------|--------------|--------------------|-----------|
| Lost City hydrothermal field on the Atlantis Massif near the Mid-Atlantic Ridge | White smokers; submarine seeps from fault-bounded peridotite | sulfur-cycling bacteria; methane-cycling archaea (Anaerobic methane-oxidizing Archaea (ANME-1); Methanosarcinales) and bacteria (methylobacter, methylphaga); H₂-utilizing and producing; aerobic carbon monoxide utilization and anaerobic carbon fixation | <14mmol/kg H₂; <1-2mmol/kg methane | Kelley et al., 2005; Kelley et al., 2007; Brazeton et al., 2006; Brazeton et al., 2012; Schrenk et al., 2004; |
| Tablelands ophiolite in Newfoundland | Ground water springs | H₂-utilizing and producing; aerobic carbon monoxide utilization and anaerobic carbon fixation | <~500μM H₂ | Szponar et al., 2013; Brazeton et al., 2012 |

Additional references

Schrenk, Brazelton, and Lang [2013] have compiled types of analysis performed and characteristic Achaean found in both marine and terrestrial serpentinite habitats including Rainbow and Lost City hydrothermal fields, CRO, South Chamorro Seamount, Tablelands, and more.

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Table A2: Mössbauer and wet chemistry %Fe$^{3+}$, and Fe concentrations from literature for fresh and serpentinized peridotites.

| Site                                      | Peridotite Type/ Geologic Setting/ Mineralogy                                                                 | Fe conc. (ppm) | Fe$^{3+}$ %Fe | Citation                          |
|-------------------------------------------|----------------------------------------------------------------------------------------------------------------|----------------|---------------|-----------------------------------|
| Cassiar Serpentinite, North-central British Columbia | 100% serpentinized harzburgite tectonite; ~13,400 - 25,000 | 22-88‡         |                | O’Hanley and Dyar, 1993; O’Hanley and Dyar, 1998 |
| United Mine Serpentinite, East-Central Ontario | 100% serpentinized dunite cumulate from differentiated mafic-ultramafic sill | ~88‡           |                | O’Hanley and Dyar, 1993 |
| Jeffery Serpentinite, Southeastern Quebec | Partially to completely serpentinized and recrystallized harzburgite tectonite; part of Ordovician ophiolite | ~12,100 - 12,000 | 33-53‡       | O’Hanley and Dyar, 1993; O’Hanley and Dyar, 1998 |
| Woodsreef Serpentinite, Eastern New South Wales | Partially to completely serpentinized harzburgite tectonite; ~17,200 – 29,000 | 40-72‡         |                | O’Hanley and Dyar, 1993; O’Hanley and Dyar, 1998 |
| ODP leg 125 | 40-100% serpentinized harzburgites and dunites; Marina Forarc; subduction zone forearc | ~51,800 - 57,100 | 14-46‡        | Klein et al., 2013 |
| ODP leg 153, MARK area | 40-100% serpentinized harzburgites and dunites; mid-ocean ridge | ~54,800 – 65,600 | 59-66‡       | Klein et al., 2013 |
| ODP leg 153, MARK 7, bulk rock | 50-100% serpentinized harzburgites | ~54344         | ~69*          | Andreani et al., 2013B |
| MARK 7** | 100% serpentinized harzburgites | ~13059         | ~61†          | Andreani et al., 2013B |
| ODP leg 153, MARK 9, bulk rock | 50-100% serpentinized harzburgites | ~50917         | ~66*          | Andreani et al., 2013B |
| MARK 9** | 100% serpentinized harzburgites | ~11,300-15,400 | 54-100†       | Andreani et al., 2013B |
Table A2: Continued

| Site | Peridotite Type/ Geologic Setting/ Mineralogy | Fe conc. (ppm) | Fe$^{3+}$ %Fe | Citation |
|------|---------------------------------------------|----------------|---------------|----------|
| ODP leg 153, MARK 11, bulk rock | 50-100% serpentinized harzburgites | ~58611 | ~34* | Andreani et al., 2013B |
| MARK 11** | 55-79% serpentinized harzburgites | ~31,900-42,700 | 58-63† | Andreani et al., 2013B |
| ODP leg 153, MARK 24, bulk rock | 50-100% serpentinized harzburgites | ~59660 | ~42* | Andreani et al., 2013B |
| MARK 24** | 17-98% serpentinized harzburgites | ~23,000-59,100 | ~4-77† | Andreani et al., 2013B |
| ODP leg 173 | 40-100% serpentinized harzburgites and dunites; Iberia Margin; passive margin | ~54,400–59,200 | ~58-63† | Klein et al., 2013 |
| 84-402 | Spinel lherzolite from Porndon, Southeastern Australia | ~60631 | ~2 | Canil et al., 1994 |
| 89-772 | Dunite from Olmani Tanzania | ~97164 | ~0 | Canil et al., 1994 |
| 89-680 | Garnet harzburgite; Lashaine, Tanzania | ~51303 | ~2 | Canil et al., 1994 |
| 89-719 | Garnet harzburgite; Lashaine, Tanzania | ~52857 | ~1 | Canil et al., 1994 |
| 89-773 | Harzburgite; Olmani Tanzania | ~46406 | ~1 | Canil et al., 1994 |
| BD1201 | Garnet lherzolite, coarse, Low T; Wesselton, Southern Africa | ~52857 | ~3 | Canil et al., 1994 |
| PHN5273 | Garnet harzburgite, coarse, Low T; Premier, Southern Africa | ~50525 | ~0 | Canil et al., 1994 |
| Site            | Peridotite Type/ Geologic Setting/ Mineralogy                                                                 | Fe conc. (ppm) | Fe$^{3+}$ \%Fe | Citation        |
|-----------------|-------------------------------------------------------------------------------------------------------------|----------------|----------------|----------------|
| FRB909          | Garnet lherzolite, sheared, high T; Premier, Southern Africa                                              | ~62963         | ~2             | Canil et al., 1994 |
| F865            | Garnet harzburgite, coarse, Low T; Finsch, Southern Africa                                              | ~52857         | ~1             | Canil et al., 1994 |
| F556            | Garnet harzburgite, coarse, Low T; Finsch, Southern Africa                                              | ~71513         | ~2             | Canil et al., 1994 |
| UV417/89        | Garnet lherzolite, coarse low T; Udachnaya, Siberia                                                      | ~64517         | ~2             | Canil et al., 1994 |
| Fr1             | Spinel lherzolite; Landoz, Massif Central                                                              | ~58765         | ~4             | Canil et al., 1994 |
| Monte Fico North quarry | Recrystallized, granoblastic lizardite; Monte Fico, Island of Elba, Italy                         | ~95800-114,000 | ~13-15        | Fuch et al., 1998 |
| American-Antarctic Ridge | Spinels from abyssal spinel peridotites                                                                | ~85700-125,000 | ~5-15          | Bryndzia and Wood, 1990 |
| South West Indian Ridge | Spinels from abyssal spinel peridotites                                                                | ~101,000-129,000 | ~11-22        | Bryndzia and Wood, 1990 |
| Mid-Atlantic Ridge | Spinels from abyssal spinel peridotites                                                                | ~94400-105,000 | ~9             | Bryndzia and Wood, 1990 |
| Mid Cayman Rift | Spinels from abyssal spinel peridotites                                                                | ~102,000-158,000 | ~11-25        | Bryndzia and Wood, 1990 |
| Central Indian Ridge | Spinels from abyssal spinel peridotites                                                                | ~95800-114,000 | ~13-15        | Bryndzia and Wood, 1990 |
Table A2: Continued

| Site                                      | Peridotite Type/ Geologic Setting/ Mineralogy                                                                 | Fe conc. (ppm) | Fe$^{3+}$/%Fe | Citation                  |
|-------------------------------------------|-------------------------------------------------------------------------------------------------------------|----------------|--------------|---------------------------|
| 9 spinel separates                        | Spinel and garnet peridotite xenoliths in the Udachnaya kimerlite                                          |                | ~10-27       | Goncharov et al., 2012    |
| 28 garnet separates                       | Spinel and garnet peridotite xenoliths in the Udachnaya kimerlite                                          |                | ~2-19        | Goncharov et al., 2012    |
| Mexico spinels                            | Spinel-peridotite xenoliths                                                                               |                | ~3-28        | Peslier et al., 2002      |
| Simcoe, WA, USA spinels                   | Spinel-peridotite xenoliths                                                                               |                | ~27-39       | Peslier et al., 2002      |
| Abyssal Serp, average 20 bulk samples     | Dunite                                                                                                     | ~59870         |              | Deschamps et al., 2013    |
| Abyssal Serp, average of 48 bulk samples  | Harzburgite                                                                                                 | ~50428         |              | Deschamps et al., 2013    |
| Mantle wedge, average of 88 bulk samples  | Dunite                                                                                                     | ~52596         |              | Deschamps et al., 2013    |
| Mantle wedge, average of 73 bulk samples  | Harzburgite                                                                                                 | ~53505         |              | Deschamps et al., 2013    |
| Subducted serp, average of 39 bulk samples| Dunite                                                                                                     | ~56163         |              | Deschamps et al., 2013    |
| Subducted serp, average of 109 bulk samples| Harzburgite                                                                                               | ~55463         |              | Deschamps et al., 2013    |

Mag= magnetite. ODP=Drilling Project. ‡Magnetite factored out as an impurity. *Obtained from titration of bulk samples. **Measurements from veins, mesh rims and mesh cores. †μXANES measurements.
## STANDARDS

Table A3: Normalized average Fe concentration converted to FeO wt%.

| Sample name               | Fe avg. normalized concentration (ppm) | Fe avg. normalized concentration (FeO wt%) |
|---------------------------|---------------------------------------|-------------------------------------------|
| DTS-1                     | 60710                                 | 7.81                                      |
| DTS-2                     | 41396                                 | 5.33                                      |
| PCC-1                     | 58759                                 | 7.56                                      |
| XRF Empty sample holder   | 170                                   | 0.02                                      |
Table A4: Raw XRF elemental data for USGS standards—Mo, Zr, Sr, Rb, Th, Pb, Zn, Cu, Ni, Co, Fe, Mn, Cr, V, Ti, Sc, Ca, K.

| SAMPLE | Type | Duration (s) | Units | Run | Mo | Mo Error | Zr | Zr Error |
|--------|------|--------------|-------|-----|----|----------|----|----------|
| BCR-2  | SOIL | 201.41       | ppm   | 1   | 163.11 | 7.43 | 210.17 | 11.02   |
| BCR-2  | SOIL | 201.41       | ppm   | 2   | 127.55 | 7.50 | 195.04 | 11.68   |
| BCR-2  | SOIL | 201.77       | ppm   | 3   | 175.62 | 8.02 | 233.21 | 12.05   |
| BCR-2  | SOIL | 207.85       | ppm   | 4   | 142.62 | 7.56 | 193.18 | 11.34   |
| BCR-2  | SOIL | 204.05       | ppm   | 5   | 141.53 | 7.74 | 208.14 | 11.89   |
| BCR-2  | SOIL | 201.59       | ppm   | 6   | 143.30 | 7.88 | 205.58 | 12.02   |
| BHVO-2 | SOIL | 202.00       | ppm   | 1   | < LOD | 7.11 | 215.17 | 11.57   |
| BHVO-2 | SOIL | 201.95       | ppm   | 2   | < LOD | 8.35 | 203.72 | 12.83   |
| BHVO-2 | SOIL | 201.95       | ppm   | 3   | < LOD | 8.19 | 200.48 | 12.78   |
| BHVO-2 | SOIL | 201.89       | ppm   | 4   | < LOD | 7.09 | 192.87 | 11.04   |
| BHVO-2 | SOIL | 200.85       | ppm   | 5   | < LOD | 7.22 | 197.42 | 11.36   |
| BHVO-2 | SOIL | 201.26       | ppm   | 6   | < LOD | 7.01 | 188.96 | 11.04   |
| BIR-1  | SOIL | 201.33       | ppm   | 1   | < LOD | 6.68 | < LOD  | 8.56    |
| BIR-1  | SOIL | 200.98       | ppm   | 2   | < LOD | 7.12 | 12.49  | 6.41    |
| BIR-1  | SOIL | 201.10       | ppm   | 3   | < LOD | 6.92 | < LOD  | 9.01    |
| BIR-1  | SOIL | 201.10       | ppm   | 4   | < LOD | 7.23 | < LOD  | 9.40    |
| BIR-1  | SOIL | 200.89       | ppm   | 5   | < LOD | 7.23 | < LOD  | 9.36    |
| BIR-1  | SOIL | 201.13       | ppm   | 6   | < LOD | 7.17 | 10.20  | 6.28    |
| DTS-1  | SOIL | 200.88       | ppm   | 1   | < LOD | 6.77 | < LOD  | 6.56    |
| DTS-1  | SOIL | 201.06       | ppm   | 2   | < LOD | 6.18 | < LOD  | 6.07    |
| DTS-1  | SOIL | 201.19       | ppm   | 3   | < LOD | 6.83 | < LOD  | 6.27    |
| DTS-1  | SOIL | 201.80       | ppm   | 4   | < LOD | 6.47 | < LOD  | 5.86    |
| DTS-1  | SOIL | 201.06       | ppm   | 5   | < LOD | 6.31 | < LOD  | 6.11    |
| DTS-1  | SOIL | 201.12       | ppm   | 6   | < LOD | 6.26 | < LOD  | 6.16    |
| DTS-2  | SOIL | 201.90       | ppm   | 1   | < LOD | 5.29 | < LOD  | 5.12    |
| DTS-2  | SOIL | 201.29       | ppm   | 2   | < LOD | 5.69 | < LOD  | 5.45    |
| DTS-2  | SOIL | 201.18       | ppm   | 3   | < LOD | 5.49 | < LOD  | 5.16    |
| DTS-2  | SOIL | 200.85       | ppm   | 4   | < LOD | 5.89 | < LOD  | 5.49    |
| DTS-2  | SOIL | 210.19       | ppm   | 5   | < LOD | 5.59 | < LOD  | 5.18    |
| DTS-2  | SOIL | 201.08       | ppm   | 6   | < LOD | 5.92 | < LOD  | 5.62    |
| PCC-1  | SOIL | 201.24       | ppm   | 1   | < LOD | 5.44 | < LOD  | 5.20    |
| PCC-1  | SOIL | 200.72       | ppm   | 2   | < LOD | 7.73 | < LOD  | 7.99    |
| PCC-1  | SOIL | 201.87       | ppm   | 3   | < LOD | 5.62 | < LOD  | 5.15    |
| PCC-1  | SOIL | 200.90       | ppm   | 4   | < LOD | 6.96 | < LOD  | 6.80    |
| PCC-1  | SOIL | 201.37       | ppm   | 5   | < LOD | 6.90 | < LOD  | 6.74    |
| PCC-1  | SOIL | 200.72       | ppm   | 6   | < LOD | 7.01 | < LOD  | 6.87    |
Table A4: continued

| SAMPLE | Sr    | Sr Error | Rb    | Rb Error | Th    | Th Error | Pb    | Pb Error |
|--------|-------|----------|-------|----------|-------|----------|-------|----------|
| BCR-2  | 352.95| 11.09    | 45.89 | 5.02     | < LOD |          | 8.74  | 15.87    | 7.62     |
| BCR-2  | 355.72| 12.04    | 45.45 | 5.43     | 10.56 | 6.58     | 17.59 | 8.62     |
| BCR-2  | 379.48| 12.07    | 50.16 | 5.51     | < LOD |          | 8.72  | 17.87    | 8.36     |
| BCR-2  | 346.74| 11.60    | 43.14 | 5.26     | 10.15 | 6.43     | 24.58 | 8.95     |
| BCR-2  | 348.12| 11.91    | 35.33 | 5.05     | 12.49 | 6.75     | 21.56 | 9.06     |
| BCR-2  | 349.85| 12.12    | 43.06 | 5.39     | < LOD |          | 9.49  | 19.43    | 8.96     |
| BHVO-2 | 433.20| 12.51    | 7.85  | 3.06     | < LOD |          | 7.38  | < LOD    | 10.63    |
| BHVO-2 | 447.31| 14.17    | 9.80  | 3.78     | 11.29 | 6.79     | < LOD | 12.28    |
| BHVO-2 | 442.44| 14.14    | 7.45  | 3.73     | < LOD |          | 9.45  | < LOD    | 12.35    |
| BHVO-2 | 408.74| 12.06    | 7.31  | 3.21     | < LOD |          | 7.55  | < LOD    | 9.94     |
| BHVO-2 | 421.17| 12.46    | 10.39 | 3.41     | < LOD |          | 8.05  | < LOD    | 11.06    |
| BHVO-2 | 403.35| 12.07    | 5.83  | 3.08     | < LOD |          | 7.96  | < LOD    | 9.70     |
| BIR-1  | 108.25| 6.66     | < LOD | 3.58     | < LOD |          | 7.93  | < LOD    | 10.96    |
| BIR-1  | 123.61| 7.46     | < LOD | 3.88     | < LOD |          | 7.71  | 14.34    | 8.09     |
| BIR-1  | 116.95| 7.08     | < LOD | 3.63     | < LOD |          | 7.73  | < LOD    | 11.12    |
| BIR-1  | 128.61| 7.58     | < LOD | 3.90     | < LOD |          | 7.42  | 19.14    | 8.41     |
| BIR-1  | 127.05| 7.51     | < LOD | 4.05     | < LOD |          | 7.56  | < LOD    | 10.98    |
| BIR-1  | 121.85| 7.36     | < LOD | 3.66     | < LOD |          | 7.35  | < LOD    | 11.59    |
| DTS-1  | < LOD | 3.33     | < LOD | 3.19     | < LOD |          | 7.28  | 22.68    | 8.23     |
| DTS-1  | < LOD | 3.01     | < LOD | 3.05     | < LOD |          | 6.91  | 14.85    | 7.01     |
| DTS-1  | < LOD | 3.37     | < LOD | 3.41     | < LOD |          | 6.82  | 21.91    | 8.02     |
| DTS-1  | < LOD | 3.22     | < LOD | 2.89     | < LOD |          | 5.88  | 12.91    | 6.96     |
| DTS-1  | < LOD | 3.12     | < LOD | 2.92     | < LOD |          | 6.54  | < LOD    | 9.71     |
| DTS-1  | < LOD | 3.07     | < LOD | 2.97     | < LOD |          | 6.77  | 14.41    | 7.05     |
| DTS-2  | < LOD | 2.53     | < LOD | 2.62     | < LOD |          | 5.81  | < LOD    | 8.31     |
| DTS-2  | < LOD | 2.82     | < LOD | 2.71     | < LOD |          | 6.27  | < LOD    | 8.36     |
| DTS-2  | < LOD | 2.51     | < LOD | 2.41     | < LOD |          | 5.19  | < LOD    | 7.81     |
| DTS-2  | < LOD | 2.89     | < LOD | 2.92     | < LOD |          | 5.89  | < LOD    | 9.06     |
| DTS-2  | < LOD | 2.78     | < LOD | 2.50     | < LOD |          | 6.03  | 8.85     | 5.84     |
| DTS-2  | < LOD | 2.86     | < LOD | 2.91     | < LOD |          | 5.78  | < LOD    | 8.90     |
| PCC-1  | < LOD | 2.70     | < LOD | 2.56     | < LOD |          | 6.06  | 14.76    | 6.25     |
| PCC-1  | < LOD | 4.16     | < LOD | 3.61     | < LOD |          | 8.45  | < LOD    | 12.54    |
| PCC-1  | < LOD | 2.72     | < LOD | 2.44     | < LOD |          | 5.31  | 15.95    | 6.25     |
| PCC-1  | < LOD | 3.40     | < LOD | 3.31     | < LOD |          | 7.48  | 11.73    | 7.31     |
| PCC-1  | < LOD | 3.46     | < LOD | 3.44     | < LOD |          | 7.64  | 11.29    | 7.36     |
| PCC-1  | < LOD | 3.21     | < LOD | 3.62     | < LOD |          | 7.71  | 26.59    | 8.70     |
Table A4: continued

