Magnesium isotope analysis of olivine and pyroxene by SIMS: Evaluation of matrix effects

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Abstract

The performance of multi-collector secondary ion mass spectrometry (MC-SIMS) for Mg isotope ratio analysis was evaluated using 17 olivine and 5 pyroxene reference materials (RMs). The Mg isotope composition of these RMs was accurately and precisely determined by multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS), and these measured isotope ratios were used to evaluate SIMS instrumental mass bias as a function of the forsterite (Fo) content of olivine. The magnitude of the Mg isotope matrix effects were ~3‰ in δ^{25}Mg, and are a complex function of olivine Fo content, that ranged from $Fo_{59.3}$ to Fo_{100}. In addition to these Mg isotope matrix effects, Si^+ ion yields and Mg^+/Si^+ ion ratios varied as a complex function of the Fo content of the olivine RMs. For example, Si^+ ion yields varied by ~33%. Based on the observations, we propose instrumental bias correction procedures for SIMS Mg isotope analysis of olivine using a combination of Mg^+/Si^+ ratios and Fo content of olivine. Using this correction method, the accuracy of δ^{25}Mg analyses is 0.3‰, except for analysis of olivine with $Fo_{86\text{-}88}$ where instrumental biases and Mg^+/Si^+ ratios change dramatically with Fo content, making it more difficult to assess the accuracy of Mg isotope ratio measurements by SIMS over this narrow range of Fo content.

Five pyroxene RMs (3 orthopyroxenes and 2 clinopyroxenes) show smaller ranges of instrumental bias (~1.4‰ in δ^{25}Mg) as compared to the olivine RMs. The instrumental bias for the 3 orthopyroxene RMs do not define a linear relationship with respect to enstatite (En) content, that ranged from $En_{85.5\text{-}96.3}$. The clinopyroxene RMs have similar En and wollastonite (Wo) contents but have δ^{25}Mg values that differ by 0.5‰ relative to their δ^{25}Mg values determined by MC-ICP-MS. These results indicate that additional factors (e.g., minor element abundances) likely contribute to SIMS instrumental mass fractionation. In order to better correct for these SIMS matrix effects, additional pyroxene RMs with various chemical compositions and known Mg isotope ratios are needed.

1. Introduction

Magnesium is a major rock-forming element and seventh most abundant element in the Solar System. Magnesium has three naturally occurring stable isotopes (^{24}Mg, ^{25}Mg, and ^{26}Mg) allowing us to study mass-dependent and mass-independent isotope fractionation induced by natural processes. Three analytical approaches are commonly taken to obtain high precision Mg isotope data: solution nebulization multi-collector inductively coupled plasma mass spectrometry (SN-MC-ICP-MS), laser ablation MC-ICP-MS (LA-MC-ICP-MS), and multi-collector secondary ion mass spectrometry (MC-SIMS). Among them, SN-MC-ICP-MS analyses of Mg isotopes are the most reliable. This method entails dissolution of the sample followed by quantitative separation of Mg from all other cations by ion exchange chromatography and Mg isotope ratio analysis using a standard bracketing technique (e.g., Galy et al., 2001; Teng et al., 2010). SN-MC-ICP-MS has been applied to solve important geochemical and cosmochemical questions, such as mantle metasomatism (e.g., Xiao et al., 2013; Hu et al., 2016a; Teng, 2017 and references therein), continental weathering (e.g., Tipper et al., 2006; Pogge von Strandmann et al., 2008), distribution of Mg isotopes in the Earth and early solar system (e.g., Handler et al., 2009; Teng et al., 2010; Schiller et al., 2010; Bourdon et al., 2010; Sedaghatpour and Teng, 2016; Van Kooten et al., 2016; Olsen et al., 2016), radiogenic ^{26}Mg excesses produced by the decay of short-lived ^{26}Al (e.g., Jacobsen et al., 2008; Larsen et al., 2011; Wasserburg et al., 2012), and condensation and evaporation processes in the solar nebula (e.g., Richter et al., 2007; Davis et al., 2015). Meteoritic samples, such as Ca, Al-rich inclusions (CAIs), show micro-scale variations in radiogenic ^{26}Mg and/or the degree of mass-dependent fractionation, and these Mg isotope composition have been determined by both LA-MC-ICP-MS and MC-SIMS at the 5-100 µm spatial resolutions (e.g., Young et al., 2002; Kita et al., 2012; MacPherson et al., 2012, 2017; Bullock et al., 2013; Kawasaki et al., 2015, 2017, 2018, 2019; Ushikubo et al., 2017; Mendybaev et al., 2017; Williams et al., 2017).

Isotope ratios measured by the above three mass spectrometric techniques are inherently different from the absolute Mg isotope ratios of samples due to instrumental mass fractionation (IMF) (e.g., Eiler et al., 1997; Albarède et al., 2004; Horn and von Blanckenburg, 2007). Typically, IMF is corrected by normalization to a standard run under the same conditions as the sample. A bias in this IMF correction can be produced if the sample and standard are not identical in composition, and this bias is often referred to as a matrix or non-spectral interference (e.g., Albarede and Beard, 2004). For SN-MC-ICP-MS, matrix effects are eliminated by purifying samples by ion exchange chromatography and matching the Mg concentration of samples and standards when doing isotope ratio measurements. In contrast, for in-situ techniques, this purification step is not possible and thus LA-ICP-MS and SIMS analysis can be strongly affected by sample matrix. Chaussidon et al. (2017) argued that matrix correction is typically much larger for SIMS than LA-ICP-MS. Thus, matrix-matched standards are always required to obtain accurate Mg isotope data using SIMS techniques. For LA-ICP-MS matrix effects can be minimized or eliminated by use of lasers with ultra-short pulse widths and by loading the plasma with small amounts of water that is co-aspirated into the instrument with the ablated material (Oeser et al., 2014).

In spite of matrix effects that compromise the accuracy of in-situ Mg isotope analyses, the SIMS technique has been successfully used to identify large mass-dependent isotope fractionations (>10‰/amu) in Mg isotopes that have been observed in CAIs with Fractionation and Unidentified Nuclear (FUN) effects (e.g., Krot et al., 2014 and reference therein; Park et al., 2017 and reference therein). Magnesium isotope ratios of FUN CAIs are positively fractionated up to 45‰/amu (e.g., Park et al., 2017), suggesting that FUN CAIs experienced intense evaporation events under near vacuum conditions (Mendybaev et al., 2013; 2017). Technical improvements on the MC-SIMS Mg isotope analysis over the last decade (e.g., Kita et al., 2012; Luu et al., 2013) allow us to investigate mass-dependent fractionation effects smaller than 10‰/amu in CAIs. For example, Mg isotope zoning of melilite in coarse grained CAIs was successfully determined at sub‰ level by MC-SIMS by correcting the SIMS matrix effects of

δ^{25}Mg in melilite solid-solution that changes linearly with Åkermanite contents (Kita et al., 2012; Bullock et al., 2013).

Ushikubo et al. (2013) conducted high precision SIMS Mg isotope analysis of multiple phases in chondrules and calibrated instrumental bias on olivine based on a linear correlation between instrumental bias and Fo content (Fo = [Mg]/[Mg + Fe] molar %) observed in 4 olivine standards (Fo_{59} to Fo_{100}). Olivine in chondrules tends to show positively fractionated Mg isotope ratios (up to 2.3‰/amu) relative to coexisting phases (pyroxene and plagioclase). Based on these observations, Ushikubo et al. (2013) suggested that chondrule melting occurred in an open system. Recently, however, Chaussidon et al. (2017) evaluated matrix effects on Mg isotope analyses of olivine and silicate glasses by SIMS and found complex IMF in olivine as a function of Fo content. Consequently, Mg isotope ratios of olivine in chondrules reported in Ushikubo et al. (2013) might not be accurate due to unrecognized matrix effects. Furthermore, Ushikubo et al. (2013) assumed that the Mg isotope composition of these four olivine standards (including one synthetic olivine) is the same as the Earth's mantle (–0.13‰ relative to the DSM-3 standard; Teng et al., 2010). This assumption, at least for the synthetic olivine standard, may not be valid because Mg isotope compositions of starting materials do not need to be the same as the Earth's mantle and synthetic processes may induce mass-dependent fractionation (e.g., Kita et al., 2012). In order to evaluate mass-dependent fractionation effects in olivine and pyroxene from extraterrestrial materials, it is important to develop suitable reference materials so that the matrix effects associated with SIMS analysis can be fully evaluated.

In this paper, we evaluate matrix effects on SIMS Mg isotope analysis of olivine and pyroxene. We prepared 17 olivine and 5 pyroxene reference materials (RMs) with various chemical compositions. The Mg isotope ratios of individual RMs were determined relative to the DSM-3 scale by either SN-MC-ICP-MS or by LA-MC-ICP-MS techniques, depending on the quantity of available RM and the degree to which high purity mineral separates could be produced. RMs with limited amounts of material, or which were difficult to separate, were analyzed by LA-MC-ICP-MS. These RMs were then subjected to MC-SIMS three Mg isotope ratio measurements. Moreover, major- and minor-element analyses of these olivine RMs were also performed by SIMS and electron microprobe in order to evaluate the relationship between instrumental biases and ionization efficiencies of each element as compared to the chemical composition of the olivine RMs that were determined by electron microprobe analysis. Our goal is to evaluate the applicability of high precision and high spatial resolution SIMS Mg isotope analysis. This work is critical to allow one to assess the accuracy of Mg isotope ratio analysis of extraterrestrial olivine and pyroxene samples, such as those in chondrule and amoeboid olivine aggregate from primitive meteorites, as well as small and precious particles obtained by sample return missions (e.g., *Stardust*, *Hayabusa2*, and *OSIRIS-REx*).

2. Sample preparation

Seventeen olivine (11 terrestrial, 5 meteoritic, and one synthetic) and 5 terrestrial pyroxene RMs were used in this study. Four olivine (SC-Ol, HN-Ol, IG-Ol, and OR-Ol) and all pyroxene RMs in the suite of standards have been used as SIMS calibration standards for oxygen isotope analyses (Kita et al. 2010). Mg isotope ratios of 3 olivine RMs (CL09-08, 19, and 33-Ol) were previously reported in the literature (Xiao et al., 2013). Importantly, the RMs considered in this study also include 5 meteoritic olivine samples. Meteoritic olivine has distinct chemical compositions (in terms of both Fo contents and minor-element abundances), as compared to terrestrial olivine samples. A list of the RMs is reported in Table 1. Eleven olivine and all pyroxene RMs were either taken from mineral separates or handpicked from sieved grain-size fractions that had a range of grain sizes from 100 µm-1000 µm. Aliquots of 5 olivine RMs (KN-Ol, CL09-19-Ol, CL09-08-Ol, CL09-33-Ol, and WN-Ol) were separated from host rocks and meteorites in this study. Olivine grains in Winona meteorite (WN-Ol) were small (~100 µm) and intermixed with metals, so several ~1 mm sized chips of Winona meteorites were mounted in epoxy resin and polished; chips containing olivine-rich areas were then extracted from the epoxy resin and used for this study. The RM, N7325-Ol, is from olivine grains from an ungrouped achondrite (NWA 7325), that has Mg-rich olivine ($Fo_{97.4}$). This RM was obtained from a polished thick section studied by Goodrich et al. (2017). Detail descriptions of each RM, and procedures used for separating olivine grains are summarized in Appendix EA1. Except the WN-Ol and N7325-Ol, 1 to 42 grains (typically 20 grains) of each RM were handpicked under a binocular microscope and mounted in 25 mm diameter epoxy disks for electron microprobe, LA-MC-ICP-MS, and SIMS analysis. Among them, limited numbers of grains (one or two grains) were handpicked for SC-Ol and HN-Ol because they have larger grain sizes (~1 mm) and are known to be homogeneous in their Mg isotope ratios (e.g., Ushikubo et al., 2013). In addition, only two grains of A77257-Ol were handpicked and used for this study because we only have 3 olivine grains of this RM. All grains and Winona chips were placed within a radius of 7 mm from the geometrical center of the mount to minimize instrumental mass fractionation effects due to sample geometry and topography (Kita et al., 2009; Peres et al., 2013). San Carlos olivine (hereafter, SC-Ol) grains were placed near the center of each mount and these grains were used as a running standard during LA-MC-ICP-MS and SIMS analysis (the NWA 7325 thick section was originally mounted with a grain of SC-Ol). All grain mounts of olivine and pyroxene RMs and the NWA 7325 thick section were coated with carbon (20 nm thickness) for electron microprobe and SIMS analyses.

3. Experimental methods

3.1. Electron microprobe analysis

Olivine RMs were measured by electron probe micro analyzer (EPMA) in two sessions. The first session (August 2018) considered the three major and two minor element oxide (MgO, SiO_2, CaO, MnO, and FeO) concentrations of 17 olivine RMs using a Cameca SXFive FE electron microprobe at the University of Wisconsin-Madison. Analyses were performed with an accelerating voltage of 15 kV and a beam current of 20 nA, with a 3 micron diameter beam. Counting time for the peak was 10 seconds. Backgrounds were determined using the mean atomic number procedure (Donovan and Tingle, 1996). The following standards were used for olivine analyses: synthetic forsterite (Mg, Si), NMNH 122142 Kakanui augite (Ca), synthetic FeO (Fe), and synthetic Mn_2SiO_4 (Mn). The probe for EPMA™ (PFE) software was used for data reduction. Calculated detection limits (99% confidence) for the measured oxides listed above were 0.01, 0.02, 0.02, 0.06, and 0.04 wt%, respectively.

A second session (January 2019) for olivines added Cr_2O_3 and NiO to the list of elements, with the same column conditions. Here off peak backgrounds were acquired, with 10 second counts on the background and 10 seconds on the peaks. The same standards were used as above, with the addition of synthetic Cr_2O_3 for Cr and synthetic Ni_2SiO_4 for Ni. Detection limits (wt%) were: MgO-0.02, SiO_2-0.03, CaO-0.02, Cr_2O_3-0.07, MnO-0.07, FeO-0.06 and NiO-0.08.

Major and minor element oxide (Na_2O, MgO, Al_2O_3, SiO_2, CaO, TiO_2 , Cr_2O_3, MnO, and FeO) concentrations of 5 pyroxene RMs were obtained with the SXFive FE electron microprobe under the same column condition for olivine analyses. Off peak backgrounds were acquired, with 10 seconds background and 10 seconds peak counting time. The following standards were used for analyses: Burma jadeite (Na), NMNH 122142 Kakanui augite (Mg, Ca), Grass Valley anorthite (Al), synthetic enstatite (Mg, Si), synthetic TiO_2 (Ti), synthetic Cr_2O_3 (Cr), synthetic Mn_2SiO_4 (Mn) and synthetic FeO (Fe). Calculated detection limits for the measured oxides in wt% were Na_2O-0.02, MgO-0.02, Al_2O_3-0.03, SiO_2-0.03, CaO-0.02, TiO_2-0.05, Cr_2O_3-0.06, MnO-0.05, and FeO-0.06 wt%. In order to evaluate grain-scale homogeneity of each of olivine and pyroxene RMs, 10-20 or 5-8 grains were typically analyzed for each of the olivine or pyroxene RMs, respectively, and individual grains were analyzed by 5 times.

In the following, Mg contents in olivine and pyroxene RMs are expressed as a Fo (= Mg/[Mg + Fe] molar %) and an En (= Mg/[Mg + Fe + Ca] molar %) contents, respectively. Likewise, Ca content in pyroxene RMs is expressed as a Wo (= Ca/[Mg + Fe + Ca] molar %) content. The Fo, En, and Wo contents were calculated by considering total iron as ferrous iron.

3.2. Chemical procedures and Mg isotope analysis by SN-MC-ICP-MS

Aliquots of 4 olivine RMs (SC-Ol, HN-Ol, IG-Ol, and OR-Ol) and all pyroxene RMs, weighing between 4 mg and 19 mg, were used for SN-MC-ICP-MS analysis.
All sample processing was performed under clean laboratory conditions in the Isotope Cosmochemistry and Geochronology Laboratory (ICGL) at Arizona State University (ASU). Each aliquot was cleaned by ultrasonication in Milli-Q® H_2O and then crushed using an agate mortar and pestle. These aliquots were dissolved using in-house distilled, high-purity acids. All olivine fractions were treated with 6 N HCl on a hotplate at 120 °C for 48 hours followed by evaporation to dryness and further treated with a 3:1 mixture of HNO_3:HF at 120 °C for 24 hours. After evaporating to dryness, a final treatment in 12N HCl was used to ensure complete dissolution was achieved. The pyroxene fractions were digested in a 3:1 mixture of HNO_3:HF on a hotplate at 120°C for 48 hours followed by evaporation to dryness; this process was repeated until the sample was fully converted to fluorides. The fluorides were subsequently dissolved using 6N HCl on the hotplate at 120 °C for 48 hr. Following complete dissolution, a 1% fraction was taken from each aliquot for bulk chemical analysis on the iCAP-Q quadrupole ICP-MS at ASU.

A ~10 µg Mg equivalent fraction of each of the dissolved RM aliquots was loaded onto a quartz column packed with AG® 50W-X8 200-400 mesh cation resin. The Mg was purified using procedures similar to those described previously in Spivak-Birndorf et al. (2009). Following this chemical separation procedure, the Mg yields were verified using the iCAP-Q ICP-MS and were consistently >99%. The purified Mg cuts were dried and then brought into 250 ppb Mg solutions in 3% HNO_3 for analysis of Mg isotopes via SN-MC-ICP-MS.

Magnesium isotope analyses were performed on the ThermoFinnigan Neptune MC-ICP-MS in medium-resolution mode following procedures described in Spivak-Birndorf et al. (2009) and Bouvier et al. (2011). Instrumental mass fractionation was corrected by sample-standard bracketing using the DSM-3 Mg standard (Galy et al., 2003), and the mass-dependent Mg isotope composition of each RM is reported as $\delta^{25,26}Mg$ values relative to this standard. To verify the accuracy and precision of our measured Mg isotope compositions, the USGS basaltic rock standard BCR-2 was processed through the entire chemical procedure alongside the olivine and pyroxene RMs and analyzed using the same SN-MC-ICP-MS protocols as these RMs during two analytical session. The reproducibility of our Mg isotope measurements was evaluated using repeat analyses of the DSM-3 Mg standard and the BCR-2 rock standard over the course of these two analytical sessions and was ± 0.06‰ (2SD) and ± 0.11‰ (2SD) for $\delta^{25}Mg$ and $\delta^{26}Mg$, respectively.

3.3. Mg isotope analysis by LA-MC-ICP-MS

Magnesium three-isotope analyses of 14 olivine RMs were made using a Nu plasma II MC-ICP-MS with a Nd:YLF-pumped Ti:sapphire femtosecond laser ablation (fs-LA) system at the University of Wisconsin-Madison. Typical operating conditions of fs-LA and MC-ICP-MS are summarized in Table 2. The laser spot size at the sample surface was ~13 µm in diameter as determined by the measured width of a line scan conducted using the laser and raster conditions reported in Table 2 on a grain of SC-Ol. For this laser ablation system, the laser spot size is controlled by adjusting the distance between sample and laser objective lens and by an adjustable iris placed before the objective lens. For each analysis, a raster ablation was used that ranged in size from ~1200-6000 μm^2 with various scan speeds (~2-10 µm/sec) and laser repetition rates such that the dosage of laser shots delivered to a spot was similar using different conditions. These changes in laser repetition rate and raster settings were done so that the ion intensity of the RM's matched the ion intensity of the SC-Ol used as a bracketing standard. The ICP-MS was operated in low-mass-resolution mode using a 0.3 mm defining slit. Magnesium isotope ratios were measured using a standard-sample-bracketing method; SC-Ol grains ($Fo_{88.8}$) were used as the bracketing standard. A 60-second on-peak gas blank (laser not firing) was analyzed before each analysis, and this gas blank was subtracted from the signal analyzed for 60 seconds for both unknown samples and the bracketing standard. In general, fs-LA-MC-ICP-MS analysis have been adopted to overcome matrix effects compared with nanosecond laser ablation MC-ICP-MS analysis (e.g., Horn and von Blanckenburg 2007; Steinhoefel et al., 2009; Oeser et al., 2014; Zheng et al., 2018). In this study, to further minimize possible matrix effects on fs-LA-MC-ICP-MS, Mg isotope analyses were performed under wet plasma conditions by co-aspirating ultra-pure water along with the ablated material into the plasma (Oeser et al., 2014). Two analysis sessions were conducted. During one session, ultra-pure water was introduced at a rate of 12 µL/min to a peltier cooled (7 °C) cyclonic spray chamber (condition LA1) and in the second, water was aspirated at a rate of 40 µL/min (condition LA2). Typical $^{24}Mg^{+}$ intensities of SC-Ol under the condition LA1 and LA2 were 4.8 V and 2.9 V, respectively. The differences in ion intensities reflects the fact that instrument sensitivity is reduced as more water is added to the system (Zheng et al., 2018). The δ^{25}Mg external reproducibilities of the bracketing standard (SC-Ol) were ± 0.08‰ (2SD) and ± 0.17‰ (2SD) over the course of 12 hours for condition LA1 and LA2, respectively. Mg isotope ratios of each RM were determined as $\delta^{25,26}$Mg values relative to the SC-Ol bracket standard and these $\delta^{25,26}$Mg values were normalized to DSM-3 scale by using $\delta^{25,26}Mg_{DSM\text{-}3}$ values of SC-Ol, as determined using SN-MC-ICP-MS analysis at IGCL, ASU.

3.4. Mg isotope analysis by MC-SIMS

Magnesium three-isotope analyses of olivine and pyroxene were performed in 4 sessions utilizing the WiscSIMS Cameca IMS 1280 at the University of Wisconsin-Madison equipped with a radio-frequency (RF) plasma ion source. We used two primary ion species (O^{-} and O_2^{-}), which were accelerated by 23 kV (–13 kV at the ion source and +10 kV at the sample surface) and were focused to ~9 or ~7.5 µm in diameter at 2.6 nA or 1 nA, respectively. Beam sizes were determined by SEM observations after SIMS analyses (Fig. 1). Secondary ion optics were adjusted to 200× magnification from the sample surface to the field aperture (4000 µm square) with a 50 eV energy window. Secondary Mg ions ($^{24}Mg^{+}$, $^{25}Mg^{+}$, $^{26}Mg^{+}$) were detected on multi-collector Faraday Cups (FCs) using one 10^{10} ohm and two 10^{11} ohm resistors for $^{24}Mg^{+}$, and $^{25,26}Mg^{+}$, respectively. The mass resolving power at 10% peak height was set to ~2500 (entrance slit; 90 µm and exit slit 500 µm) and contributions of $^{48}Ca^{2+}$ and $^{24}Mg^{1}H^{+}$ to ^{24}Mg and $^{25}Mg^{+}$ peaks were negligibly small. A typical mass spectrum is provided in Appendix EA2. The secondary ion optics are similar to that described in Kita et al. (2012) and Ushikubo et al. (2013). SC-Ol ($Fo_{88.8}$) grains were used as a bracketing standard for both olivine and pyroxene measurements. Typical $^{24}Mg^{+}$ count rates of SC-Ol by using O^{-} and O_2^{-} primary beams were ~2.4×10^{8} and ~2.3×10^{8} cps, respectively. Note that secondary ionization efficiency of Mg with O_2^{-} primary beam is higher than that with O^{-} primary beam (Kita et al., 2000). A single analysis takes 8 min, including 100 s of presputtering, ~80 s for automated centering of secondary beam (DTFA-X, DTFA-Y), and 300 s of integration (10 s × 30 cycle) of the secondary ion signals. The baseline of the FC detectors was monitored during each presputtering and averaged over eight analyses. External reproducibilities (2SD) of $\delta^{25}Mg_m$ and $\delta^{26}Mg_m$ were 0.10‰ and 0.17‰ for O^{-} analysis and 0.09‰ and 0.16‰ for O_2^{-} analysis, respectively.

We follow a data reduction scheme described in Ushikubo et al. (2017). Mass-dependent instrumental bias (f^*_{25} in the unit of ‰) of a RM is expressed as:

$$f^*_{25\ (RM)} = [(1 + \delta^{25}Mg_m/1000)/(1 + \delta^{25}Mg_{DSM\text{-}3}/1000) - 1] \times 1000 \quad (1)$$

$\delta^{25}Mg_m$ represents a raw-measured, background-corrected $\delta^{25}Mg$ value of a RM measured by SIMS, which is expressed in δ-notation by normalizing to the absolute Mg isotope ratio ($^{25}Mg/^{24}Mg$ = 0.12663, Catanzaro et al., 1966). $\delta^{25}Mg_{DSM\text{-}3}$ represents a $\delta^{25}Mg$ value relative to DSM-3 that is determined by SN- or fs-LA-ICP-MS analyses. In order to correct instrumental drift during a SIMS session, the instrumental bias (f^*_{25}) of each RM was normalized to the bias of the running standard (SC-Ol). The relative bias* for a RM is defined as:

$$\text{bias}^*_{25\ (RM\text{-}SCOl)} = [(1 + f^*_{25\ (RM)}/1000)/(1 + f^*_{25\ (SCOl)}/1000) - 1] \times 1000 \quad (2)$$

The $f^*_{25\ (SCOl)}$ represents an average f^*_{25} value that is calculated from eight bracket analyses of the running standard (SC-Ol) for each bracket. In general, instrumental mass bias is better-evaluated using δ^{26}Mg values because the mass difference between ^{24}Mg and ^{26}Mg isotopes is larger as compared to the difference between ^{24}Mg and ^{25}Mg isotopes. However, the fs-LA-MC-ICP-MS analyses were done at a mass resolving power of 400, which is insufficient to resolve $^{26}Mg^+$ from possible $^{12}C^{14}N^+$ and $^{52}Cr^{2+}$ isobars, making it challenging to assess the accuracy of $\delta^{26}Mg_{DSM\text{-}3}$ values determined by fs-LA. Thus we prefer to use δ^{25}Mg values to evaluate instrumental mass bias. Moreover, meteoritic olivine RMs may have excess radiogenic ^{26}Mg, making δ^{25}Mg values the best choice for evaluating IMF.