| SAMPLE | Zn   | Zn Error | Cu   | Cu Error | Ni   | Ni Error | Co   | Co Error |
|--------|------|----------|------|----------|------|----------|------|----------|
| BCR-2  | 82.96| 21.04    | < LOD| 37.90    | < LOD| 79.20    | < LOD| 387.80   |
| BCR-2  | 92.26| 23.79    | < LOD| 44.96    | < LOD| 90.20    | < LOD| 444.58   |
| BCR-2  | 93.07| 22.81    | < LOD| 43.56    | < LOD| 86.00    | < LOD| 423.38   |
| BCR-2  | 91.64| 23.81    | < LOD| 46.31    | < LOD| 84.90    | < LOD| 443.12   |
| BCR-2  | 103.66| 24.52   | < LOD| 45.46    | < LOD| 90.35    | < LOD| 448.93   |
| BCR-2  | 81.80| 23.97    | < LOD| 45.05    | < LOD| 90.68    | < LOD| 458.09   |
| BHVO-2 | 81.85| 21.24    | 132.61| 35.13    | < LOD| 85.02    | < LOD| 372.17   |
| BHVO-2 | 66.59| 24.08    | 125.11| 41.97    | 139.78| 74.87    | < LOD| 466.87   |
| BHVO-2 | 104.21| 26.40   | 142.90| 42.71    | < LOD| 105.95   | < LOD| 464.04   |
| BHVO-2 | 60.65| 19.79    | 57.64 | 31.56    | < LOD| 88.23    | < LOD| 371.92   |
| BHVO-2 | 64.21| 20.43    | 111.00| 34.56    | < LOD| 87.69    | < LOD| 381.10   |
| BHVO-2 | 58.86| 20.01    | 112.45| 34.20    | < LOD| 88.96    | < LOD| 374.23   |
| BIR-1  | 32.38| 18.50    | 128.31| 36.25    | 125.96| 62.73    | < LOD| 369.37   |
| BIR-1  | 29.82| 147.63   | 40.33 | 175.56   | 70.15 | < LOD    | 410.78 |
| BIR-1  | 38.68| 121.71   | 37.36 | 167.08   | 65.73 | < LOD    | 383.69 |
| BIR-1  | < LOD| 117.33   | 38.63 | < LOD    | 100.06| < LOD    | 410.21 |
| BIR-1  | 49.35| 21.36    | 121.62| 38.85    | 164.54| 68.58    | < LOD| 406.36   |
| BIR-1  | 37.99| 105.08   | 38.27 | 199.97   | 69.50 | < LOD    | 404.38 |
| DTS-1  | < LOD| 25.64    | < LOD| 54.95    | 4146.43| 150.38   | 475.82| 248.05   |
| DTS-1  | 22.06| < LOD    | 46.85 | 3651.22  | 132.19| < LOD    | 326.74 |
| DTS-1  | 26.50| < LOD    | 53.70 | 4282.54  | 153.40| < LOD    | 377.08 |
| DTS-1  | 30.40| 16.85    | < LOD| 51.49    | 3795.93| 137.28   | 434.34| 227.00   |
| DTS-1  | < LOD| 23.48    | < LOD| 49.50    | 3668.76| 135.22   | 359.13| 226.72   |
| DTS-1  | < LOD| 25.13    | < LOD| 49.79    | 3687.61| 135.10   | < LOD| 336.68   |
| DTS-2  | < LOD| 19.19    | < LOD| 42.75    | 4716.41| 131.07   | < LOD| 242.14   |
| DTS-2  | < LOD| 21.42    | < LOD| 48.84    | 5379.99| 148.73   | < LOD| 276.93   |
| DTS-2  | < LOD| 19.16    | < LOD| 44.67    | 4805.85| 133.99   | < LOD| 247.15   |
| DTS-2  | < LOD| 21.72    | < LOD| 51.09    | 5522.56| 153.54   | 400.32| 191.01   |
| DTS-2  | 25.48| 14.37    | < LOD| 47.83    | 5411.46| 143.44   | 389.15| 179.57   |
| DTS-2  | 27.14| 15.38    | < LOD| 50.52    | 5605.10| 153.74   | < LOD| 284.56   |
| PCC-1  | < LOD| 19.84    | < LOD| 41.47    | 3144.28| 112.68   | 388.91| 181.99   |
| PCC-1  | < LOD| 33.01    | < LOD| 68.72    | 5481.92| 194.52   | < LOD| 458.34   |
| PCC-1  | < LOD| 19.63    | < LOD| 40.39    | 3025.99| 109.50   | < LOD| 266.63   |
| PCC-1  | < LOD| 27.57    | < LOD| 56.97    | 4565.26| 162.60   | < LOD| 390.11   |
| PCC-1  | < LOD| 26.89    | < LOD| 61.33    | 4619.18| 162.94   | < LOD| 390.08   |
| PCC-1  | < LOD| 27.71    | < LOD| 59.14    | 4551.79| 163.12   | < LOD| 393.04   |
Table A4: continued

| SAMPLE | Fe    | Fe Error | Mn    | Mn Error | Cr    | Cr Error | V    | V Error |
|--------|-------|----------|-------|----------|-------|----------|------|---------|
| BCR-2  | 118422.48 | 902.64  | 1810.10 | 173.09   | < LOD  | 44.35    | 385.33 | 84.37   |
| BCR-2  | 134716.19 | 1040.08 | 2087.95 | 199.76   | < LOD  | 40.39    | 372.72 | 76.74   |
| BCR-2  | 128138.24 | 986.22  | 2299.80 | 200.45   | < LOD  | 42.31    | 373.39 | 81.17   |
| BCR-2  | 138761.06 | 1029.92 | 2411.87 | 205.95   | < LOD  | 41.20    | 305.31 | 78.75   |
| BCR-2  | 138442.64 | 1054.00 | 2503.39 | 214.18   | < LOD  | 40.92    | 343.15 | 78.53   |
| BCR-2  | 139390.48 | 1073.77 | 2441.34 | 215.53   | < LOD  | 41.91    | 382.65 | 78.47   |
| BHVO-2 | 105403.20 | 870.43  | 1590.76 | 168.56   | 195.31 | 30.48    | 324.85 | 75.21   |
| BHVO-2 | 132517.16 | 1087.61 | 2150.53 | 215.56   | 227.56 | 31.61    | 231.66 | 77.38   |
| BHVO-2 | 131647.09 | 1087.53 | 2266.48 | 219.06   | 204.84 | 30.44    | 277.31 | 74.30   |
| BHVO-2 | 105036.20 | 861.68  | 1787.37 | 174.30   | 220.24 | 31.74    | 226.50 | 76.97   |
| BHVO-2 | 106298.99 | 882.36  | 1628.76 | 171.90   | 213.18 | 31.62    | 279.84 | 77.30   |
| BHVO-2 | 104927.68 | 867.36  | 1825.57 | 176.00   | 220.57 | 31.52    | 352.46 | 77.30   |
| BIR-1  | 98982.34  | 858.50  | 1919.08 | 182.26   | 240.77 | 29.03    | 244.71 | 50.12   |
| BIR-1  | 110751.69 | 958.69  | 2087.59 | 201.06   | 255.49 | 29.19    | 225.61 | 50.03   |
| BIR-1  | 103446.48 | 900.34  | 1897.47 | 187.17   | 263.62 | 29.04    | 192.86 | 48.82   |
| BIR-1  | 109882.01 | 951.75  | 2029.93 | 197.53   | 206.54 | 28.32    | 260.58 | 50.64   |
| BIR-1  | 110774.65 | 952.85  | 1937.77 | 194.13   | 265.55 | 29.53    | 214.23 | 49.57   |
| BIR-1  | 110449.42 | 952.44  | 1959.26 | 195.61   | 211.18 | 28.53    | 253.55 | 51.06   |
| DTS-1  | 102595.43 | 857.46  | 1731.42 | 205.56   | 352.99 | 71.97    | < LOD  | 44.92   |
| DTS-1  | 91365.79  | 758.47  | 1683.11 | 184.24   | 3584.77 | 72.66   | < LOD  | 44.66   |
| DTS-1  | 107422.77 | 885.72  | 1908.17 | 214.26   | 3695.75 | 73.41   | < LOD  | 45.15   |
| DTS-1  | 94530.18  | 784.71  | 1577.97 | 186.17   | 3557.05 | 72.22   | < LOD  | 45.30   |
| DTS-1  | 94878.32  | 786.38  | 1735.92 | 190.35   | 3445.07 | 71.32   | < LOD  | 46.29   |
| DTS-1  | 94693.48  | 785.56  | 1711.26 | 189.53   | 3461.89 | 72.12   | < LOD  | 45.08   |
| DTS-2  | 61917.10  | 559.98  | 1118.93 | 197.26   | 14467.74 | 138.63  | < LOD  | 45.93   |
| DTS-2  | 71787.61  | 641.33  | 1073.31 | 220.55   | 14141.71 | 136.65  | < LOD  | 47.42   |
| DTS-2  | 63397.38  | 574.63  | 1262.48 | 204.84   | 14683.96 | 139.97  | < LOD  | 50.03   |
| DTS-2  | 72855.77  | 657.59  | 1502.78 | 233.74   | 13919.52 | 135.79  | < LOD  | 47.13   |
| DTS-2  | 72427.46  | 618.50  | 1423.95 | 216.76   | 13848.33 | 133.45  | < LOD  | 46.14   |
| DTS-2  | 73922.34  | 659.74  | 1242.54 | 227.31   | 13853.78 | 135.77  | < LOD  | 46.97   |
| PCC-1  | 74439.40  | 627.28  | 1347.29 | 145.93   | 2538.99 | 62.65   | 51.34  | 30.53   |
| PCC-1  | 126578.55 | 1084.25 | 2381.20 | 252.56   | 2557.21 | 61.27   | 64.58  | 30.15   |
| PCC-1  | 73596.48  | 618.22  | 1332.83 | 143.42   | 2449.48 | 61.38   | < LOD  | 43.29   |
| PCC-1  | 108575.68 | 915.84  | 1777.29 | 206.35   | 2448.98 | 59.57   | < LOD  | 42.22   |
| PCC-1  | 108789.84 | 913.47  | 1930.45 | 210.22   | 2497.66 | 60.56   | < LOD  | 45.01   |
| PCC-1  | 108119.17 | 916.32  | 1867.04 | 209.94   | 2452.03 | 60.07   | < LOD  | 44.92   |
Table A4: continued

| SAMPLE | Ti       | Ti Error | Sc     | Sc Error | Ca     | Ca Error | K       | K Error |
|--------|----------|----------|--------|----------|--------|----------|--------|---------|
| BCR-2  | 11454.68 | 246.05   | 79.51  | 35.53    | 37052.39 | 570.29   | 12599.45 | 497.13  |
| BCR-2  | 10481.78 | 224.12   | 79.29  | 34.28    | 37466.61 | 551.76   | 12507.76 | 477.42  |
| BCR-2  | 11586.90 | 238.82   | 69.71  | 34.86    | 37771.21 | 563.19   | 12923.05 | 492.12  |
| BCR-2  | 10513.73 | 230.70   | < LOD  | 50.42    | 37284.17 | 555.15   | 12632.83 | 483.29  |
| BCR-2  | 10420.38 | 228.46   | < LOD  | 50.74    | 37214.88 | 552.07   | 13510.72 | 494.64  |
| BCR-2  | 10511.71 | 227.88   | < LOD  | 50.47    | 37436.92 | 557.63   | 12967.36 | 489.85  |
| BHVO-2 | 11557.15 | 226.36   | 84.89  | 42.32    | 63066.06 | 691.18   | 3664.64  | 309.37  |
| BHVO-2 | 11970.98 | 236.56   | 77.35  | 42.96    | 62741.05 | 702.75   | 3769.00  | 318.08  |
| BHVO-2 | 11574.00 | 226.30   | 88.18  | 42.43    | 62904.45 | 692.43   | 3674.35  | 310.63  |
| BHVO-2 | 11992.14 | 236.50   | 69.50  | 43.28    | 63116.95 | 709.81   | 3649.93  | 317.35  |
| BHVO-2 | 11935.86 | 234.86   | < LOD  | 64.22    | 63156.02 | 706.53   | 3434.22  | 310.36  |
| BHVO-2 | 11892.21 | 231.98   | 93.98  | 43.03    | 63540.17 | 701.10   | 3741.23  | 315.08  |
| BIR-1  | 3811.98  | 137.51   | 122.61 | 44.10    | 74997.05 | 719.07   | 326.24   | 208.31  |
| BIR-1  | 3966.46  | 138.96   | 104.85 | 43.84    | 74882.21 | 717.79   | < LOD    | 306.93  |
| BIR-1  | 3810.69  | 136.31   | 70.54  | 43.29    | 75768.41 | 715.25   | < LOD    | 304.81  |
| BIR-1  | 3912.17  | 138.10   | < LOD  | 65.48    | 76268.52 | 724.19   | < LOD    | 307.04  |
| BIR-1  | 3759.29  | 137.47   | 115.70 | 44.54    | 76237.20 | 727.94   | 413.64   | 213.32  |
| BIR-1  | 3757.72  | 138.71   | 79.01  | 44.12    | 76339.86 | 727.51   | < LOD    | 307.53  |
| DTS-1  | < LOD    | 101.21   | < LOD  | 14.48    | 297.37  | 111.94   | 267.11   | 142.80  |
| DTS-1  | < LOD    | 102.71   | < LOD  | 14.39    | 487.19  | 117.99   | < LOD    | 204.12  |
| DTS-1  | < LOD    | 97.98    | < LOD  | 14.29    | 435.33  | 115.78   | < LOD    | 210.23  |
| DTS-1  | < LOD    | 97.50    | < LOD  | 13.66    | 344.30  | 113.23   | < LOD    | 206.72  |
| DTS-1  | < LOD    | 101.80   | < LOD  | 13.27    | 333.95  | 112.92   | < LOD    | 206.81  |
| DTS-1  | < LOD    | 97.68    | < LOD  | 13.92    | 348.65  | 114.32   | < LOD    | 204.26  |
| DTS-2  | < LOD    | 102.33   | < LOD  | 14.94    | 261.46  | 112.62   | 288.59   | 145.97  |
| DTS-2  | < LOD    | 105.37   | < LOD  | 13.80    | 356.81  | 115.38   | 287.72   | 145.60  |
| DTS-2  | < LOD    | 112.71   | < LOD  | 13.92    | 232.34  | 112.22   | 228.91   | 143.60  |
| DTS-2  | < LOD    | 105.10   | < LOD  | 13.71    | 256.19  | 111.74   | < LOD    | 208.96  |
| DTS-2  | < LOD    | 102.71   | < LOD  | 13.20    | 342.70  | 112.79   | < LOD    | 206.57  |
| DTS-2  | < LOD    | 102.37   | < LOD  | 13.14    | 279.83  | 112.75   | 239.43   | 143.54  |
| PCC-1  | < LOD    | 96.98    | < LOD  | 18.18    | 2990.79 | 177.43   | < LOD    | 211.66  |
| PCC-1  | < LOD    | 94.68    | < LOD  | 18.26    | 2973.70 | 172.99   | < LOD    | 207.11  |
| PCC-1  | < LOD    | 96.09    | < LOD  | 12.58    | 2676.08 | 169.63   | < LOD    | 195.55  |
| PCC-1  | 93.65    | 60.84    | < LOD  | 17.45    | 2648.24 | 164.48   | 207.24   | 137.44  |
| PCC-1  | < LOD    | 97.38    | < LOD  | 17.56    | 2693.53 | 166.45   | < LOD    | 195.50  |
| PCC-1  | < LOD    | 96.57    | < LOD  | 17.04    | 2771.80 | 168.21   | < LOD    | 207.31  |

The first 4 runs were not shaken between each run and used to gauge precision. The last 3 runs (4-6) were not shaken between each run and used to gauge precision.
Figure A3: XRD diffractograms for USGS rock standards DTS-1 (a) and DTS-2 (b).
Figure A4: XRD diffractograms for USGS rock standards PCC-1 (a) and BIR-1 (b).
Figure A5: XRD diffractograms for USGS rock standards BCR-2 (a) and BHVO-2 (b).
Table A5: Full sample names and shortened name.

| SAMPLE                  | Sample short name |
|-------------------------|-------------------|
| HLSC_1_A                | HLSC_1            |
| HLSC_4                  | HLSC_4            |
| McL_81-167_238 to EOH_B22_B | 167_238          |
| McL_M81-309_84_B8_A1    | 309_84            |
| McL_M81-309_105_B11_B1  | 309_105_A         |
| McL_M81-309_105_B11_B2  | 309_105_B         |
| McL_M81-309_150_B15_A   | 309_150           |
| McL_M81-313_210_B22_A3  | 313_210           |
| McL_M81-313_318_B34_B   | 313_318           |
| McL_M81-313_329         | 313_329           |
| McL_M81-313_356-356.6_B38_B | 313_356         |
| CSW1_27/28_SHOE?_A*     | CROMO1_1_A        |
| CSW1_27/28_SHOE?_B*     | CROMO1_1_B        |
| CSW1_28a_CLAY_A*        | CROMO1_2_AA       |
| CSW1_28a_CLAY_B*        | CROMO1_2_AB       |
| CSW1_28a_hard           | CROMO1_2_AC       |
| CSW1_28c_A*             | CROMO1_2_CA       |
| CSW1_28c_B*             | CROMO1_2_CB       |
| MLC_QV1_140_M-BMIX_A*   | CROMO2_1A         |
| MLC_QV1_140_M-BMIX_B*   | CROMO2_1B         |
| MLC_QV1_140_Mdkgrn      | CROMO2_2          |
| MLC_QV1_140_SERPMUD_A*  | CROMO2_3A         |
| MLC_QV1_140_SERPMUD_B*  | CROMO2_3B         |
| MLC_QV2_140_SHOE_A*     | CROMO2_4A         |
| MLC_QV2_140_SHOE_B*     | CROMO2_4B         |
| PHL_PB_1_BULK           | PHL_1             |
| PHL_PB_2_GRN_BULK       | PHL_2A            |
| PHL_PB_2_MIX_BULK       | PHL_2B            |
| PHL_PB_2_RED_BULK       | PHL_2C            |
| PHL_PB_3_BULK           | PHL_3             |
| PHL_PB_4_BULK           | PHL_4             |
| PHL_PB_5_BULK           | PHL_5             |
| Empty sample holder     | ESH               |