In addition to the above analysis conditions, a limited numbers of olivine RMs were analyzed for 300 cycles for each spot (~50 min) in order to examine the drift of f^*_{25} with the depth of the analysis. To obtain complete depth profile from the surface, only a short presputtering time (10s) was applied and no secondary deflector adjustments (DTFA-X, DTFA-Y) were performed for these analyses. Secondary deflector adjustments for these analyses were performed on a spot adjacent to and just prior to the depth profile analysis.

3.5. Major and minor element analyses by SIMS

Major and minor element analyses (Na, Mg, Al, Si, Ca, Cr, Mn, Fe, and Ni) of 17 olivine RMs were performed with the WiscSIMS Cameca IMS 1280. As with the case for Mg isotope analysis, two different primary ion species (O^- and O_2^-) were used, which were focused to ~2 or ~1.5 µm diameter at 16 pA or 6 pA, respectively. Secondary ion optics was operated under the same conditions for Mg isotope analysis described in 3.4, except for the mass resolving power that was set to ~3000. A secondary $^{24}Mg^+$ ion was detected by an axial FC (FC2) with a 10^{11} ohm resistor and the other secondary ions ($^{23}Na^+$, $^{27}Al^+$, $^{28}Si^+$, $^{40}Ca^+$, $^{52}Cr^+$, $^{55}Mn^+$, $^{56}Fe^+$, and $^{60}Ni^+$) and the mass 22.7 for stabilizing magnetic field for $^{23}Na^+$ were detected by an axial electron multiplier (EM) with magnetic peak jumping mode. SC-Ol grains were used as a running standard. Typical $^{24}Mg^+$ count rates of SC-Ol for O^- and O_2^- analyses were ~8.5×10^5

and ~8.6 × 10^5 cps, respectively. Per cycle, the count duration for $^{24}Mg^+$, $^{28}Si^+$, and $^{56}Fe^+$ ions were 2 seconds, and for the mass 22.7 and $^{23}Na^+$, $^{27}Al^+$, $^{40}Ca^+$, $^{52}Cr^+$, $^{55}Mn^+$, and $^{60}Ni^+$ ions were 1 second. The waiting duration for $^{23}Na^+$, $^{27}Al^+$, $^{28}Si^+$, $^{55}Mn^+$, $^{56}Fe^+$, and $^{60}Ni^+$ ions were 1.6 seconds, for $^{24}Mg^+$ and $^{52}Cr^+$ ions were 2.4 seconds, for the $^{40}Ca^+$ ion was 3.0 second, and for the mass 22.7 was 2.0 second. A single analysis takes 6 min, including 100 s of presputtering, ~80 s for automated centering of secondary beam (DTFA-X, DTFA-Y), and 160 s of integration (32 s × 5 cycle) of the secondary ion signals.

For SIMS analyses, an ion yield of Mg (or Si) is defined as count rate (per second) of Mg (or Si) divided by primary ion beam intensity (nA). A relative sensitivity factor (RSF) of the $^{24}Mg^+/^{28}Si^+$ ratio (hereafter referred as Mg/Si RSF) is expressed as

$$\text{Mg/Si RSF} = (^{24}\text{Mg}^+/^{28}\text{Si}^+)/(\text{Mg cpfu/Si cpfu}) \tag{3}$$

where ($^{24}Mg^+/^{28}Si^+$) is a ratio of count rates of secondary ions $^{24}Mg^+$ and $^{28}Si^+$, and Mg (or Si) cpfu represents a number of cations of Mg (or Si) per oxygen in the oxide formula, which is determined by EPMA analyses.

4. Results

Definitions of measured parameters used in the following are summarized in Table 3.

4.1. EPMA analyses

Representative chemical compositions of olivine and pyroxene RMs are summarized in Table 4. Complete electron microprobe data of olivine and pyroxene RMs are given in Appendix EA3. Electron microprobe data were collected during three analytical sessions. The first session (August 2018) was carried out to evaluate the Fo homogeneity of 8 olivine RMs (Table EA3-1).

The second session (January 2019) was carried out to evaluate Fo homogeneity of additional 9 olivine RMs (Table EA3-1) and to determine minor element abundances including Cr and Ni in all of olivine RMs (Table EA3-2). The third session (September 2019) was carried out to determine the major and minor element compositions and homogeneity of all pyroxene RMs (Table EA3-1). Homogeneities of Fo and En contents are summarized in Appendix EA4. The Fo contents of 17 olivine RMs and the En contents of 5 pyroxene RMs range from 59.3 to 100 and 48.6 to 96.3, respectively. Variations in Fo or En contents for each olivine or pyroxene RM are within ± 0.7 unit (1SD) and most of them are within ± 0.3 unit (1SD).

4.2. SN- and LA-MC-ICP-MS analyses

The Mg isotope ratios of the USGS basaltic rock standard (BCR-2), 4 olivine (HN-Ol, IG-Ol, SC-Ol, and OR-Ol), and 5 pyroxene (Sp79-11, IG-Opx, IG-Cpx, JE En, and 95AK-6) RMs analyzed by SN-MC-ICP-MS are reported as $\delta^{25,26}Mg_{DSM\text{-}3}$ values (Table 5). The $\delta^{25,26}Mg_{DSM\text{-}3}$ values of 3 olivine RMs (CL09-08-Ol, CL09-19-Ol, and CL09-33-Ol) which have been determined by Xiao et al. (2013) are also shown in Table 5. The BCR-2 standard resulted in $\delta^{25}Mg_{DSM\text{-}3}$ = –0.05 ± 0.08‰ (2SD), which is in agreement with the recommended value ($\delta^{25}Mg_{DSM\text{-}3}$ = –0.12 ± 0.02‰, 2SD; Teng, 2017) within uncertainties. Four olivine and 5 pyroxene RMs have $\delta^{25}Mg_{DSM\text{-}3}$ values ranging from –0.37 ± 0.09‰ to –0.01 ± 0.06‰ and –0.74 ± 0.05‰ to –0.04 ± 0.08‰ (2SD), respectively. The $\delta^{25}Mg_{DSM\text{-}3}$ value of the SC-Ol is determined to be –0.07 ± 0.09‰ (2SD), which is also in agreement with the average value of San Carlos olivine ($\delta^{25}Mg_{DSM\text{-}3}$ = –0.13 ± 0.03‰, 2SD) reported in Hu et al. (2016b).

We analyzed 14 olivine RMs by fs-LA-MC-ICP-MS under the two different analytical conditions (LA1 and LA2, see the section 3.3). Under the condition LA1, $\delta^{25}Mg_{DSM\text{-}3}$ values of OR-Ol ($Fo_{59.3}$) and IG-Ol ($Fo_{89.6}$) are determined to be –0.06 ± 0.08‰ (2SD) and –0.04 ± 0.05‰ (2SD), respectively, which are consistent with those obtained by SN-MC-ICP-MS (–0.01 ± 0.06‰ (2SD) and –0.03 ± 0.09‰ (2SD), respectively). $\delta^{25}Mg_{DSM\text{-}3}$ values of SW-Ol ($Fo_{81.8}$) from the Springwater meteorite and N7325-Ol ($Fo_{97.4}$) from the NWA 7325 meteorite are determined to be –0.09 ± 0.06‰ and –0.32 ± 0.07‰ (2SD), respectively. The $\delta^{25}Mg_{DSM-3}$ value of SW-Ol is also agreement with a literature value (–0.11 ± 0.03‰, 2SE; Handler et al., 2009). However, the $\delta^{25}Mg_{DSM-3}$ value of N7325-Ol with high $Fo_{97.4}$ is ~0.16‰ lower than a literature value (–0.16 ± 0.02‰, 2SE; Koefoed et al., 2016). Interestingly, the $\delta^{25}Mg_{DSM-3}$ value of WN-Ol with high $Fo_{95.5}$ from the Winona meteorite, is –0.29 ± 0.07‰ (2SD), which is also ~0.14‰ lower than that of a bulk Winona meteorite (–0.15 ± 0.04‰, 2SD; Sedaghatpour and Teng, 2016). Although it is possible that Mg isotope ratios of WN-Ol and the bulk Winona meteorite are different, the low $\delta^{25}Mg_{DSM-3}$ values observed in high Fo samples relative to the literature values suggest that small extent of matrix effects (~0.16‰/amu) exist on fs-LA-MC-ICP-MS analyses of olivine with high Mg contents under the condition LA1.

In order to overcome the problem, we introduced more water to the ICP (40 µL/min, condition LA2) compare to the condition LA1 (12 µL/min). The Mg isotope ratios of 13 olivine RMs analyzed under the condition LA2 are reported as $\delta^{25,26}Mg_{DSM-3}$ values in Table 5. Thirteen olivine RMs have $\delta^{25}Mg_{DSM-3}$ values ranging from –0.89 ± 0.20‰ to 0.04 ± 0.17‰ (2SD). For comparison, $\delta^{25,26}Mg_{DSM-3}$ values of olivine grains from the Springwater and NWA 7325 meteorites, which have been determined by Handler et al. (2009) and Koefoed et al. (2016), respectively, are also shown in Table 5. Under the condition LA2, high Fo content samples (WN-Ol and N7325-Ol) have greater $\delta^{25}Mg_{DSM-3}$ values (–0.04 ± 0.08‰ (2SD) and –0.07 ± 0.14‰ (2SD), respectively) relative to those obtained using LA1 conditions. The $\delta^{25}Mg_{DSM-3}$ values for these forsteritic olivines measured using LA2 conditions agree with the literature values of the bulk Winona meteorite (Sedaghatpour and Teng, 2016) and olivine from NWA 7325 meteorite (Koefoed et al., 2016), respectively. Likewise, $\delta^{25}Mg_{DSM-3}$ values determined using LA2 conditions for OR-Ol ($Fo_{59.3}$), IG-Ol ($Fo_{89.5}$), and HN-Ol (Fo_{100}) are consistent with those obtained by SN-MC-ICP-MS within 2SD uncertainties (see Table. 5). The lower precision obtained for LA2 is likely driven by the decrease in sensitivity associated with the large amount of water co-aspirated with the ablated material as compared to LA1 conditions. The consistency between fs-LA- and SN-MC-ICP-MS results verifies no significant matrix effects on fs-LA-MC-

ICP-MS measurements within analytical uncertainties (≤ 0.20‰ in δ^{25}Mg, 2SD) under LA2 conditions.

4.3. SIMS analyses

4.3.1. Instrumental bias of olivine RMs

Multiple sessions of SIMS Mg isotope analysis were conducted (Appendix EA5). Olivine RMs were evaluated for Mg isotope heterogeneities by conducting multiple grain analyses (Appendix EA4). The measured $\delta^{25}Mg_m$ values of each olivine RM had limited variability (≤ 0.23‰, 2SD). The f^*_{25} and bias$^*_{25\ (RM\text{-}SCOl)}$ values of all RMs are shown in Table 6 and complete SIMS Mg isotope data for each session are provided in Appendix EA6.

Correction for IMF of isotope ratio analysis by SIMS is typically done by applying an empirical correction. This empirical correction is established by determining a calibration line or curve of IMF values for standards that have a range of major element compositions (e.g., Eiler et al., 1997; Valley and Kita, 2009; Kita et al., 2012; Śliwiński et al., 2016a; 2016b; 2018; Isa et al., 2017; Chaussidon et al., 2017; Scicchitano et al., 2018). The IMF for the 17 olivine RMs that range from Fo_{59} to Fo_{100} defined a ~3‰ range of f^*_{25} values. The f^*_{25} value for olivine analyses using a O^- primary beam ranged from –3.5 to –0.3‰, and from –3.5 to –0.7‰ using an O_2^- primary beam (Table 6). The bias$^*_{25\ (RM\text{-}SCOl)}$ values of 17 olivine RMs defines a complex function versus Fo content. This function is slightly different if an O^- or O_2^- primary ion beam is used (Fig. 2a and 2b, respectively). In general, bias$^*_{25\ (RM\text{-}SCOl)}$ values are maximum at around Fo_{80} and are lowest for near-pure forsterite RMs (SK-Ol and HN-Ol). The change in IMF for olivine from Fo_{59} to Fo_{80} is approximately 1 ‰. There is a 3 ‰ change in IMF from Fo_{80} to Fo_{100}, but this change is not a smooth function of Fo content. In the case of O^- analysis, A77257-Ol ($Fo_{85.7}$) shows the bias$^*_{25\ (RM\text{-}SCOl)}$ value ~1.5‰ higher those of RMs with similar Fo contents (Fig. 2a). The same RM shows a slightly enhanced bias$^*_{25\ (RM\text{-}SCOl)}$ value if an O_2^- primary beam was used (Fig. 2b). In both primary beam conditions, the bias$^*_{25\ (RM\text{-}SCOl)}$ values zigzag between

Fo_{89} and Fo_{97}, and decrease by ~1‰ at Fo_{100}. We conducted four sessions of SIMS Mg isotope analyses (FI1 and FI3 with O_2^- and FI2 and FI4 with O^-) and confirmed that the complex relationship between IMFs and Fo contents was reproduced. The comparisons of the relationships between IMF and Fo content obtained from each session are shown in Appendix EA6. Overall, the complex instrumental biases against Fo content observed in 17 olivine RMs suggest that the instrumental bias on olivine is not entirely controlled by Mg and Fe contents.

Eleven olivine RMs were analyzed for a longer analysis time (total 300 cycles, ~50 min) to determine the changes of IMF as a function of the depth of sputtering. The results are shown in Figs. 3a-d as f^*_{25} values versus analysis cycle numbers. During the first 100 cycles (1000 sec) there are large changes in f^*_{25} values, especially for O^- analysis (Figs. 3a-b). For the rest of the cycles, f^*_{25} values is nearly constant or monotonically decreasing. Figure 4a and 4b show the average bias$^*_{25\ (RM\text{-}SCOl)}$ values for each depth (per 50 cycles) as a function of Fo content. In both O^- and O_2^- analyses, the bias$^*_{25\ (RM\text{-}SCOl)}$ values for first ~100 cycles are not a smooth function of Fo content and those for after 100 cycles tend to be smoother than those for first ~100 cycles.

4.3.2. Ion yields of Mg and Si among olivine RMs

Results of SIMS major and minor element analyses of olivine RMs are listed in Appendix EA7. We examined the variations in ion yields of Mg and Si among 17 olivine RMs (Figs. 5a-d). Ion yields of Mg are not positively correlated with Fo content and show a complex behavior as a function of Fo content (Figs. 5a-b). Ion yields of Si vary by ~33% and ~26% for O^- and O_2^- analyses, respectively (Figs. 5c-d). In the case of O^- and O_2^- analysis, Si ion yield of olivine RMs with $Fo_{59.3}$ to $Fo_{78.0}$ decreases with Fo content, whereas Si ion yield increases in RMs from $Fo_{78.0}$ to $Fo_{91.9}$, except for A77257-Ol ($Fo_{85.7}$). The Si ion yield for RMs with Fo contents from $Fo_{91.9}$ to Fo_{100} defines a complex behavior. For analyses done using a O^- primary beam the Si ion yield largely decreases but for analysis done with a O_2^- primary beam the Si ion yield defines a "zig-zag" pattern showing an overall decrease in Si ion yield (Figs. 5c-d). We do not find a complex behavior for Fe^+ yields against Fo contents (see Appendix EA7).

The ion yields of Mg^+ and Si^+ may also change depending on the sputter-rate of each RM that would differ by Fo contents (e.g., Isa et al., 2017). Thus, we calculate RSFs of secondary ion yields $^{24}Mg^+/^{28}Si^+$ ratios in Figs. 5e-f. The Mg/Si RSF is a complex function of Fo content and it is very similar to the trend in bias*$_{25\ (RM\text{-}SCOl)}$ as a function of Fo content (Figs. 2a-b). The Mg/Si RSFs are nearly constant for RMs with $Fo_{59.3}$ to $Fo_{78.0}$ or from $Fo_{59.3}$ to $Fo_{85.7}$ for O^- or O_2^- analyses, respectively. The Mg/Si RSFs are negatively correlated with olivine RMs of $Fo_{78.0}$ to $Fo_{91.9}$ (at the exception of A77257-Ol) or from $Fo_{85.7}$ to $Fo_{91.9}$ for O^- or O_2^- analyses, respectively. The exact same systematic is observed in bias*$_{25\ (RM\text{-}SCOl)}$. Moreover, irregularity of Mg/Si RSFs against Fo content follows that of bias*$_{25\ (RM\text{-}SCOl)}$, such as A77257-Ol ($Fo_{85.7}$), WK-Ol ($Fo_{94.3}$), WN-Ol ($Fo_{95.5}$), and N7325-Ol ($Fo_{97.4}$) for both O^- or O_2^- analyses.

4.3.3. Instrumental bias of pyroxene RMs

Five pyroxene RMs that range from $En_{48.6}$ to $En_{96.3}$ were analyzed for their Mg isotope ratios using an O_2^- primary beam and the IMF, (f^*_{25}), ranged from 0 to 1.4‰ (Table 6). The range of the pyroxene IMF (1.4‰/amu for $En_{48.6}$ to $En_{96.3}$) is two times smaller than the IMF determined for the olivine RMs (3.3‰/amu for $Fo_{59.3}$ to Fo_{100}). However, the absolute magnitude of the IMF for the pyroxene RMs is more positive than the IMF for the olivine RMs (Table 6). The bias*$_{25\ (RM\text{-}SCOl)}$ values of three orthopyroxene RMs (JE En, IG-Opx, and Sp79-11 En) are not a smooth function of En content (Fig. 6). The two clinopyroxene RMs, IG-Cpx and 95AK-6 Di, have identical En content ($En_{48.6}$) but the bias*$_{25\ (RM\text{-}SCOl)}$ value of IG-Cpx is ~0.5‰ higher than that bias value of 95AK-6 Di.

5. Discussion

5.1. Matrix effects on SIMS Mg isotope analysis of olivine and pyroxene

5.1.1. Instrumental bias of olivine and calibration against Fo contents

Longer SIMS Mg isotope analyses (total 300 cycles, ~50 min) of 11 olivine RMs show significant IMF changes ($f^*_{25,}$ up to ~2.9‰) as a function of sputtering depth (Figs. 3a-d). The present results suggest that instrumental biases with different depth should be characterized for depth profiling Mg isotope analysis of olivine even if samples have homogeneous chemical compositions. The depth-dependent IMF changes also indicate that the IMF behaves differently depending on different analytical conditions such as primary beam current, beam size, integration time, and cycle numbers.

For olivine RMs with $Fo_{59.3}$ to $Fo_{78.0}$, the instrumental biases on both O^- and O_2^- analyses varies by ≤ 0.3‰/amu. Thus, both accurate and precise Mg isotope analysis of olivine with low Fo can be performed. Moreover, Mg/Si RSFs of these low Fo content olivine RMs are near-constant (Figs. 5e-f), suggesting no irregular behavior of secondary ion generation of Mg and Si. For olivine with Fo > 78.0, instrumental biases range over ~3‰/amu and this variability is a complex function of the olivine Fo content. Fitting the variation of IMF as a function of Fo content would result in a poor fit to these data indicating that the IMF is not solely a function of Fo content.

As noted previously, the variation in Mg/Si RSFs as a function of Fo content and the variation in IMF as a function of Fo content are similar, and we consider this to imply that the variations in IMF are in part a result in changes in the ionization efficiency of Mg and Si. The complex relationship between Mg and Si ion yields and Mg and Si contents has been observed in other studies (Steele et al., 1981; Chaussidon et al., 2017, Villeneuve et al., 2019). For example, Villeneuve et al. (2019) found large matrix effects on Si ion yield and instrumental mass fractionation in SIMS Si isotope analysis of olivine and low-Ca pyroxene using two different primary ion species (Cs^+ and O^-). In both cases, relationships between Si ion yield of olivine as a function of Fo content changed at ~ $Fo_{80,}$ although the trends for Cs^+ and O^- analyses were in opposite directions (see Fig. 2 in Villeneuve et al., 2019). The reasons for such complex instrumental bias and ionization efficiency are not well understood (Villeneuve et al., 2019).

The observed relationships between ion yields of Mg^+ and Si^+ and Fo content in this study are broadly consistent with the results for O^- analyses by Chaussidon et al. (2017) and Villeneuve et al. (2019). However, previous studies did not include olivine RMs similar to A77257-Ol ($Fo_{85.7}$) and Mg-rich samples (Fo > 95) that resulted in a significant irregularities in bias*$_{25\ (RM\text{-}SCOl)}$ - against Fo content as observed in this work.

5.1.2. Effect of minor element concentrations in olivine

Olivine RMs with higher Cr concentrations (Cr_2O_3 > 0.2 wt %) tend to have higher bias*$_{25\ (RM\text{-}SCOl)}$ values relative to those of olivine RMs without Cr (Figs. 2a-b). Many meteoritic olivine samples, in which Cr occurs as divalent cation (Cr^{2+}) under relatively reducing conditions, tend to have higher Cr contents as compared to terrestrial olivine samples. As shown in Figs. 2a-b, Cr-bearing olivine RMs (Cr_2O_3 > 0.2 wt%) tend to show larger bias*$_{25\ (RM\text{-}SCOl)}$ values relative to those of olivine RMs with similar Fo contents, although this is not the case for all of them. Figure 7 shows the difference between bias*$_{25\ (RM\text{-}SCOl)}$ values of Cr-bearing olivine RMs compared to mean bias*$_{25\ (RM\text{-}SCOl)}$ values of other olivine RMs with similar Fo contents (hereafter referred as residual bias). The detail calculation of the residual biases are shown in Appendix EA8. In the case of O^- analysis, the residual biases of Cr-bearing olivine RMs with Fo contents ≥ 86 are positively correlated with Cr_2O_3 contents (Fig. 7), and those with Fo ≥ 94 for O_2^- analysis follow a similar correlation (Fig. 7). The other Cr-bearing olivine RMs with lower Fo contents (Fo_{78} for O^- and Fo_{86} and greater for O_2^-) do not follow these correlations. Note that both the IMF and Mg/Si RSFs as a function of Fo content (Figs. 5e-f) are nearly constant for olivine with a Fo content below Fo_{78} for O^- and Fo_{86} for O_2^-, suggesting that secondary ionization processes are not sensitive to sample matrix below these Fo contents. In contrast, small changes in Cr contents (< 1 wt% as Cr_2O_3) in Mg-rich olivine (Fo > 78 for O^- and > 86 for O_2^-) might drastically change the secondary ionization yields and bias*$_{25\ (RM\text{-}SCOl)}$ values. These observations suggest that the secondary ionization process is sensitive to sample matrix in Mg-rich olivine.

5.1.3. Alternative bias correction scheme for olivine

Here, we explore an alternate calibration scheme using the ion yield $^{24}Mg^{+}/^{28}Si^{+}$ ratios for the $bias^{*}_{25\ (RM\text{-}SCOl)}$ values. Figure 8a and 8b show the relationships between $bias^{*}_{25\ (RM\text{-}SCOl)}$ and $^{24}Mg^{+}/^{28}Si^{+}$ ratio divided by Fo content. Since olivine should have near-constant Si atomic abundances, differences in the $^{24}Mg^{+}/^{28}Si^{+}$/Fo content values represent differences in Mg/Si RSFs among olivine RMs. Although it may be logical to use molar Mg/Si ratio instead of Fo content for the normalization, calibrations using Fo content and molar Mg/Si ratio are very similar to each other. In addition, the Fo content of unknown olivine samples can be easily determined by electron microscopic techniques (e.g., SEM-EDS). Therefore, we use ($^{24}Mg^{+}/^{28}Si^{+}$/Fo) values instead of Mg/Si RSFs for the sake of convenience. In the case of O^{-} analysis (Fig. 8a), the $bias^{*}_{25\ (RM\text{-}SCOl)}$ values of 15 olivine RMs with various Fo contents ranging from 59.3 to 97.4 are positively correlated with ($^{24}Mg^{+}/^{28}Si^{+}$/Fo) values and can be fitted with a quadratic function. However, two olivine RMs that are near-pure forsterite (SK-Ol and HN-Ol) do not follow the regression curve from other 15 olivine RMs. In the case of O_2^{-} analysis (Fig. 8b), the $bias^{*}_{25\ (RM\text{-}SCOl)}$ values can be fitted into two separate quadratic curves for Fo contents ranging from 59.3 to 88.8 and 88.8 to 100, respectively. These calibration curves are much smoother than those against Fo contents, and this would improve the accuracy of SIMS Mg isotope analyses of unknown olivine samples. Figure 8c and 8d show residual $bias^{*}_{25\ (RM\text{-}SCOl)}$ values calculated from these calibration curves, which are plotted as a function of Fo content. In the case of O^{-} analysis (Fig. 8c), the residual $bias^{*}_{25\ (RM\text{-}SCOl)}$ values are within ±0.4‰, except for two forsterite (SK-Ol and HN-Ol). In the case of O_2^{-} analysis (Fig. 8d), the residual $bias^{*}_{25\ (RM\text{-}SCOl)}$ values of all olivine RMs are within ±0.2‰ that is smaller than analytical uncertainties (≤ ±0.3‰, 2σ). According the calibration scheme, precision and accuracy of $bias^{*}_{25\ (RM\text{-}SCOl)}$ correction for O_2^{-} analysis would be 0.3‰ for olivine samples with $Fo_{59\text{-}100}$.

Note that the current suite of olivine RMs does not cover the range of Fo contents at around 87 and between 98 and 100, where both the bias*$_{25\ (RM\text{-}SCOl)}$ and ($^{24}Mg^+/^{28}Si^+$/Fo) change significantly within a small range of Fo content. Unknown analyses of olivine with these Fo contents may require additional RMs that match the minor element content of the unknown sample. Confirmation of consistent ionization yields of Mg and Si between RM and unknown olivine with similar Fo content could be used to evaluate reliability of SIMS Mg isotope analyses. It should be noted that we combine the IMF and $^{24}Mg^+/^{28}Si^+$ ratios obtained with very different primary ion intensities (e.g., 1 nA and 6 pA for analyses with O_2^-), suggesting that these data are acquired from different depths. As mentioned above, the functionality of IMF against Fo content changes significantly with depth (Fig. 4), while relative $^{24}Mg^+/^{28}Si^+$ ratios do not (see Appendix EA7). As a result, the proposed calibration scheme would not work very well for Mg isotope analyses obtained from greater depths. This also means that the complex matrix effects in unknown olivine samples can be properly corrected only if a series of RMs are analyzed under the same analytical conditions, such as primary beam setting, integration time and cycle numbers, differences in which may change the depths of the analyses. The new RF plasma ion source maintains constant primary beam intensity (typically ± 2%, 1SD) without changes in beam diameters in a week-long analysis session, in contrast to significant changes observed for a Duoplasmatron ion source (>30% in intensity and >50% in beam diameters; e.g., Tenner et al. 2019). Thus, the use of stable ion source, like RF plasma ion source, would be critical in obtaining more reliable SIMS Mg isotope analyses.

5.1.4. Instrumental bias of pyroxene

Five pyroxene RMs define a complex variation in IMF as a function of En content for O_2^- analysis (Fig. 6). Ushikubo et al. (2013, 2017) evaluated IMF on the same set of pyroxene RMs using an O^- primary ion beam, and assuming that the $\delta^{25,26}Mg_{DSM\text{-}3}$ values of these pyroxenes matched that of pyroxene from the Earth's mantle (–0.13 ± 0.04‰, 2SD; Teng et al., 2010). Here the bias*$_{25\ (RM\text{-}SCOl)}$ values reported in Ushikubo et al. (2013, 2017) are recalculated by using

$\delta^{25}Mg_{DSM-3}$ values of each pyroxene RM obtained by SN-MC-ICP-MS analyses and these, along with the values determined using a O_2^- primary beam from this study are shown in Table 6 and Fig. 6. Ushikubo et al. (2013, 2017) also conducted multiple grain analyses of 5 pyroxene RMs so that we used the results as $\delta^{25}Mg$ homogeneities of each pyroxene RM to evaluate errors for bias*$_{25\ (RM\text{-}SCOl)}$ values. The original SIMS raw data obtained by Ushikubo et al. (2013, 2017) are shown in Appendix EA6. Homogeneities on $\delta^{25}Mg_m$ values of each pyroxene RM are summarized in Appendix EA4 and are within ± 0.23‰ (2SD).

For the three orthopyroxene RMs (JE En, IG-Opx, and Sp79-11 En), bias*$_{25\ (RM\text{-}SCOl)}$ values obtained by O^- and O_2^- analyses are similar to each other (Fig. 6). However, the bias*$_{25\ (RM\text{-}SCOl)}$ values of two clinopyroxene RMs (IG-Cpx and 95AK-6 Di) differ by ~2‰ between O^- and O_2^- analyses. In both cases of O^- and O_2^- analyses, the bias*$_{25\ (RM\text{-}SCOl)}$ values of IG-Cpx are ~0.5‰ higher than that of 95AK-6 Di even though these clinopyroxenes have identical En content ($En_{48.6}$). Note that IG-Cpx contains Cr (Cr_2O_3 = 0.9 wt%), but 95AK-6 Di does not (Cr_2O_3 < 0.07 wt%). Moreover, the two clinopyroxene RMs differ in their Al_2O_3 contents (4.5 wt% in IG-Cpx and 0.9 wt% in 96AK-6 Di), implying that the instrumental bias on pyroxene may be sensitive to minor element abundances. However, because only 5 pyroxene RMs have been studied, further studies on a range of pyroxenes that differ in their En and Wo contents is needed to fully evaluate matrix effects on SIMS Mg isotope analysis of pyroxene.

5.2. Selection and preparation of olivine and pyroxene reference materials for SIMS Mg isotope analysis

In order to conduct SIMS analyses on olivine and pyroxene that are both accurate and precise it is a best practice to characterize the Mg isotope composition of the RM using either SN-MC-ICP-MS or fs-LA-MC-ICP-MS with water addition. However, for some materials such as olivine and pyroxene from terrestrial mantle-derived peridotites (e.g., mantle xenoliths) or igneous rocks one can assume the material has a mantle-like Mg isotope composition ($\delta^{25}Mg_{DSM-3}$ = –0.13 ± 0.04‰, 2SD; Teng et al., 2010). For example, four terrestrial olivine (SC-Ol, UWOl-

1, IG-Ol, and HaK-Ol) and 2 pyroxene (IG-Opx and IG-Cpx) RMs were obtained from mantle-derived peridotites and these RMs have $\delta^{25}Mg_{DSM-3}$ that ranged from –0.14 ± 0.10 to –0.03 ± 0.09‰ (2SD). Moreover, a terrestrial olivine RM from a gabbro (FJ-Ol), a terrestrial olivine RM from a komatiite (WK-Ol), and a terrestrial orthopyroxene (Sp79-11 En) also have mantle-like $\delta^{25}Mg_{DSM-3}$ values ranging from –0.09 ± 0.13‰ to –0.06 ± 0.05‰ (2SD). Meteoritic samples also tend to have a limited range in Mg isotope compositions. Where, for example, chondrites have an average $\delta^{25}Mg_{DSM-3}$ = –0.15 ± 0.04‰ (2SD; Teng et al., 2010), and bulk achondrites overlap with the terrestrial mantle and chondritic Mg isotope ratios (Sedaghatpour and Teng, 2016). In our study, meteorite olivine RMs include samples from an ureilites (Kenna and ALH77257), a pallasite (Springwater), a winonaite (Winona), and an ungrouped achondrite (NWA 7325). These meteoritic olivine RMs have a limited variation in $\delta^{25}Mg_{DSM-3}$ values ranging from –0.07 ± 0.14 to 0.04 ± 0.17‰ (2SD) that are indistinguishable from the average $\delta^{25}Mg_{DSM-3}$ value of the Earth's mantle and chondrites.

Olivine and pyroxene RMs that were either synthetically produced or came from a metamorphosed carbonate have Mg isotope compositions that are significantly different as compared to terrestrial mantle or chondritic Mg isotope compositions. For these types of samples, one must determine their Mg isotope composition by either SN-MC-ICP-MS or fs-LA-MC-ICP-MS if they are to be used to conduct accurate and precise Mg isotope analysis by SIMS. The synthetic pure forsterite RM (HN-Ol), that is endmember Fo, has a $\delta^{25}Mg_{DSM-3}$ value –0.37 ± 0.09 ‰ (2SD) as determined by SN-MC-ICP-MS. This Mg isotope composition reflects the Mg isotope composition of the reagents used to synthesize the olivine, as well as any mass-dependent fractionation that occurred during its synthesis (e.g., Kita et al., 2012). Additionally, olivine and pyroxene RMs that were obtained from metamorphosed carbonate rocks have Mg isotope compositions that are significantly different than mantle or chondritic compositions. These differences arise because Mg-bearing carbonates have lower $\delta^{25}Mg_{DSM-3}$ values as compared to silicates (e.g., Young and Galy, 2004). These low $\delta^{25}Mg_{DSM-3}$ values reflect the fact that at equilibrium Mg-bearing carbonates have low $\delta^{25}Mg_{DSM-3}$ values by 2-3‰ relative to aqueous Mg at room temperature (Li et al., 2015). Moreover, Mg-bearing dolomite in hydrothermally altered rocks show $\delta^{25}Mg_{DSM-3}$ values ranging from –1.15 to –0.23‰ (e.g., Azmy et al., 2013; Lavoie et al., 2014; Geske et al., 2015). Two of the olivine RMs are from metamorphosed carbonates (SK-Ol and 95AK-6 Di) and these samples have distinct Mg isotope ratios compared to igneous rocks. SK-Ol is nearly pure forsterite ($Fo_{99.8}$) that came from a marble from the Beinn an Dubhaich aureole, Isle of Skye, Scotland, where the olivine was produced by the contact metamorphism of dolomite (e.g., Ferry et al., 2011). This olivine has the lowest $\delta^{25}Mg_{DSM-3}$ value (–0.89 ± 0.20‰, 2SD) of all the RMs considered in this study. Additionally, 95AK-6 Di is a clinopyroxene RM, that is from a marble, and this sample has the second lowest $\delta^{25}Mg_{DSM-3}$ value (–0.74 ± 0.05‰, 2SD).

5.3. Implications for Mg isotope fractionations of olivine in meteoritic components

In the WiscSIMS laboratory, 4 out of 17 olivine RMs (SC-Ol, HN-Ol, IG-Ol, and OR-Ol) have been used for instrumental bias corrections for Mg isotope analyses of olivine in Ca, Al-rich inclusions (CAIs), amoeboid olivine aggregates (AOAs), and chondrules (MacPherson et al., 2012, 2017; Ushikubo et al., 2013, 2017; Hertwig et al., 2019; Tenner et al., 2019). Although these previous analyses were conducted to determine the excess $\delta^{26}Mg^*$ after mass fractionation corrections, MacPherson et al. (2012, 2017) and Ushikubo et al. (2017) reported $\delta^{25}Mg$ values of olivine grains in CAIs and AOAs, which show large variations ranging from –2.8 to 11.3‰. The observed variations are much larger than the observed range of the instrumental bias on 17 olivine RMs in this study so that some extent of variations may exist in Mg isotope ratios of olivine among CAIs and AOAs. Furthermore, Ushikubo et al. (2013) reported $\delta^{25}Mg$ values of olivine grains in chondrules, which are systematically higher (up to 2.3‰) than those of coexisting phases (pyroxene and plagioclase). Based on the observations, Ushikubo et al. (2013) suggested that chondrule melting likely occurred in an open system process. However, these data were corrected for IMF using a calibration scheme based on the relationship between instrumental bias and Fo content (Fig. 2a), which fortuitously showed linear relationship if only these 4 RMs (SC-Ol, HN-Ol, IG-Ol, and OR-Ol) were utilized. The IMF of these 4 RMs that were obtained by using the Duoplasmatron source (Ushikubo et al., 2013) are consistent with our results that are obtained by using the RF plasma ion source (Fig. 2a), suggesting that the complex IMF observed in this study is not due to the difference in the primary ion sources (i.e., Duoplasmatron versus RF plasma). Moreover, as noted in section 5.1.2, Cr-bearing olivine RMs (up to 0.8 wt% in Cr_2O_3) tend to show larger $\text{bias*}_{25\ (\text{RM-SCOl})}$ values relative to those of olivine RMs with similar Fo contents (Fig. 7), which were not included for the calibration during the analysis session (Fig. 2a). Olivine grains in chondrules measured by Ushikubo et al. (2013) typically have substantial amount of Cr (up to 1.1 wt% in Cr_2O_3) so that at least a part of the observed Mg isotope variability identified in chondrule olivine may be an analytical artifacts caused by matrix effects. Note that the simple linear regression between IMF and Fo content as done by Ushikubo et al. (2013) may induce additional uncertainties on the IMF correction even if Cr-bearing RMs are not considered for the regression. Further studies based on a suitable set of standards and new calibration scheme based on the combination of Mg^+/Si^+ ratios and Fo contents is required to more accurately determine Mg isotope compositions in chondrule olivine grains. Accurate Mg isotope data that is free of matrix effects will allow one to better address if chondrules formed in an open system in the protoplanetary disk.

6. Conclusion

We performed Mg isotope analyses of 17 olivine and 5 pyroxene RMs using MC-ICP-MS and MC-SIMS and evaluated SIMS matrix effects on Mg isotope analysis.

(1) No significant matrix effects on fs-LA-MC-ICP-MS analysis of olivine ($Fo_{59.3}$ to Fo_{100}) within analytical uncertainties (≤ 0.2‰ in $\delta^{25}Mg$, 2SD) under the wet plasma condition (a rate of introducing water = 40 µL/min).

(2) The IMF for SIMS Mg isotope analysis of olivine ($Fo_{59.3}$ to Fo_{100}) ranges over ~3.3‰ in δ^{25}Mg and is a complex function of Fo content. Moreover, the inferred IMF changes by ~2.9‰ in δ^{25}Mg during a long duration (50 min) spot analysis, suggesting that the IMF of an olivine analysis may change as a function of the depth of the analysis.

(3) For olivine analyses, the relationship between variations in the Mg/Si RSF and IMF, as a function of olivine Fo content, are similar suggesting that the instrumental mass bias changes in part because of differences in the ionization efficiency of Mg and Si. Minor element abundances (e.g., Cr) may also influence secondary ionization processes, especially for Mg-rich olivine. This minor element variability may be the cause of the complex behavior of the IMF as a function of Fo content for the high Fo olivine RMs.

(4) The instrumental bias among most olivine RMs can be fitted using a quadratic function relative to the sensitivity of Mg and Si ions, expressed as ($^{24}Mg^{+}/^{28}Si^{+}$/Fo). According to the regression curve, precision and accuracy of bias*$_{25\ (RM\text{-}SCOl)}$ correction would be 0.3‰ for O_2^{-} analysis.

(5) The magnitudes of IMF on SIMS Mg isotope analysis of pyroxene ($En_{48.6}$ to $En_{96.3}$) range over ~1.4‰ in δ^{25}Mg, which is approximately one half the range as measured in olivine over a similar range in Fe/Mg variation. The Mg isotope IMF on pyroxene is not a smooth function of En content, indicating that additional factors (e.g., minor element abundances) may influence matrix effects. Further studies are required for accurate SIMS Mg isotope analysis of pyroxene.

(6) Most olivine and pyroxene RMs from igneous rocks do not show significant variations in $\delta^{25}Mg_{DSM\text{-}3}$ values ($\leq$ 0.3‰). Therefore, $\delta^{25}Mg_{DSM\text{-}3}$ values of these samples may be assumed to have the same value of the Earth's mantle (–0.13‰: Teng et al., 2010) and such samples can be used as RMs for SIMS Mg isotope analysis. In contrast, $\delta^{25}Mg_{DSM\text{-}3}$ values of RMs from olivine and pyroxene derived from metamorphosed carbonate rocks have $\delta^{25}Mg_{DSM\text{-}3}$ values that are ~1‰ lower than that of the Earth's mantle. Synthetic olivine and pyroxene are also likely to have $\delta^{25}Mg_{DSM\text{-}3}$ values that do not match the

terrestrial mantle and for these samples the $\delta^{25}Mg_{DSM-3}$ values of these RMs must be determined by independent methods such as SN-MC-ICP-MS or fs-LA-MC-ICP-MS.

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Figure captions

Fig. 1. A secondary electron image of an example of SIMS pit. This image was taken after Mg isotope analyses by using O_2^- primary ion beam (1 nA, session FI3). One analysis takes 8 min.

Fig. 2. The bias$^*_{25\ (\text{RM-SCOl})}$ values of 17 olivine RMs obtained by (a) O^- and (b) O_2^- analyses as a function of Fo content. The dashed line in Fig. 2a represents the best-fit line for data obtained by using the Duoplasmatron source reported in Ushikubo et al. (2013). Cr-bearing (~0.8 wt% in Cr_2O_3) RMs tend to show higher bias$^*_{25\ (\text{RM-SCOl})}$ values relative to those of RMs with similar Fo contents, except for KN-Ol ($Fo_{78.0}$). Errors are 2σ.

Fig. 3. The f^*_{25} values of 11 olivine RMs for (a and b) O^- and (c and d) O_2^- analyses against cycle number. One cycle takes 10 seconds so that one analysis (300 cycles) takes ~50 min. Gray bands represent cycle numbers correspond to depths that Mg isotope data (listed in Table 6) were obtained.

Fig. 4. The bias$^*_{25\ (\text{RM-SCOl})}$ values of 11 olivine RMs with different depths obtained by (a) O^- and (b) O_2^- analyses as a function of Fo content. The different symbols and lines represent the average of 50 cycles taken over the total 300 cycle analysis. Error bars are not shown for clarity, but would typically be ± 0.5‰ (2SD), except for the first 100 cycles of O^- analysis that show large changes in f^*_{25} values (Figs. 3a-b) so that errors are larger (~ 1‰) than those for the rest of the cycles.

Fig. 5. Compositional dependences of secondary ion yields and relative sensitivities of Mg^+/Si^+ as a function of olivine Fo content. (a, b) Secondary $^{24}Mg^+$ ion yields vs. Fo contents for O^- and O_2^- analyses, respectively. (c, d) Secondary $^{28}Si^+$ ion yields vs. Fo contents for O^- and O_2^- analyses, respectively. (e, f) Relative sensitivity factors of Mg^+/Si^+ (Mg/Si RSFs) vs. Fo contents for O^- and O_2^- analyses, respectively. Errors of ion yields and Mg/Si RSFs are 2SE. For comparison, the bias$^*_{25\ (\text{RM-SCOl})}$ values of 17 olivine RMs as shown in Fig. 2a and 2b are also plotted as gray square symbols. Errors of the bias$^*_{25\ (\text{RM-SCOl})}$ values are 2σ. Yield = count rate (per second) / primary ion beam intensity (nA). Mg/Si RSF = ($^{24}Mg^+/^{28}Si^+$)/(Mg cpfu/Si cpfu).

Fig. 6. The bias*$_{25\ (\mathrm{RM\text{-}SCOl})}$ values of 5 pyroxene RMs obtained by O^- and O_2^- analyses as a function of En content. Data for O^- analysis (open symbols) are from Ushikubo et al. (2013, 2017), which are re-normalized to the DSM-3 scale using the $\delta^{25}Mg_{DSM\text{-}3}$ values reported in this study. Errors are 2σ.

Fig. 7. Differences between bias*$_{25\ (\mathrm{RM\text{-}SCOl})}$ and modelled bias*$_{25\ (\mathrm{RM\text{-}SCOl})\_calc}$ values of Cr-bearing olivine RMs as a function of Cr_2O_3 content obtained by EPMA analyses. The modelled value (bias*$_{25\ (\mathrm{RM\text{-}SCOl})\_calc}$) is calculated by assuming linear correlation between bias*$_{25\ (\mathrm{RM\text{-}SCOl})}$ value and Fo content among olivine RMs with similar Fo contents (see Appendix EA8 for details). A solid and dashed lines represent least-squares regression lines for Cr-bearing olivine RMs with Fo ≥ 86 (O^- analysis) and that with Fo ≥ 94 (O_2^- analysis), respectively. Assuming intercepts with zero, the slopes are determined to be 1.7 ± 0.3 (2 σ, MSDW = 0.6) for O^- analysis and 1.4 ± 0.4 (2 σ, MSDW = 0.4) for O_2^- analysis, respectively. Errors of Cr_2O_3 (wt%) and residual bias are 2SD and 2σ, respectively.

Fig. 8. The relationships between bias*$_{25\ (\mathrm{RM\text{-}SCOl})}$ values and $^{24}Mg^+/^{28}Si^+$ ratios divided by Fo contents of 17 olivine RMs. (a) In the case of O^- analysis, the bias*$_{25\ (\mathrm{RM\text{-}SCOl})}$ values of 15 olivine RMs with $Fo_{59.3}$ to $Fo_{97.4}$ are positively correlated with ($^{24}Mg^+/^{28}Si^+$/Fo) values. The dashed curve represents a quadratic function regression curve (bias*$_{25\ (\mathrm{RM\text{-}SCOl})}$ = – 0.08 × ($^{24}Mg^+/^{28}Si^+$/Fo)^2 + 1.76 × ($^{24}Mg^+/^{28}Si^+$/Fo) – 7.48; R^2 = 0.98). Note that two nearly pure forsterite RMs (SK-Ol and HN-Ol) do not follow the regression curve. (b) In the case of O_2^- analysis, the bias*$_{25\ (\mathrm{RM\text{-}SCOl})}$ values can be fitted into two separate quadratic curves for Fo contents ranging from 59.3 to 88.8 and 88.8 to 100, respectively. The dashed curve represents the quadratic function regression curve for Fo content ≤ 88.8 (bias*$_{25\ (\mathrm{RM\text{-}SCOl})}$ = – 0.31 × ($^{24}Mg^+/^{28}Si^+$/Fo)^2 + 6.77 × ($^{24}Mg^+/^{28}Si^+$/Fo) – 36.14; R^2 = 0.96) and the solid curve represents the quadratic function regression curve for Fo content ≥ 88.8 (bias*$_{25\ (\mathrm{RM\text{-}SCOl})}$ = – 0.87 × ($^{24}Mg^+/^{28}Si^+$/Fo)^2 + 15.43 × ($^{24}Mg^+/^{28}Si^+$/Fo) – 68.67; R^2 = 0.97). (c, d) Plots of the calibration

residuals as a function of Fo content for O^{-} and O_2^{-} analyses, respectively. For O_2^{-} analysis, $bias^*_{25\ (RM\text{-}SCOl)}$ values of all RMs differs by < 0.3‰ (depicted by dashed lines) from the value predicted by the calibration (solid line). Errors are 2σ.

Appendix

Appendix EA1: Sample descriptions and laser fluorination oxygen isotope data

Appendix EA2: Typical mass spectrum for SIMS Mg isotope analysis

Appendix EA3: EPMA data

Appendix EA4: Summary of Fo and En contents, and $\delta^{25}Mg_m$ homogeneities

Appendix EA5: List of SIMS analytical sessions

Appendix EA6: SIMS Mg isotope data

Appendix EA7: SIMS major and minor element data

Appendix EA8: Calculation of residual biases for Cr-bearing olivine reference materials

Table 1
List of olivine and pyroxene RMs used in this study.

Sample name	Fo or En content[a]	Provenance / Meteorite name (type)	Rock type
Olivine			
OR-Ol	59.3	Orikabe plutonic complex, Japan	gabbro
FJ-Ol	73.4	Mount Fuji, Japan	gabbro
KN-Ol	78.0	Kenna (Ureilite)	meteorite
CL09-19-Ol	79.4	Beiyan, China	peridotite
CL09-08-Ol	80.5	Beiyan, China	peridotite
SW-Ol	81.8	Springwater (pallasite)	meteorite
A77257-Ol	85.7	ALHA77257 (Ureilite)	meteorite
CL09-33-Ol	86.6	Beiyan, China	peridotite
SC-Ol	88.8	San Carlos, USA	peridotite
UWOL-1	89.2	Kilbourne Hole, USA	peridotite
IG-Ol	89.6	Ichinome-gata, Japan	peridotite
HaK-Ol	91.9	Harrat al Kishb, Saudi Arabia	peridotite
WK-Ol	94.3	Barberton, South Africa	komatiite
WN-Ol	95.5	Winona (Winonaite)	meteorite
N7325-Ol	97.4	NWA 7325 (ungrouped achondrite)	meteorite
SK-Ol	99.8	Isle of Skye, Scotland	marble
HN-Ol	100.0	Synthetic forsterite	
Pyroxene			
95AK-6 Di	48.6	Adirondack Mt., USA	marble
IG-Cpx	48.6	Ichinome-gata, Japan	peridotite
JE En	85.5	Unknown	unknown
IG-Opx	88.9	Ichinome-gata, Japan	peridotite
Sp79-11 En	96.3	Adirondack Mt., USA	enstatite

[a] Molar % of forsterite or enstatite end-members based on EPMA analyses performed in this study

Table 2
Summary of operating conditions of LA-MC-ICP-MS measurements.