* ‘A’ samples are the harder residue left after vibrating the samples in water; ‘B’ samples are the clay minerals suspended in the water during vibration. Both A and B samples were oven-dried at 60°C.
Figure A6: XRD diffractograms for sample HLSC_4 (a) with background subtracted and (b) peak d-spacing numbers and mineral diffraction patterns identified (serpentine, garnet, magnetite/spinel, chlorite, and possibly brucite) using XPowder.
Figure A7: XRD diffractograms for sample HLSC_2 chrysotile raw file without background subtraction. Peak locations probably indicate serpentine, spinel group minerals, and possibly other minerals.
Figure A8: XRD diffractograms for sample 309_84 (a) with background subtracted and (b) peak d-spacing numbers and mineral diffraction patterns identified (serpentine, pyroxene, chlorite, and calcite) using XPowder.
Figure A9: XRD diffractograms for sample 309_105_B (a) with background subtracted and (b) peak d-spacing numbers and mineral diffraction patterns identified (serpentine, magnetite/spinel, chlorite, and possibly olivine) using XPowder.
Figure A10: Stacked XRD diffractograms for samples CROMO1_1_B, CROMO1_1_A, CROMO1_2_CB, CROMO1_2_AC, CROMO1_2_AB, and CROMO1_2_AA
Figure A11: XRD diffractograms for samples CROMO1_1_A (a) with background subtracted and (b) peak d-spacing numbers and mineral diffraction patterns identified (chlorite and amphiboles) using XPowder.
Figure A12: XRD diffractograms for sample CROMO1_1_B (a) with background subtracted and (b) peak d-spacing numbers and mineral diffraction patterns identified (chlorite and amphiboles) using XPowder.
Figure A13: XRD diffractograms for sample CROMO1_2_AA (a) with background subtracted and (b) peak d-spacing numbers and mineral diffraction patterns identified (chlorite and amphiboles) using XPowder.
Figure A14: XRD diffractograms for sample CROMO1_2_CA (a) with background subtracted and peak mineral diffraction patterns identified (b-amphiboles, c-chlorite, d-serpentine and maybe cordierite) using XPowder.
Figure A15: XRD diffractograms with peak d-spacing numbers for samples (a) CROMO2_1B and (b) CROMO2_3B.
Figure A16: XRD diffractograms with peak d-spacing numbers for samples (a) CROMO2_4B and (b) PHL_2A.
Figure A17: XRD diffractogram for sample PHL_3 with background subtracted, peak d-spacing numbers, and mineral diffraction patterns identified (serpentine, olivine, spinel, pyroxene, and chlorite) using XPowder
Figure A18: XRD diffractograms with peak d-spacing numbers for sample PHL_4 (a) with background subtracted and (b) peak d-spacing numbers and mineral diffraction patterns identified (amphibole, pyroxene) using XPowder.
Table A6: Additional samples’ Fe concentrations averaged and normalized to DTS-1.

| Sample       | Run | Fe (ppm) | Fe Error (ppm) | Avg. (ppm) | Std Dev | Avg Error of 3 runs | Norm. factor (DTS-1) | Norm. Avg (ppm) |
|--------------|-----|----------|----------------|------------|---------|---------------------|----------------------|-----------------|
| 309_84       | 1   | 225056.98| 1270.07        | 221539     | 5948    | 1251                | 0.613                | 135803          |
|              | 2   | 224888.53| 1267.51        |            |         |                     |                      |                 |
|              | 3   | 214671.36| 1215.55        |            |         |                     |                      |                 |
| 309_105_B    | 1   | 48973.15 | 462.79         | 59039      | 8827    | 552                 | 0.613                | 36191           |
|              | 2   | 62686.34 | 582.55         |            |         |                     |                      |                 |
|              | 3   | 65457.8  | 611.89         |            |         |                     |                      |                 |
| CROMO1_1_A   | 1   | 80662.95 | 702.97         | 72875      | 11914   | 1089                | 0.613                | 44672           |
|              | 2   | 59160.3  | 521.08         |            |         |                     |                      |                 |
|              | 3   | 78801.42 | 688.07         |            |         |                     |                      |                 |
| CROMO1_1_B   | 1   | 116188.96| 1092.01        | 116675     | 3584    | 1089                | 0.613                | 71522           |
|              | 2   | 120477.61| 1105.82        |            |         |                     |                      |                 |
|              | 3   | 113358.7 | 1070.41        |            |         |                     |                      |                 |
| CROMO1_2_AA  | 1   | 53738.29 | 507.00         | 54678      | 1137    | 513                 | 0.613                | 33518           |
|              | 2   | 54353.24 | 507.37         |            |         |                     |                      |                 |
|              | 3   | 55942.11 | 524.35         |            |         |                     |                      |                 |
| CROMO1_2_AB  | 1   | 97748.95 | 801.78         | 98824      | 2342    | 807                 | 0.613                | 60579           |
|              | 2   | 97212.96 | 793.13         |            |         |                     |                      |                 |
|              | 3   | 101510.9 | 825.13         |            |         |                     |                      |                 |
| CROMO1_2_AC  | 1   | 91002.48 | 702.93         | 87714      | 3743    | 680                 | 0.613                | 53768           |
|              | 2   | 88496.77 | 686.92         |            |         |                     |                      |                 |
|              | 3   | 83641.25 | 650.70         |            |         |                     |                      |                 |
| CROMO1_2_CA  | 1   | 88302.38 | 752.58         | 89281      | 3076    | 767                 | 0.613                | 54729           |
|              | 2   | 86812.97 | 749.12         |            |         |                     |                      |                 |
|              | 3   | 92726.28 | 798.86         |            |         |                     |                      |                 |
| CROMO1_2_CB  | 1   | 110297.95| 1019.36        | 115318     | 9048    | 1079                | 0.613                | 70690           |
|              | 2   | 109892.79| 1039.11        |            |         |                     |                      |                 |
|              | 3   | 125762.21| 1178.53        |            |         |                     |                      |                 |
| CROMO2_1B    | 1   | 69066.38 | 724.97         | 72767      | 3347    | 753                 | 0.613                | 44606           |
|              | 2   | 75582.87 | 780.68         |            |         |                     |                      |                 |
|              | 3   | 73652.82 | 753.47         |            |         |                     |                      |                 |
| CROMO2_3B    | 1   | 134003.28| 1149.10        | 136339     | 9007    | 1187                | 0.613                | 83576           |
|              | 2   | 128730.48| 1109.87        |            |         |                     |                      |                 |
|              | 3   | 146283.61| 1301.87        |            |         |                     |                      |                 |
| CROMO2_4B    | 1   | 119009.69| 1025.93        | 132135     | 13883   | 1157                | 0.613                | 80999           |
|              | 2   | 130727.7 | 1141.79        |            |         |                     |                      |                 |
|              | 3   | 146668.91| 1302.27        |            |         |                     |                      |                 |
| PHL_2A       | 1   | 59311.35 | 529.75         | 54264      | 4731    | 485                 | 0.613                | 33264           |
|              | 2   | 49929.81 | 448.40         |            |         |                     |                      |                 |
|              | 3   | 53550.11 | 476.96         |            |         |                     |                      |                 |
| PHL_2C       | 1   | 78372.31 | 619.80         | 66184      | 17951   | 529                 | 0.613                | 40571           |
|              | 2   | 74610.47 | 592.38         |            |         |                     |                      |                 |
|              | 3   | 45569.93 | 374.98         |            |         |                     |                      |                 |
Table A6: continued

| Sample   | Run | Fe (ppm) | Fe Error (ppm) | Avg. (ppm) | Std Dev | Avg Error of 3 runs | Norm. factor (DTS-1) | Norm. Avg (ppm) |
|----------|-----|----------|----------------|------------|---------|---------------------|----------------------|-----------------|
| PHL_4    | 1   | 50564.68 | 507.16         | 50585      | 385     | 510                 | 0.613                | 31009           |
|          | 2   | 50980.34 | 517.53         |            |         |                     |                      |                 |
|          | 3   | 50210.2  | 504.86         |            |         |                     |                      |                 |
| HLSC_4   | 1   | 72466.3  | 614.58         | 71320      | 10220   | 597                 | 0.613                | 43719           |
|          | 2   | 60575.23 | 521.90         |            |         |                     |                      |                 |
|          | 3   | 80918.5  | 654.09         |            |         |                     |                      |                 |
| ESH      | 1   | 408.6    | 128.14         | 278        | 115     | 100                 | 0.613                | 170             |
|          | 2   | 196.51   | 84.89          |            |         |                     |                      |                 |
|          | 3   | 227.71   | 87.57          |            |         |                     |                      |                 |

Empty sample holder (ESH)
Table A7: Normalized average Fe concentration in ppm and FeO wt%.

| Sample name     | Fe avg. normalized concentration (ppm) | Fe avg. normalized concentration (FeO wt%) |
|-----------------|----------------------------------------|--------------------------------------------|
| HLSC_1          | 28741                                  | 3.7                                        |
| 167_238         | 29910                                  | 3.8                                        |
| 309_105_A       | 31705                                  | 4.1                                        |
| 309_105_B       | 36191                                  | 4.7                                        |
| 309_150         | 34651                                  | 4.5                                        |
| 309_84          | 135803                                 | 17.5                                       |
| 313_210         | 50673                                  | 6.5                                        |
| 313_318         | 32835                                  | 4.2                                        |
| 313_329         | 41989                                  | 5.4                                        |
| 313_356         | 37335                                  | 4.8                                        |
| CROMO1_1_A      | 44672                                  | 5.7                                        |
| CROMO1_1_B      | 71522                                  | 9.2                                        |
| CROMO1_2_AA     | 33518                                  | 4.3                                        |
| CROMO1_2_AB     | 60579                                  | 7.8                                        |
| CROMO1_2_AC     | 53768                                  | 6.9                                        |
| CROMO1_2_CA     | 54729                                  | 7.0                                        |
| CROMO1_2_CB     | 70690                                  | 9.1                                        |
| CROMO2_1A       | 30803                                  | 4.0                                        |
| CROMO2_1B       | 44606                                  | 5.7                                        |
| CROMO2_2        | 30966                                  | 4.0                                        |
| CROMO2_3A       | 37889                                  | 4.9                                        |
| CROMO2_3B       | 83576                                  | 10.8                                       |
| CROMO2_4A       | 30290                                  | 3.9                                        |
| CROMO2_4B       | 80999                                  | 10.4                                       |
| PHL_1           | 47976                                  | 6.2                                        |
| PHL_2A          | 33264                                  | 4.3                                        |
| PHL_2B          | 35777                                  | 4.6                                        |
| PHL_2C          | 40571                                  | 5.2                                        |
| PHL_3           | 47745                                  | 6.1                                        |
| PHL_4           | 31009                                  | 4.0                                        |
| HLSC_4          | 43719                                  | 5.6                                        |
| PHL_5           | 41969                                  | 5.4                                        |
Table A8: Samples raw elemental XRF data. Elements analyzed for include As, Ca, Co, Cr, Cu, Fe, Hg, K, Mn, Mo, Ni, Pb, Rb, S, Sb, Sc, Se, Sr, Th, Ti, V, Zn, and Zr. Additional elements below the limits of detection (<LOD): U, W, Ba, Cs, Te, Sn, Cd, Ag and Pd.

| SAMPLE       | Sample short name | Type | Duration (s) | Units | Mo  | Mo Error | Zr  | Zr Error | Sr  | Sr Error | Rb  | Rb Error |
|--------------|-------------------|------|--------------|-------|-----|----------|-----|----------|-----|----------|-----|----------|
| McL_81-167_238 to EOH_B22_B | 167_238 | SOIL | 208.70 | ppm  | < LOD | 4.48 | < LOD | 5.46 | 153.78 | 5.51 | < LOD | 2.27 |
| McL_81-167_238 to EOH_B22_B | 167_238 | SOIL | 243.97 | ppm  | < LOD | 4.74 | < LOD | 5.88 | 171.78 | 5.99 | < LOD | 2.51 |
| McL_81-167_238 to EOH_B22_B | 167_238 | SOIL | 244.33 | ppm  | < LOD | 4.42 | < LOD | 5.45 | 154.06 | 5.43 | < LOD | 2.18 |
| HLSC_1_A     | HLSC_1           | SOIL | 221.31 | ppm  | < LOD | 4.83 | < LOD | 6.03 | 177.18 | 6.21 | < LOD | 2.42 |
| HLSC_1_A     | HLSC_1           | SOIL | 207.46 | ppm  | < LOD | 4.83 | < LOD | 6.17 | 180.12 | 6.31 | < LOD | 2.45 |
| HLSC_4       | HLSC_4           | SOIL | 213.75 | ppm  | < LOD | 4.99 | < LOD | 6.25 | 183.16 | 6.36 | < LOD | 2.51 |
| HLSC_4       | HLSC_4           | SOIL | 205.99 | ppm  | < LOD | 5.53 | < LOD | 5.70 | < LOD | 2.84 | < LOD | 2.73 |
| HLSC_4       | HLSC_4           | SOIL | 205.52 | ppm  | < LOD | 4.95 | < LOD | 5.01 | < LOD | 2.49 | < LOD | 2.33 |
| HLSC_4       | HLSC_4           | SOIL | 228.54 | ppm  | < LOD | 5.60 | < LOD | 5.75 | < LOD | 2.85 | < LOD | 2.56 |
| McL_M81-313_210_B22_A3 | 313_210 | SOIL | 219.25 | ppm  | < LOD | 5.93 | < LOD | 6.63 | 69.24 | 4.80 | < LOD | 2.97 |
| McL_M81-313_210_B22_A3 | 313_210 | SOIL | 204.64 | ppm  | < LOD | 5.07 | < LOD | 6.01 | 66.03 | 4.27 | < LOD | 2.34 |
| McL_M81-313_210_B22_A3 | 313_210 | SOIL | 205.33 | ppm  | < LOD | 5.78 | < LOD | 6.64 | 61.47 | 4.50 | < LOD | 2.95 |
| McL_M81-313_329      | 313_329 | SOIL | 203.86 | ppm  | < LOD | 6.30 | < LOD | 6.57 | 39.55 | 3.96 | < LOD | 2.87 |
| McL_M81-313_329      | 313_329 | SOIL | 202.94 | ppm  | < LOD | 6.33 | < LOD | 6.39 | 41.89 | 4.09 | < LOD | 2.82 |
| McL_M81-313_329      | 313_329 | SOIL | 203.45 | ppm  | < LOD | 5.85 | < LOD | 6.11 | 37.01 | 3.70 | < LOD | 2.73 |
| McL_M81-313_356-356.6_B38_B | 313_356 | SOIL | 210.15 | ppm  | < LOD | 6.22 | < LOD | 6.42 | 44.53 | 4.22 | < LOD | 3.06 |
| McL_M81-313_356-356.6_B38_B | 313_356 | SOIL | 204.20 | ppm  | < LOD | 5.50 | < LOD | 5.84 | 44.22 | 3.82 | < LOD | 2.61 |
| McL_M81-313_356-356.6_B38_B | 313_356 | SOIL | 204.29 | ppm  | < LOD | 5.03 | < LOD | 5.30 | 37.84 | 3.36 | < LOD | 2.50 |
| McL_M81-313_318_B34_B | 313_318 | SOIL | 203.64 | ppm  | < LOD | 5.12 | < LOD | 5.24 | 36.70 | 3.35 | < LOD | 2.53 |
| McL_M81-313_318_B34_B | 313_318 | SOIL | 203.81 | ppm  | < LOD | 5.11 | < LOD | 5.73 | 41.44 | 3.68 | < LOD | 2.59 |
| McL_M81-313_318_B34_B | 313_318 | SOIL | 202.57 | ppm  | < LOD | 5.25 | < LOD | 5.45 | 34.98 | 3.31 | < LOD | 2.49 |
| McL_M81-309_105_B11_B2 | 309_105_B | SOIL | 202.69 | ppm  | < LOD | 4.92 | < LOD | 5.03 | 3.88 | 1.92 | < LOD | 2.25 |
| McL_M81-309_105_B11_B2 | 309_105_B | SOIL | 203.18 | ppm  | < LOD | 5.67 | < LOD | 6.08 | < LOD | 3.21 | < LOD | 2.73 |
| McL_M81-309_105_B11_B2 | 309_105_B | SOIL | 203.16 | ppm  | < LOD | 5.83 | < LOD | 6.14 | 6.97 | 2.42 | < LOD | 2.78 |
| McL_M81-309_105_B11_B1 | 309_105_A | SOIL | 217.46 | ppm  | < LOD | 4.69 | < LOD | 4.61 | 10.21 | 2.12 | < LOD | 2.15 |
| McL_M81-309_105_B11_B1 | 309_105_A | SOIL | 202.94 | ppm  | < LOD | 4.92 | < LOD | 5.07 | 8.57 | 2.15 | < LOD | 2.17 |
| McL_M81-309_105_B11_B1 | 309_105_A | SOIL | 202.41 | ppm  | < LOD | 4.73 | < LOD | 4.74 | 7.12 | 2.03 | < LOD | 2.20 |
| SAMPLE                        | Sample short name | Type | Duration (s) | Units | Mo  | Mo Error | Zr  | Zr Error | Sr  | Sr Error | Rb  | Rb Error |
|-------------------------------|-------------------|------|--------------|-------|-----|----------|-----|----------|-----|----------|-----|----------|
| McL_M81-309_150_B15_A        | 309_150           | SOIL | 202.48       | ppm   | < LOD | 5.05     | < LOD | 5.09     | 16.11 | 2.54     | < LOD | 2.22     |
| McL_M81-309_150_B15_A        | 309_150           | SOIL | 202.19       | ppm   | < LOD | 5.46     | < LOD | 5.33     | 16.93 | 2.72     | < LOD | 2.58     |
| McL_M81-309_150_B15_A        | 309_150           | SOIL | 202.17       | ppm   | < LOD | 4.99     | < LOD | 4.75     | 11.45 | 2.29     | < LOD | 2.27     |
| McL_M81-309_84_B8_A1         | 309_84            | SOIL | 202.26       | ppm   | < LOD | 6.61     | 96.96 | 7.79     | 44.44 | 4.53     | 8.96  | 3.04     |
| McL_M81-309_84_B8_A1         | 309_84            | SOIL | 203.76       | ppm   | < LOD | 6.62     | 96.01 | 7.79     | 47.81 | 4.66     | 8.80  | 2.96     |
| McL_M81-309_84_B8_A1         | 309_84            | SOIL | 203.67       | ppm   | < LOD | 6.50     | 99.03 | 7.68     | 43.76 | 4.42     | 7.42  | 2.97     |
| Empty sample holder           | ESH               | SOIL | 202.11       | ppm   | < LOD | 13.82    | < LOD | 12.64    | < LOD | 7.54     | < LOD | 6.98     |
| Empty sample holder           | ESH               | SOIL | 205.11       | ppm   | < LOD | 11.04    | < LOD | 10.59    | < LOD | 6.20     | < LOD | 5.82     |
| CSW1_28a_hard                 | CROMO1_2_AC       | SOIL | 203.07       | ppm   | < LOD | 10.91    | < LOD | 10.78    | < LOD | 6.02     | < LOD | 6.11     |
| CSW1_28a_hard                 | CROMO1_2_AC       | SOIL | 202.68       | ppm   | < LOD | 5.39     | < LOD | 7.03     | 130.29 | 6.16     | < LOD | 3.24     |
| CSW1_28a_hard                 | CROMO1_2_AC       | SOIL | 202.35       | ppm   | < LOD | 5.33     | < LOD | 7.07     | 129.26 | 6.08     | < LOD | 3.28     |
| CSW1_28a_CLAY_A               | CROMO1_2_AA       | SOIL | 203.70       | ppm   | < LOD | 5.20     | 12.92 | 4.89     | 124.57 | 5.82     | 3.67  | 2.14     |
| CSW1_28a_CLAY_A               | CROMO1_2_AA       | SOIL | 202.72       | ppm   | < LOD | 5.07     | < LOD | 6.52     | 119.70 | 5.52     | < LOD | 2.33     |
| CSW1_28a_CLAY_A               | CROMO1_2_AA       | SOIL | 203.22       | ppm   | < LOD | 5.13     | < LOD | 6.88     | 124.85 | 5.74     | < LOD | 2.70     |
| CSW1_28a_CLAY_B               | CROMO1_2_AB       | SOIL | 202.09       | ppm   | < LOD | 6.41     | < LOD | 9.00     | 225.43 | 8.75     | < LOD | 3.39     |
| CSW1_28a_CLAY_B               | CROMO1_2_AB       | SOIL | 202.72       | ppm   | < LOD | 6.44     | < LOD | 8.84     | 229.80 | 8.76     | < LOD | 3.35     |
| CSW1_27/28_SHOE?_A            | CROMO1_1_A        | SOIL | 202.40       | ppm   | < LOD | 6.45     | < LOD | 9.03     | 232.53 | 8.97     | < LOD | 3.31     |
| CSW1_27/28_SHOE?_A            | CROMO1_1_A        | SOIL | 202.70       | ppm   | < LOD | 6.14     | 20.76 | 6.08     | 200.68 | 7.99     | 6.49  | 2.60     |
| CSW1_27/28_SHOE?_A            | CROMO1_1_A        | SOIL | 202.50       | ppm   | < LOD | 4.91     | 18.15 | 4.93     | 160.55 | 6.22     | 4.30  | 2.04     |
| CSW1_27/28_SHOE?_B            | CROMO1_1_B        | SOIL | 202.61       | ppm   | < LOD | 6.02     | 17.44 | 5.91     | 201.57 | 7.93     | 5.51  | 2.62     |
| CSW1_27/28_SHOE?_B            | CROMO1_1_B        | SOIL | 202.83       | ppm   | < LOD | 8.61     | < LOD | 11.39    | 207.32 | 10.54    | < LOD | 5.23     |
| CSW1_27/28_SHOE?_B            | CROMO1_1_B        | SOIL | 208.08       | ppm   | < LOD | 8.64     | < LOD | 11.45    | 194.11 | 10.17    | < LOD | 5.14     |
| CSW1_27/28_SHOE?_B            | CROMO1_1_B        | SOIL | 203.42       | ppm   | < LOD | 8.60     | < LOD | 11.44    | 207.37 | 10.45    | 7.05  | 3.56     |
| Sample          | Sample short name | Type | Duration (s) | Units | Mo  | Mo Error | Zr  | Zr Error | Sr  | Sr Error | Rb  | Rb Error |
|-----------------|-------------------|------|--------------|-------|-----|----------|-----|----------|-----|----------|-----|----------|
| CSW1_28c_A      | CROMO1_2_CA       | SOIL | 202.04       | ppm   | < LOD | 6.26     | < LOD | 8.73     | 185.00 | 7.87    | < LOD | 3.43     |
| CSW1_28c_A      | CROMO1_2_CA       | SOIL | 201.72       | ppm   | < LOD | 6.44     | 10.66 | 5.91     | 184.69 | 7.89    | < LOD | 3.57     |
| CSW1_28c_A      | CROMO1_2_CA       | SOIL | 201.77       | ppm   | < LOD | 6.54     | 20.21 | 6.32     | 178.74 | 8.02    | < LOD | 3.62     |
| CSW1_28c_B      | CROMO1_2_CB       | SOIL | 203.87       | ppm   | < LOD | 8.13     | < LOD | 10.80    | 228.04 | 10.54   | < LOD | 4.43     |
| CSW1_28c_B      | CROMO1_2_CB       | SOIL | 201.59       | ppm   | < LOD | 8.27     | < LOD | 11.01    | 227.66 | 10.77   | < LOD | 4.76     |
| CSW1_28c_B      | CROMO1_2_CB       | SOIL | 202.28       | ppm   | 9.24  | 6.05     | < LOD | 11.95    | 239.25 | 11.69   | < LOD | 4.79     |
| MLC_QV2_140_SHOE_A | CROMO2_4A       | SOIL | 202.47       | ppm   | < LOD | 5.16     | < LOD | 4.97     | 8.23   | 2.19    | < LOD | 2.48     |
| MLC_QV2_140_SHOE_A | CROMO2_4A       | SOIL | 202.78       | ppm   | < LOD | 4.82     | < LOD | 4.51     | 7.30   | 2.04    | < LOD | 2.04     |
| MLC_QV2_140_SHOE_B | CROMO2_4B       | SOIL | 202.34       | ppm   | 9.02  | 5.31     | < LOD | 7.71     | 21.30  | 3.95    | < LOD | 3.93     |
| MLC_QV2_140_SHOE_B | CROMO2_4B       | SOIL | 202.49       | ppm   | < LOD | 8.38     | < LOD | 8.36     | 17.64  | 4.03    | < LOD | 4.26     |
| MLC_QV2_140_SHOE_B | CROMO2_4B       | SOIL | 202.72       | ppm   | < LOD | 8.99     | < LOD | 9.50     | 21.67  | 4.64    | < LOD | 4.39     |
| MLC_QV1_140_Mdkgrn | CROMO2_2       | SOIL | 202.68       | ppm   | < LOD | 4.72     | < LOD | 4.78     | 18.73  | 2.54    | < LOD | 2.20     |
| MLC_QV1_140_Mdkgrn | CROMO2_2       | SOIL | 204.20       | ppm   | < LOD | 5.19     | < LOD | 5.02     | 20.31  | 2.73    | < LOD | 2.28     |
| MLC_QV1_140_Mdkgrn | CROMO2_2       | SOIL | 203.48       | ppm   | < LOD | 5.05     | < LOD | 4.79     | 12.10  | 2.37    | < LOD | 2.46     |
| MLC_QV1_140_SERPMUD_A | CROMO2_3A     | SOIL | 202.06       | ppm   | < LOD | 5.88     | 19.86 | 4.87     | 40.29  | 3.83    | 6.05  | 2.35     |
| MLC_QV1_140_SERPMUD_A | CROMO2_3A     | SOIL | 202.22       | ppm   | < LOD | 4.60     | 7.65  | 3.63     | 30.80  | 2.90    | 4.65  | 1.86     |
| MLC_QV1_140_SERPMUD_B | CROMO2_3B     | SOIL | 204.18       | ppm   | < LOD | 8.35     | 27.97 | 7.08     | 47.86  | 5.54    | 6.95  | 3.51     |
| MLC_QV1_140_SERPMUD_B | CROMO2_3B     | SOIL | 202.41       | ppm   | 8.08  | 15.77    | 6.51  | 45.84    | 5.33   | 8.32    | 3.54  | 3.54     |
| MLC_QV1_140_M-BMIX_A | CROMO2_1A     | SOIL | 202.41       | ppm   | < LOD | 8.97     | 21.87 | 7.46     | 43.81  | 5.80    | 6.57  | 3.93     |
| MLC_QV1_140_M-BMIX_A | CROMO2_1A     | SOIL | 203.12       | ppm   | < LOD | 5.21     | < LOD | 5.15     | 8.28   | 2.22    | < LOD | 2.57     |
| MLC_QV1_140_M-BMIX_B | CROMO2_1B     | SOIL | 201.84       | ppm   | < LOD | 5.40     | < LOD | 5.50     | 9.66   | 2.38    | < LOD | 2.53     |
| MLC_QV1_140_M-BMIX_B | CROMO2_1B     | SOIL | 202.15       | ppm   | < LOD | 6.95     | < LOD | 6.84     | 5.30   | 2.73    | < LOD | 3.46     |
| MLC_QV1_140_M-BMIX_B | CROMO2_1B     | SOIL | 202.67       | ppm   | < LOD | 7.31     | < LOD | 7.12     | 5.33   | 2.78    | < LOD | 3.22     |
| MLC_QV1_140_M-BMIX_B | CROMO2_1B     | SOIL | 201.74       | ppm   | < LOD | 7.04     | < LOD | 7.22     | 6.63   | 2.80    | < LOD | 3.38     |