Laser ablation system	
Laser type	Analyte-fs Ti:sapphire laser (Teledyne-Photon Machines)
Wavelength	266 nm
Pulse-width	~150 fs
beam profile	Gaussian
Ablation cell	two-volume HelEX (CETAC)
He gas flow	~0.55 L min^{-1} [a]
Ar make-up gas flow	~0.8 L min^{-1} [b]
Pulse energy at sample	15 µJ
Repetition rate	9-19 Hz
Ablation mode	Raster
Raster scan speed	2-10 µm s^{-1} (typically 2 µm)
Raster iteration	1 pass
H_2O addition rate	12 or 40 µL min^{-1}
MC-ICP-MS: Nu plasma II	
Mass resolution	low mass resolution
Data collection mode	Time-resolved analysis (TRA) 0.2 s integrations
RF power	1300 W
Coolant Ar gas flow	13.2 L min^{-1}
Auxiliary Ar gas flow	0.8 L min^{-1}
^{24}Mg ion intensity	~3-5 V
On-peak gas blank	~60 s
Data acquisition time	~60 s

[a] Total He gas flow. Sub-equal amounts were delivered to the arm and the chamber
[b] Total Ar flow. Sub-equal amounts were delivered from the nebulizer used for water addition and Ar delivered directly to the aerosol stream

Table 3
Measured parameters used in this study

Parameter	Method	Definition
Fo[a]	EPMA	Fo = Mg/[Mg + Fe] molar %
En[a]	EPMA	En = Mg/[Mg + Fe + Ca] molar %
Wo[a]	EPMA	Wo = Ca/[Mg + Fe + Ca] molar %
$\delta^{x}Mg_{DSM\text{-}3}$[b]	ICP-MS	$\delta^{x}Mg_{DSM\text{-}3} = [(^{x}Mg/^{24}Mg)_{RM}/(^{x}Mg/^{24}Mg)_{DSM\text{-}3} - 1] \times 1000$ (‰)
$\delta^{25}Mg_{m}$[c]	SIMS	$\delta^{25}Mg_{m} = [(^{25}Mg/^{24}Mg)_{RM}/0.12663 - 1] \times 1000$ (‰)
$f^{*}_{25\ (RM)}$	SIMS	$f^{*}_{25\ (RM)} = [(1 + \delta^{25}Mg_{m}/1000)/(1 + \delta^{25}Mg_{DSM\text{-}3}/1000) - 1] \times 1000$ (‰)
$bias^{*}_{25\ (RM\text{-}SCOl)}$	SIMS	$bias^{*}_{25\ (RM\text{-}SCOl)} = [(1 + f^{*}_{25\ (RM)}/1000)/(1 + f^{*}_{25\ (SCOl)}/1000) - 1] \times 1000$ (‰)
Mg/Si RSF[d]	SIMS	Mg/Si RSF = $(^{24}Mg^{+}/^{28}Si^{+})$/(Mg cpfu/Si cpfu)

[a] Fo, En and Wo contents are calculated by considering total iron as ferrous iron.
[b] X = 25 or 26
[c] Absolute $^{25}Mg/^{24}Mg$ ratio (=0.12663) is from Catanzaro et al. (1966)
[d] cpfu = cations per formula unit

Table 4
Major and minor element compositions (wt%) of 17 olivine and 5 pyroxene RMs obtained by EPMA

Sample name	EPMA session	Fo or En content	Na_2O	MgO	Al_2O_3	SiO_2	CaO	TiO_2	Cr_2O_3	FeO	NiO	MnO	Total
Olivine													
OR-Ol	2018 Aug & 2019 Jan.[a]	59.3	-	28.42	-	35.72	0.02	-	b.d.	34.81	b.d.	0.67	99.64
FJ-Ol	2018 Aug & 2019 Jan.[a]	73.4	-	37.24	-	37.63	0.06	-	b.d.	24.11	0.14	0.42	99.60
KN-Ol	2018 Aug & 2019 Jan.[a]	78.0	-	39.42	-	38.58	0.38	-	0.80	19.85	b.d.	0.42	99.45
CL09-19-Ol	2019 Jan.	79.4	-	41.41	-	38.26	0.08	-	b.d.	18.98	0.18	0.22	99.13
CL09-08-Ol	2019 Jan.	80.5	-	42.08	-	38.54	0.05	-	b.d.	18.13	0.29	0.24	99.33
SW-Ol	2018 Aug & 2019 Jan.[a]	81.8	-	42.87	-	38.91	b.d.	-	b.d.	16.99	b.d.	0.31	99.08
A77257-Ol	2019 Jan.	85.7	-	44.95	-	39.07	0.32	-	0.80	13.37	b.d.	0.46	98.97
CL09-33-Ol	2019 Jan.	86.6	-	46.19	-	39.17	0.06	-	b.d.	12.70	0.40	0.17	98.69
SC-Ol	2019 Jan.	88.8	-	48.22	-	40.01	0.07	-	b.d.	10.82	0.42	0.16	99.69
UWOL-1	2018 Aug & 2019 Jan.[a]	89.2	-	47.77	-	39.85	0.06	-	b.d.	10.27	0.41	0.14	98.50
IG-Ol	2019 Jan.	89.6	-	48.63	-	40.12	0.05	-	b.d.	10.09	0.42	0.16	99.48
HaK-Ol	2018 Aug & 2019 Jan.[a]	91.9	-	50.07	-	40.74	0.02	-	b.d.	7.92	0.51	0.10	99.36
WK-Ol	2018 Aug & 2019 Jan.[a]	94.3	-	51.44	-	41.17	0.12	-	0.23	5.54	0.47	0.09	99.05
WN-Ol	2018 Aug & 2019 Jan.[a]	95.5	-	53.63	-	41.80	b.d.	-	b.d.	4.49	b.d.	0.33	100.26
N7325-Ol	2019 Jan.	97.4	-	54.69	-	41.61	0.32	-	0.45	2.58	b.d.	0.12	99.77
SK-Ol	2019 Jan.	99.8	-	56.73	-	41.48	0.04	-	b.d.	0.19	b.d.	0.08	98.52
HN-Ol	2019 Jan.	100.0	-	57.31	-	42.04	b.d.	-	b.d.	b.d.	b.d.	b.d.	99.35
Pyroxene													
95AK-6 Di	2019 Sep.	48.6	0.10	17.92	0.92	54.91	25.41	b.d.	b.d.	1.26	-	0.07	100.59
IG-Cpx	2019 Sep.	48.6	0.50	16.70	4.52	51.70	22.51	0.45	0.91	2.65	-	0.09	100.05
JE En	2019 Sep.	85.5	b.d.	33.16	0.11	56.21	0.22	b.d.	b.d.	9.72	-	0.07	99.49
IG-Opx	2019 Sep.	88.9	b.d.	33.38	3.56	54.38	0.57	0.13	0.44	6.70	-	0.16	99.31
Sp79-11 En	2019 Sep.	96.3	b.d.	37.89	1.42	57.20	0.44	0.09	b.d.	2.03	-	0.41	99.49

b.d. (below detection limit)
- (not measured)
[a] Combined data obtained by two different sessions are summarized in this table. Fo content, MgO, SiO_2, CaO, FeO, and MnO are from session_2018Aug (Table EA3-1). Cr_2O_3 and NiO are from session_2019Jan. (Table EA3-2).

Table 5
Mg isotope data of 17 olivine and 5 pyroxene RMs obtained by SN- and/or LA-MC-ICP-MS

Sample name	Fo or En content[a]	SN-MC-ICP-MS								fs-LA-MC-ICP-MS			
		$\delta^{25}Mg_{DSM-3}$	2SD	2SE	$\delta^{26}Mg_{DSM-3}$	2SD	2SE	N[b]	Ref.	$\delta^{25}Mg_{DSM-3}$	$2\sigma^{c}$	$\delta^{26}Mg_{DSM-3}$	$2\sigma^{c}$
Standards													
DSM-3 250 ppb		0.00	0.06		0.00	0.11		147	This study				
Spex Mg		-1.08	0.04		-2.09	0.07		8	This study				
BCR-2		-0.05	0.08		-0.08	0.13		10	This study				
Olivine													
OR-Ol	59.3	-0.01	0.06		-0.02	0.13		27	This study	0.02	0.09	-0.05	0.24
FJ-Ol	73.4									-0.07	0.20	-0.10	0.30
KN-Ol	78.0									0.04	0.18	-0.01	0.30
SW-Ol	81.8									-0.02	0.14	-0.03	0.16
A77257-Ol	85.7									-0.07	0.14	-0.29	0.13
SC-Ol	88.8	-0.07	0.09		-0.15	0.16		10	This study				
UWOL-1	89.2									-0.14	0.10	-0.24	0.20
IG-Ol	89.6	-0.03	0.09		-0.05	0.15		10	This study	-0.08	0.18	-0.19	0.20
HaK-Ol	91.9									-0.06	0.13	-0.16	0.19
WK-Ol	94.3									-0.09	0.13	-0.17	0.20
WN-Ol	95.5									-0.04	0.09	-0.14	0.16
N7325-Ol	97.4									-0.07	0.14	-0.06	0.10
SK-Ol	99.8									-0.89	0.20	-1.72	0.54
HN-Ol	100.0	-0.37	0.09		-0.70	0.14		10	This study	-0.49	0.14	-0.95	0.17
Pyroxene													
95AK-6 Di	48.6	-0.74	0.05		-1.43	0.11		8	This study				
IG-Cpx	48.6	-0.14	0.10		-0.28	0.19		8	This study				
JE En	85.5	-0.26	0.06		-0.50	0.11		8	This study				
IG-Opx	88.9	-0.04	0.08		-0.07	0.13		8	This study				
Sp79-11 En	96.3	-0.06	0.05		-0.11	0.11		18	This study				
Olivine (Literature data)													
CL09-19-Ol	79.4	-0.21	0.06		-0.37	0.06		2	[1]				
CL09-08-Ol	80.5	-0.21	0.05		-0.41	0.07		4	[1]				
CL09-33-Ol	86.6	-0.25	0.05		-0.47	0.06		2	[1]				
Springwater olivine		-0.11		0.03	-0.22		0.04	7	[2]				
NWA 7325 olivine		-0.16		0.02	-0.23		0.04	6	[3]				

[a] Molar % of forsterite or enstatite end-members based on EPMA analyses performed in this study
[b] Number of analyses
[c] 2σ errors (‰) are propagated both 2SD of fs-LA-MC-ICP-MS analyses and 2SE of $\delta^{25}Mg_{DSM-3}$ (SC-Ol) obtained by SN-MC-ICP-MS analyses.
References; [1] Xiao et al. (2013); [2] Handler et al. (2009); [3] Koefoed et al. (2016).

Table 6

SIMS δ^{25}Mg instrumental biases of 17 olivine and 5 pyroxene RMs and ($^{24}Mg^{+}/^{28}Si^{+}$)/Fo values of 17 olivine RMs

Sample name	Fo or En content	Session_UI1 and UI2 (Duo O^-)				Session_FI4 (RF O^-)			Session_FI3 (RF O_2^-)			Session_FE2 (RF O^-)		Session_FE1 (RF O_2^-)	
		$f^*_{25\,(RM)}$ (‰)	bias$^*_{25\,(RM-SCOl)}$ (‰)	2 σ_a	Ref.	$f^*_{25\,(RM)}$ (‰)	bias$^*_{25\,(RM-SCOl)}$ (‰)	2 σ_a	$f^*_{25\,(RM)}$ (‰)	bias$^*_{25\,(RM-SCOl)}$ (‰)	2 σ_a	($^{24}Mg^{+}/^{28}Si^{+}$)/Fo (× 100)	2 σ_b	($^{24}Mg^{+}/^{28}Si^{+}$)/Fo (× 100)	2 σ_b
Olivine															
OR-Ol	59.3	-0.54	2.31	0.18	[1]	-0.49	1.93	0.23	-1.44	0.42	0.15	8.74	0.78	12.45	0.57
FJ-Ol	73.4					-0.27	2.15	0.30	-1.23	0.62	0.24	8.85	0.29	12.25	0.48
KN-Ol	78.0					-0.27	2.14	0.28	-1.18	0.70	0.23	8.86	0.39	11.92	0.51
CL09-19-Ol	79.4					-1.26	1.35	0.23	-0.94	0.86	0.17	7.59	0.36	11.67	0.46
CL09-08-Ol	80.5					-1.53	1.07	0.23	-0.86	0.94	0.20	7.10	0.35	11.73	0.48
SW-Ol	81.8					-1.60	0.77	0.26	-0.97	0.90	0.20	6.77	0.18	11.78	0.45
A77257-Ol	85.7					-0.63	1.87	0.27	-0.72	1.10	0.27	7.70	0.24	11.45	0.47
CL09-33-Ol	86.6					-2.16	0.44	0.23	-1.31	0.53	0.15	5.89	0.16	9.71	0.43
SC-Ol	88.8	-2.84	0.00	0.17	[1]	-2.41	0.00	0.24	-1.83	0.00	0.17	5.59	0.15	9.11	0.29
UWOL-1	89.2					-2.39	-0.03	0.24	-2.01	-0.12	0.18	5.55	0.28	9.04	0.29
IG-Ol	89.6	-3.09	-0.25	0.15	[1]	-2.67	-0.07	0.24	-1.96	-0.12	0.17	5.52	0.16	8.75	0.32
HaK-Ol	91.9					-2.61	-0.23	0.26	-2.22	-0.34	0.19	5.38	0.15	8.28	0.26
WK-Ol	94.3					-2.38	0.03	0.25	-2.00	-0.19	0.19	5.63	0.15	8.57	0.31
WN-Ol	95.5					-2.62	-0.22	0.24	-2.31	-0.51	0.19	5.55	0.19	8.04	0.26
N7325-Ol	97.4					-2.07	0.25	0.26	-1.98	-0.21	0.20	5.87	0.27	8.57	0.27
SK-Ol	99.8					-3.35	-1.01	0.30	-3.14	-1.30	0.25	5.46	0.24	7.75	0.25
HN-Ol	100.0	-3.80	-0.97	0.15	[1]	-3.54	-1.17	0.24	-3.49	-1.62	0.16	5.40	0.23	7.55	0.24
Pyroxene															
95AK-6 Di	48.6	0.83	3.72	0.18	[2]				0.00	1.81	0.18				
IG-Cpx	48.6	1.33	4.23	0.19	[2]				0.55	2.36	0.17				
JE En	85.5	0.43	3.42	0.15	[1]				1.28	3.09	0.15				
IG-Opx	88.9	0.39	3.38	0.24	[1]				1.41	3.22	0.24				
Sp79-11 En	96.3	-0.27	2.72	0.15	[1]				0.65	2.46	0.15				

[a] 2σ error (‰) = $\sqrt{(2SD_{SIMS})^2 + (2SD_{ICPMS})^2}$, where $2SD_{SIMS}$ represents either δ^{25}Mg homogeneity of each RM or long-term reproducibility of the running standard (SC-Ol), whichever is larger.

[b] 2σ error represents either 2 standard error (2SE) of each measurement or long-term reproducibility (2SD) of the running standard (SC-Ol), whichever is larger.

References; [1] Ushikubo et al. (2013); [2] Ushikubo et al. (2017). All data from Ushikubo et al. (2013, 2017) were renormalized to DSM-3 scale using SN-MC-ICP-MS results.

Figure 1

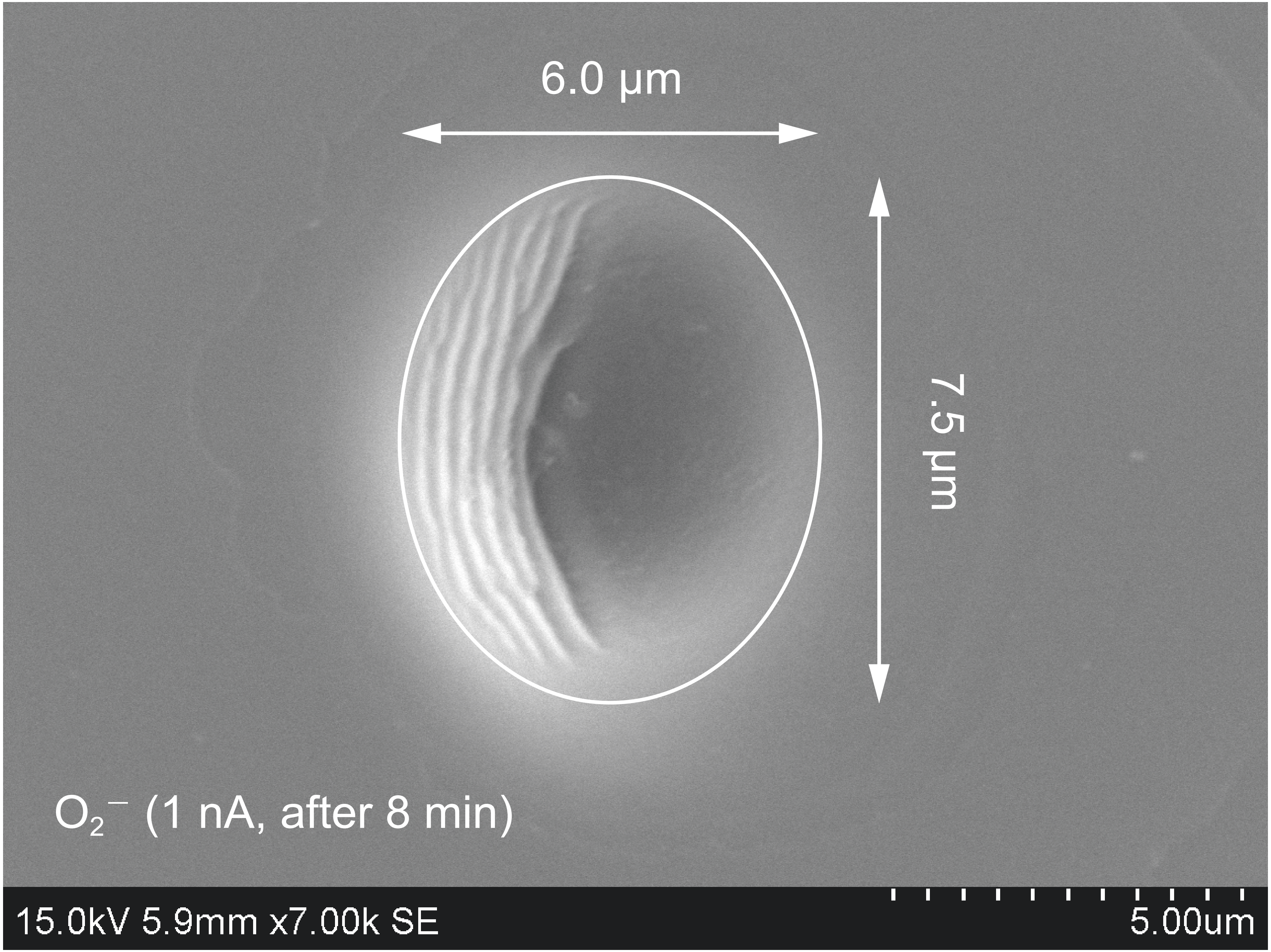
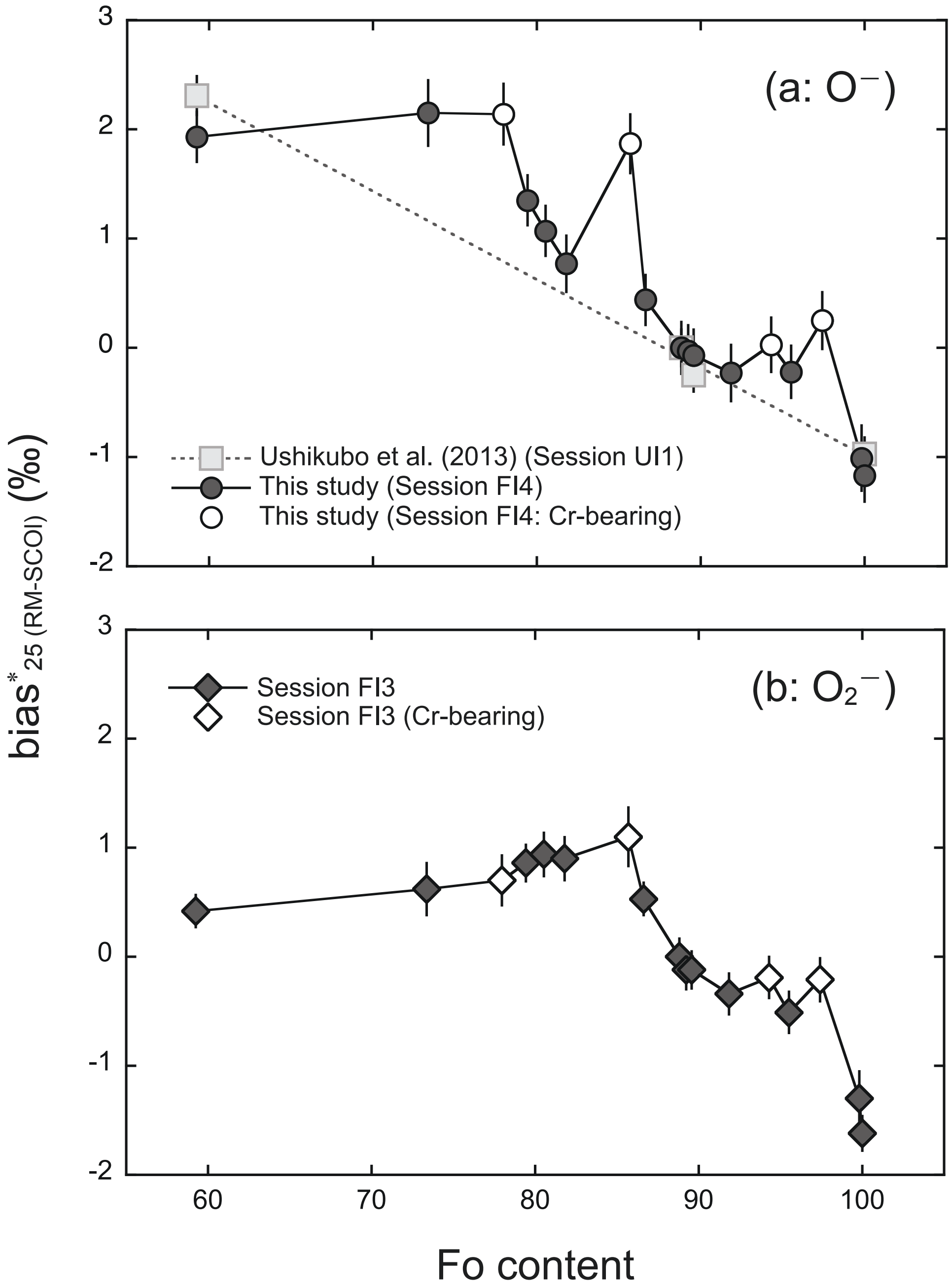


Figure 2



(a: O⁻)
Ushikubo et al. (2013) (Session UI1)
This study (Session FI4)
This study (Session FI4: Cr-bearing)
(b: O_2^-)
Session FI3
Session FI3 (Cr-bearing)
bias*$_{25\ (RM\text{-}SCOl)}$ (‰)
Fo content
3
2
1
0
-1
-2
60
70
80
90
100

Figure 3

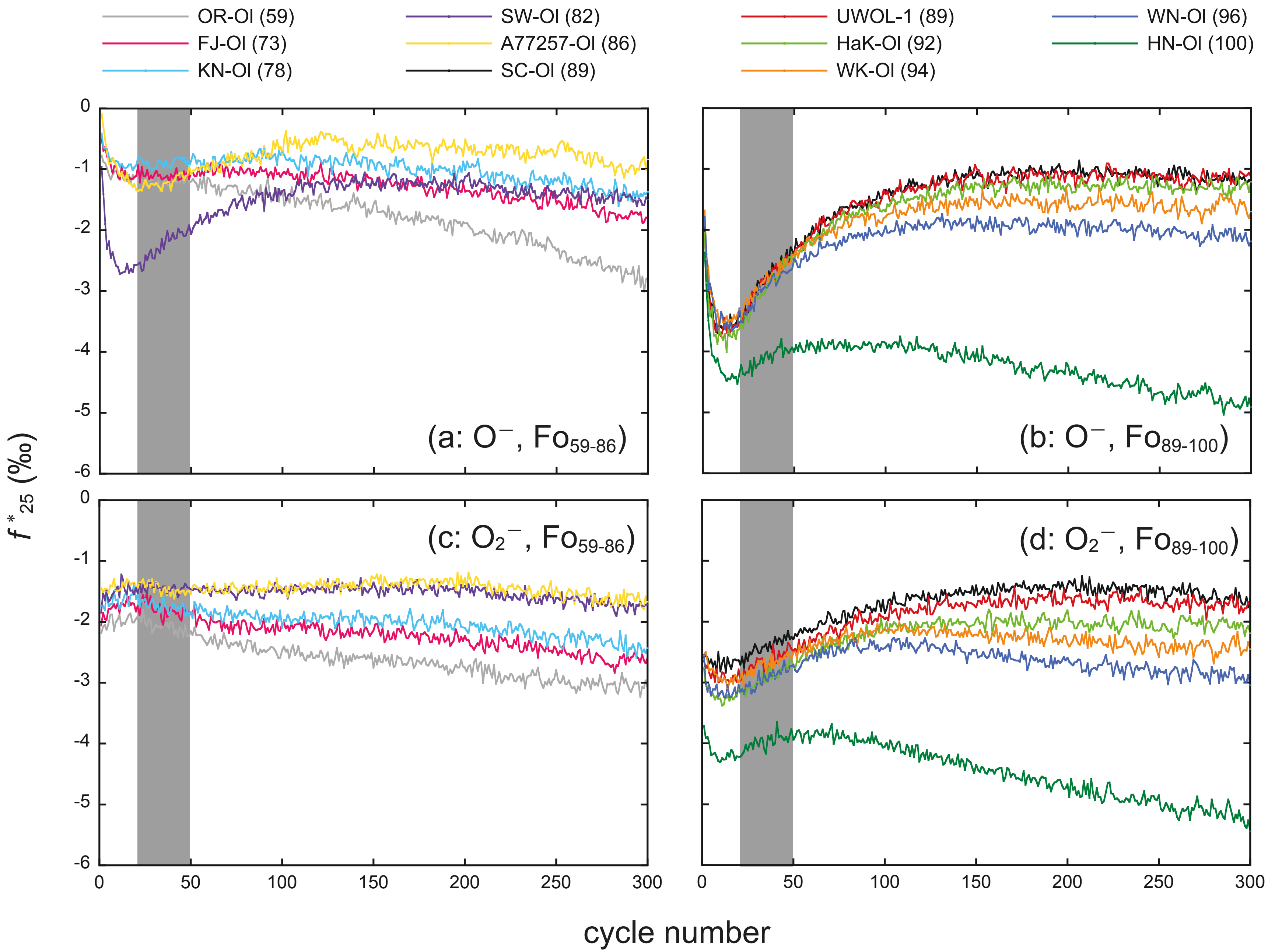
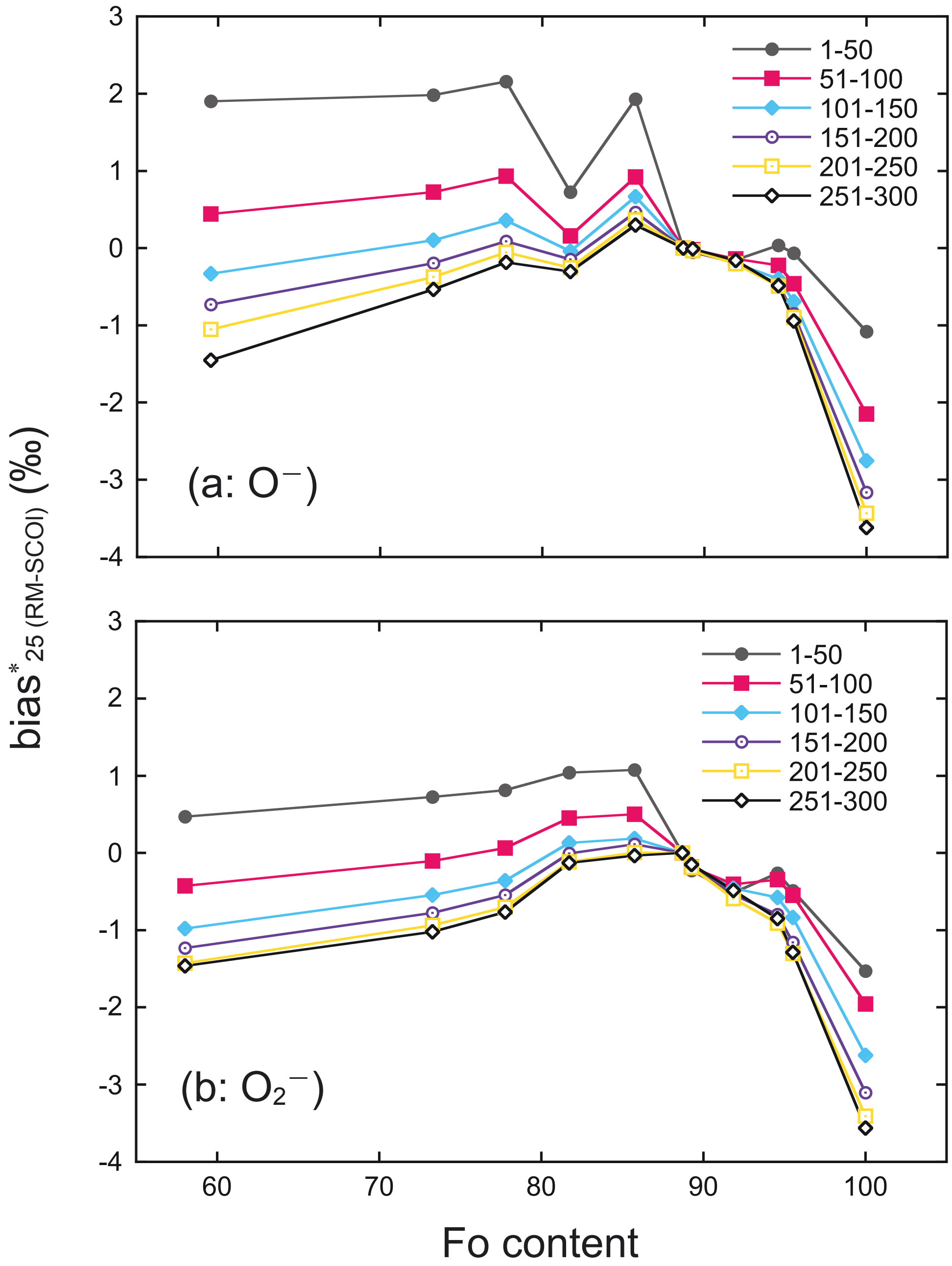
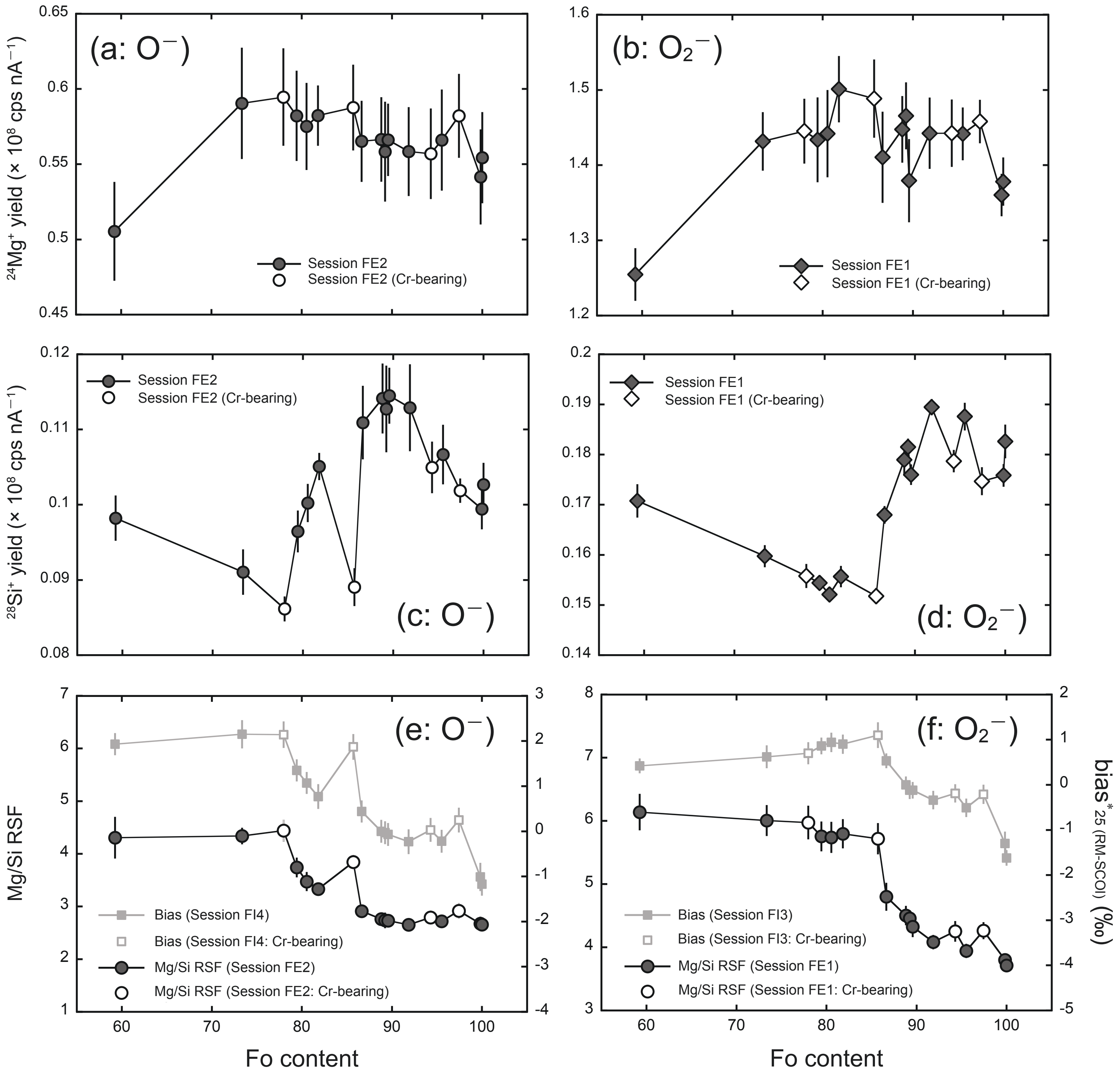

OR-Ol (59)
FJ-Ol (73)
KN-Ol (78)
SW-Ol (82)
A77257-Ol (86)
SC-Ol (89)
UWOL-1 (89)
HaK-Ol (92)
WK-Ol (94)
WN-Ol (96)
HN-Ol (100)
(a: O⁻, Fo59-86)
(b: O⁻, Fo89-100)
(c: O2⁻, Fo59-86)
(d: O2⁻, Fo89-100)
f*25 (‰)
cycle number
0
-1
-2
-3
-4
-5
-6
0
50
100
150
200
250
300

Figure 4



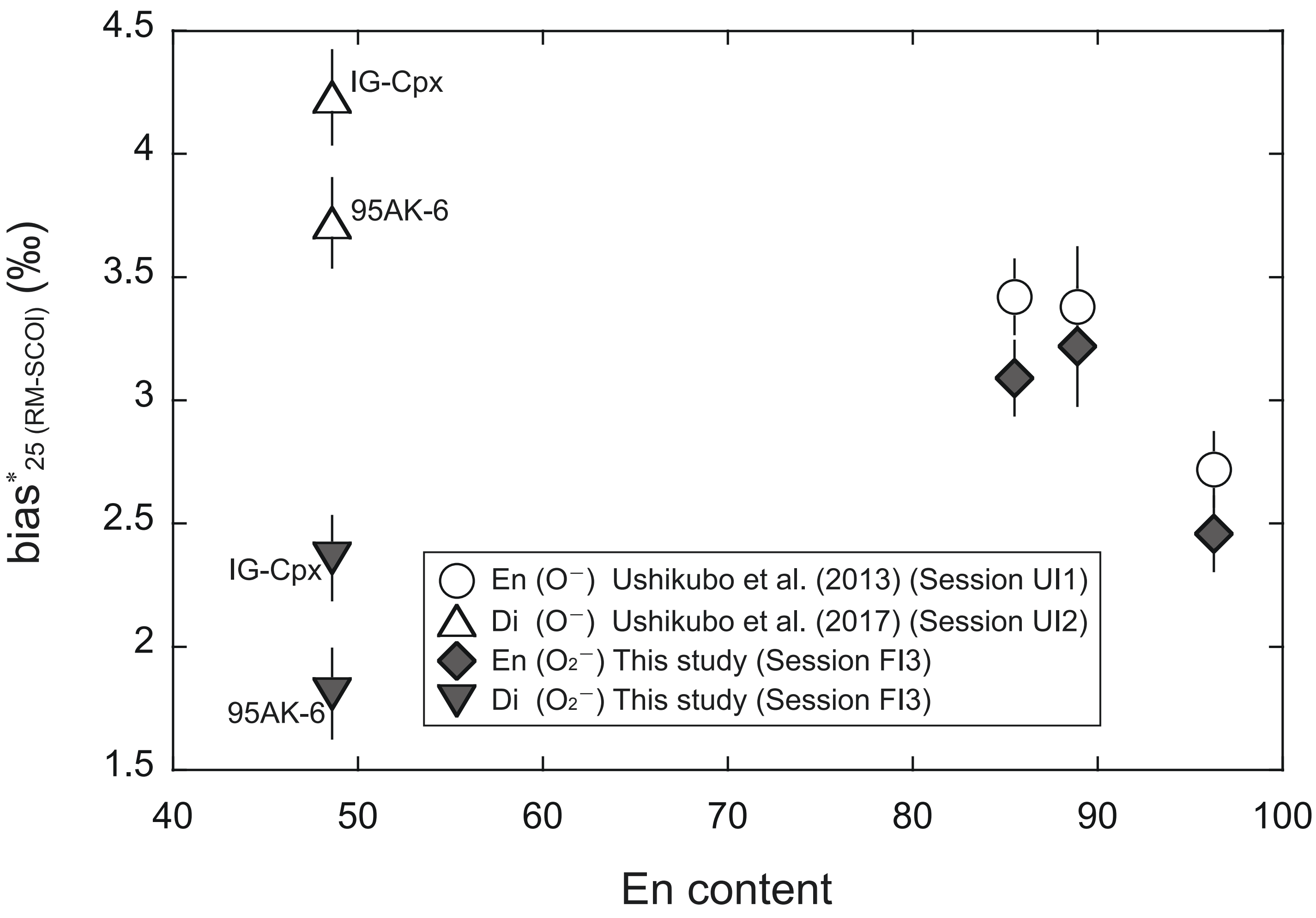
3
2
1
0
-1
-2
-3
-4
1-50
51-100
101-150
151-200
201-250
251-300
(a: O⁻)
bias*25 (RM-SCOl) (‰)
1-50
51-100
101-150
151-200
201-250
251-300
(b: O2⁻)
60
70
80
90
100
Fo content

Figure 5



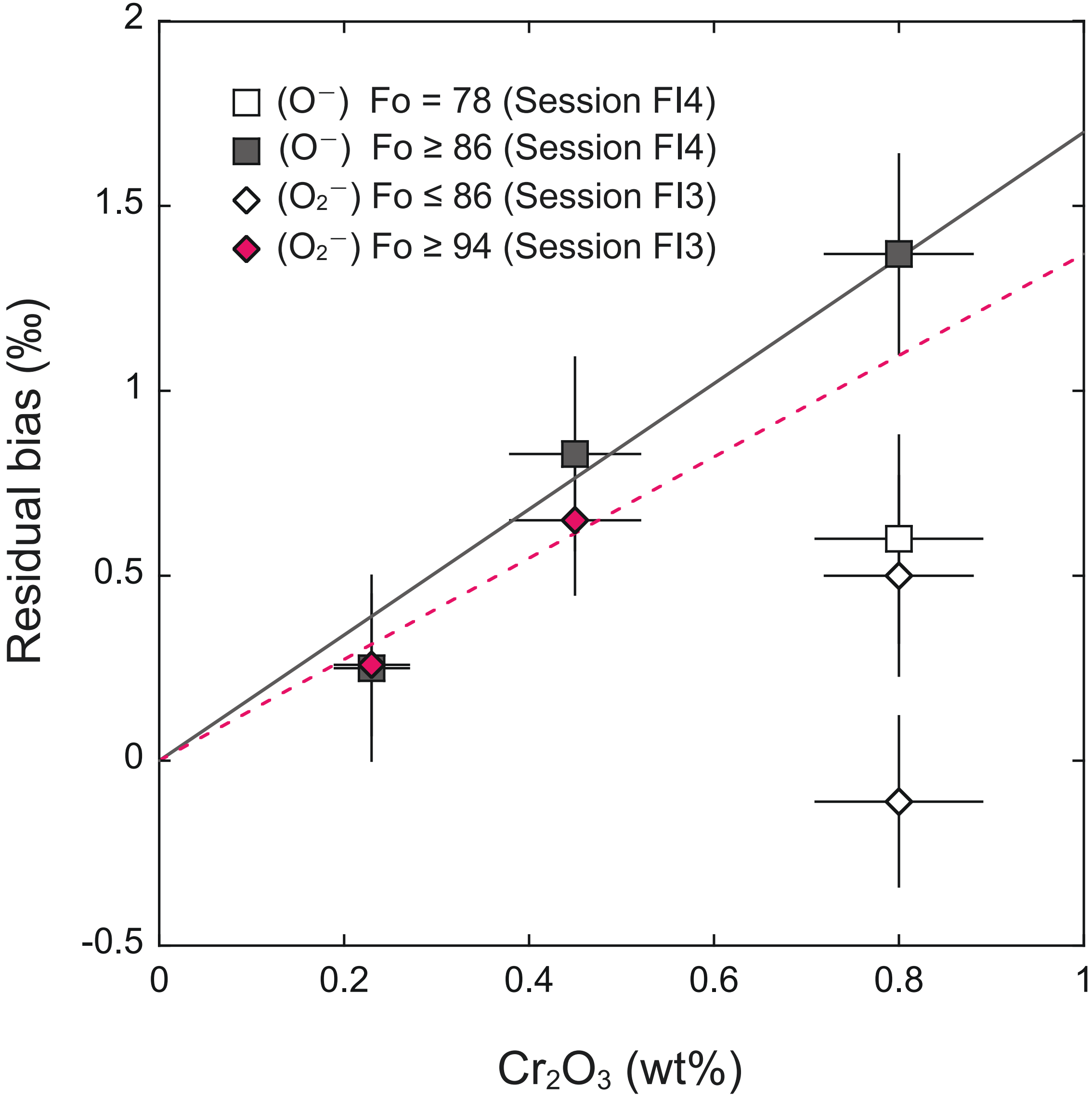
(a: O⁻)
(b: O₂⁻)
(c: O⁻)
(d: O₂⁻)
(e: O⁻)
(f: O₂⁻)
²⁴Mg⁺ yield (× 10⁸ cps nA⁻¹)
²⁸Si⁺ yield (× 10⁸ cps nA⁻¹)
Mg/Si RSF
bias*25 (RM-SCOl) (‰)
Fo content
Session FE2
Session FE2 (Cr-bearing)
Session FE1
Session FE1 (Cr-bearing)
Bias (Session FI4)
Bias (Session FI4: Cr-bearing)
Mg/Si RSF (Session FE2)
Mg/Si RSF (Session FE2: Cr-bearing)
Bias (Session FI3)
Bias (Session FI3: Cr-bearing)
Mg/Si RSF (Session FE1)
Mg/Si RSF (Session FE1: Cr-bearing)

Figure 6



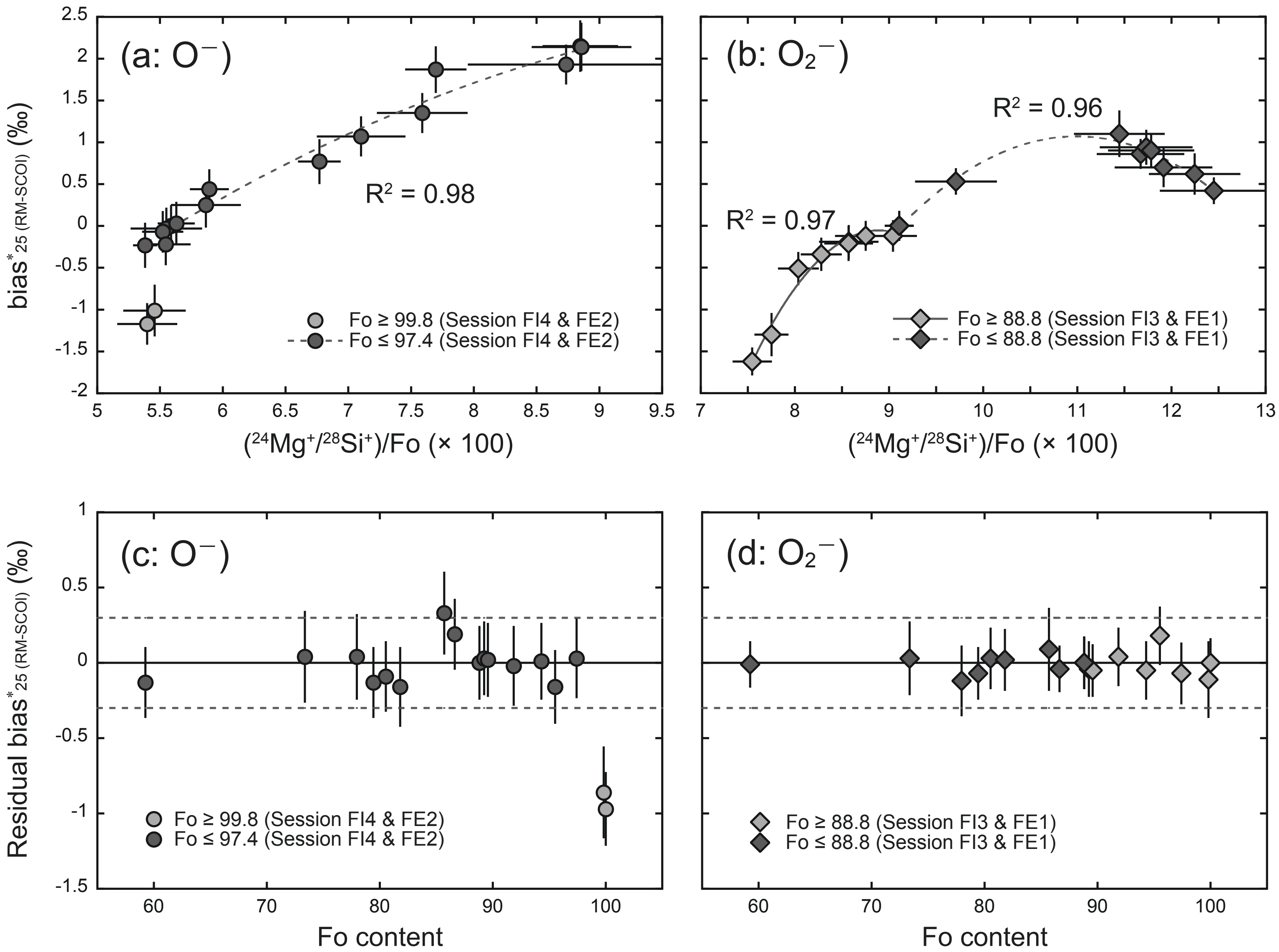
4.5
4
3.5
3
2.5
2
1.5
bias*25 (RM-SCOl) (‰)
40
50
60
70
80
90
100
En content
IG-Cpx
95AK-6
IG-Cpx
95AK-6
En (O⁻) Ushikubo et al. (2013) (Session UI1)
Di (O⁻) Ushikubo et al. (2017) (Session UI2)
En (O2⁻) This study (Session FI3)
Di (O2⁻) This study (Session FI3)

Figure 7



(O⁻) Fo = 78 (Session FI4)
(O⁻) Fo ≥ 86 (Session FI4)
(O₂⁻) Fo ≤ 86 (Session FI3)
(O₂⁻) Fo ≥ 94 (Session FI3)
Residual bias (‰)
Cr₂O₃ (wt%)
2
1.5
1
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1

Figure 8



(a: O⁻)
R² = 0.98
Fo ≥ 99.8 (Session FI4 & FE2)
Fo ≤ 97.4 (Session FI4 & FE2)
bias*25 (RM-SCOl) (‰)
(²⁴Mg⁺/²⁸Si⁺)/Fo (× 100)
(b: O₂⁻)
R² = 0.96
R² = 0.97
Fo ≥ 88.8 (Session FI3 & FE1)
Fo ≤ 88.8 (Session FI3 & FE1)
(²⁴Mg⁺/²⁸Si⁺)/Fo (× 100)
(c: O⁻)
Residual bias*25 (RM-SCOl) (‰)
Fo ≥ 99.8 (Session FI4 & FE2)
Fo ≤ 97.4 (Session FI4 & FE2)
Fo content
(d: O₂⁻)
Fo ≥ 88.8 (Session FI3 & FE1)
Fo ≤ 88.8 (Session FI3 & FE1)
Fo content

Appendix EA1: Sample descriptions and laser fluorination oxygen isotope data

Olivine Reference Materials

1. Orikabe Plutonic Complex, Kitakami Mountains, northeast Japan (OR-Ol)
   Olivine grains were sampled from a hornblende-biotite-olivine-clinopyroxene gabbro from Tokusenjo type, Orikabe Plutonic Complex (sample No. 841022B-9; Mikoshiba et al., 2004) as hand-picked 250-500 µm sized fraction by Kita et al. (1998). Fe and Ni concentrations were measured by atomic absorption analysis (Kita et al., 1998). Fe, Co, and Ni concentrations were also obtained by INAA (Kita et al., 1998). Oxygen isotope ratio was obtained by laser fluorination analyses (Kita et al. 2010). An aliquot of the same fraction was used for the solution MC-ICP-MS analyses of Mg isotope ratios. Additional olivine grains were newly handpicked from 250-500 µm separate of the remaining sample in order to mount them in epoxy disk as SIMS standard.

2. Hoei Gabbro, Mount Fuji, Japan (FJ-Ol)
   These olivine grains were hand-picked from the 500-1000 µm fraction of a gabbro from 1707 Hoei eruption, Mount Fuji (Sample No. FH NTK-3) by Kita et al. (1998). A host rock was among those collected from 1707 Hoei eruption gabbros by Dr. Shigeko Togashi (GSJ-AIST). A specific specimen (FH NTK-3) was selected with the purpose of extracting olivine grains for SIMS standards according to the occurrence of coarse (>1mm) and clean olivine. Fe and Ni concentrations were measured by atomic absorption analysis (Kita et al., 1998). Fe, Co, and Ni concentrations were also obtained by INAA (Kita et al., 1998).

3. Kenna, Ureilite meteorite (KN-Ol), USNM5825
   Kenna is an ureilite meteorite that was found in 1972, New Mexico, USA. Olivine from

Kenna shows a xenoblastic texture, which is commonly rimmed by forsterite (Berkley et al., 1976). A chip of the meteorite was provided by National Museum of Natural History (Smithsonian Institute). The chip (425 mg) was crushed and sieved to a grain size of 112 - 425 μm. The sieved grains were separated into three fractions (1. highly magnetic fraction, 2. less magnetic fraction, and 3. non-magnetic fraction) by hand magnet and then several grains from fraction 1 and 2 were handpicked under a binocular microscope (labeled as KN-Ol1 and KN-Ol2, respectively). Backscattered electron images of representative grains from KN-Ol1 and KN-Ol2 fractions are shown in Fig. EA1-1. Some of KN-Ol2 grains show chemical zoning and darker areas with tiny grains of metal (Fig. EA1-1d) tend to be MgO-rich compositions, suggesting that these olivine grains were reduced by carbonaceous matrix (Berkley et al., 1976; Goodrich, 1992). The apparent chemically zoned grains like KN-Ol2-7 (Fig. EA1-1d) were not used for electron probe, LA-MC-ICP-MS, and SIMS analyses.

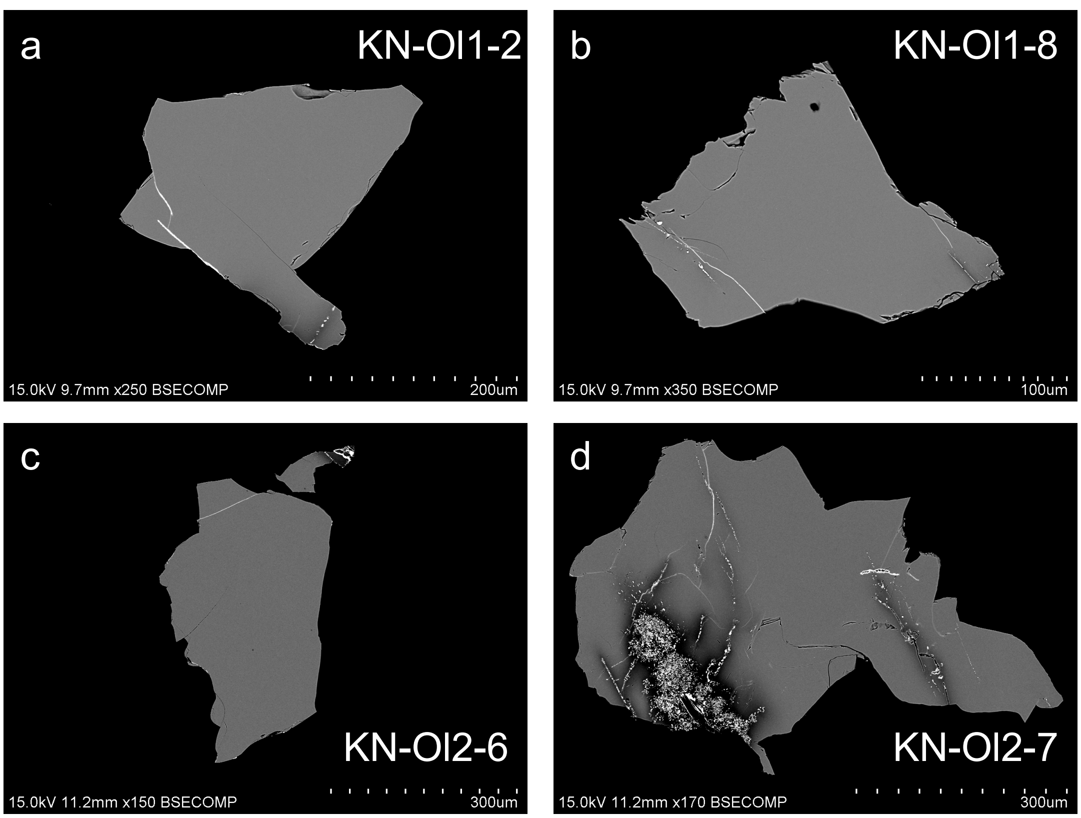


Fig. EA1-1. Backscattered electron images of olivine grains from the Kenna meteorite. (a, b) from the non-magnetic fraction KN-Ol1. (c, d) from the less magnetic fraction KN-Ol2.