Table A8: continued
| SAMPLE               | Sample short name | Type | Duration (s) | Units | Mo   | Mo Error | Zr   | Zr Error | Sr   | Sr Error | Rb  | Rb Error |
|----------------------|-------------------|------|--------------|-------|------|----------|------|----------|------|----------|-----|----------|
| PHL_PB_1_BULK        | PHL_1             | SOIL | 202.49       | ppm   | < LOD|          | 5.07 | < LOD    | 4.66 | < LOD    | 2.65| < LOD    |
| PHL_PB_1_BULK        | PHL_1             | SOIL | 202.71       | ppm   | < LOD|          | 4.94 | < LOD    | 4.83 | < LOD    | 2.59| < LOD    |
| PHL_PB_1_BULK        | PHL_1             | SOIL | 214.89       | ppm   | < LOD|          | 4.57 | < LOD    | 4.45 | < LOD    | 2.29| < LOD    |
| PHL_PB_2_MIX_BULK    | PHL_2B            | SOIL | 202.57       | ppm   | < LOD|          | 4.95 | < LOD    | 4.86 | < LOD    | 2.60| < LOD    |
| PHL_PB_2_MIX_BULK    | PHL_2B            | SOIL | 201.42       | ppm   | < LOD|          | 5.00 | < LOD    | 4.90 | < LOD    | 2.62| < LOD    |
| PHL_PB_2_MIX_BULK    | PHL_2B            | SOIL | 202.66       | ppm   | < LOD|          | 5.09 | < LOD    | 4.87 | < LOD    | 2.75| < LOD    |
| PHL_PB_2_MIX_BULK    | PHL_2B            | SOIL | 202.57       | ppm   | < LOD|          | 5.00 | < LOD    | 4.90 | < LOD    | 2.62| < LOD    |
| PHL_PB_2_MIX_BULK    | PHL_2B            | SOIL | 201.42       | ppm   | < LOD|          | 5.00 | < LOD    | 4.90 | < LOD    | 2.62| < LOD    |
| PHL_PB_2_MIX_BULK    | PHL_2B            | SOIL | 202.66       | ppm   | < LOD|          | 5.09 | < LOD    | 4.87 | < LOD    | 2.75| < LOD    |
| PHL_PB_2_MIX_BULK    | PHL_2B            | SOIL | 202.57       | ppm   | < LOD|          | 5.00 | < LOD    | 4.90 | < LOD    | 2.62| < LOD    |
| PHL_PB_2_MIX_BULK    | PHL_2B            | SOIL | 201.42       | ppm   | < LOD|          | 5.00 | < LOD    | 4.90 | < LOD    | 2.62| < LOD    |
| PHL_PB_2_MIX_BULK    | PHL_2B            | SOIL | 202.66       | ppm   | < LOD|          | 5.09 | < LOD    | 4.87 | < LOD    | 2.75| < LOD    |
| PHL_PB_2_MIX_BULK    | PHL_2B            | SOIL | 202.57       | ppm   | < LOD|          | 5.00 | < LOD    | 4.90 | < LOD    | 2.62| < LOD    |
| PHL_PB_2_MIX_BULK    | PHL_2B            | SOIL | 201.42       | ppm   | < LOD|          | 5.00 | < LOD    | 4.90 | < LOD    | 2.62| < LOD    |
Table A8: continued

| Sample  | Th   | Th Error | Pb   | Pb Error | Se   | Se Error | As   | As Error | Hg   | Hg Error | Zn   | Zn Error | Cu   | Cu Error |
|---------|------|----------|------|----------|------|----------|------|----------|------|----------|------|----------|------|----------|
| 167_238 | < LOD | 4.60     | < LOD | 6.13     | < LOD | 4.12     | < LOD | 5.13     | < LOD | 10.83    | < LOD | 13.38    | < LOD | 33.70    |
| 167_238 | < LOD | 5.22     | < LOD | 6.25     | < LOD | 4.07     | < LOD | 5.10     | < LOD | 11.83    | < LOD | 13.35    | < LOD | 35.84    |
| 167_238 | < LOD | 4.09     | < LOD | 6.46     | < LOD | 4.06     | < LOD | 5.15     | < LOD | 10.48    | < LOD | 13.12    | < LOD | 34.05    |
| HLSC_1  | < LOD | 5.47     | < LOD | 6.94     | < LOD | 4.45     | < LOD | 5.66     | < LOD | 11.93    | < LOD | 15.67    | < LOD | 34.02    |
| HLSC_1  | < LOD | 4.68     | < LOD | 7.08     | < LOD | 4.63     | < LOD | 5.89     | < LOD | 11.73    | < LOD | 16.19    | < LOD | 34.67    |
| HLSC_1  | < LOD | 4.88     | < LOD | 7.42     | < LOD | 4.94     | < LOD | 5.75     | < LOD | 12.22    | 17.77  | 11.45    | < LOD | 36.75    |
| HLSC_4  | < LOD | 5.48     | < LOD | 6.88     | < LOD | 5.08     | < LOD | 5.67     | < LOD | 13.05    | < LOD | 17.91    | < LOD | 41.58    |
| HLSC_4  | < LOD | 5.31     | < LOD | 6.81     | < LOD | 4.32     | < LOD | 5.56     | < LOD | 11.01    | < LOD | 15.17    | < LOD | 34.45    |
| HLSC_4  | < LOD | 5.88     | < LOD | 8.45     | < LOD | 5.37     | < LOD | 5.97     | < LOD | 13.90    | < LOD | 20.04    | < LOD | 43.36    |
| 313_210 | < LOD | 5.63     | < LOD | 8.26     | < LOD | 5.49     | < LOD | 6.28     | < LOD | 14.63    | < LOD | 22.86    | < LOD | 47.97    |
| 313_210 | < LOD | 5.33     | < LOD | 7.81     | < LOD | 4.42     | < LOD | 5.65     | < LOD | 11.87    | < LOD | 18.04    | < LOD | 35.98    |
| 313_210 | < LOD | 6.75     | < LOD | 7.83     | < LOD | 5.64     | < LOD | 6.11     | < LOD | 13.85    | < LOD | 20.67    | < LOD | 43.44    |
| 313_329 | < LOD | 6.67     | < LOD | 8.62     | < LOD | 5.90     | < LOD | 6.54     | < LOD | 14.41    | < LOD | 20.25    | < LOD | 44.27    |
| 313_329 | < LOD | 5.42     | < LOD | 8.66     | < LOD | 5.84     | < LOD | 6.74     | < LOD | 14.63    | < LOD | 21.11    | < LOD | 44.17    |
| 313_329 | < LOD | 5.99     | < LOD | 7.27     | < LOD | 5.25     | < LOD | 5.66     | < LOD | 12.44    | < LOD | 19.21    | < LOD | 40.92    |
| 313_356 | < LOD | 6.02     | < LOD | 8.25     | < LOD | 6.06     | < LOD | 6.37     | < LOD | 16.66    | < LOD | 21.98    | < LOD | 51.66    |
| 313_356 | < LOD | 5.69     | < LOD | 8.11     | < LOD | 5.11     | < LOD | 5.79     | < LOD | 13.75    | < LOD | 18.46    | < LOD | 41.69    |
| 313_356 | < LOD | 5.05     | < LOD | 7.43     | < LOD | 4.49     | < LOD | 5.61     | < LOD | 11.69    | < LOD | 15.89    | < LOD | 35.67    |
| 313_318 | < LOD | 5.25     | < LOD | 6.91     | < LOD | 4.67     | < LOD | 5.18     | < LOD | 11.82    | 40.35  | 12.77    | < LOD | 37.26    |
| 313_318 | < LOD | 5.50     | < LOD | 7.58     | < LOD | 5.08     | < LOD | 6.17     | < LOD | 13.13    | 27.51  | 13.41    | 53.19  | 29.90    |
| 313_318 | < LOD | 4.75     | < LOD | 6.50     | < LOD | 4.72     | < LOD | 5.26     | < LOD | 12.33    | 26.04  | 12.31    | < LOD | 38.27    |
| 309_105_B| < LOD | 4.46     | < LOD | 7.00     | < LOD | 4.69     | 21.23  | 5.04     | < LOD | 13.73    | 43.41  | 13.01    | < LOD | 41.37    |
| 309_105_B| < LOD | 5.77     | < LOD | 7.55     | < LOD | 5.59     | 32.88  | 6.20     | 20.99  | 11.13    | 37.56  | 14.89    | < LOD | 50.01    |
| 309_105_B| < LOD | 6.44     | < LOD | 7.74     | < LOD | 6.10     | 32.66  | 6.37     | < LOD | 18.05    | 26.41  | 15.39    | < LOD | 53.55    |
| 309_105_A| < LOD | 4.62     | < LOD | 6.48     | < LOD | 4.27     | 22.32  | 4.78     | < LOD | 12.63    | 25.49  | 11.51    | < LOD | 37.13    |
| 309_105_A| < LOD | 5.03     | < LOD | 6.96     | < LOD | 4.63     | 24.44  | 5.17     | < LOD | 12.96    | 27.35  | 12.09    | < LOD | 40.14    |
| 309_105_A| < LOD | 4.39     | < LOD | 7.04     | < LOD | 4.33     | 17.30  | 4.78     | < LOD | 12.56    | 41.62  | 12.33    | < LOD | 36.23    |
Table A8: continued