4. Peridotite xenoliths from eastern North China craton, China (CL09-08, 19, and 33-Ol)

   Three different peridotite chips were provided by Dr. Shichun Huang (University of Nevada Las Vegas). The Mg isotope ratios of olivine from three peridotite samples were obtained by solution-MC-ICP-MS measurements (Xiao et al., 2013).

5. Springwater, pallasite meteorite (SW-Ol)

   Springwater is a pallasite meteorite that was found in 1931, Saskatchewan, Canada. Olivine grains (< 15 mg, sample No. USNM2566) provided by National Museum of Natural History (Smithsonian Institute), were previously separated from the host rock.

6. ALHA77257, ureilite meteorite (A77257-Ol)

   ALHA77257 is an ureilite meteorite that was collected by the U.S.-Japan joint team in the 1977 and 1978 sessions in Antarctica. Two olivine grains provided by Dr. Katsuyuki Yamashita (Department of Earth Science, Okayama University), were previously separated from the host rock. Backscattered electron images of the two grains are shown in Fig. EA1-2a and 2b. One of the grain (A77257-Ol5) is chemically zoned (see Fig. EA1-2b), which is similar to the feature found in olivine grains from the Kenna meteorite (see Fig. EA1-1d). The other grain (A77257-Ol4) shows chemically homogeneous compositions in terms of MgO contents ($Fo = 85.63 \pm 0.13$, 1SD). Both two grains were used for electron probe, LA-MC-ICP-MS, and SIMS analyses. Regarding the A77257-Ol5 grain, center part without chemically zoned MgO-rich parts was only used for these analyses. The Fo content of the center part of the A77257-Ol5 grain is determined to be

85.77 ± 0.19 (1SD), which is identical to that of the A77257-Ol4 grain within uncertainties.

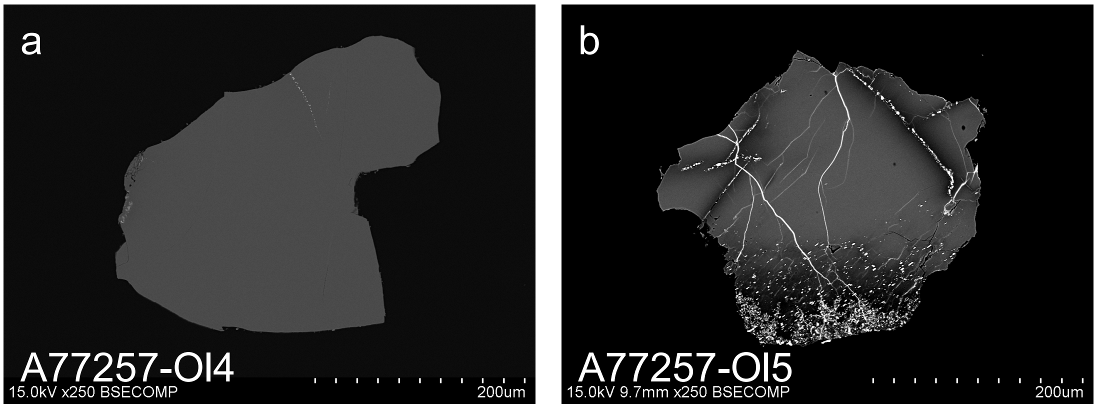


Fig. EA1-2a, b. Backscattered electron images of olivine grains from the ALHA77257 meteorite.

7. San Carlos, USA (SC-Ol)

   Sample No. M-81-43-4, Gila Co. Arizona, USA, purchased from a private mineral collector. A large (1-2 cm) single olivine crystal was broken to fragments for SIMS standard (Kita et al., 1988; 2010). A small aliquot of fragments was used for solution ICP-MS analyses of Mg isotope ratios.

8. Mantle xenolith, Kilbourne Hole, USA (UWOL-1)

   A peridotite from the Kilbourne Hole was provided by Dr. John Valley (University of Wisconsin-Madison). The peridotite was crushed and then olivine grains were separated from a host rock and hand-picked from the 300-500 μm fraction (sample name UWOL-1). All processes were done by Dr. Ilya Bindeman (University of Oregon).

9. Ichinome-gata spinel lherzolite nodule, Japan (IG-Ol)

   These olivine grains were hand-picked from the 500-1000 μm fraction processed by Kita et al. (1998), using a specimen GSJ R57877 that was originally collected by Dr. Shigeko

Togashi (GSJ-AIST). Fe and Ni concentrations were measured by atomic absorption analysis (Kita et al., 1998). Fe, Co, and Ni concentrations were also obtained by INAA (Kita et al., 1998). A small aliquot of the separate was used for solution MC-ICP-MS analyses of Mg isotope ratios.

10. Harrat al Kishb mantle xenolith, Saudi Arabia (HaK-Ol)

    Petrology of the Harrat al Kishb mantle xenolith was studied by McGuire 1987. Olivine grains from the mantle xenolith (Sample name H30-82-1) were provided by Dr. Brian Beard (University of Wisconsin-Madison). Three olivine grains (30-47 mg per each) were crushed separately and then 27 grains were hand-picked from each crushed fraction (9 grains per each fraction).

11. Weltevreden komatiite, Barberton, South Africa (WK-Ol)

    Olivine grains from the Weltevreden komatiite (sample No. 1521) were provided by Dr. Alexander Sobolev (ISTerre Institute of Earth Science). Backscattered electron images of representative grains are shown in Fig. EA1-3. Olivine grains are slightly chemically zoned, especially a rim of these grains. Center parts of the grains were only used for electron probe, LA-MC-ICP-MS, and SIMS analyses.

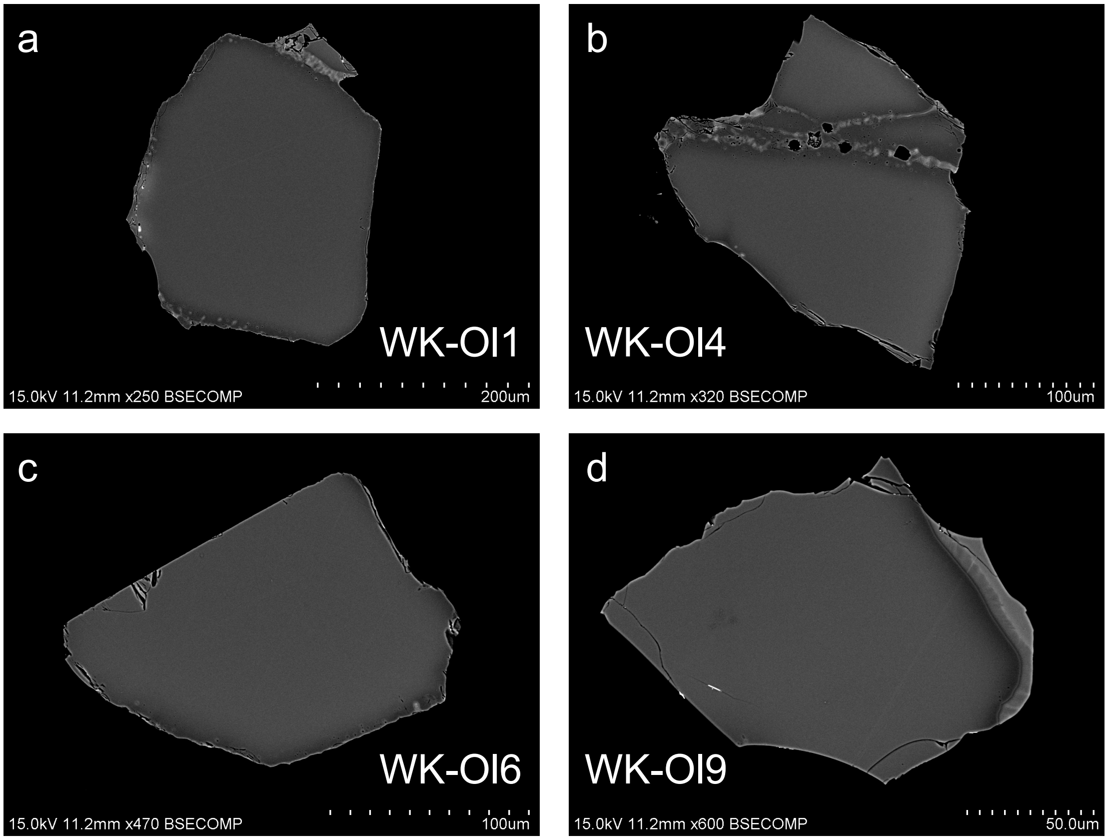


Fig. EA1-3a-d. Backscattered electron images of olivine grains from the Weltevreden komatiite.

12. Winona, winonaite meteorite (WN-Ol)

Winona is a winonaite meteorite that was found in 1928, Arizona, USA. A chip (1.4 g, sample No. USNM854) of the meteorite was provided by National Museum of Natural History (Smithsonian Institute). Since sizes of olivine grains are relatively small, several chips of the Winona meteorite were mounted in an epoxy round and then polished to obtain flat surfaces. After polishing, several chips were extracted from the epoxy round and were mounted again with the other olivine samples.

13. NWA7325 ungrouped achondrite (N7325-Ol)

    NWA7325 is an ungrouped achondrite that was found in 2012, Morocco. Comprehensive study of this meteorite (e.g., Petrology, trace elements, oxygen, chromium and titanium isotopes, and mid-IR spectroscopy) was carried out by Goodrich et al. (2017). In this study, we used an olivine grain (N7325-Ol7) on a thick section that was studied by Goodrich et al. (2017). The oxygen isotope ratios of the grain are determined as $\delta^{18}O_{VSMOW}$ = 7.45, $\delta^{17}O_{VSMOW}$ = 3.07, and $\Delta^{17}O$ = –0.8‰ by Goodrich et al. (2017; see supporting information).

14. Marble rock from Isle of Skye, Scotland (SK-Ol)

    We do not have information about the exact sampling location of the marble rock. However, it is certain that the rock from the Beinn an Dubhaich aureole, Isle of Skye, Scotland.

15. Synthetic forsterite (HN-Ol)

    The synthetic pure forsterite (sample name Fo16) was produced by Dr. Hiroko Nagahara (The University of Tokyo), which was previously used as oxygen isotope standard (Kita et al. 2010). An aliquot containing small fragments of the forsterite was used for the solution MC-ICP-MS analyses of Mg isotope ratios.

Pyroxene Reference Materials

1. Enstatite, Mg-rich gneisses, Adirondack Mountains, New York, USA (Sp79-11 En)

   Petrology and chemistry of the host rock (Sample No. SP79-11) are described in Lamb and Valley (1988). The specific specimen was selected due to the low FeO contents in enstatite reported in the paper. Enstatite was hand-picked from the host rock for SIMS oxygen isotope standard by Kita et al. (2010). An aliquot of the same separate was used for the solution MC-ICP-MS analyses of Mg isotope ratios.

2. JE enstatite (JE En).
   Enstatite separate from John Eiler (Eiler et al. 1997).

3. Orthopyroxene and clinopyroxene, Ichinome-gata spinel lherzolite nodule, Japan (IG-Opx and IG-Cpx)
   Orthopyroxene and clinopyroxene separates were originally prepared by Kita et al. (1998) from the same 500-1000 μm fraction of Ichinome-gata nodule (GSJ R57877, spinel lherzolite) that was used to extract olivine standard IG-Ol. Orthopyroxene separate was analyzed by INAA and AAA for Fr, Ni, and Co concentrations (Kita et al. 1998). Both pyroxene standards were analyzed for oxygen isotopes to be used as SIMS standard (Kita et al. 2010). Aliquot from each separate was used for the solution MC-ICP-MS analyses of Mg isotope ratios.

4. Diopside from diopside marble, Adirondack mountains, New York, USA (95AK-6 Di).
   The diopside grains are among seven samples studied by Edwards and Valley (1998). Sample number 6 was selected as SIMS oxygen isotope standard (Kita et al. 2010) because of their internally homogeneous oxygen isotope ratios. Aliquot of the diopside separate was used for the solution MC-ICP-MS analyses of Mg isotope ratios.

Laser fluorination oxygen isotope analyses

In order to use 4 olivine RMs (FJ-Ol, SW-Ol, UWOL-1, and HaK-Ol) as SIMS calibration standards for future oxygen isotope analyses, $\delta^{18}O_{VSMOW}$ values of 4 olivine RMs were obtained with a laser fluorination and a gas-source mass spectrometer at University of Wisconsin-Madison. Analytical procedures are described in Valley et al. (1995). The UWG-2 garnet was used as a running standard. External reproducibility of $\delta^{18}O$ is ± 0.11‰ (2SD).

The results of laser fluorination analyses of 4 olivine RMs (FJ-Ol, SW-Ol, UWOL-1 and HaK-Ol) are shown in Table EA1. $\delta^{18}O_{VSMOW}$ values of 4 olivine RMs (FJ-Ol, SW-Ol, UWOL-1 and HaK-Ol) are determined to be 4.89‰, 3.51‰, 5.48‰, and 5.25‰, respectively. $\delta^{18}O_{VSMOW}$ values of 4 olivine RMs (SC-Ol, HN-Ol, IG-Ol, and OR-Ol) and all pyroxene RMs obtained by previous laser fluorination studies (Eiler et al., 1997; Edwards and Valley, 1998; Kita et al., 2010) are also shown in Table EA1.

Table EA1
Laser fluorination oxygen isotope ratios of olivine and pyroxene RMs used in this study.

Sample name	Fo or En content[a]	$\delta^{18}O_{VSMOW}$ (‰)	References [b]
Olivine			
OR-Ol	59.3	5.88	[3]
FJ-Ol	73.4	4.89	This study
KN-Ol	78.0		
CL09-19-Ol	79.4		
CL09-08-Ol	80.5		
SW-Ol	81.8	3.51	This study
A77257-Ol	85.7		
CL09-33-Ol	86.6		
SC-Ol	88.8	5.32	[3]
UWOL-1	89.2	5.48	This study
IG-Ol	89.6	5.23	[3]
HaK-Ol	91.9	5.25	This study
WK-Ol	94.3		
WN-Ol	95.5		
N7325-Ol	97.4		
SK-Ol	99.8		
HN-Ol	100.0	8.90	[3]
Pyroxene			
95AK-6 Di	48.6	24.14	[2]
IG-Cpx	48.6	5.15	[3]
JE En	85.5	9.20	[1]
IG-Opx	88.9	5.89	[3]
Sp79-11 En	96.3	13.31	[3]

[a] Molar % of forsterite or enstatite end-members based on EPMA analyses performed in this study
[b] Data sources [1] Eiler et al. (1997); [2] Edwards and Valley (1998); [3] Kita et al. (2010)

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Edwards, K.J., Valley, J.W., 1998. Oxygen isotope diffusion and zoning in diopside: The importance of water fugacity during cooling. Geochim. Cosmochim. Acta 62, 2265–2277.

Eiler, J.M., Graham, C., Valley, J.W., 1997. SIMS analysis of oxygen isotopes: Matrix effects in complex minerals and glasses. Chem. Geol. 138, 221–244.

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Magmatic evolution in a zoned pluton and significance of a subduction-related mafic parental magma. Contrib. to Mineral. Petrol. 146, 433–449.

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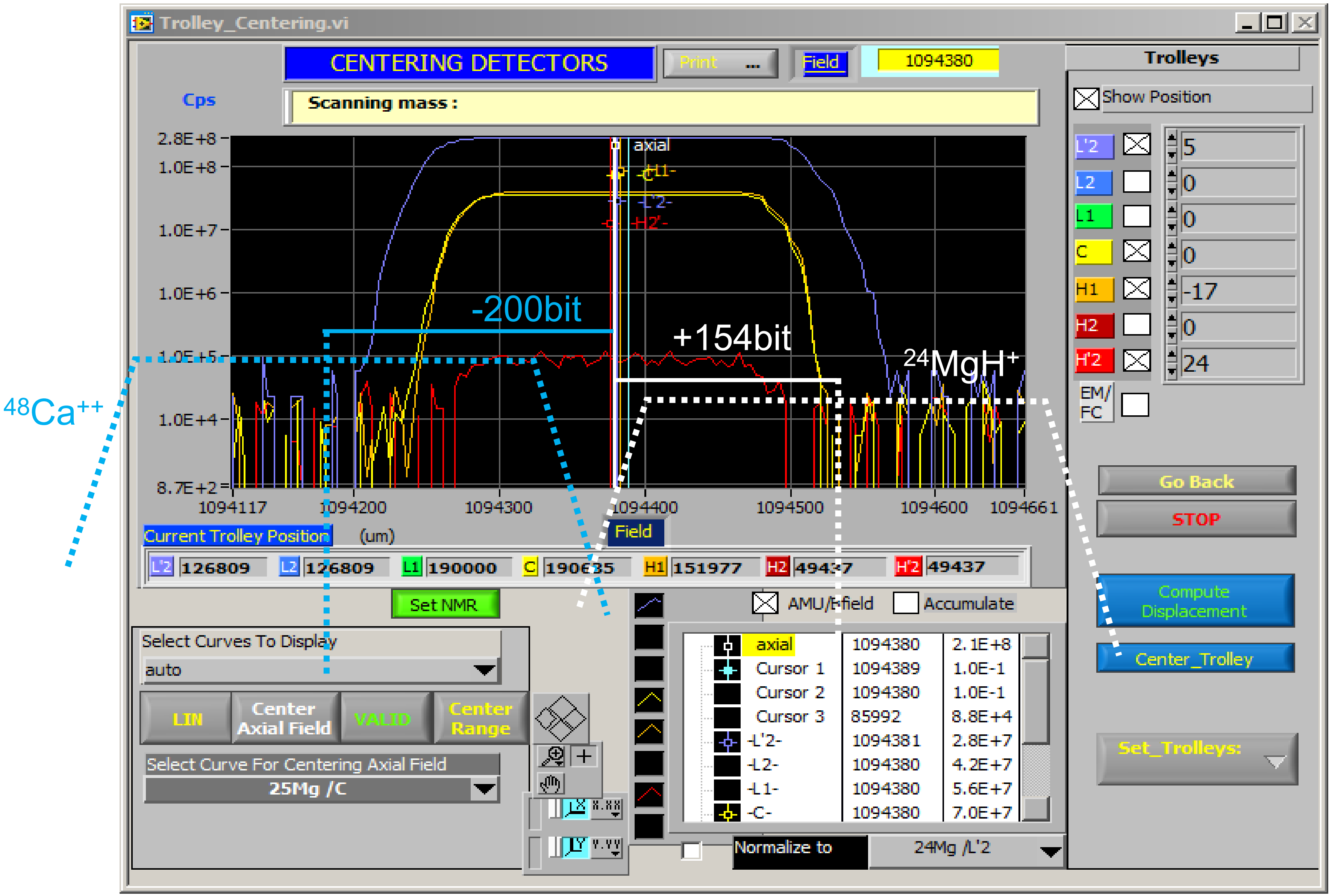
Appendix EA2: typical mass spectrum



(Fig. EA2-1)
A typical mass spectrum of a running standard SC-Ol (Fo_{88}) collected during a session FI3 showing peaks of $^{24}Mg^{+}$, $^{25}Mg^{+}$, $^{26}Mg^{+}$, and $^{27}Al^{+}$. Expected interference peaks ($^{48}Ca^{++}$ and $^{24}MgH^{+}$) are also shown as dotted lines. The possible contribution of both interferences to the signal intensities ($^{24}Mg^{+}$ and $^{25}Mg^{+}$) is less than 10^{-5} at the center of these peaks.

Table EA4-1

Summary of homogeneities of Fo, En, and δ^{25}Mg values in 17 olivine and 5 pyro:

Sample name	EPMA session	No. of analyzed grains	No. of EPMA analyses	Fo[a] or En[b] content
Olivine				
OR-Ol	2018. Aug.	20	103	59.27
FJ-Ol	2018. Aug.	20	99	73.36
KN-Ol	2018. Aug.	22	102	77.97
CL09-19-Ol	2019 Jan.	18	18	79.44
CL09-08-Ol	2019 Jan.	19	19	80.53
SW-Ol	2018. Aug.	22	109	81.81
A77257-Ol	2019 Jan.	2	10	85.70
CL09-33-Ol	2019 Jan.	19	19	86.63
SC-Ol	2019 Jan.	1	10	88.82
UWOL-1	2018. Aug.	42	213	89.23
IG-Ol	2019 Jan.	8	12	89.58
HaK-Ol	2018. Aug.	27	134	91.85
WK-Ol	2018. Aug.	22	101	94.30
WN-Ol	2018. Aug.	10	67	95.52
N7325-Ol	2019 Jan.	1	5	97.42
SK-Ol	2019 Jan.	5	21	99.81
HN-Ol	2019 Jan.	1	5	100.00
Pyroxene				
95AK-6	2019 Sep.	8	40	48.55
IG-Cpx	2019 Sep.	6	30	48.60
JE En	2019 Sep.	6	30	85.53
IG-Opx	2019 Sep.	5	25	88.89
Sp79-11 En	2019 Sep.	7	35	96.31

[a] Fo = Mg/[Mg + Fe] × 100 (molar %)

[b] En = Mg/[Mg + Fe + Ca] × 100 (molar %)

[a, b] Fo and En contents are calculated by considering total iron as ferrous iron.

[c] Standard deviations (Fo or En units) were calclated from averaged Fo or En cont
Regarding three olivine RMs (SC-Ol, N7325-Ol, and HN-Ol), each one grain w

[b] FeO wt% of all 5 analyses are below detection limit.

[c] Four individual grains on 4 individual SIMS mounts were measured.

References; [1] Ushikubo et al. (2013).GCA, [2] Ushikubo et al. (2017).GCA.

xene RMs

1SD[c]	SIMS session i.d.	No. of grains	No. of SIMS analyses	SIMS 2SD ($\delta^{25}Mg_m$)	Ref.
0.74	FI1	10	10	0.12	This study
0.29	FI1	8	8	0.08	This study
0.14	FI1	13	15	0.13	This study
0.24	FI3	8	8	0.16	This study
0.62	FI3	8	8	0.19	This study
0.10	FI1	8	8	0.06	This study
0.10	FI3	2	6	0.23	This study
0.33	FI3	8	8	0.12	This study
0.11	FI3	4[c]	62	0.14	This study
0.08	FI3	11	15	0.15	This study
0.09	FI3	8	8	0.05	This study
0.09	FI1	8	8	0.10	This study
0.52	FI1	8	8	0.12	This study
0.47	FI3	4	8	0.17	This study
0.08	FI3	1	4	0.14	This study
0.02	FI3	3	6	0.07	This study
-[b]	FI3	2	6	0.08	This study
0.19	UI2	4	4	0.18	[2]
0.58	UI2	4	4	0.09	[2]
0.15	UI1	4	4	0.06	[1]
0.12	UI1	4	4	0.23	[1]
0.56	UI1	4	11	0.14	[1]

tents of each grain.
as measured so that 1SD for three RMs represent intra-grain homogeneity.

Table EA5-1
List of analytical sessions for SIMS data used in this study

Date	session i.d.	analysis	Primary	
			source	species
2018. Sept.	FI1	Mg isotopes	Radio frequency	$^{16}O_2^-$
2018. Sept.	FI2	Mg isotopes	Radio frequency	$^{16}O^-$
2019. Jan.	FI3	Mg isotopes	Radio frequency	$^{16}O_2^-$
2019. Apr.	FI4	Mg isotopes	Radio frequency	$^{16}O^-$
2019. Jan.	FE1	Major & minor elements	Radio frequency	$^{16}O_2^-$
2019. Apr.	FE2	Major & minor elements	Radio frequency	$^{16}O^-$
2009. Sep.	UI1	Mg isotopes	Duoplasmatron	$^{16}O^-$
2013. Apr.	UI2	Mg isotopes	Duoplasmatron	$^{16}O^-$

[a] in diameter
[b] FC = faraday cup, EM = electron multiplier
[c] Ol = olivine, Px = pyroxene
References; [1] Ushikubo et al. (2013); [2] Ushikubo et al. (2017).

ion		detection[b]	Measured mineral[c]	Ref.
intensity	beam size[a]			
1 nA	7.5 µm	Multi-FC	Ol	This study
2.4 nA	9 µm	Multi-FC	Ol	This study
1 nA	7.5 µm	Multi-FC	Ol & Px	This study
2.6 nA	9 µm	Multi-FC	Ol	This study
6 pA	1.5 µm	Mono-EM or FC	Ol	This study
16 pA	2 µm	Mono-EM or FC	Ol	This study
4.5 nA	15 µm	Multi-FC	Ol & Px	[1]
2.2 nA	10 µm	Multi-FC	Px	[2]

Appendix EA6-1: SIMS Mg isotope data (session FI1, 1nA, O_2^- prima

[a] 2σ error (A) = $\sqrt{(2SE_{SIMS})^2+(2SD_{ICPMS})^2}$

[b] 2σ error = $\sqrt{(A)^2+(2SD_{SIMS\_bracket})^2}$

Erros of averaged values are 2SD.