| Sample  | Th      | Th Error | Pb      | Pb Error | Se      | Se Error | As      | As Error | Hg      | Hg Error | Zn      | Zn Error | Cu      | Cu Error |
|---------|---------|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|----------|---------|----------|
| 309_150 | < LOD   | 4.97     | < LOD   | 6.56     | < LOD   | 4.44     | < LOD   | 5.43     | < LOD   | 11.82    | 23.41   | 11.93    | < LOD   | 36.22    |
| 309_150 | < LOD   | 5.20     | < LOD   | 8.11     | < LOD   | 4.71     | < LOD   | 5.94     | < LOD   | 12.87    | 33.20   | 13.53    | < LOD   | 39.14    |
| 309_150 | < LOD   | 6.80     | < LOD   | 9.78     | < LOD   | 6.28     | < LOD   | 8.26     | < LOD   | 14.47    | 112.58  | 26.10    | 175.11  | 36.96    |
| 309_84  | < LOD   | 7.70     | < LOD   | 9.81     | < LOD   | 6.25     | 49.36   | 8.69     | < LOD   | 14.88    | 141.25  | 27.23    | 186.84  | 37.51    |
| 309_84  | < LOD   | 7.11     | < LOD   | 9.24     | < LOD   | 5.97     | 45.60   | 8.20     | < LOD   | 13.96    | 139.79  | 26.28    | 180.32  | 36.05    |
| ESH     | < LOD   | 16.74    | < LOD   | 25.86    | < LOD   | 19.53    | < LOD   | 19.03    | < LOD   | 45.36    | < LOD   | 54.90    | < LOD   | 125.35   |
| ESH     | 22.44   | 10.71    | 23.06   | 14.10    | < LOD   | 13.71    | < LOD   | 15.17    | < LOD   | 29.85    | 49.10   | 26.99    | < LOD   | 96.80    |
| CROMO1_2_AC | < LOD   | 14.17    | < LOD   | 20.15    | 16.26   | 9.63     | < LOD   | 15.60    | < LOD   | 30.09    | < LOD   | 35.01    | < LOD   | 94.00    |
| CROMO1_2_AC | < LOD   | 5.75     | < LOD   | 7.50     | < LOD   | 4.93     | < LOD   | 5.61     | < LOD   | 10.65    | < LOD   | 20.88    | 57.12   | 24.85    |
| CROMO1_2_AC | < LOD   | 5.25     | < LOD   | 6.91     | < LOD   | 4.68     | < LOD   | 5.63     | < LOD   | 10.17    | 21.48   | 13.87    | 85.50   | 25.70    |
| CROMO1_2_AC | < LOD   | 5.48     | < LOD   | 7.43     | < LOD   | 4.33     | < LOD   | 5.85     | < LOD   | 9.95     | < LOD   | 19.78    | 62.67   | 23.59    |
| CROMO1_2_AA | < LOD   | 5.17     | < LOD   | 8.08     | < LOD   | 4.57     | < LOD   | 5.99     | < LOD   | 10.84    | 20.26   | 11.69    | < LOD   | 33.40    |
| CROMO1_2_AA | < LOD   | 4.84     | < LOD   | 7.25     | < LOD   | 4.39     | < LOD   | 6.17     | < LOD   | 11.44    | < LOD   | 16.73    | < LOD   | 32.98    |
| CROMO1_2_AA | < LOD   | 5.75     | < LOD   | 8.29     | < LOD   | 4.40     | < LOD   | 6.35     | < LOD   | 11.31    | 29.66   | 12.78    | < LOD   | 36.00    |
| CROMO1_2_AB | < LOD   | 6.48     | < LOD   | 9.12     | < LOD   | 6.21     | < LOD   | 7.31     | < LOD   | 15.31    | < LOD   | 23.53    | < LOD   | 51.00    |
| CROMO1_2_AB | < LOD   | 6.64     | < LOD   | 9.62     | < LOD   | 5.93     | < LOD   | 7.15     | < LOD   | 16.07    | < LOD   | 23.20    | < LOD   | 47.40    |
| CROMO1_2_AB | < LOD   | 6.82     | < LOD   | 9.70     | < LOD   | 6.13     | < LOD   | 7.72     | < LOD   | 16.40    | < LOD   | 23.66    | < LOD   | 47.97    |
| CROMO1_1_A | < LOD   | 6.91     | < LOD   | 8.61     | < LOD   | 5.10     | < LOD   | 6.54     | < LOD   | 12.33    | < LOD   | 19.09    | < LOD   | 34.39    |
| CROMO1_1_A | < LOD   | 4.85     | < LOD   | 6.86     | < LOD   | 4.30     | < LOD   | 5.59     | < LOD   | 8.68     | < LOD   | 13.76    | < LOD   | 26.86    |
| CROMO1_1_A | < LOD   | 5.79     | 14.29   | 6.75     | < LOD   | 5.14     | < LOD   | 7.16     | < LOD   | 11.73    | < LOD   | 18.01    | < LOD   | 33.37    |
| CROMO1_1_B | < LOD   | 9.00     | 12.65   | 8.84     | < LOD   | 10.05    | < LOD   | 20.09    | < LOD   | 30.76    | < LOD   | 58.88    | < LOD   | 60.12    |
| CROMO1_1_B | < LOD   | 9.49     | 13.03   | 9.15     | < LOD   | 9.71     | < LOD   | 21.34    | < LOD   | 33.20    | < LOD   | 60.12    | < LOD   | 60.12    |
| CROMO1_1_B | < LOD   | 9.67     | 11.01   | 8.36     | < LOD   | 9.65     | < LOD   | 20.85    | < LOD   | 31.31    | < LOD   | 61.08    | < LOD   | 61.08    |
| Sample    | Th  | Th Error | Pb | Pb Error | Se  | Se Error | As  | As Error | Hg  | Hg Error | Zn  | Zn Error | Cu  | Cu Error |
|-----------|-----|----------|----|----------|-----|----------|-----|----------|-----|----------|-----|----------|-----|----------|
| CROMO1_2_CA | < LOD | 7.43 | < LOD | 8.93 | < LOD | 5.83 | < LOD | 7.09 | < LOD | 12.51 | < LOD | 21.15 | < LOD | 34.07 |
| CROMO1_2_CA | < LOD | 7.37 | < LOD | 9.64 | < LOD | 6.22 | < LOD | 7.28 | < LOD | 12.49 | < LOD | 21.84 | < LOD | 36.77 |
| CROMO1_2_CA | < LOD | 6.66 | < LOD | 9.44 | < LOD | 6.21 | < LOD | 7.28 | < LOD | 12.95 | < LOD | 22.08 | < LOD | 36.84 |
| CROMO1_2_CB | < LOD | 9.59 | < LOD | 11.99 | < LOD | 7.90 | < LOD | 9.45 | < LOD | 18.34 | < LOD | 29.32 | < LOD | 53.68 |
| CROMO1_2_CB | < LOD | 8.13 | < LOD | 12.16 | < LOD | 8.99 | < LOD | 10.03 | < LOD | 20.27 | < LOD | 30.46 | < LOD | 57.97 |
| CROMO1_2_CB | < LOD | 9.22 | < LOD | 11.28 | < LOD | 9.93 | < LOD | 10.00 | < LOD | 21.24 | < LOD | 31.12 | < LOD | 64.45 |
| CROMO2_4A | < LOD | 5.21 | < LOD | 6.87 | < LOD | 4.58 | < LOD | 5.35 | < LOD | 13.26 | < LOD | 15.74 | < LOD | 40.59 |
| CROMO2_4A | < LOD | 4.79 | < LOD | 7.30 | < LOD | 4.34 | < LOD | 5.17 | < LOD | 11.90 | < LOD | 14.07 | < LOD | 36.27 |
| CROMO2_4A | < LOD | 4.61 | < LOD | 6.76 | < LOD | 4.24 | < LOD | 5.15 | < LOD | 11.65 | < LOD | 13.82 | < LOD | 37.20 |
| CROMO2_4B | < LOD | 8.06 | < LOD | 11.40 | < LOD | 8.37 | < LOD | 8.53 | < LOD | 22.69 | < LOD | 30.35 | < LOD | 70.75 |
| CROMO2_4B | < LOD | 9.12 | < LOD | 12.48 | < LOD | 9.15 | < LOD | 10.03 | < LOD | 26.03 | < LOD | 34.49 | < LOD | 76.67 |
| CROMO2_4B | < LOD | 9.03 | < LOD | 12.99 | 12.98 | 7.61 | < LOD | 10.24 | < LOD | 29.90 | < LOD | 38.43 | < LOD | 89.08 |
| CROMO2_2 | < LOD | 4.34 | < LOD | 6.97 | < LOD | 4.38 | < LOD | 4.96 | < LOD | 12.64 | < LOD | 13.56 | < LOD | 38.84 |
| CROMO2_2 | < LOD | 4.46 | < LOD | 6.61 | < LOD | 4.64 | < LOD | 5.34 | < LOD | 13.98 | < LOD | 16.18 | < LOD | 44.38 |
| CROMO2_2 | < LOD | 5.15 | < LOD | 7.34 | < LOD | 4.71 | < LOD | 5.29 | < LOD | 13.40 | < LOD | 15.40 | < LOD | 42.83 |
| CROMO2_3A | < LOD | 5.84 | < LOD | 8.23 | < LOD | 5.63 | < LOD | 6.68 | < LOD | 13.91 | 23.70 | 14.32 | < LOD | 44.62 |
| CROMO2_3A | < LOD | 4.53 | < LOD | 6.84 | < LOD | 4.19 | < LOD | 5.61 | < LOD | 10.18 | 23.71 | 10.69 | < LOD | 30.05 |
| CROMO2_3A | < LOD | 5.61 | < LOD | 7.15 | < LOD | 4.37 | < LOD | 5.63 | < LOD | 11.22 | < LOD | 16.70 | < LOD | 34.94 |
| CROMO2_3B | < LOD | 8.91 | < LOD | 12.52 | < LOD | 8.57 | < LOD | 9.95 | 29.55 | 15.92 | 88.83 | 26.88 | < LOD | 75.50 |
| CROMO2_3B | < LOD | 9.05 | < LOD | 12.63 | < LOD | 8.74 | < LOD | 10.44 | < LOD | 23.96 | 81.33 | 26.59 | < LOD | 72.00 |
| CROMO2_3B | < LOD | 8.78 | < LOD | 14.88 | < LOD | 10.82 | < LOD | 11.45 | < LOD | 28.24 | 51.21 | 28.79 | < LOD | 86.45 |
| CROMO2_3B | < LOD | 5.30 | < LOD | 6.75 | < LOD | 5.04 | < LOD | 5.40 | < LOD | 13.48 | < LOD | 17.39 | < LOD | 41.69 |
| CROMO2_3B | < LOD | 5.02 | < LOD | 7.92 | < LOD | 4.36 | < LOD | 5.56 | < LOD | 12.65 | < LOD | 15.25 | < LOD | 39.72 |
| CROMO2_3B | < LOD | 5.51 | < LOD | 7.58 | < LOD | 5.16 | < LOD | 5.72 | < LOD | 13.36 | < LOD | 16.17 | < LOD | 42.08 |
| CROMO2_1B | < LOD | 6.52 | < LOD | 9.90 | < LOD | 7.46 | < LOD | 7.99 | < LOD | 19.49 | < LOD | 24.36 | < LOD | 59.70 |
| CROMO2_1B | < LOD | 6.59 | < LOD | 10.46 | < LOD | 7.46 | < LOD | 8.45 | < LOD | 21.63 | < LOD | 24.79 | < LOD | 65.10 |
| CROMO2_1B | < LOD | 6.85 | < LOD | 10.75 | < LOD | 7.48 | < LOD | 7.88 | < LOD | 20.31 | < LOD | 24.85 | < LOD | 61.38 |
Table A8: continued

| Sample  | Th   | Th Error | Pb   | Pb Error | Se   | Se Error | As   | As Error | Hg   | Hg Error | Zn   | Zn Error | Cu   | Cu Error |
|---------|------|----------|------|----------|------|----------|------|----------|------|----------|------|----------|------|----------|
| PHL_1   | < LOD| 5.11     | < LOD| 6.99     | < LOD| 4.36     | < LOD| 5.13     | < LOD| 11.70    | < LOD| 18.14    | < LOD| 36.29    |
| PHL_1   | < LOD| 5.05     | < LOD| 7.04     | < LOD| 4.24     | < LOD| 5.45     | < LOD| 11.34    | < LOD| 17.29    | < LOD| 35.99    |
| PHL_1   | < LOD| 4.43     | < LOD| 6.50     | < LOD| 4.03     | < LOD| 4.74     | < LOD| 10.48    | < LOD| 16.78    | < LOD| 32.40    |
| PHL_2B  | < LOD| 4.85     | < LOD| 6.45     | < LOD| 4.39     | < LOD| 4.98     | < LOD| 11.28    | < LOD| 16.63    | < LOD| 57.51    |
| PHL_2B  | < LOD| 4.89     | < LOD| 6.60     | < LOD| 4.19     | < LOD| 4.77     | < LOD| 11.51    | < LOD| 16.23    | < LOD| 53.96    |
| PHL_2B  | < LOD| 4.98     | < LOD| 7.08     | < LOD| 4.54     | < LOD| 5.39     | < LOD| 11.10    | < LOD| 16.39    | < LOD| 62.91    |
| PHL_2B  | < LOD| 4.98     | < LOD| 7.18     | < LOD| 5.00     | < LOD| 5.64     | < LOD| 12.51    | < LOD| 17.65    | < LOD| 36.40    |
| PHL_2C  | < LOD| 5.13     | < LOD| 7.33     | < LOD| 4.63     | < LOD| 5.59     | < LOD| 11.86    | < LOD| 17.19    | < LOD| 37.50    |
| PHL_2C  | < LOD| 4.15     | < LOD| 5.15     | < LOD| 3.34     | < LOD| 3.98     | < LOD| 8.07     | < LOD| 11.79    | < LOD| 23.99    |
| PHL_2A  | < LOD| 4.59     | < LOD| 6.88     | < LOD| 4.58     | < LOD| 5.09     | < LOD| 11.75    | < LOD| 16.76    | < LOD| 86.12    |
| PHL_2A  | < LOD| 4.66     | < LOD| 6.05     | < LOD| 4.14     | < LOD| 4.82     | < LOD| 10.54    | < LOD| 14.73    | < LOD| 51.04    |
| PHL_2A  | < LOD| 4.78     | < LOD| 6.63     | < LOD| 4.12     | < LOD| 4.90     | < LOD| 11.24    | < LOD| 15.52    | < LOD| 72.82    |
| PHL_3   | < LOD| 5.39     | < LOD| 7.02     | < LOD| 5.06     | < LOD| 5.73     | < LOD| 12.94    | < LOD| 18.55    | < LOD| 41.02    |
| PHL_3   | < LOD| 5.09     | < LOD| 6.93     | < LOD| 4.47     | < LOD| 5.52     | < LOD| 12.53    | < LOD| 16.84    | < LOD| 38.14    |
| PHL_3   | < LOD| 6.08     | < LOD| 7.68     | < LOD| 5.30     | < LOD| 5.82     | < LOD| 13.69    | < LOD| 19.47    | < LOD| 43.66    |
| PHL_4   | < LOD| 5.46     | < LOD| 7.18     | < LOD| 4.55     | < LOD| 5.87     | < LOD| 10.20    | < LOD| 18.18    | < LOD| 348.63   |
| PHL_4   | < LOD| 5.94     | < LOD| 7.34     | < LOD| 4.82     | < LOD| 6.25     | < LOD| 10.37    | < LOD| 13.18    | < LOD| 358.54   |
| PHL_4   | < LOD| 6.13     | < LOD| 8.04     | < LOD| 4.70     | < LOD| 6.02     | < LOD| 10.34    | < LOD| 18.10    | < LOD| 374.58   |
| PHL_5   | < LOD| 5.03     | < LOD| 6.40     | < LOD| 4.26     | < LOD| 4.77     | < LOD| 10.81    | < LOD| 15.22    | < LOD| 32.71    |
| PHL_5   | < LOD| 4.28     | < LOD| 5.86     | < LOD| 4.12     | < LOD| 4.46     | < LOD| 10.53    | < LOD| 14.15    | < LOD| 33.58    |
| PHL_5   | < LOD| 5.15     | < LOD| 7.08     | < LOD| 4.06     | < LOD| 5.24     | < LOD| 11.00    | < LOD| 16.05    | < LOD| 33.31    |
Table A8: continued
Sample

170

167_238
167_238
167_238
HLSC_1
HLSC_1
HLSC_1
HLSC_4
HLSC_4
HLSC_4
313_210
313_210
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309_105_B
309_105_B
309_105_B
309_105_A
309_105_A
309_105_A

Ni
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3214.69
2442.97
2923.15
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5789.82
6155.90
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4085.77
4073.97

Ni
Error
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94.72
92.73
96.42
106.26
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113.58
119.01
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100.63
101.33
94.19
135.41
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96.24
99.59
111.34
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121.47
149.30
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108.24
113.18
110.30

Co
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219.96
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< LOD
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< LOD
< LOD
353.63
< LOD
270.22
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< LOD
< LOD
302.97
335.73
310.35
467.39
299.99
307.97
198.45

Co
Error
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132.66
120.94
128.24
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131.52
177.49
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188.54
311.55
247.86
198.19
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177.28
293.79
159.48
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234.72
143.45
135.38
168.99
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132.63
138.78
131.62

Fe
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47098.51
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Fe Error

Mn

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414.06
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438.63
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614.58
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687.13
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476.57
455.36

1331.67
1495.75
1227.17
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1450.29
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1331.50
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120.57

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1576.32
1564.19
1392.28
1395.20
1421.55
990.13
927.04
910.61
1458.91
1384.70
1372.99
3634.48
3556.75
3559.70
1111.61
1016.32
1065.65
4391.95
4230.49
4354.20

Cr
Error
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33.35
32.46
44.56
47.14
46.39
49.79
48.63
43.92
45.96
49.29
49.10
39.00
37.42
37.79
43.79
43.75
42.69
67.26
65.74
66.66
41.22
39.87
40.20
73.44
74.62
76.24

V
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< LOD
< LOD
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47.82
49.89
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< LOD
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V
Error
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36.93
29.22
30.23
30.54


| Sample   | Ni    | Ni Error | Co    | Co Error | Fe    | Fe Error | Mn    | Mn Error | Cr    | Cr Error | V    | V Error |
|----------|-------|----------|-------|----------|-------|----------|-------|----------|-------|----------|------|---------|
| 309_150  | 2703.41 | 96.50 | < LOD | 215.22 | 54727.32 | 498.42 | 994.61 | 121.21 | 2939.46 | 60.11 | 83.34 | 30.93 |
| 309_150  | 2889.50 | 105.20 | 337.20 | 160.80 | 61134.53 | 553.21 | 964.81 | 128.69 | 2889.03 | 60.26 | 75.84 | 29.79 |
| 309_150  | 2541.58 | 92.84 | < LOD | 211.23 | 53718.55 | 488.20 | 987.27 | 117.59 | 2825.78 | 58.97 | 82.96 | 29.90 |
| 309_84   | 148.18 | 65.73 | < LOD | 536.78 | 225056.98 | 1270.07 | 4678.70 | 270.79 | 295.94 | 49.87 | 582.32 | 103.13 |
| 309_84   | 150.69 | 67.15 | < LOD | 538.82 | 224888.53 | 1267.51 | 4457.99 | 264.96 | 284.90 | 47.50 | 589.07 | 97.41 |
| 309_84   | 126.08 | 63.40 | < LOD | 515.48 | 214671.36 | 1215.55 | 4414.56 | 257.70 | 218.22 | 45.50 | 448.94 | 96.39 |
| ESH      | < LOD | 187.95 | < LOD | 77.79 | 408.60 | 128.14 | < LOD | 153.28 | 13.21 | 8.28 | < LOD | 14.25 |
| ESH      | < LOD | 136.16 | < LOD | 54.54 | 196.51 | 84.89 | < LOD | 125.28 | < LOD | 12.30 | < LOD | 13.55 |
| ESH      | < LOD | 146.53 | < LOD | 66.70 | 227.71 | 87.57 | < LOD | 120.65 | < LOD | 12.60 | < LOD | 13.88 |
| CROMO1_2_AC | < LOD | 64.51 | < LOD | 300.04 | 91002.48 | 702.93 | 1699.55 | 145.11 | < LOD | 42.05 | 359.02 | 56.38 |
| CROMO1_2_AC | < LOD | 64.39 | < LOD | 295.44 | 88496.77 | 686.92 | 1562.83 | 139.14 | < LOD | 42.89 | 306.36 | 54.22 |
| CROMO1_2_AC | < LOD | 57.62 | < LOD | 277.02 | 83641.25 | 650.70 | 1520.65 | 133.73 | < LOD | 41.17 | 305.27 | 55.67 |
| CROMO1_2_AA | 1780.69 | 83.36 | < LOD | 218.26 | 53738.29 | 507.00 | 963.57 | 116.12 | 1531.57 | 48.18 | 114.72 | 35.33 |
| CROMO1_2_AA | 1729.61 | 82.26 | < LOD | 219.66 | 54353.24 | 507.37 | 951.29 | 114.94 | 1616.50 | 49.58 | 93.99 | 36.11 |
| CROMO1_2_AA | 1815.98 | 85.74 | 262.51 | 151.92 | 55942.11 | 524.35 | 973.41 | 123.40 | 1970.29 | 53.10 | 131.05 | 35.37 |
| CROMO1_2_AB | 3046.67 | 125.68 | < LOD | 345.26 | 97748.95 | 801.78 | 1376.59 | 165.22 | 2109.70 | 58.47 | 96.94 | 37.87 |
| CROMO1_2_AB | 3026.97 | 124.39 | < LOD | 342.24 | 97212.96 | 793.13 | 1292.00 | 161.72 | 2092.50 | 58.24 | 90.16 | 36.59 |
| CROMO1_2_AB | 3047.88 | 127.17 | < LOD | 354.77 | 101510.90 | 825.13 | 1493.67 | 173.73 | 2124.97 | 59.00 | 97.44 | 36.28 |
| CROMO1_1_A | < LOD | 68.19 | < LOD | 300.31 | 80662.95 | 702.97 | 1761.48 | 154.26 | < LOD | 33.88 | 166.88 | 41.36 |
| CROMO1_1_A | < LOD | 53.33 | < LOD | 220.84 | 59160.30 | 521.08 | 1236.31 | 113.37 | < LOD | 34.81 | 191.92 | 41.58 |
| CROMO1_1_A | < LOD | 65.74 | < LOD | 293.60 | 78801.42 | 688.07 | 1766.78 | 152.69 | < LOD | 34.32 | 156.65 | 40.88 |
| CROMO1_1_B | < LOD | 116.02 | < LOD | 454.88 | 116188.96 | 1092.01 | 2763.97 | 246.26 | < LOD | 32.47 | 129.57 | 35.82 |
| CROMO1_1_B | < LOD | 113.68 | < LOD | 461.79 | 120477.61 | 1105.82 | 2881.82 | 249.92 | 66.23 | 22.34 | 121.86 | 35.63 |
| CROMO1_1_B | 164.88 | 80.49 | < LOD | 452.58 | 113358.70 | 1070.41 | 2720.24 | 243.21 | 43.36 | 22.08 | 160.69 | 36.42 |
Table A8: continued