File	Analysis spot	Cycle# (measured)	Cycle# (used)
20180904@18.asc	WI-STD-91 SCOL	30	30
20180904@19.asc	WI-STD-91 SCOL	30	30
20180904@20.asc	WI-STD-91 SCOL	30	30
20180904@21.asc	WI-STD-91 SCOL	30	30
20180904@30.asc	WI-STD-91 SCOL	30	30
20180904@31.asc	WI-STD-91 SCOL	30	30
20180904@32.asc	WI-STD-91 SCOL	30	30
20180904@33.asc	WI-STD-91 SCOL	30	30
	Average (SC-Ol)		
20180904@8.asc	WI-STD-91 KNOL1-2_O2_1	30	30
20180904@9.asc	WI-STD-91 KNOl1-4	30	30
20180904@10.asc	WI-STD-91 KNOl1-8	30	30
20180904@11.asc	WI-STD-91 KNOl1-5	30	30
20180904@12.asc	WI-STD-91 KNOl1-9	30	30
20180904@13.asc	WI-STD-91 KNOL1-10_O2_1	30	30
20180904@14.asc	WI-STD-91 KNOL1-12	30	30
20180904@15.asc	WI-STD-91 KNOl1-14	30	30
20180904@97.asc	WI-STD-91 KNOL2-6	30	30
20180904@98.asc	WI-STD-91 KNOL2-7	30	30
20180904@99.asc	WI-STD-91 KNOL2-8	30	30
20180904@100.asc	WI-STD-91 KNOL2-9_O2_1	30	30
20180904@102.asc	WI-STD-91 KNOL2-5_O2_1	30	30
20180904@104.asc	WI-STD-91 KNOL1-10_O2_2	30	30
20180904@105.asc	WI-STD-91 KNOL1-10_O2_3	30	30
	Average (KN-Ol)		
20180904@22.asc	WI-STD-91 WKOL-1_1	30	30
20180904@23.asc	WI-STD-91 WKOL-3	30	30
20180904@24.asc	WI-STD-91 WKOL-5_O2_1	30	30
20180904@25.asc	WI-STD-91 WKOL-8	30	30
20180904@26.asc	WI-STD-91 WKOL-10_O2_1	30	30
20180904@27.asc	WI-STD-91 WKOL-11	30	30
20180904@28.asc	WI-STD-91 WKOL-12	30	30
20180904@29.asc	WI-STD-91 WKOL-17	30	30
	Average (WK-Ol)		
20180904@37.asc	WI-STD-91 WNOL-1_O2_2	30	30

20180904@38.asc	WI-STD-91 WNOL-1_O2_3	30	30
20180904@39.asc	WI-STD-91 WNOL-1_O2_4	30	30
20180904@40.asc	WI-STD-91 WNOL-1_O2_5	30	30
20180904@41.asc	WI-STD-91 WNOL-1_O2_6	30	30
20180904@42.asc	WI-STD-91 WNOL-1_O2_7	30	30
20180904@43.asc	WI-STD-91 WNOL-1_O2_8	30	30
20180904@123.asc	WI-STD-91 WNOL-4_O2_1	30	30
20180904@124.asc	WI-STD-91 WNOL-4_O2_2	30	30
	Average (WN-Ol)		
20180904@54.asc	WI-STD-91 FJOL-2_O2_1	30	30
20180904@55.asc	WI-STD-91 FJOL-3_O2_1	30	30
20180904@56.asc	WI-STD-91 FJOL-4	30	30
20180904@57.asc	WI-STD-91 FJOL-5	30	30
20180904@58.asc	WI-STD-91 FJOL-6	30	30
20180904@59.asc	WI-STD-91 FJOL-10	30	30
20180904@60.asc	WI-STD-91 FJOL-9	30	30
20180904@61.asc	WI-STD-91 FJOL-11	30	30
	Average (FJ-Ol)		
20180904@66.asc	WI-STD-91 HaK-g1-2_O2_1	30	30
20180904@67.asc	WI-STD-91 HaK-g1-3_O2_1	30	30
20180904@68.asc	WI-STD-91 HaK-g1_5	30	30
20180904@69.asc	WI-STD-91 HaK-g1_8	30	30
20180904@70.asc	WI-STD-91 HaK-g2_1	30	30
20180904@71.asc	WI-STD-91 HaK-g2_2	30	30
20180904@72.asc	WI-STD-91 HaK-g3_1	30	30
20180904@73.asc	WI-STD-91 HaK-g3_3	30	30
	Average (HaK-Ol)		
20180904@16.asc	WI-STD-91 HNOL	30	30
20180904@34.asc	WI-STD-91 HNOL	30	30
20180904@74.asc	WI-STD-91 HNOL	30	30
20180904@75.asc	WI-STD-91 HNOL	30	30
20180904@76.asc	WI-STD-91 HNOL	30	30
20180904@77.asc	WI-STD-91 HNOL	30	30
20180904@130.asc	WI-STD-91 HNOL	30	30
	Average (HN-Ol)		
20180904@81.asc	WI-STD-91 SWOL-1_O2_1	30	30
20180904@82.asc	WI-STD-91 SWOL-3_O2_1	30	30
20180904@83.asc	WI-STD-91 SWOL-4	30	30
20180904@84.asc	WI-STD-91 SWOL-5	30	30
20180904@85.asc	WI-STD-91 SWOL-8	30	30
20180904@86.asc	WI-STD-91 SWOL-12	30	30
20180904@87.asc	WI-STD-91 SWOL-15_O2_1	30	30
20180904@88.asc	WI-STD-91 SWOL-16	30	30
	Average (SW-Ol)		
20180904@89.asc	WI-STD-91 A77257-5_O2_1	30	30

20180904@90.asc	WI-STD-91 A77257-5_O2_2	30	30
20180904@92.asc	WI-STD-91 A77257-5_O2_4	30	30
	Average (A77257-Ol)		
20180904@110.asc	WI-STD-91 UWOL1-42_O2_1	30	30
20180904@111.asc	WI-STD-91 UWOL1-41_O2_1	30	30
20180904@112.asc	WI-STD-91 UWOL1-5	30	30
20180904@113.asc	WI-STD-91 UWOL1-6	30	30
	Average (UW-Ol)		
20180904@17.asc	WI-STD-91 OROL-1	30	30
20180904@114.asc	WI-STD-91 OROL-2_O2_1	30	30
20180904@115.asc	WI-STD-91 OROL-3_O2_1	30	30
20180904@116.asc	WI-STD-91 OROL-4_O2_1	30	30
20180904@117.asc	WI-STD-91 OROL-6_O2_1	30	30
20180904@118.asc	WI-STD-91 OROL-12	30	30
20180904@119.asc	WI-STD-91 OROL-17_O2_1	30	30
20180904@120.asc	WI-STD-91 OROL-18	30	30
20180904@121.asc	WI-STD-91 OROL-19	30	30
20180904@122.asc	WI-STD-91 OROL-20	30	30
	Average (OR-Ol)		

ry ion beam)

24Mg (100M cps)	Yield (10^8 cps/nA)	Measured d25Mg-m ‰	2SE ‰	d26Mg-m ‰	2SE ‰	d26Mg*-m ‰
1.80	1.93	-2.61	0.06	-4.78	0.11	0.31
1.80	1.92	-2.58	0.07	-4.68	0.12	0.34
1.81	1.94	-2.51	0.06	-4.58	0.10	0.32
1.81	1.94	-2.59	0.06	-4.71	0.11	0.34
1.79	1.93	-2.56	0.06	-4.63	0.12	0.37
1.79	1.93	-2.60	0.06	-4.66	0.11	0.40
1.78	1.92	-2.68	0.06	-4.76	0.11	0.47
1.79	1.94	-2.68	0.06	-4.83	0.10	0.39
		-2.60	0.11	-4.70	0.17	0.37
1.80	1.92	-1.47	0.04	-2.54	0.04	0.32
1.80	1.92	-1.50	0.03	-2.59	0.03	0.33
1.78	1.90	-1.61	0.04	-2.79	0.03	0.35
1.79	1.91	-1.57	0.03	-2.73	0.03	0.32
1.78	1.91	-1.48	0.03	-2.56	0.04	0.31
1.78	1.91	-1.58	0.03	-2.76	0.03	0.32
1.78	1.91	-1.55	0.04	-2.69	0.04	0.32
1.78	1.91	-1.56	0.02	-2.67	0.03	0.38
1.81	1.95	-1.47	0.03	-2.45	0.03	0.41
1.81	1.95	-1.55	0.03	-2.62	0.04	0.40
1.81	1.95	-1.50	0.03	-2.47	0.04	0.45
1.82	1.96	-1.59	0.03	-2.65	0.03	0.46
1.83	1.97	-1.56	0.03	-2.60	0.04	0.44
1.79	1.93	-1.69	0.04	-2.80	0.04	0.50
1.81	1.95	-1.61	0.03	-2.74	0.03	0.41
		-1.55	0.13	-2.64	0.22	0.38
1.82	1.96	-2.69	0.06	-4.84	0.11	0.41
1.82	1.96	-2.57	0.05	-4.70	0.11	0.31
1.81	1.95	-2.66	0.07	-4.92	0.11	0.27
1.82	1.96	-2.61	0.05	-4.68	0.10	0.41
1.81	1.96	-2.75	0.06	-4.94	0.11	0.41
1.81	1.95	-2.74	0.06	-4.94	0.11	0.40
1.81	1.93	-2.72	0.06	-4.90	0.10	0.40
1.81	1.95	-2.71	0.06	-4.89	0.11	0.40
		-2.68	0.12	-4.85	0.21	0.38
1.78	1.96	-3.05	0.06	-5.54	0.10	0.41

1.77	1.95	-3.00	0.06	-5.42	0.12	0.43
1.76	1.93	-3.16	0.05	-5.74	0.12	0.42
1.78	1.96	-3.01	0.06	-5.43	0.12	0.43
1.78	1.96	-3.08	0.06	-5.55	0.11	0.44
1.77	1.95	-3.19	0.07	-5.75	0.13	0.45
1.77	1.95	-2.97	0.06	-5.37	0.11	0.41
1.81	1.95	-2.94	0.06	-5.32	0.13	0.40
1.80	1.95	-3.01	0.06	-5.39	0.12	0.49
		-3.05	0.17	-5.50	0.32	0.43
1.76	1.90	-1.64	0.04	-2.80	0.04	0.40
1.76	1.89	-1.74	0.03	-2.96	0.04	0.43
1.77	1.91	-1.67	0.03	-2.87	0.03	0.39
1.77	1.91	-1.62	0.03	-2.72	0.04	0.43
1.75	1.89	-1.62	0.03	-2.75	0.03	0.41
1.77	1.91	-1.69	0.03	-2.86	0.03	0.43
1.76	1.90	-1.68	0.03	-2.82	0.04	0.46
1.77	1.91	-1.63	0.03	-2.86	0.03	0.32
		-1.66	0.08	-2.83	0.15	0.41
1.83	1.97	-2.93	0.08	-5.21	0.15	0.50
1.83	1.97	-2.90	0.07	-5.20	0.15	0.45
1.83	1.98	-2.87	0.08	-5.11	0.15	0.48
1.83	1.97	-2.90	0.09	-5.13	0.15	0.53
1.83	1.97	-2.99	0.07	-5.28	0.16	0.55
1.83	1.98	-2.87	0.07	-5.14	0.15	0.45
1.82	1.97	-2.99	0.08	-5.31	0.15	0.51
1.83	1.97	-2.97	0.08	-5.26	0.15	0.52
		-2.93	0.10	-5.21	0.15	0.50
1.71	1.84	-4.25	0.06	-7.82	0.11	0.45
1.70	1.84	-4.32	0.05	-7.94	0.11	0.47
1.73	1.87	-4.28	0.07	-7.75	0.13	0.58
1.73	1.87	-4.29	0.07	-7.80	0.13	0.55
1.73	1.86	-4.28	0.06	-7.78	0.11	0.55
1.73	1.86	-4.31	0.07	-7.90	0.13	0.49
1.74	1.88	-4.27	0.07	-7.84	0.13	0.48
		-4.29	0.05	-7.83	0.14	0.51
1.88	2.03	-1.36	0.03	-2.23	0.04	0.41
1.89	2.04	-1.34	0.03	-2.23	0.04	0.39
1.88	2.03	-1.34	0.03	-2.22	0.04	0.39
1.90	2.05	-1.30	0.03	-2.10	0.04	0.44
1.89	2.04	-1.35	0.02	-2.17	0.03	0.46
1.90	2.04	-1.31	0.03	-2.13	0.03	0.42
1.91	2.06	-1.34	0.03	-2.18	0.03	0.44
1.89	2.04	-1.28	0.03	-2.12	0.03	0.37
		-1.33	0.06	-2.18	0.11	0.41
1.89	2.04	-1.11	0.03	-1.75	0.03	0.42

1.90	2.05	-1.14	0.03	-1.82	0.03	0.39
1.89	2.04	-1.11	0.03	-1.73	0.04	0.45
		-1.12	0.03	-1.77	0.10	0.42
1.82	1.96	-2.66	0.07	-4.79	0.12	0.40
1.83	1.97	-2.65	0.06	-4.77	0.12	0.40
1.83	1.97	-2.60	0.06	-4.67	0.11	0.40
1.83	1.97	-2.63	0.07	-4.72	0.12	0.39
		-2.64	0.05	-4.74	0.10	0.40
1.53	1.64	-1.87	0.03	-3.29	0.04	0.36
1.54	1.66	-1.89	0.02	-3.36	0.04	0.32
1.55	1.67	-1.84	0.03	-3.26	0.04	0.32
1.56	1.68	-1.78	0.04	-3.08	0.04	0.39
1.53	1.65	-1.82	0.03	-3.19	0.03	0.35
1.51	1.63	-1.82	0.04	-3.21	0.05	0.34
1.51	1.63	-1.77	0.04	-3.14	0.03	0.31
1.51	1.63	-1.94	0.04	-3.46	0.04	0.33
1.52	1.63	-1.77	0.04	-3.20	0.04	0.26
1.55	1.67	-1.75	0.03	-3.18	0.04	0.24
		-1.83	0.12	-3.24	0.22	0.32

2SE ‰	f_{25}*	2σ [a]	bias*$_{25(RM\text{-}SCOl)}$	Corrected 2σ [b]	f_{26}*	2σ [a]
0.06	-2.54	0.11			-4.63	0.19
0.07	-2.50	0.11			-4.53	0.20
0.06	-2.44	0.11			-4.43	0.19
0.06	-2.52	0.11			-4.56	0.19
0.06	-2.49	0.11			-4.48	0.20
0.05	-2.53	0.11			-4.51	0.19
0.06	-2.61	0.11			-4.61	0.19
0.06	-2.61	0.11			-4.68	0.19
0.11	-2.53	0.11			-4.55	0.17
0.06	-1.51	0.18	1.03	0.18	-2.53	0.30
0.06	-1.54	0.18	0.99	0.18	-2.58	0.30
0.08	-1.65	0.18	0.88	0.18	-2.78	0.30
0.05	-1.61	0.18	0.93	0.18	-2.72	0.30
0.06	-1.52	0.18	1.02	0.18	-2.55	0.30
0.05	-1.62	0.18	0.91	0.18	-2.75	0.30
0.07	-1.59	0.18	0.94	0.18	-2.68	0.30
0.05	-1.60	0.18	0.93	0.18	-2.66	0.30
0.05	-1.51	0.18	1.02	0.18	-2.44	0.30
0.06	-1.59	0.18	0.94	0.18	-2.61	0.30
0.07	-1.54	0.18	0.99	0.18	-2.46	0.30
0.05	-1.63	0.18	0.90	0.18	-2.64	0.30
0.05	-1.60	0.18	0.93	0.18	-2.59	0.30
0.06	-1.73	0.18	0.80	0.18	-2.79	0.30
0.06	-1.65	0.18	0.88	0.18	-2.73	0.30
0.12	-1.59	0.13	0.94	0.13	-2.63	0.22
0.07	-2.60	0.14	-0.07	0.15	-4.67	0.22
0.06	-2.49	0.14	0.04	0.15	-4.53	0.22
0.07	-2.58	0.14	-0.05	0.15	-4.75	0.23
0.06	-2.53	0.14	0.00	0.15	-4.52	0.22
0.07	-2.66	0.14	-0.13	0.15	-4.77	0.22
0.06	-2.65	0.14	-0.12	0.15	-4.78	0.22
0.07	-2.63	0.14	-0.10	0.15	-4.74	0.22
0.07	-2.63	0.14	-0.09	0.15	-4.72	0.22
0.11	-2.60	0.12	-0.07	0.12	-4.69	0.21
0.06	-3.02	0.10	-0.45	0.13	-5.40	0.19

0.07	-2.97	0.10	-0.40	0.13	-5.27	0.20
0.07	-3.13	0.10	-0.56	0.13	-5.60	0.20
0.06	-2.97	0.10	-0.41	0.13	-5.28	0.20
0.06	-3.04	0.10	-0.47	0.13	-5.41	0.19
0.04	-3.15	0.10	-0.58	0.13	-5.61	0.21
0.06	-2.93	0.10	-0.37	0.13	-5.23	0.19
0.07	-2.90	0.10	-0.40	0.13	-5.18	0.21
0.07	-2.98	0.10	-0.47	0.13	-5.24	0.20
0.05	-3.01	0.17	-0.46	0.15	-5.36	0.32
0.08	-1.57	0.20	0.91	0.20	-2.71	0.30
0.06	-1.67	0.20	0.81	0.20	-2.86	0.30
0.07	-1.60	0.20	0.88	0.20	-2.77	0.30
0.06	-1.55	0.20	0.94	0.20	-2.62	0.30
0.06	-1.55	0.20	0.93	0.20	-2.65	0.30
0.06	-1.62	0.20	0.87	0.20	-2.76	0.30
0.08	-1.61	0.20	0.87	0.20	-2.72	0.30
0.06	-1.56	0.20	0.92	0.20	-2.77	0.30
0.08	-1.59	0.08	0.89	0.08	-2.73	0.15
0.06	-2.87	0.15	-0.37	0.15	-5.05	0.24
0.05	-2.84	0.15	-0.34	0.15	-5.04	0.24
0.07	-2.81	0.15	-0.31	0.16	-4.95	0.24
0.07	-2.84	0.16	-0.34	0.16	-4.97	0.24
0.07	-2.93	0.15	-0.43	0.15	-5.12	0.25
0.06	-2.81	0.15	-0.31	0.15	-4.98	0.24
0.06	-2.93	0.15	-0.42	0.16	-5.15	0.24
0.05	-2.91	0.15	-0.40	0.16	-5.10	0.24
0.07	-2.87	0.10	-0.36	0.10	-5.05	0.15
0.06	-3.88	0.10	-1.36	0.13	-7.13	0.17
0.06	-3.96	0.10	-1.39	0.13	-7.25	0.17
0.05	-3.91	0.11	-1.41	0.11	-7.06	0.19
0.05	-3.92	0.11	-1.42	0.11	-7.11	0.19
0.06	-3.91	0.10	-1.41	0.11	-7.09	0.17
0.07	-3.94	0.11	-1.44	0.12	-7.20	0.19
0.07	-3.91	0.11	-1.41	0.13	-7.15	0.19
0.10	-3.92	0.05	-1.41	0.05	-7.14	0.14
0.05	-1.33	0.14	1.20	0.15	-2.20	0.16
0.07	-1.32	0.14	1.22	0.15	-2.20	0.16
0.07	-1.32	0.15	1.22	0.15	-2.19	0.16
0.05	-1.28	0.15	1.26	0.15	-2.07	0.16
0.06	-1.33	0.14	1.21	0.15	-2.14	0.16
0.06	-1.29	0.15	1.25	0.15	-2.10	0.16
0.07	-1.32	0.14	1.22	0.15	-2.15	0.16
0.06	-1.25	0.14	1.28	0.15	-2.09	0.16
0.06	-1.31	0.06	1.23	0.06	-2.14	0.11
0.06	-1.04	0.14	1.50	0.15	-1.47	0.13

0.05	-1.07	0.14	1.47	0.15	-1.54	0.13
0.06	-1.04	0.14	1.50	0.15	-1.44	0.13
0.05	-1.05	0.03	1.49	0.03	-1.48	0.10
0.06	-2.53	0.12	-0.02	0.13	-4.55	0.23
0.05	-2.51	0.12	-0.01	0.13	-4.53	0.23
0.05	-2.47	0.12	0.04	0.13	-4.43	0.23
0.06	-2.49	0.12	0.02	0.13	-4.48	0.23
0.01	-2.50	0.05	0.01	0.05	-4.50	0.10
0.06	-1.86	0.07	0.67	0.13	-3.27	0.13
0.05	-1.87	0.07	0.63	0.13	-3.33	0.13
0.06	-1.83	0.07	0.68	0.13	-3.24	0.13
0.07	-1.77	0.07	0.74	0.13	-3.06	0.13
0.06	-1.81	0.07	0.70	0.13	-3.17	0.13
0.06	-1.81	0.07	0.70	0.13	-3.19	0.14
0.07	-1.75	0.07	0.76	0.13	-3.12	0.13
0.06	-1.93	0.07	0.58	0.13	-3.44	0.13
0.09	-1.76	0.08	0.75	0.13	-3.18	0.13
0.07	-1.74	0.07	0.77	0.13	-3.16	0.13
0.09	-1.81	0.12	0.70	0.12	-3.21	0.22

bias*$_{26(RM-SCOI)}$	2σ [b]
2.06	0.31
2.00	0.31
1.80	0.31
1.86	0.31
2.03	0.31
1.83	0.31
1.90	0.31
1.92	0.31
2.03	0.31
1.86	0.31
2.01	0.31
1.83	0.31
1.88	0.31
1.68	0.31
1.74	0.31
1.90	0.23
-0.12	0.25
0.02	0.25
-0.20	0.25
0.03	0.25
-0.22	0.25
-0.23	0.25
-0.18	0.25
-0.17	0.25
-0.13	0.21
-0.81	0.23

-0.68	0.23
-1.01	0.23
-0.69	0.23
-0.82	0.23
-1.02	0.23
-0.63	0.23
-0.73	0.25
-0.79	0.25
-0.80	0.27
1.72	0.31
1.56	0.31
1.65	0.31
1.80	0.31
1.77	0.31
1.66	0.31
1.70	0.31
1.65	0.31
1.69	0.15
-0.61	0.25
-0.60	0.25
-0.51	0.25
-0.52	0.25
-0.68	0.25
-0.54	0.25
-0.71	0.25
-0.66	0.25
-0.60	0.15
-2.56	0.22
-2.67	0.23
-2.62	0.20
-2.67	0.20
-2.65	0.20
-2.77	0.20
-2.70	0.25
-2.66	0.13
2.28	0.19
2.28	0.19
2.29	0.19
2.41	0.19
2.34	0.19
2.38	0.19
2.33	0.19
2.39	0.19
2.34	0.11
3.02	0.19

2.95	0.19
3.04	0.19
3.00	0.10
-0.09	0.25
-0.07	0.25
0.02	0.25
-0.03	0.25
-0.04	0.10
1.31	0.22
1.13	0.25
1.22	0.25
1.40	0.25
1.29	0.25
1.27	0.25
1.35	0.25
1.02	0.25
1.29	0.25
1.31	0.25
1.26	0.22

Appendix EA6-2: SIMS Mg isotope data (session FI2, 2.6nA, O^- prima

[a] 2σ error (A) = $\sqrt{(2SE_{SIMS})^2+(2SD_{ICPMS})^2}$

[b] 2σ error = $\sqrt{(A)^2+(2SD_{SIMS\_bracket})^2}$

Erros of averaged values are 2SD.