| Sample         | Ni  | Ni Error | Co  | Co Error | Fe  | Fe Error | Mn  | Mn Error | Cr  | Cr Error | V   | V Error |
|----------------|-----|----------|-----|----------|-----|----------|-----|----------|-----|----------|-----|---------|
| CROMO1_2_CA    | < LOD | 74.47 | < LOD | 323.36 | 88302.38 | 752.58 | 1922.24 | < LOD | 165.20 | < LOD | 34.59 | 172.09 | 41.65 |
| CROMO1_2_CA    | < LOD | 73.16 | < LOD | 322.22 | 86812.97 | 749.12 | 2089.01 | < LOD | 169.94 | < LOD | 35.99 | 184.11 | 41.48 |
| CROMO1_2_CA    | < LOD | 77.52 | < LOD | 341.55 | 92726.28 | 798.86 | 2047.86 | < LOD | 175.91 | < LOD | 35.22 | 212.81 | 41.66 |
| CROMO1_2_CB    | 392.55 | 81.99 | < LOD | 420.07 | 110297.95 | 1019.36 | 2532.72 | 229.70 | 161.84 | 25.03 | 130.18 | 35.67 |
| CROMO1_2_CB    | 289.43 | 81.63 | < LOD | 434.50 | 109892.79 | 1039.11 | 2586.39 | 235.22 | 174.84 | 24.89 | 128.43 | 34.47 |
| CROMO1_2_CB    | 331.24 | 90.38 | < LOD | 487.48 | 125762.21 | 1178.53 | 2860.96 | 263.62 | 168.69 | 25.04 | 143.31 | 35.70 |
| CROMO2_4A      | 4451.60 | 121.52 | 452.80 | 142.47 | 50800.18 | 483.10 | 648.93 | 95.99 | 561.95 | 30.47 | < LOD | 33.69 |
| CROMO2_4A      | 4107.47 | 111.42 | 210.64 | 131.63 | 49182.21 | 454.53 | 541.97 | 86.73 | 549.55 | 31.19 | < LOD | 35.20 |
| CROMO2_4A      | 4016.99 | 110.27 | 264.43 | 130.95 | 48254.96 | 449.99 | 522.42 | 87.07 | 770.91 | 33.87 | < LOD | 35.20 |
| CROMO2_4B      | 6630.28 | 206.33 | < LOD | 433.30 | 119009.69 | 1025.93 | 1134.67 | 173.47 | 257.44 | 26.02 | < LOD | 37.39 |
| CROMO2_4B      | 7505.56 | 233.52 | < LOD | 489.13 | 130727.70 | 1141.79 | 1181.14 | 190.39 | 321.03 | 26.49 | < LOD | 34.47 |
| CROMO2_4B      | 8186.73 | 262.21 | < LOD | 547.51 | 146668.91 | 1302.27 | 1390.38 | 219.02 | 306.31 | 25.96 | < LOD | 35.48 |
| CROMO2_4B      | 4824.22 | 119.55 | 308.86 | 129.44 | 46999.31 | 442.87 | 769.95 | 96.70 | 752.70 | 35.28 | 47.93 | 25.34 |
| CROMO2_4B      | 5554.99 | 134.65 | 386.05 | 145.49 | 53525.53 | 496.68 | 752.67 | 104.64 | 761.68 | 35.69 | < LOD | 38.29 |
| CROMO2_4B      | 5317.52 | 130.39 | 232.53 | 139.21 | 51019.72 | 480.18 | 713.58 | 102.07 | 792.77 | 35.73 | < LOD | 38.13 |
| CROMO2_3A      | 3781.32 | 126.12 | 373.79 | 189.22 | 75864.01 | 652.94 | 1397.20 | 154.75 | 2192.13 | 55.32 | < LOD | 50.02 |
| CROMO2_3A      | 2431.36 | 85.51 | 246.60 | 131.35 | 52121.28 | 453.27 | 1090.27 | 112.19 | 2285.62 | 57.41 | 67.18 | 34.68 |
| CROMO2_3A      | 2671.35 | 93.61 | < LOD | 215.40 | 57443.68 | 498.23 | 1055.18 | 118.69 | 1972.33 | 53.67 | 71.61 | 33.81 |
| CROMO2_3B      | 5515.54 | 201.58 | < LOD | 482.18 | 134003.28 | 1149.10 | 2001.84 | 232.71 | 980.44 | 39.73 | 74.19 | 32.69 |
| CROMO2_3B      | 5405.32 | 197.64 | < LOD | 475.09 | 128730.48 | 1109.87 | 1819.99 | 220.39 | 933.86 | 39.10 | < LOD | 47.05 |
| CROMO2_3B      | 5918.07 | 226.97 | < LOD | 544.64 | 146283.61 | 1301.87 | 2074.58 | 259.90 | 962.38 | 38.48 | 59.77 | 31.84 |
| CROMO2_1A      | 4047.89 | 121.96 | 338.93 | 148.86 | 51628.15 | 509.48 | 708.01 | 100.84 | 327.33 | 26.01 | < LOD | 32.91 |
| CROMO2_1A      | 3690.55 | 112.90 | 354.39 | 140.02 | 48556.89 | 477.83 | 777.45 | 98.93 | 269.99 | 25.22 | < LOD | 33.56 |
| CROMO2_1A      | 3904.00 | 121.09 | 530.16 | 150.54 | 50564.79 | 507.40 | 639.82 | 98.01 | 306.99 | 25.83 | < LOD | 34.29 |
| CROMO2_1B      | 5034.05 | 167.60 | < LOD | 310.29 | 69066.38 | 724.97 | 857.96 | 136.11 | 208.50 | 22.75 | < LOD | 32.03 |
| CROMO2_1B      | 5744.64 | 184.06 | < LOD | 337.80 | 75582.87 | 780.68 | 1220.76 | 157.63 | 206.43 | 22.87 | < LOD | 32.48 |
| CROMO2_1B      | 5310.24 | 173.17 | < LOD | 324.03 | 73652.82 | 753.47 | 993.46 | 144.15 | 185.59 | 22.54 | < LOD | 31.99 |
### Table A8: continued

| Sample   | Ni      | Ni Error | Co     | Co Error | Fe     | Fe Error | Mn     | Mn Error | Cr     | Cr Error | V     | V Error |
|----------|---------|----------|--------|----------|--------|----------|--------|----------|--------|----------|-------|---------|
| PHL_1    | 2809.97 | 100.50   | 382.58 | 177.62   | 80763.18 | 613.56  | 1329.35 | 130.23   | 1313.04 | 51.12    | < LOD | 47.89   |
| PHL_1    | 2718.53 | 97.71    | 368.13 | 172.82   | 78394.73 | 597.02  | 1241.70 | 127.23   | 1530.65 | 54.58    | < LOD | 50.27   |
| PHL_2B   | 1655.92 | 88.67    | 284.31 | 150.29   | 58750.50 | 518.51  | 1037.73 | 117.61   | 1890.39 | 53.50    | 65.26  | 31.92   |
| PHL_2B   | 2069.52 | 86.61    | 340.77 | 150.29   | 57221.90 | 509.30  | 984.15  | 114.64   | 1835.24 | 52.78    | 68.34  | 31.23   |
| PHL_2C   | 2229.52 | 90.06    | 227.43 | 150.91   | 59120.38 | 522.72  | 1043.06 | 118.36   | 1884.94 | 52.96    | 63.59  | 30.35   |
| PHL_2C   | 2831.10 | 103.33   | 288.56 | 178.69   | 78372.31 | 619.80  | 1244.51 | 133.04   | 1479.67 | 51.92    | < LOD | 44.27   |
| PHL_2C   | 2745.78 | 99.63    | 280.58 | 170.85   | 74610.47 | 592.38  | 1198.55 | 127.61   | 1390.46 | 51.50    | < LOD | 46.37   |
| PHL_2C   | 1650.42 | 63.35    | 181.48 | 108.39   | 45569.93 | 374.98  | 751.84  | 81.31    | 1238.46 | 49.20    | < LOD | 46.73   |
| PHL_2A   | 2896.22 | 101.63   | < LOD  | 227.61   | 59311.35 | 529.75  | 911.61  | 118.74   | 2231.59 | 57.08    | 68.84  | 31.34   |
| PHL_2A   | 2504.46 | 87.45    | 199.40 | 129.62   | 49929.81 | 448.40  | 776.82  | 101.74   | 2292.26 | 57.92    | 61.90  | 30.00   |
| PHL_2A   | 2686.15 | 92.93    | 218.94 | 137.89   | 53550.11 | 476.96  | 870.66  | 108.86   | 2240.21 | 57.71    | < LOD | 46.48   |
| PHL_3    | 3090.42 | 111.86   | 531.18 | 186.09   | 77207.58 | 637.25  | 1294.85 | 141.89   | 2247.84 | 60.00    | 66.98  | 32.92   |
| PHL_3    | 2859.16 | 103.49   | 287.34 | 172.43   | 73148.43 | 597.45  | 1315.77 | 135.68   | 2190.65 | 59.25    | < LOD | 48.07   |
| PHL_3    | 3317.70 | 118.01   | < LOD  | 291.03   | 83304.90 | 679.64  | 1364.77 | 151.06   | 2329.26 | 61.07    | < LOD | 47.72   |
| PHL_4    | 270.34  | 48.94    | < LOD  | 216.10   | 50564.68 | 507.16  | 959.80  | 108.47   | < LOD  | 33.59    | 343.84 | 59.18   |
| PHL_4    | 275.62  | 50.24    | < LOD  | 221.40   | 50980.34 | 517.53  | 919.52  | 108.46   | < LOD  | 33.30    | 346.40 | 58.34   |
| PHL_4    | 290.88  | 50.32    | < LOD  | 218.71   | 50210.20 | 504.86  | 889.23  | 105.60   | < LOD  | 33.35    | 318.87 | 57.88   |
| PHL_5    | 2752.68 | 94.60    | 373.12 | 156.82   | 68477.06 | 539.98  | 1161.57 | 117.71   | 1685.87 | 55.47    | < LOD | 47.12   |
| PHL_5    | 2627.79 | 91.12    | 301.64 | 151.42   | 66160.68 | 523.18  | 1079.51 | 111.73   | 1411.48 | 51.90    | < LOD | 47.53   |
| PHL_5    | 3031.60 | 98.77    | 240.46 | 158.50   | 70756.62 | 550.29  | 1195.72 | 120.63   | 1723.83 | 55.70    | < LOD | 51.22   |
Table A8: continued

| Sample  | Ti    | Ti Error | Sc   | Sc Error | Ca   | Ca Error | K    | K Error | S     | S Error | Sb   | Sb Error |
|---------|-------|----------|------|----------|------|----------|------|---------|-------|---------|------|----------|
| 167_238 | < LOD | 85.99    | < LOD| 27.55    | 13070.62 | 297.21   | 212.63 | 137.52  | < LOD | 739.55  | < LOD | 12.16    |
| 167_238 | < LOD | 70.67    | < LOD| 22.30    | 12805.88 | 237.21   | 296.90 | 113.94  | < LOD | 598.73  | < LOD | 12.04    |
| 167_238 | < LOD | 67.88    | < LOD| 22.36    | 12666.83 | 236.63   | < LOD  | 162.89  | < LOD | 591.75  | < LOD | 12.23    |
| HLSC_1  | 136.15| 51.93    | 33.65| 20.30    | 22904.92 | 328.43   | < LOD  | 181.11  | < LOD | 665.47  | < LOD | 12.00    |
| HLSC_1  | 93.15 | 57.52    | < LOD| 31.85    | 22381.04 | 345.71   | < LOD  | 191.34  | < LOD | 666.33  | < LOD | 12.11    |
| HLSC_1  | 99.69 | 56.77    | < LOD| 31.64    | 22360.15 | 342.46   | < LOD  | 188.63  | < LOD | 617.68  | < LOD | 12.21    |
| HLSC_4  | 98.84 | 65.00    | < LOD| 33.66    | 18098.57 | 357.12   | < LOD  | 222.14  | < LOD | 731.40  | < LOD | 13.35    |
| HLSC_4  | 113.85| 63.45    | 36.85| 21.67    | 16943.48 | 341.81   | < LOD  | 219.18  | < LOD | 790.22  | < LOD | 13.36    |
| HLSC_4  | 145.63| 58.11    | < LOD| 29.51    | 17343.23 | 313.73   | 238.51 | 134.92  | < LOD | 712.76  | < LOD | 13.12    |
| 313_210 | 222.35| 64.88    | 31.12| 18.01    | 10792.62 | 276.00   | 302.37 | 144.29  | < LOD | 835.33  | < LOD | 13.55    |
| 313_210 | 354.05| 75.67    | < LOD| 30.53    | 13694.44 | 327.67   | 275.48 | 155.21  | < LOD | 850.42  | < LOD | 12.82    |
| 313_210 | 262.82| 72.14    | < LOD| 29.04    | 11376.88 | 298.27   | < LOD  | 210.89  | < LOD | 909.39  | < LOD | 12.43    |
| 313_329 | < LOD | 87.69    | < LOD| 14.97    | 1973.56  | 135.00   | 256.16 | 125.05  | < LOD | 658.25  | < LOD | 12.24    |
| 313_329 | < LOD | 83.32    | < LOD| 13.83    | 1973.72  | 132.82   | 354.66 | 127.74  | < LOD | 626.39  | < LOD | 12.51    |
| 313_329 | < LOD | 84.26    | < LOD| 13.88    | 1933.40  | 133.31   | < LOD  | 180.43  | < LOD | 611.46  | < LOD | 11.86    |
| 313_356 | < LOD | 84.30    | < LOD| 14.73    | 2538.72  | 142.47   | 289.38 | 124.44  | < LOD | 665.21  | < LOD | 12.17    |
| 313_356 | 112.34| 53.75    | < LOD| 15.26    | 2466.29  | 142.92   | 317.67 | 126.78  | < LOD | 687.09  | < LOD | 11.85    |
| 313_356 | < LOD | 85.48    | < LOD| 15.07    | 2448.41  | 139.68   | 290.87 | 122.45  | < LOD | 676.22  | < LOD | 11.63    |
| 313_318 | 144.76| 65.63    | < LOD| 26.38    | 12075.60 | 283.91   | < LOD  | 201.40  | < LOD | 747.90  | < LOD | 11.82    |
| 313_318 | 147.77| 62.33    | < LOD| 26.64    | 12582.32 | 285.72   | 284.11 | 138.62  | < LOD | 769.40  | < LOD | 11.64    |
| 313_318 | 181.28| 65.02    | < LOD| 27.54    | 13523.69 | 299.09   | 208.29 | 137.83  | < LOD | 709.60  | < LOD | 11.71    |
| 309_105_B| 89.80 | 58.20    | < LOD| 11.30    | 238.99   | 90.27    | 275.52 | 124.28  | < LOD | 491.64  | < LOD | 11.81    |
| 309_105_B| 111.20| 55.78    | < LOD| 11.21    | 382.41   | 94.48    | < LOD  | 172.91  | 1174.84 | 521.26  | < LOD | 12.10    |
| 309_105_B| < LOD | 83.13    | < LOD| 11.68    | 270.48   | 90.44    | < LOD  | 178.24  | 1458.22 | 542.67  | < LOD | 11.84    |
| 309_105_A| 223.07| 63.47    | < LOD| 12.41    | 480.62   | 103.59   | < LOD  | 181.53  | 1177.78 | 547.57  | < LOD | 12.16    |
| 309_105_A| 159.67| 65.90    | < LOD| 12.80    | 447.40   | 105.83   | < LOD  | 189.02  | 837.16  | 533.21  | < LOD | 11.94    |
| 309_105_A| 149.47| 65.04    | < LOD| 13.16    | 553.11   | 110.16   | < LOD  | 194.40  | < LOD  | 760.00  | < LOD | 12.40    |
Table A8: continued.

| Sample  | Ti       | Ti Error | Sc    | Sc Error | Ca      | Ca Error | K     | K Error | S       | S Error | Sb    | Sb Error |
|---------|----------|----------|-------|----------|---------|----------|-------|---------|---------|---------|-------|----------|
| 309_150 | 470.44   | 69.70    | < LOD | 12.03    | 414.00  | 95.87    | 270.83| 124.29  | < LOD   | 697.44  | < LOD | 12.12    |
| 309_150 | 548.06   | 67.86    | < LOD | 11.70    | 376.19  | 95.72    | 218.03| 123.11  | < LOD   | 685.38  | < LOD | 12.07    |
| 309_84  | 489.67   | 67.20    | < LOD | 12.02    | 473.42  | 97.53    | 265.77| 124.03  | 754.28  | 484.39  | < LOD | 12.17    |
| 309_84  | 9243.00  | 283.21   | 78.17 | 39.94    | 25707.33| 612.95   | 760.39| 279.72  | < LOD   | 1627.94 | < LOD | 18.48    |
| 309_84  | 8624.25  | 264.79   | 61.60 | 37.97    | 25474.83| 588.84   | 980.24| 279.19  | < LOD   | 1439.50 | < LOD | 18.89    |
| 309_84  | 8484.45  | 267.09   | 63.46 | 37.70    | 25324.74| 582.82   | 861.54| 271.50  | < LOD   | 1616.48 | 21.29 | 13.44    |
| ESH     | < LOD    | 28.90    | < LOD | 3.92     | 635.81  | 40.89    | < LOD | 101.36  | < LOD   | 229.90  | < LOD | 19.62    |
| ESH     | < LOD    | 27.60    | < LOD | 4.02     | 584.23  | 39.32    | < LOD | 101.82  | < LOD   | 253.06  | < LOD | 18.98    |
| ESH     | < LOD    | 28.51    | < LOD | 4.01     | 591.12  | 39.65    | 124.66| 68.97   | < LOD   | 238.16  | < LOD | 17.99    |
| CROMO1_2_AC | 2566.92  | 138.48   | 94.47 | 43.25    | 57789.48| 702.56   | 2247.04| 283.50  | < LOD   | 1143.99 | < LOD | 16.79    |
| CROMO1_2_AC | 2635.52  | 136.47   | 83.68 | 42.71    | 57737.67| 696.31   | 2559.25| 290.23  | < LOD   | 1133.94 | < LOD | 16.92    |
| CROMO1_2_AC | 2521.87  | 139.00   | < LOD | 63.79    | 58853.18| 699.14   | 2124.58| 276.77  | < LOD   | 1202.31 | < LOD | 16.07    |
| CROMO1_2_AA | 1096.15  | 88.83    | < LOD | 58.41    | 62509.09| 643.36   | 321.61| 192.05  | < LOD   | 1006.23 | < LOD | 14.50    |
| CROMO1_2_AA | 986.21   | 91.25    | 70.38 | 39.53    | 62990.42| 650.18   | < LOD | 280.41  | < LOD   | 1034.89 | < LOD | 14.46    |
| CROMO1_2_AA | 1020.89  | 87.22    | 60.66 | 38.92    | 62655.52| 642.18   | < LOD | 282.72  | < LOD   | 1014.69 | < LOD | 14.33    |
| CROMO1_2_AB | 617.37   | 88.65    | < LOD | 32.22    | 14209.68| 337.12   | < LOD | 232.43  | < LOD   | 866.85  | < LOD | 12.91    |
| CROMO1_2_AB | 639.46   | 85.91    | < LOD | 31.97    | 14338.89| 338.54   | 293.01| 160.36  | < LOD   | 820.15  | < LOD | 13.00    |
| CROMO1_2_AB | 681.88   | 85.09    | < LOD | 32.66    | 14527.41| 343.08   | 387.73| 166.11  | < LOD   | 944.59  | < LOD | 12.78    |
| CROMO1_1_A | 1884.52  | 105.47   | 52.65 | 29.10    | 33313.57| 471.35   | 2725.73| 244.10  | < LOD   | 848.24  | < LOD | 13.27    |
| CROMO1_1_A | 2015.25  | 105.52   | 47.98 | 29.41    | 33565.10| 477.80   | 2620.74| 243.57  | < LOD   | 853.74  | < LOD | 14.01    |
| CROMO1_1_A | 1949.93  | 105.78   | 82.44 | 30.03    | 33962.97| 479.34   | 2269.19| 233.85  | < LOD   | 862.71  | < LOD | 13.58    |
| CROMO1_1_B | 1239.37  | 89.55    | 73.71 | 27.53    | 31582.04| 440.25   | 1864.44| 209.93  | < LOD   | 848.38  | < LOD | 14.43    |
| CROMO1_1_B | 1116.47  | 88.70    | 79.32 | 27.67    | 31524.12| 441.14   | 2097.57| 217.26  | < LOD   | 849.55  | < LOD | 15.20    |
| CROMO1_1_B | 1267.81  | 89.28    | 58.48 | 27.48    | 31749.75| 443.24   | 1930.24| 212.81  | < LOD   | 861.80  | < LOD | 14.58    |
| Sample       | Ti      | Ti Error | Sc      | Sc Error | Ca      | Ca Error | K       | K Error | S      | S Error | Sb      | Sb Error |
|-------------|---------|----------|---------|----------|---------|----------|---------|---------|--------|---------|---------|----------|
| CROMO1_2 CA | 1688.89 | 104.26   | 60.27   | 27.92    | 2882.60 | 446.19   | 922.04  | 189.01  | < LOD  | 892.00  | < LOD   | 13.11    |
| CROMO1_2 CA | 1853.60 | 104.16   | < LOD   | 40.79    | 29381.91| 446.11   | 949.56  | 188.99  | < LOD  | 968.44  | < LOD   | 13.51    |
| CROMO1_2 CA | 1718.14 | 101.89   | < LOD   | 40.61    | 29012.79| 443.96   | 1149.43 | 195.67  | < LOD  | 876.79  | < LOD   | 13.22    |
| CROMO1_2 CB | 967.63  | 86.02    | 37.07   | 23.60    | 22760.47| 379.15   | 738.17  | 168.65  | < LOD  | 805.33  | < LOD   | 13.96    |
| CROMO1_2 CB | 1024.33 | 83.43    | < LOD   | 34.38    | 22850.04| 374.11   | 555.88  | 159.40  | < LOD  | 727.45  | < LOD   | 14.42    |
| CROMO1_2 CB | 1089.99 | 86.38    | 39.63   | 23.45    | 22517.97| 375.86   | 845.84  | 171.83  | < LOD  | 772.05  | < LOD   | 14.60    |
| CROMO2_4A   | < LOD   | 71.71    | < LOD   | 9.71     | < LOD   | 110.99   | < LOD   | 154.87  | < LOD  | 616.98  | < LOD   | 11.52    |
| CROMO2_4A   | < LOD   | 73.73    | < LOD   | 9.71     | 186.67  | 79.56    | < LOD   | 160.08  | < LOD  | 640.06  | < LOD   | 12.02    |
| CROMO2_4A   | < LOD   | 75.93    | < LOD   | 9.15     | 125.31  | 76.27    | < LOD   | 160.45  | < LOD  | 614.34  | < LOD   | 12.00    |
| CROMO2_4B   | < LOD   | 81.08    | < LOD   | 10.99    | 385.29  | 90.82    | < LOD   | 171.74  | < LOD  | 681.27  | < LOD   | 13.19    |
| CROMO2_4B   | < LOD   | 74.72    | < LOD   | 10.38    | 376.71  | 88.48    | < LOD   | 168.64  | < LOD  | 681.21  | < LOD   | 14.08    |
| CROMO2_4B   | < LOD   | 77.17    | < LOD   | 10.35    | 322.13  | 85.96    | < LOD   | 165.17  | 906.34 | 463.66  | < LOD   | 15.32    |
| CROMO2_2    | 102.79  | 53.02    | < LOD   | 10.28    | 201.17  | 85.21    | 184.56  | 115.91  | < LOD  | 864.37  | 476.41  | < LOD   | 11.90    |
| CROMO2_2    | < LOD   | 81.66    | < LOD   | 11.05    | 271.74  | 88.47    | < LOD   | 172.43  | 946.84 | 489.24  | < LOD   | 11.73    |
| CROMO2_2    | < LOD   | 81.83    | < LOD   | 10.63    | 343.82  | 89.68    | 192.47  | 117.68  | 952.46 | 484.46  | < LOD   | 11.18    |
| CROMO2_3A   | 653.79  | 80.35    | < LOD   | 16.24    | 2253.23 | 151.97   | 1756.12 | 192.76  | < LOD  | 752.95  | < LOD   | 12.23    |
| CROMO2_3A   | 742.60  | 82.97    | < LOD   | 16.92    | 2745.11 | 165.08   | 1788.79 | 197.39  | < LOD  | 751.12  | < LOD   | 12.53    |
| CROMO2_3A   | 736.91  | 80.53    | < LOD   | 16.94    | 2725.02 | 163.74   | 1955.59 | 201.69  | < LOD  | 808.44  | < LOD   | 12.33    |
| CROMO2_3B   | 685.47  | 77.78    | < LOD   | 13.64    | 1704.22 | 137.49   | 1748.40 | 191.16  | < LOD  | 734.80  | < LOD   | 14.57    |
| CROMO2_3B   | 737.62  | 78.39    | < LOD   | 14.22    | 1410.96 | 130.70   | 1711.15 | 189.62  | < LOD  | 666.29  | < LOD   | 14.25    |
| CROMO2_3B   | 691.00  | 77.18    | < LOD   | 14.01    | 1570.50 | 130.97   | 1634.79 | 184.01  | < LOD  | 658.15  | < LOD   | 15.12    |
| CROMO2_1A   | < LOD   | 71.30    | < LOD   | 10.23    | 327.28  | 79.07    | < LOD   | 159.27  | 1054.57| 449.48  | < LOD   | 11.24    |
| CROMO2_1A   | < LOD   | 72.96    | < LOD   | 9.68     | 259.57  | 77.68    | < LOD   | 159.13  | < LOD  | 569.54  | < LOD   | 11.38    |
| CROMO2_1A   | < LOD   | 72.71    | < LOD   | 9.79     | 346.40  | 79.95    | < LOD   | 157.58  | < LOD  | 575.05  | < LOD   | 11.67    |
| CROMO2_1B   | < LOD   | 68.84    | < LOD   | 8.58     | < LOD   | 102.93   | < LOD   | 158.49  | < LOD  | 590.82  | < LOD   | 12.69    |
| CROMO2_1B   | < LOD   | 69.86    | < LOD   | 8.50     | 124.29  | 70.59    | 221.26  | 109.31  | 796.53 | 416.76  | < LOD   | 13.02    |
| CROMO2_1B   | < LOD   | 69.46    | < LOD   | 8.77     | 109.98  | 70.27    | 190.43  | 107.92  | < LOD  | 542.77  | < LOD   | 12.85    |
| Sample   | Ti     | Ti Error | Sc     | Sc Error | Ca     | Ca Error | K      | K Error | S      | S Error | Sb    | Sb Error |
|----------|--------|----------|--------|----------|--------|----------|--------|----------|--------|----------|-------|----------|
| PHL_1    | < LOD  | 106.88   | < LOD  | 13.55    | < LOD  | 154.23   | 290.94 | 150.55   | < LOD  | 858.98   | < LOD | 12.18    |
| PHL_1    | < LOD  | 110.58   | < LOD  | 14.63    | < LOD  | 158.15   | 310.18 | 152.86   | < LOD  | 826.60   | < LOD | 12.58    |
| PHL_1    | 132.73 | 71.13    | < LOD  | 13.61    | < LOD  | 144.17   | 207.09 | < LOD    | 798.40 | < LOD    | 12.18 |          |
| PHL_2B   | 270.15 | 70.92    | 37.49  | 19.34    | 11906.07 | 296.57   | < LOD  | 214.40   | < LOD  | 662.92   | < LOD | 12.36    |
| PHL_2B   | 313.15 | 70.16    | < LOD  | 27.15    | 10903.87 | 284.72   | 215.57 | < LOD    | 806.94 | < LOD    | 12.49 |          |
| PHL_2B   | 250.91 | 67.29    | < LOD  | 27.52    | 11476.23 | 289.15   | < LOD  | 209.00   | < LOD  | 791.43   | < LOD | 12.25    |
| PHL_2C   | 105.18 | 64.19    | < LOD  | 13.87    | < LOD  | 161.36   | < LOD  | 209.75   | < LOD  | 780.89   | < LOD | 12.65    |
| PHL_2C   | < LOD  | 99.99    | < LOD  | 14.42    | < LOD  | 166.59   | 269.26 | 147.49   | < LOD  | 781.86   | < LOD | 12.56    |
| PHL_2C   | < LOD  | 104.22   | < LOD  | 14.03    | < LOD  | 168.51   | 278.64 | 146.45   | < LOD  | 828.34   | < LOD | 12.29    |
| PHL_2A   | 311.34 | 70.22    | < LOD  | 28.36    | 12224.85 | 299.55   | < LOD  | 208.01   | < LOD  | 826.52   | < LOD | 12.30    |
| PHL_2A   | 336.36 | 68.47    | < LOD  | 30.08    | 13823.78 | 318.20   | 224.89 | 147.33   | < LOD  | 681.76   | < LOD | 12.90    |
| PHL_2A   | 265.46 | 70.77    | < LOD  | 29.48    | 13245.48 | 313.65   | < LOD  | 213.90   | < LOD  | 782.31   | < LOD | 13.11    |
| PHL_3    | 139.63 | 71.20    | < LOD  | 21.28    | 4857.25  | 213.29   | < LOD  | 213.06   | < LOD  | 789.13   | < LOD | 12.71    |
| PHL_3    | 120.34 | 71.87    | < LOD  | 21.10    | 4859.33  | 212.99   | < LOD  | 213.38   | < LOD  | 707.96   | < LOD | 12.83    |
| PHL_3    | 140.82 | 71.33    | < LOD  | 20.45    | 4920.45  | 215.53   | < LOD  | 216.99   | < LOD  | 799.55   | < LOD | 12.66    |
| PHL_4    | 7456.69 | 170.75   | 105.87 | 44.99    | 87853.82 | 740.54   | < LOD  | 308.32   | < LOD  | 998.59   | < LOD | 16.23    |
| PHL_4    | 7462.30 | 168.70   | 128.41 | 44.80    | 87578.43 | 733.80   | < LOD  | 303.14   | < LOD  | 1061.48  | < LOD | 16.20    |
| PHL_4    | 7394.78 | 167.93   | 106.52 | 44.31    | 87460.70 | 729.08   | < LOD  | 302.50   | < LOD  | 1063.51  | < LOD | 15.89    |
| PHL_5    | < LOD  | 102.88   | < LOD  | 13.17    | < LOD  | 151.99   | < LOD  | 212.40   | < LOD  | 785.08   | < LOD | 13.02    |
| PHL_5    | < LOD  | 102.51   | < LOD  | 14.18    | < LOD  | 154.46   | < LOD  | 211.62   | < LOD  | 793.93   | < LOD | 12.88    |
| PHL_5    | < LOD  | 114.87   | < LOD  | 13.24    | < LOD  | 149.84   | < LOD  | 207.49   | < LOD  | 766.64   | < LOD | 12.88    |
Figure A19: SEM-EDS spectra images for sample 313_329 for the inside of olivine grains (1). See also Table 7 and Figure 25.
Figure A20: SEM-EDS spectra images for sample 313_329 along edges of olivine grains. See also Table 8 and Figure 26.
Figure A21: SEM-EDS spectra for sample 313_329 for the inside of olivine grains. See also Table 9 and Figure 27.
Figure A22: SEM-EDS spectra for sample 313_329 for the inside of pyroxene grains. See also Table 10 and Figure 28.
Figure A23: SEM-EDS spectra for sample 313_329 inside of a spinel grain. See also Table 11 and Figure 29.
Table A9: Mössbauer parameters for other samples collected from prospecting cores, CROMO well cores, and Philippines hand samples.

| Sample          | 309_84 | 309_105_B | CROMO1_1_A‡ | CROMO1_1_B‡ |
|-----------------|--------|-----------|-------------|-------------|
| Sextet 1 Magnetite | IS     | QS        | W           | A           |
|                 |        |           |             |             |
|                 |        |           |             |             |
| Sextet 2 Magnetite | IS     | QS        | W           | A           |
|                 |        |           |             |             |
|                 |        |           |             |             |
| Ferric 1 Silicate | IS     | QS        | W           | A           |
|                 |        |           |             |             |
|                 |        |           |             |             |
| Ferric 2 Silicate | IS     | QS        | W           | A           |
|                 |        |           |             |             |
|                 |        |           |             |             |
| Ferrous 1 Silicate | IS    | QS        | W           | A           |
|                 |        |           |             |             |
|                 |        |           |             |             |
| Ferrous 2 Silicate | IS    | QS        | W           | A           |
|                 |        |           |             |             |
|                 |        |           |             |             |
| X²              | 3081.07| 575.85    | 534.21      | 520.74      |
| [X²]            | 5.6865 | 1.1206    | 1.0436      | 1.0125      |
| Sum areas       | 100    | 100       | 100         | 100         |
| Magnetite       | 0      | 0         | 0           | 0           |
| Fe(III)         | 17     | 32        | 16          | 18          |
| Fe(II)          | 83     | 68        | 84          | 82          |
| %Fe³⁺ in silicates | 17     | 32        | 16          | 18          |
Table A9: continued

| Sample          | CROMO1_2_AA | CROMO1_2_AB | CROMO1_2_AC‡ |
|-----------------|------------|------------|--------------|
| **Sextet 1 Magnetite** | IS         | QS         | W            | A | B\textsubscript{hf} |
|                 | 0.33       | 0.39       | 0.45         |   |               |
| **Sextet 2 Magnetite** | IS         | QS         | W            | A | B\textsubscript{hf} |
|                 | 0.67       | 1.19       | 0.41         |   |               |
| **Ferric 1 Silicate** | IS         | QS         | W            | A |               |
|                 | 0.42       | 1.23       | 0.52         |   |               |
| **Ferric 2 Silicate** | IS         | QS         | W            | A |               |
|                 | 0.42       | 1.23       | 0.52         |   |               |
| **Ferrous 1 Silicate** | IS         | QS         | W            | A |               |
|                 | 1.16       | 1.13       | 1.14         |   |               |
| **Ferrous 2 Silicate** | IS         | QS         | W            | A |               |
|                 | 1.13       | 2.77       | 0.23*        |   |               |
|                  | 60         | 63         | 78           |   |               |

\[ X^2 \] & 597.75 & 684.34 & 760.45 \\
\[ |X^2| \] & 1.1645 & 1.3276 & 1.4754 \\

|                     | CROMO1_2_AA | CROMO1_2_AB |   |
|---------------------|------------|------------|---|
| Sum areas           | 100        | 100        | 100 |
| Magnetite           | 0          | 0          | 0  |
| Fe(III)             | 29         | 37         | 15 |
| Fe(II)              | 71         | 63         | 85 |
| %Fe\textsuperscript{3+} in silicates | 29 | 37 | 15 |
| Sample          | CROMO1_2_CA‡ | CROMO1_2_CB‡ | CROMO2_1B‡ | CROMO2_3B‡ |
|-----------------|-------------|-------------|------------|------------|
| Sextet 1 Magnetite |             |             |            |            |
| IS              | 0.28        | 0.26        |            |            |
| QS              | 0.00        | -0.04       |            |            |
| W               | 0.30        | 0.30        |            |            |
| A               | 10          | 13          |            |            |
| B_{mf}          | 493.1       | 488.6       |            |            |
| Sextet 2 Magnetite |             |             |            |            |
| IS              | 0.69        | 0.68        |            |            |
| QS              | -0.01       | -0.02       |            |            |
| W               | 0.32        | 0.25        |            |            |
| A               | 11          | 17          |            |            |
| B_{mf}          | 461.5       | 461.2       |            |            |
| Ferric 1 Silicate |             |             |            |            |
| IS              | 0.43        | 0.31        | 0.36       | 0.35       |
| QS              | 0.82        | 1.03        | 0.71       | 0.68       |
| W               | 0.50        | 0.91        | 0.64       | 0.56       |
| A               | 8           | 25          | 42         | 27         |
| Ferric 2 Silicate |             |             |            |            |
| IS              | 0.99        |             |            |            |
| QS              | 0.80        |             |            |            |
| W               | 0.34        |             |            |            |
| A               | 4           |             |            |            |
| Ferrous 1 Silicate |             |             |            |            |
| IS              | 1.13        | 1.13        | 1.15       | 1.14       |
| QS              | 2.69        | 2.69        | 2.70       | 2.67       |
| W               | 0.20        | 0.12        | 0.31       | 0.30       |
| A               | 88          | 75          | 37         | 44         |
| Ferrous 2 Silicate |             |             |            |            |
| IS              |             |             |            |            |
| QS              |             |             |            |            |
| W               |             |             |            |            |
| A               |             |             |            |            |
| X^2             | 1012.73     | 481.61      | 959.7      | 1582.26    |
| [X^2]           | 1.9766      | 0.9379      | 1.8725     | 3.086      |
| Sum areas       | 100         | 100         | 100        | 100        |
| Magnetite       | 0           | 0           | 21         | 29         |
| Fe(III)         | 12          | 25          | 42         | 27         |
| Fe(II)          | 88          | 75          | 37         | 44         |
| %Fe^{3+} in silicates | 12 | 25 | 53 | 38 |
| Sample          | IS   | QS   | W    | A    | B_{hf} | Magnetite | PHL_2A‡ | PHL_2C‡ | PHL_4 |
|-----------------|------|------|------|------|--------|-----------|---------|---------|-------|
| **Sextet 1**    |      |      |      |      |        |           |         |         |       |
| Magnetite       | 0.27 | -0.02| 0.23 | 19   | 498.8  | 0.30      | 0.35    | 14      | 0.29  |
| **Sextet 2**    |      |      |      |      |        |           |         |         |       |
| Magnetite       | 0.67 | 0.00 | 0.30 | 33   | 458.7  | 1.16      | 0.35    | 31      | 1.01  |
| **Ferric 1**    |      |      |      |      |        |           |         |         |       |
| Silicate        | 0.34 | 0.70 | 0.60 | 23   |        | 0.35      | 0.35    | 2       | 0.54  |
| **Ferric 2**    |      |      |      |      |        |           |         |         |       |
| Silicate        |      |      |      |      |        | 100       | 100     | 100     | 100   |
| **Ferrous 1**   |      |      |      |      |        |           |         |         |       |
| Silicate        | 1.13 | 2.68 | 0.29 | 25   |        | 1.14      | 2.79    | 9       | 5     |
| **Ferrous 2**   |      |      |      |      |        |           |         |         |       |
| Silicate        |      |      |      |      |        | 0.64      | 2.67    | 0.3*    | 6     |
| **Ferrous 3**   |      |      |      |      |        |           |         |         |       |
| Silicate        |      |      |      |      |        | 1.15      | 2.66    | 0.25*   | 72    |
| X²              | 965.96 | 1975.26 | 1483.44 | 1321.81 |
| [X²]            | 1.8841 | 3.7966 | 2.8448  | 2.5599  |
| Sum areas       | 100  | 100  | 100  | 100  |        |           |         |         |       |
| Magnetite       | 52   | 8    | 19   | 0    |        |           |         |         |       |
| Fe(III)         | 23   | 58   | 56   | 14   |        |           |         |         |       |
| Fe(II)          | 25   | 34   | 25   | 86   |        |           |         |         |       |
| %Fe^{3+} in silicates | 48   | 63   | 69   | 14   |        |           |         |         |       |

Isomer shift (IS) is in mm/s; Quadrupole splitting (QS) is in mm/s; Peak width (W) is in mm/s; magnetic hyperfine field (B_{hf}) is in tesla; % Area (A) under the curve; CHI-squared (X²), and normalized CHI-squared ([X²]). Silicates are serpentine, pyroxene, and/or chlorite.

*Indicates restricted (fixed) parameter.

‡MOSS curves fit by M.Nelms in Dyar Lab and rest were fit by A.Stander.
The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), Fe$^{3+}$ (blue) and Fe$^{2+}$ (green) curves.
Figure A25. Mössbauer Spectroscopy 309_105_B plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), Fe$^{3+}$ (blue) and Fe$^{2+}$ (green) curves.
Figure A26. Mössbauer Spectroscopy CROMO1_1_A plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), Fe$^{3+}$ (blue and green) and Fe$^{2+}$ (brown and purple) curves.
Figure A27. Mössbauer Spectroscopy CROMO1_1_B plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), Fe$^{3+}$ (blue and green) and Fe$^{2+}$ (brown) curves.
Figure A28. Mössbauer Spectroscopy CROMO1_2_AA plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), Fe$^{3+}$ (blue and green) and Fe$^{2+}$ (brown and purple) curves.
Figure A29. Mössbauer Spectroscopy CROMO1_2_AB plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), Fe$^{3+}$ (blue) and Fe$^{2+}$ (green) curves.
Figure A30. Mössbauer Spectroscopy CROMO1_2_AC plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), Fe$^{3+}$ (blue) and Fe$^{2+}$ (green and brown) curves.
Figure A31. Mössbauer Spectroscopy CROMO1_2_CA plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), Fe$^{3+}$ (blue and brown) and Fe$^{2+}$ (green) curves.
Figure A32. Mössbauer Spectroscopy CROMO1_2_CB plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), Fe$^{3+}$ (blue) and Fe$^{2+}$ (green) curves.
Figure A33. Mössbauer Spectroscopy CROMO2_1B plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), magnetite (blue and green), Fe$^{3+}$ (purple) and Fe$^{2+}$ (brown) curves.
Figure A34. Mössbauer Spectroscopy CROMO2_3B plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), magnetite (blue and green), Fe$^{3+}$ (purple) and Fe$^{2+}$ (brown) curves.
Figure A35. Mössbauer Spectroscopy CROMO2_4B plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), magnetite (blue and green), Fe$^{3+}$ (purple) and Fe$^{2+}$ (brown) curves.
Figure A36. Mössbauer Spectroscopy PHL_2A plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), magnetite (blue and green), Fe$^{3+}$ (purple) and Fe$^{2+}$ (brown) curves.
Figure A37. Mössbauer Spectroscopy PHL_2C plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), magnetite (blue and green), Fe$^{3+}$ (purple) and Fe$^{2+}$ (brown) curves.
Figure A38. Mössbauer Spectroscopy PHL_4 plot. The data (black dots) were fit using the Ghent program to obtain a best fit curve (red), Fe$^{3+}$ (blue and green) and Fe$^{2+}$ (purple, brown, black) curves. PHL_4 still requires additional fitting because the parameters are not within the general range of values for Fe$^{2+}$ and Fe$^{3+}$. 

Absorption (%) vs. Velocity (mm/s)
Figure A39. Sample depth vs. %Fe$^{3+}$. (a) All samples with magnetite split up and included in %Fe$^{3+}$ and (b) only cores 309 and 313; (c) Silicates only (no magnetite) %Fe$^{3+}$ for all samples and (d) only cores 309 and 313.
Table A10: H₂ generation using average density (2.68 g cm⁻³) and mg/kg conversion.

| Sample       | MOSS   | % Mag | % Fe³⁺ | % Fe²⁺ | Fe conc. (ppm)* | mol H₂/kg rock to be released | mol H₂/kg rock released | Volume Peridotite (km³)* | H₂gas released (mol) | H₂gas to be released (mol) | H₂gas released (Tmol) | H₂gas to be released (Tmol) |
|--------------|--------|-------|--------|--------|-----------------|-----------------------------|-------------------------|------------------------|----------------------|-----------------------------|--------------------|-----------------------------|
| 309_84       | MOSS   | 0     | 17     | 83     | 135803          | 1.01                        | 0.40                    | 7730                   | 1.08                 | 2.72                        | 8.34182E+15        | 2.10157E+16                 |
| 309_105_B    | MOSS   | 0     | 32     | 68     | 36191           | 0.22                        | 0.21                    | 7730                   | 0.55                 | 0.59                        | 4.27296E+15        | 4.57567E+15                 |
| CROMO1_1_A   | MOSS   | 0     | 16     | 84     | 44672           | 0.34                        | 0.13                    | 7730                   | 0.34                 | 0.90                        | 2.64195E+15        | 6.96427E+15                 |
| CROMO1_1_B   | MOSS   | 0     | 18     | 82     | 71522           | 0.53                        | 0.23                    | 7730                   | 0.62                 | 1.41                        | 4.75782E+15        | 1.08864E+16                 |
| CROMO1_2_AA  | MOSS   | 0     | 29     | 71     | 33518           | 0.21                        | 0.17                    | 7730                   | 0.46                 | 0.57                        | 3.57319E+15        | 4.42981E+15                 |
| CROMO1_2_AB  | MOSS   | 0     | 37     | 63     | 60579           | 0.34                        | 0.40                    | 7730                   | 1.07                 | 0.92                        | 8.3096E+15         | 7.08046E+15                 |
| CROMO1_2_AC  | MOSS   | 0     | 15     | 85     | 53768           | 0.41                        | 0.15                    | 7730                   | 0.39                 | 1.10                        | 3.01156E+15        | 8.46598E+15                 |
| CROMO1_2_CA  | MOSS   | 0     | 12     | 88     | 54729           | 0.43                        | 0.12                    | 7730                   | 0.32                 | 1.15                        | 2.46652E+15        | 8.91703E+15                 |
| CROMO1_2_CB  | MOSS   | 0     | 25     | 75     | 70690           | 0.48                        | 0.31                    | 7730                   | 0.84                 | 1.28                        | 6.50281E+15        | 9.85909E+15                 |
| CROMO2_1B    | MOSS   | 21    | 42     | 37     | 44606           | 0.18                        | 0.44                    | 7730                   | 1.19                 | 0.47                        | 9.20347E+15        | 3.67085E+15                 |
| CROMO2_3B    | MOSS   | 29    | 27     | 44     | 83576           | 0.40                        | 0.69                    | 7730                   | 1.85                 | 1.08                        | 1.43079E+16        | 8.34644E+15                 |
| CROMO2_4B    | MOSS   | 52    | 23     | 25     | 80999           | 0.31                        | 0.83                    | 7730                   | 2.23                 | 0.83                        | 1.72738E+16        | 6.38554E+15                 |
| PHL_2A       | MOSS   | 8     | 58     | 34     | 33264           | 0.11                        | 0.38                    | 1455                   | 1.02                 | 0.29                        | 1.48001E+15        | 4.21331E+14                 |
| PHL_2C       | MOSS   | 19    | 56     | 25     | 40571           | 0.11                        | 0.50                    | 1455                   | 1.34                 | 0.30                        | 1.94876E+15        | 4.42009E+14                 |
| PHL_4        | MOSS   | 0     | 14     | 86     | 31009           | 0.24                        | 0.08                    | 1455                   | 0.20                 | 0.64                        | 2.93101E+14        | 9.35928E+14                 |

Mag = % Fe in magnetite; mol is mole; *normalized average Fe concentration in ppm; % Fe³⁺ was used in H₂gas released calculations; % Fe²⁺ was used in H₂gas to be released calculations.
Table A1: \( \text{H}_2 \) generation using mg/L conversion units.

| Sample         | mol \( \text{H}_2 \)/L rock to be released | mol \( \text{H}_2 \)/L rock released | \( \text{H}_\text{gas} \) released (mol) | \( \text{H}_\text{gas} \) to be released (mol) | \( \text{H}_\text{gas} \) released per 1km\(^3\) (Tmol) | \( \text{H}_\text{gas} \) to be released per 1km\(^3\) (Tmol) |
|----------------|-------------------------------------------|--------------------------------------|------------------------------------------|-----------------------------------------------|------------------------------------------------|-----------------------------------------------|
| 309_84         | 1.01                                      | 0.40                                 | 3.1126E+15                              | 7.8417E+15                                   | 0.40                                          | 1.01                                          | 3113                                          | 7842                                          |
| 309_105_B      | 0.22                                      | 0.21                                 | 1.5944E+15                              | 1.7073E+15                                   | 0.21                                          | 0.22                                          | 1594                                          | 1707                                          |
| CROMO1_1_A     | 0.34                                      | 0.13                                 | 1.6082E+15                              | 4.2392E+15                                   | 0.13                                          | 0.34                                          | 1608                                          | 4239                                          |
| CROMO1_1_B     | 0.53                                      | 0.23                                 | 2.8961E+15                              | 6.6266E+15                                   | 0.23                                          | 0.53                                          | 2896                                          | 6627                                          |
| CROMO1_2_AA    | 0.21                                      | 0.17                                 | 2.175E+15                               | 2.6964E+15                                   | 0.17                                          | 0.21                                          | 2175                                          | 2696                                          |
| CROMO1_2_AB    | 0.34                                      | 0.40                                 | 5.0581E+15                              | 4.3099E+15                                   | 0.40                                          | 0.34                                          | 5058                                          | 4310                                          |
| CROMO1_2_AC    | 0.41                                      | 0.15                                 | 1.8332E+15                              | 5.1533E+15                                   | 0.15                                          | 0.41                                          | 1833                                          | 5153                                          |
| CROMO1_2_CA    | 0.43                                      | 0.12                                 | 1.5014E+15                              | 5.4278E+15                                   | 0.12                                          | 0.43                                          | 1501                                          | 5428                                          |
| CROMO1_2_CB    | 0.48                                      | 0.31                                 | 3.9583E+15                              | 6.0012E+15                                   | 0.31                                          | 0.48                                          | 3958                                          | 6001                                          |
| CROMO2_1B      | 0.18                                      | 0.44                                 | 3.4341E+15                              | 1.3697E+15                                   | 0.44                                          | 0.18                                          | 3434                                          | 1370                                          |
| CROMO2_3B      | 0.40                                      | 0.69                                 | 5.3388E+15                              | 3.1143E+15                                   | 0.69                                          | 0.40                                          | 5339                                          | 3114                                          |
| CROMO2_4B      | 0.31                                      | 0.83                                 | 6.4455E+15                              | 2.3827E+15                                   | 0.83                                          | 0.31                                          | 6445                                          | 2383                                          |
| PHL_2A         | 0.11                                      | 0.38                                 | 5.5224E+14                              | 1.5721E+14                                   | 0.38                                          | 0.11                                          | 552                                           | 157                                           |
| PHL_2C         | 0.11                                      | 0.50                                 | 7.2715E+14                              | 1.6493E+14                                   | 0.50                                          | 0.11                                          | 727                                           | 165                                           |
| PHL_4          | 0.24                                      | 0.08                                 | 1.7841E+14                              | 5.697E+14                                    | 0.08                                          | 0.24                                          | 178                                           | 570                                           |

\( \% \text{Fe}^{3+} \) (Table A10) was used in \( \text{H}_2\text{gas} \) released calculations; \( \% \text{Fe}^{2+} \) was used in \( \text{H}_2\text{gas} \) to be released calculations.
Table A12: IC-PMS concentration data for standards and CRO sample 313-329. Standards analyzed include BCR, BHVO, BIR, GOR, StHls, T1, ML3B, KL2, and San Carlos olivine. Data was collected in 4 different areas of the thin section and the mineral grains are labeled accordingly (sp1 for spinel grain in area 1, opx1 orthopyroxene grain in area 1, ol 1 for olivine grain in area 1, cpx2 for clinopyroxene in area 2, etc…). Ol3-2 is probably actually cpx or opx based on the chemical data below and opx3 maybe cpx (exsolution lamelle) due to the high CaO concentrations measured. The raw data was input into the “LazyBoy” version 3.73 macro spreadsheet developed by Joel Sparks (jwsparks@bu.edu; ©2011; version date 2/1/2013). Figures A40-42 illustrate the mineral grains sampled. Concentrations are in ppm unless indicated as wt%. Electron microprobe data of major cations in spinel(s) (Mg, Al, Cr, Fe) are needed to better assess the IC-PMS data, especially in regards to further analysis of the partitioning of the trace elements, such as V which has multiple valence states and may be another way to understand the redox status of rocks [Mallmann and O’Neill, 2009].
Table A12: IC-PMS concentration data for standards and CRO sample 313-329.

| Atomic number | Sample / Beam information | M026 Conc. | 26   | 27   | 43   | 45   | 47   | 51   | 52   | 55   | 57   | 59   | 60   | 65   | 85   | 88   | 89   | 208  |
|---------------|--------------------------|------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|               |                          | MgO%       | Al2O3% | CaO% | Sc   | TiO2% | V    | Cr   | MnO% | FeO*% | Co   | Ni   | Cu   | Zn   | Rb   | Sr   | Y    | Pb   |
| BCR 70% 10Hz 80um | 3.56                    | 3.56       | 13.41 | 6.94 | 31.15 | 2.28 | 401.44 | 20.92 | 0.19 | 11.20 | 34.71 | 12.28 | 17.37 | 149.50 | 45.71 | 332.33 | 34.64 | 10.91 |
| BHVO 70% 10Hz 80um | 7.13                    | 7.13       | 13.62 | 11.57 | 31.24 | 2.75 | 296.68 | 306.94 | 0.17 | 11.32 | 42.80 | 112.01 | 122.93 | 115.40 | 8.98  | 399.53 | 26.27 | 1.80  |
| BIR 70% 10Hz 80um | 9.4                     | 9.40       | 15.46 | 13.17 | 41.71 | 0.91 | 283.90 | 385.87 | 0.17 | 9.87  | 46.36 | 149.34 | 109.48 | 62.90  | 0.20  | 106.95 | 16.41 | 3.16  |
| GOR132 70% 10Hz 80um | 22.4                    | 22.40      | 10.33 | 7.91 | 33.32 | 0.27 | 207.82 | 2522.57 | 0.17 | 10.95 | 95.18 | 1188.10 | 211.28 | 66.17  | 2.12  | 14.00  | 13.68 | 20.25 |
| StHIs 70% 10Hz 80um | 1.97                    | 1.97       | 17.99 | 5.15 | 12.89 | 0.71 | 76.35  | 20.83 | 0.07 | 4.25  | 12.44 | 20.89  | 36.09  | 54.76  | 28.51 | 471.49 | 12.91 | 10.30 |
| T1 70% 10Hz 80um  | 3.75                    | 3.75       | 16.67 | 6.69 | 24.79 | 0.73 | 178.70 | 23.07 | 0.13 | 6.39  | 18.15 | 9.58   | 18.00  | 67.80  | 85.11 | 270.63 | 23.86 | 10.42 |
| ML3B 70% 10Hz 80um | 6.59                    | 6.59       | 14.24 | 10.95 | 30.90 | 2.18 | 271.98 | 175.26 | 0.17 | 11.13 | 41.67 | 100.06 | 115.55 | 112.03 | 5.98  | 329.28 | 26.76 | 1.39  |
| KL2 70% 10Hz 80um | 7.34                    | 7.34       | 13.52 | 11.36 | 30.75 | 2.61 | 296.47 | 303.48 | 0.17 | 11.05 | 41.18 | 104.84 | 90.28  | 119.22 | 8.63  | 370.67 | 26.50 | 2.10  |
| San Carlos Olivine | 49.42                   | 49.42      | 0.02  | 0.07 | 6.80  | 0.00 | 3.15   | 188.18 | 0.14 | 7.84  | 124.40 | 2281.98 | 1.69   | 50.71  | 0.01  | 0.00   | 0.01  | 0.01  |
| SP1 5 Hz 80um 70%  | 23.14                   | 23.14      | 64.11 | 0.19 | 0.27  | 0.11 | 552.49 | 78659.60 | 0.12 | 12.77 | 346.14 | 2630.19 | 1.67   | 1843.97 | 0.18  | 0.00   | -0.01 | 0.03  |
| OPX1 5Hz 95um 70% | 34.42                   | 34.42      | 4.42  | 0.72 | 25.16 | 0.13 | 149.51 | 3840.76 | 0.18 | 7.66  | 63.65 | 711.77  | 0.97   | 42.11  | 0.17  | 0.58   | 1.30  | 0.02  |
| OL1 10Hz 40um 70% | 48.74                   | 48.74      | 0.01  | 0.04 | 3.62  | 0.00 | 0.49   | 15.69  | 0.15 | 10.09 | 130.78 | 2786.68 | 0.51   | 23.01  | 0.08  | 0.18   | -0.02 | 0.02  |
| cpzx-1 10Hz 30um 70% | 16.7                   | 16.70      | 6.69  | 25.82 | 90.14 | 0.48 | 262.90 | 5568.98 | 0.09 | 2.45  | 17.69 | 275.76  | 0.48   | 5.94   | -0.22 | 10.49  | 32.48 | 0.00  |
| opxz-1 10Hz 80um 70% | 34.74                  | 34.74      | 4.95  | 0.63 | 27.63 | 0.12 | 125.96 | 2874.02 | 0.16 | 6.92  | 53.27 | 591.79  | 0.25   | 32.22  | 0.13  | 0.15   | 1.23  | 0.02  |
| opxz-2 10Hz 60um 70% | 34.82                  | 34.82      | 5.26  | 0.82 | 27.71 | 0.13 | 123.21 | 3059.35 | 0.16 | 6.73  | 55.77 | 657.34  | 0.56   | 35.32  | 0.04  | 0.25   | 1.36  | 0.00  |
| ol3-1 10Hz 80um 70% | 49.09                   | 49.09      | 0.00  | 0.01 | 3.22  | 0.00 | 0.34   | 8.30   | 0.15 | 9.34  | 124.92 | 2510.58 | 0.48   | 25.88  | 0.01  | 0.01   | 0.00  | 0.01  |
| ol3-2 10Hz 60um 70% | 16.59                   | 16.59      | 6.19  | 25.15 | 90.50 | 0.45 | 271.20 | 4426.63 | 0.09 | 2.73  | 19.70 | 278.52  | 0.21   | 8.61   | 0.04  | 10.95  | 27.09 | 0.00  |
| sp4 10Hz 80um 70%  | 21.18                   | 21.18      | 67.42 | 0.08 | 0.18  | 0.06 | 464.45 | 69469.90 | 0.10 | 11.40 | 315.43 | 2420.44 | 0.51   | 1518.13 | 0.19  | 0.06   | -0.01 | 0.03  |
Figure A40: Thin section images of sample 313-329 ICPMS area 1 before laser ablation. Areas of analysis are indicated by red circle; spinel 1 (sp1), orthopyroxene 1(opx1), and olivine 1 (ol1). From right to left, images are in plane polarized light (scale bar is ~500μm), cross-polarized light, and reflected light. See Figure 12 for thin section images after laser ablation and general field of view.
Figure A41: Thin section images of sample 313-329 ICPMS area 2 before laser ablation. Area of analysis is indicated by red circle; clinopyroxene (cpx2). From right to left, images are in plane polarized light (scale bar is ~500μm), cross-polarized light, and reflected light.
Figure A42: Thin section images of sample 313-329 ICPMS area 3 before laser ablation. Areas of analysis are indicated by red circle; orthopyroxene 3 (opx3), and olivine 3 (ol3). Ol3-2 is probably cpx not ol based on chemical analysis and the opx may be cpx based on the high Ca concentration, or an exsolution lamelle. From right to left, images are in plane polarized light (scale bar is ~500μm), cross-polarized light, and reflected light.
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