File	Analysis spot	Cycle# (measured)	Cycle# (used)
20180904@132.asc	WI-STD-91 SCOL	30	30
20180904@133.asc	WI-STD-91 SCOL	30	30
20180904@134.asc	WI-STD-91 SCOL	30	30
20180904@135.asc	WI-STD-91 SCOL	30	30
20180904@146.asc	WI-STD-91 SCOL	30	30
20180904@147.asc	WI-STD-91 SCOL	30	30
20180904@148.asc	WI-STD-91 SCOL	30	30
20180904@149.asc	WI-STD-91 SCOL	30	30
	Average (SC-Ol)		
20180904@136.asc	WI-STD-91 HNOL	30	30
20180904@137.asc	WI-STD-91 HNOL	30	30
	Average (HN-Ol)		
20180904@138.asc	WI-STD-91 OROL-2_O_1	30	30
20180904@139.asc	WI-STD-91 OROL-3_O_1	30	30
20180904@140.asc	WI-STD-91 OROL-6_O_1	30	30
20180904@141.asc	WI-STD-91 OROL-17_O_1	30	30
	Average (OR-Ol)		
20180904@142.asc	WI-STD-91 HaKOL-g1-2_O_1	30	30
20180904@143.asc	WI-STD-91 HaKOL-g1-3_O_1	30	30
	Average (HaK-Ol)		
20180904@144.asc	WI-STD-91 KN1-10_O_1	30	30
20180904@145.asc	WI-STD-91 KN1-10_O_2	30	30
	Average (KN-Ol)		
20180904@150.asc	WI-STD-91 WNOL-1_O_1	30	30
20180904@151.asc	WI-STD-91 WNOL-1_O_2	30	30
20180904@152.asc	WI-STD-91 WNOL-4_O_1	30	30
	Average (WN-Ol)		
20180904@153.asc	WI-STD-91 WKOL-10_O_1	30	30
20180904@154.asc	WI-STD-91 WKOL-1_2	30	30
20180904@155.asc	WI-STD-91 WKOL-5_O_1	30	30
20180904@156.asc	WI-STD-91 WKOL-8_O_1	30	30
	Average (WK-Ol)		
20180904@159.asc	WI-STD-91 A77257-5_O_1	30	30

20180904@160.asc	WI-STD-91 A77257-5_O_2	30	30
	Average (A77257-Ol)		
20180904@161.asc	WI-STD-91 UWOL1-42_O_1	30	30
20180904@162.asc	WI-STD-91 UWOL1-41_O_1	30	30
	Average (UW-Ol)		
20180904@163.asc	WI-STD-91 FJOL-2_O_1	30	30
20180904@164.asc	WI-STD-91 FJOL-3_O_1	30	30
	Average (FJ-Ol)		
20180904@157.asc	WI-STD-91 SWOL-1_O_1	30	30
20180904@158.asc	WI-STD-91 SWOL-3_O_1	30	30
20180904@165.asc	WI-STD-91 SWOL-15_O_1	30	30
	Average (SW-Ol)		

ary ion beam)

24Mg (100M cps)	Yield (10^8 cps/nA)	Measured d25Mg-m ‰	2SE ‰	d26Mg-m ‰	2SE ‰	d26Mg*-m ‰
1.85	0.76	-3.18	0.12	-5.69	0.24	0.51
1.85	0.76	-3.18	0.12	-5.74	0.23	0.45
1.85	0.76	-3.21	0.12	-5.80	0.23	0.45
1.85	0.76	-3.21	0.12	-5.74	0.24	0.52
1.84	0.76	-3.23	0.13	-5.85	0.24	0.45
1.84	0.76	-3.19	0.12	-5.78	0.23	0.45
1.85	0.76	-3.21	0.12	-5.74	0.24	0.50
1.85	0.76	-3.23	0.12	-5.79	0.24	0.50
		-3.21	0.04	-5.77	0.10	0.48
1.81	0.75	-4.50	0.05	-8.31	0.09	0.46
1.82	0.75	-4.49	0.06	-8.26	0.10	0.47
		-4.50	0.02	-8.29	0.06	0.47
1.68	0.69	-1.31	0.04	-2.10	0.03	0.46
1.69	0.70	-1.27	0.03	-2.07	0.03	0.40
1.68	0.69	-1.28	0.04	-2.08	0.03	0.41
1.65	0.68	-1.26	0.04	-2.07	0.05	0.38
		-1.28	0.05	-2.08	0.03	0.41
1.88	0.77	-3.33	0.14	-6.05	0.25	0.44
1.89	0.78	-3.32	0.14	-5.93	0.25	0.54
		-3.33	0.01	-5.99	0.17	0.49
1.95	0.80	-1.00	0.03	-1.55	0.03	0.39
1.95	0.80	-1.06	0.04	-1.59	0.03	0.47
		-1.03	0.08	-1.57	0.05	0.43
1.90	0.78	-3.24	0.10	-5.78	0.19	0.53
1.90	0.78	-3.34	0.10	-6.02	0.19	0.48
1.90	0.78	-3.25	0.09	-5.86	0.18	0.48
		-3.28	0.11	-5.89	0.25	0.50
1.89	0.78	-3.16	0.10	-5.60	0.20	0.54
1.90	0.78	-3.10	0.10	-5.55	0.19	0.50
1.90	0.78	-3.14	0.10	-5.56	0.20	0.56
1.90	0.78	-3.12	0.10	-5.53	0.20	0.55
		-3.13	0.05	-5.56	0.06	0.54
1.95	0.80	-1.14	0.03	-1.82	0.05	0.40

1.93	0.79	-1.28	0.06	-1.99	0.06	0.50
		-1.21	0.19	-1.91	0.24	0.45
1.85	0.76	-3.28	0.12	-5.84	0.24	0.54
1.85	0.76	-3.35	0.13	-5.89	0.25	0.63
		-3.31	0.10	-5.87	0.07	0.59
1.90	0.78	-1.11	0.03	-1.70	0.03	0.47
1.91	0.78	-1.14	0.03	-1.74	0.03	0.49
		-1.13	0.04	-1.72	0.06	0.48
1.84	0.76	-2.35	0.07	-4.09	0.12	0.48
1.85	0.76	-2.32	0.07	-4.02	0.13	0.50
1.85	0.76	-2.39	0.06	-4.12	0.11	0.54
		-2.35	0.07	-4.08	0.11	0.51

2SE ‰	f_{25} *	2σ [a]	bias*$_{25(RM-SCOI)}$	Corrected 2σ [b]	f_{26} *	2σ [a]
0.06	-3.11	0.15			-5.53	0.28
0.07	-3.11	0.15			-5.59	0.28
0.05	-3.14	0.15			-5.65	0.28
0.06	-3.14	0.15			-5.59	0.29
0.06	-3.16	0.15			-5.70	0.28
0.06	-3.12	0.15			-5.62	0.28
0.06	-3.13	0.15			-5.59	0.29
0.05	-3.16	0.15			-5.64	0.28
0.06	-3.13	0.04			-5.61	0.10
0.06	-4.14	0.10	-1.01	0.11	-7.62	0.16
0.07	-4.12	0.10	-0.99	0.11	-7.57	0.17
0.02	-4.13	0.02	-1.00	0.02	-7.59	0.06
0.08	-1.30	0.07	1.84	0.10	-2.08	0.13
0.06	-1.26	0.07	1.88	0.10	-2.05	0.13
0.06	-1.26	0.07	1.88	0.10	-2.05	0.13
0.08	-1.24	0.07	1.90	0.10	-2.05	0.13
0.07	-1.26	0.05	1.87	0.05	-2.06	0.03
0.06	-3.27	0.19	-0.14	0.19	-5.89	0.32
0.06	-3.26	0.19	-0.13	0.19	-5.77	0.32
0.15	-3.27	0.01	-0.13	0.01	-5.83	0.17
0.06	-1.04	0.18	2.10	0.18	-1.54	0.30
0.07	-1.09	0.18	2.05	0.18	-1.58	0.30
0.11	-1.06	0.08	2.08	0.08	-1.56	0.05
0.06	-3.20	0.13	-0.03	0.13	-5.63	0.25
0.07	-3.30	0.13	-0.13	0.14	-5.88	0.25
0.06	-3.22	0.12	-0.05	0.13	-5.72	0.24
0.05	-3.24	0.11	-0.07	0.11	-5.74	0.25
0.06	-3.07	0.16	0.10	0.16	-5.44	0.28
0.07	-3.02	0.16	0.16	0.17	-5.38	0.27
0.06	-3.06	0.16	0.12	0.16	-5.40	0.28
0.06	-3.04	0.16	0.14	0.17	-5.37	0.28
0.05	-3.04	0.05	0.13	0.05	-5.40	0.06
0.05	-1.07	0.14	2.11	0.15	-1.53	0.14

0.07	-1.21	0.15	1.97	0.16	-1.71	0.14
0.14	-1.14	0.19	2.04	0.19	-1.62	0.24
0.07	-3.14	0.16	0.03	0.16	-5.60	0.31
0.07	-3.22	0.16	-0.04	0.17	-5.65	0.32
0.13	-3.18	0.10	-0.01	0.10	-5.63	0.07
0.06	-1.04	0.20	2.13	0.20	-1.60	0.30
0.06	-1.07	0.20	2.10	0.20	-1.64	0.30
0.02	-1.06	0.04	2.12	0.04	-1.62	0.06
0.07	-2.33	0.16	0.85	0.16	-4.06	0.20
0.08	-2.30	0.16	0.87	0.16	-3.99	0.20
0.05	-2.37	0.15	0.80	0.16	-4.09	0.19
0.06	-2.33	0.07	0.84	0.07	-4.05	0.11

$bias^*_{26(RM-SCOI)}$	2σ [b]
-2.01	0.20
-1.97	0.20
-1.99	0.06
3.56	0.20
3.58	0.20
3.58	0.20
3.59	0.20
3.58	0.03
-0.28	0.32
-0.16	0.32
-0.22	0.17
4.09	0.30
4.06	0.31
4.08	0.05
0.02	0.25
-0.23	0.26
-0.07	0.25
-0.09	0.25
0.21	0.28
0.27	0.28
0.25	0.28
0.28	0.28
0.25	0.06
4.14	0.19

3.97	0.19
4.05	0.24
0.05	0.32
0.00	0.32
0.02	0.08
4.08	0.31
4.03	0.31
4.05	0.06
1.60	0.21
1.67	0.21
1.57	0.20
1.61	0.11

Appendix EA6-3: SIMS Mg isotope data (session FI3, 1nA, O_2^- prima

[a] 2σ error (A) = $\sqrt{(2SE_{SIMS})^2+(2SD_{ICPMS})^2}$

[b] 2σ error = $\sqrt{(A)^2+(2SD_{SIMS\_bracket})^2}$

Erros of averaged values are 2SD.

File	Analysis spot	Cycle# (measured)	Cycle# (used)
	Olivine		
20190122@21.asc	WI-STD-91 SCOL	30	30
20190122@22.asc	WI-STD-91 SCOL	30	30
20190122@23.asc	WI-STD-91 SCOL	30	30
20190122@24.asc	WI-STD-91 SCOL	30	30
20190122@41.asc	WI-STD-91 SCOL	30	30
20190122@42.asc	WI-STD-91 SCOL	30	30
20190122@43.asc	WI-STD-91 SCOL	30	30
20190122@44.asc	WI-STD-91 SCOL	30	30
	Average (SC-Ol)		
20190122@9.asc	WI-STD-91 WNOL1E_1	30	30
20190122@10.asc	WI-STD-91 WNOL1E_2	30	30
20190122@11.asc	WI-STD-91 WNOL1C_1	30	30
20190122@12.asc	WI-STD-91 WNOL1C_2	30	30
20190122@13.asc	WI-STD-91 WNOL4C_1	30	30
20190122@14.asc	WI-STD-91 WNOL4C_2	30	30
20190122@15.asc	WI-STD-91 WNOL4A_1	30	30
20190122@16.asc	WI-STD-91 WNOL4A_2	30	30
	Average (WN-Ol)		
20190122@17.asc	WI-STD-91 WKOL1_1	30	30
20190122@18.asc	WI-STD-91 WKOL1_2	30	30
20190122@19.asc	WI-STD-91 WKOL8_1	30	30
20190122@20.asc	WI-STD-91 WKOL8_2	30	30
	Average (WK-Ol)		
20190122@27.asc	WI-STD-91 HaKOL g1-2_1	30	30
20190122@28.asc	WI-STD-91 HaKOL g1-2_2	30	30
	Average (HaK-Ol)		
20190122@31.asc	WI-STD-91 SWOL15_1	30	30
20190122@32.asc	WI-STD-91 SWOL15_2	30	30
	Average (SW-Ol)		
20190122@37.asc	WI-STD-91 KNOL1-2_1	30	30
20190122@38.asc	WI-STD-91 KNOL1-2_2	30	30
	Average (KN-Ol)		
20190122@95.asc	WI-STD-15 Skye-X_1_spike25	30	29

20190122@96.asc	WI-STD-15 Skye-X_2	30	30
20190122@97.asc	WI-STD-15 Skye-W_1	30	30
20190122@98.asc	WI-STD-15 Skye-W_2	30	30
20190122@99.asc	WI-STD-15 Skye-V_1	30	30
20190122@100.asc	WI-STD-15 Skye-V_2	30	30
	Average (SK-OI)		
20190122@124.asc	WI-STD-92 CL0908-1_1	30	30
20190122@125.asc	WI-STD-92 CL0908-2	30	30
20190122@126.asc	WI-STD-92 CL0908-3	30	30
20190122@127.asc	WI-STD-92 CL0908-4	30	30
20190122@128.asc	WI-STD-92 CL0908-9	30	30
20190122@129.asc	WI-STD-92 CL0908-10	30	30
20190122@130.asc	WI-STD-92 CL0908-11	30	30
20190122@131.asc	WI-STD-92 CL0908-18	30	30
	Average (CL0908-OI)		
20190122@132.asc	WI-STD-92 CL0919-1_1	30	30
20190122@133.asc	WI-STD-92 CL0919-2	30	30
20190122@134.asc	WI-STD-92 CL0919-3	30	30
20190122@135.asc	WI-STD-92 CL0919-4	30	30
20190122@136.asc	WI-STD-92 CL0919-5	30	30
20190122@137.asc	WI-STD-92 CL0919-6	30	30
20190122@138.asc	WI-STD-92 CL0919-7	30	30
20190122@139.asc	WI-STD-92 CL0919-9	30	30
	Average (CL0919-OI)		
20190122@144.asc	WI-STD-92 CL0933-1	30	30
20190122@145.asc	WI-STD-92 CL0933-2	30	30
20190122@146.asc	WI-STD-92 CL0933-2	30	30
20190122@147.asc	WI-STD-92 CL0933-4_1	30	30
20190122@148.asc	WI-STD-92 CL0933-5	30	30
20190122@149.asc	WI-STD-92 CL0933-6	30	30
20190122@150.asc	WI-STD-92 CL0933-7	30	30
20190122@151.asc	WI-STD-92 CL0933-8	30	30
	Average (CL0933-OI)		
20190122@152.asc	WI-STD-92 IGOL1_1	30	30
20190122@153.asc	WI-STD-92 IGOL2	30	30
20190122@154.asc	WI-STD-92 IGOL3	30	30
20190122@155.asc	WI-STD-92 IGOL4	30	30
20190122@156.asc	WI-STD-92 IGOL5	30	30
20190122@157.asc	WI-STD-92 IGOL6	30	30
20190122@158.asc	WI-STD-92 IGOL7	30	30
20190122@159.asc	WI-STD-92 IGOL8	30	30
	Average (IG-OI)		
20190122@7.asc	WI-STD-91 A77257_1_spike19,20	30	28
20190122@8.asc	WI-STD-91 A77257_2	30	30
20190122@170.asc	WI-STD-92 A77257-4_1	30	30

20190122@171.asc	WI-STD-92 A77257-4_2	30	30
20190122@172.asc	WI-STD-92 A77257-4_3	30	30
20190122@173.asc	WI-STD-92 A77257-4_4	30	30
	Average (A77257-Ol)		
20190122@25.asc	WI-STD-91 HNOL	30	30
20190122@26.asc	WI-STD-91 HNOL	30	30
20190122@101.asc	WI-STD-91 HNOL	30	30
20190122@102.asc	WI-STD-91 HNOL	30	30
20190122@174.asc	WI-STD-92 HNOL	30	30
20190122@175.asc	WI-STD-92 HNOL	30	30
	Average (HN-Ol)		
20190122@29.asc	WI-STD-91 UWOL1-42_1	30	30
20190122@30.asc	WI-STD-91 UWOL1-42_2	30	30
20190122@93.asc	WI-STD-15 UWOL1 g1_1	30	30
20190122@94.asc	WI-STD-15 UWOL1 g1_2	30	30
20190122@107.asc	WI-STD-91 UWOL1-1	30	30
20190122@108.asc	WI-STD-91 UWOL1-2	30	30
20190122@109.asc	WI-STD-91 UWOL1-3	30	30
20190122@110.asc	WI-STD-91 UWOL1-5	30	30
20190122@111.asc	WI-STD-91 UWOL1-6	30	30
20190122@112.asc	WI-STD-91 UWOL1-7	30	30
20190122@113.asc	WI-STD-91 UWOL1-10	30	30
20190122@114.asc	WI-STD-91 UWOL1-11	30	30
20190122@115.asc	WI-STD-91 UWOL1-42	30	30
20190122@166.asc	WI-STD-92 UWOL1-1_1	30	30
20190122@167.asc	WI-STD-92 UWOL1-1_2	30	30
	Average (UW-Ol)		
20190122@33.asc	WI-STD-91 OROL17_1	30	30
20190122@34.asc	WI-STD-91 OROL17_2	30	30
20190122@35.asc	WI-STD-91 OROL5_1	30	30
20190122@36.asc	WI-STD-91 OROL5_2	30	30
20190122@164.asc	WI-STD-92 OROL2_1	30	30
20190122@165.asc	WI-STD-92 OROL2_2	30	30
	Average (OR-Ol)		
20190122@39.asc	WI-STD-91 FJOL2_1	30	30
20190122@40.asc	WI-STD-91 FJOL2_2	30	30
20190122@168.asc	WI-STD-92 FJOL2_1	30	30
20190122@169.asc	WI-STD-92 FJOL2_2	30	30
	Average (FJ-Ol)		
20190122@190.asc	NWA7325 OL7_1	30	30
20190122@191.asc	NWA7325 OL7_2	30	30
20190122@192.asc	NWA7325 OL7_3	150	30
20190122@193.asc	NWA7325 OL7_4	150	30
	Average (N7325-Ol)		

Pyroxene

20190122@66.asc	WI-STD-19 Sp79-11 G5	30	30
20190122@67.asc	WI-STD-19 Sp79-11 G3	30	30
20190122@68.asc	WI-STD-19 Sp79-11 G6	30	30
20190122@69.asc	WI-STD-19 Sp79-11 G7	30	30
	Average (Sp79-11 En)		
20190122@70.asc	WI-STD-19 JE En G3	30	30
20190122@71.asc	WI-STD-19 JE En G1	30	30
	Average (JE En)		
20190122@72.asc	WI-STD-19 IG Opx G2	30	30
20190122@73.asc	WI-STD-19 IG Opx G5	30	30
	Average (IG Opx)		
20190122@74.asc	WI-STD-19 IG Cpx G3	30	30
20190122@75.asc	WI-STD-19 IG Cpx G3	30	30
	Average (IG Cpx)		
20190122@76.asc	WI-STD-19 AK95-6 G1	30	30
20190122@77.asc	WI-STD-19 AK95-6 G4	30	30
	Average (AK95-6 Di)		

ry ion beam)

24Mg (100M cps)	Yield (10^8 cps/nA)	Measured d25Mg-m ‰	2SE ‰	d26Mg-m ‰	2SE ‰	d26Mg*-m ‰
2.35	2.22	-1.87	0.04	-3.09	0.08	0.56
2.33	2.21	-1.96	0.04	-3.26	0.09	0.55
2.34	2.22	-1.95	0.05	-3.20	0.10	0.59
2.34	2.22	-1.97	0.04	-3.25	0.09	0.59
2.28	2.22	-1.97	0.05	-3.24	0.09	0.61
2.30	2.21	-1.99	0.05	-3.33	0.09	0.55
2.31	2.22	-1.93	0.04	-3.21	0.08	0.55
2.27	2.20	-1.93	0.07	-3.15	0.09	0.61
		-1.95	0.08	-3.22	0.15	0.58
2.36	2.27	-2.35	0.05	-3.93	0.11	0.64
2.36	2.27	-2.51	0.07	-4.24	0.12	0.65
2.37	2.28	-2.36	0.06	-4.00	0.11	0.59
2.38	2.28	-2.43	0.05	-4.09	0.11	0.64
2.37	2.28	-2.33	0.05	-3.87	0.11	0.67
2.36	2.28	-2.28	0.06	-3.84	0.11	0.60
2.37	2.29	-2.28	0.05	-3.85	0.10	0.59
2.33	2.25	-2.27	0.05	-3.78	0.10	0.64
		-2.35	0.17	-3.95	0.30	0.63
2.35	2.27	-2.19	0.04	-3.60	0.09	0.67
2.35	2.27	-2.16	0.06	-3.62	0.11	0.60
2.31	2.23	-2.00	0.05	-3.31	0.09	0.59
2.38	2.27	-1.98	0.05	-3.28	0.10	0.58
		-2.08	0.22	-3.45	0.37	0.61
2.36	2.24	-2.25	0.06	-3.81	0.12	0.59
2.35	2.25	-2.30	0.06	-3.78	0.12	0.69
		-2.28	0.06	-3.79	0.03	0.64
2.34	2.23	-0.96	0.03	-1.42	0.03	0.46
2.31	2.22	-1.03	0.03	-1.45	0.03	0.55
		-0.99	0.09	-1.44	0.04	0.50
2.22	2.14	-1.10	0.03	-1.61	0.05	0.54
2.20	2.15	-1.18	0.04	-1.79	0.04	0.51
		-1.14	0.12	-1.70	0.27	0.53
2.25	2.20	-4.16	0.04	-7.12	0.06	0.97

2.23	2.19	-4.10	0.04	-7.07	0.07	0.91
2.24	2.20	-4.06	0.03	-6.98	0.06	0.93
2.24	2.20	-4.08	0.04	-6.98	0.06	0.96
2.22	2.19	-4.10	0.04	-7.02	0.06	0.97
2.23	2.21	-4.12	0.04	-7.09	0.07	0.94
		-4.10	0.07	-7.04	0.12	0.95
2.22	2.23	-1.08	0.05	-1.30	0.05	0.80
2.22	2.24	-0.92	0.03	-1.00	0.04	0.81
2.21	2.22	-1.11	0.04	-1.39	0.04	0.76
2.25	2.23	-1.17	0.04	-1.43	0.04	0.85
2.23	2.21	-1.16	0.03	-1.43	0.04	0.83
2.23	2.21	-1.12	0.04	-1.40	0.04	0.78
2.24	2.23	-0.92	0.03	-0.96	0.04	0.84
2.20	2.20	-1.08	0.04	-1.40	0.04	0.71
		-1.07	0.19	-1.29	0.39	0.80
2.20	2.21	-1.07	0.04	-1.31	0.04	0.78
2.18	2.20	-1.21	0.04	-1.52	0.04	0.85
2.19	2.20	-1.09	0.03	-1.39	0.04	0.73
2.19	2.21	-1.32	0.03	-1.78	0.04	0.79
2.20	2.22	-1.15	0.04	-1.46	0.04	0.78
2.19	2.20	-1.12	0.03	-1.43	0.04	0.75
2.17	2.18	-1.14	0.05	-1.40	0.05	0.83
2.18	2.20	-1.10	0.04	-1.35	0.04	0.79
		-1.15	0.16	-1.46	0.29	0.79
2.20	2.21	-1.64	0.03	-2.38	0.05	0.82
2.22	2.22	-1.56	0.03	-2.27	0.05	0.77
2.21	2.21	-1.58	0.03	-2.33	0.05	0.74
2.21	2.22	-1.53	0.03	-2.17	0.04	0.81
2.22	2.22	-1.55	0.03	-2.22	0.05	0.81
2.22	2.22	-1.62	0.04	-2.31	0.05	0.85
2.22	2.21	-1.45	0.04	-2.06	0.03	0.77
2.21	2.21	-1.59	0.03	-2.29	0.06	0.80
		-1.56	0.12	-2.25	0.20	0.80
2.24	2.24	-2.00	0.05	-3.10	0.09	0.79
2.22	2.21	-1.95	0.04	-3.03	0.09	0.78
2.25	2.22	-1.99	0.04	-3.05	0.08	0.82
2.26	2.23	-1.99	0.04	-3.10	0.08	0.79
2.24	2.20	-2.00	0.04	-3.09	0.08	0.80
2.24	2.21	-2.00	0.04	-3.13	0.07	0.77
2.24	2.22	-2.03	0.05	-3.18	0.10	0.79
2.24	2.22	-1.97	0.05	-3.09	0.08	0.75
		-1.99	0.05	-3.10	0.09	0.79
2.35	2.24	-0.88	0.03	-1.17	0.04	0.54
2.32	2.23	-0.94	0.03	-1.29	0.03	0.55
2.27	2.24	-0.68	0.03	-0.59	0.04	0.73

2.26	2.24	-0.71	0.03	-0.55	0.03	0.83
2.27	2.25	-0.73	0.04	-0.62	0.04	0.80
2.27	2.25	-0.79	0.03	-0.75	0.03	0.79
		-0.79	0.21	-0.83	0.64	0.71
2.30	2.19	-3.81	0.03	-6.77	0.07	0.65
2.30	2.18	-3.81	0.04	-6.78	0.07	0.64
2.27	2.19	-3.95	0.04	-6.78	0.06	0.92
2.27	2.20	-3.92	0.04	-6.72	0.05	0.92
2.20	2.19	-3.82	0.03	-6.52	0.06	0.91
2.20	2.18	-3.81	0.04	-6.50	0.05	0.93
		-3.85	0.13	-6.68	0.27	0.83
2.32	2.21	-2.02	0.06	-3.34	0.10	0.61
2.34	2.23	-2.04	0.05	-3.39	0.09	0.59
2.28	2.21	-2.12	0.04	-3.25	0.09	0.89
2.28	2.21	-2.07	0.05	-3.16	0.08	0.88
2.30	2.24	-2.23	0.04	-3.51	0.09	0.84
2.29	2.25	-2.20	0.04	-3.47	0.09	0.82
2.30	2.26	-2.24	0.05	-3.55	0.09	0.82
2.30	2.26	-2.19	0.06	-3.49	0.10	0.78
2.30	2.26	-2.23	0.04	-3.47	0.10	0.87
2.28	2.24	-2.24	0.05	-3.52	0.09	0.85
2.28	2.24	-2.22	0.04	-3.47	0.10	0.86
2.31	2.26	-2.23	0.04	-3.48	0.09	0.88
2.29	2.24	-2.17	0.04	-3.43	0.08	0.81
2.21	2.19	-1.98	0.05	-3.01	0.08	0.86
2.20	2.18	-1.99	0.04	-3.03	0.08	0.85
		-2.15	0.20	-3.37	0.36	0.81
1.85	1.79	-1.51	0.05	-2.40	0.07	0.55
1.83	1.77	-1.50	0.05	-2.36	0.06	0.56
1.90	1.84	-1.44	0.04	-2.22	0.06	0.58
1.90	1.84	-1.44	0.05	-2.24	0.06	0.57
1.84	1.82	-1.42	0.04	-2.03	0.07	0.74
1.83	1.81	-1.42	0.07	-2.07	0.07	0.71
		-1.46	0.08	-2.22	0.30	0.62
2.19	2.12	-1.31	0.03	-1.98	0.04	0.57
2.14	2.09	-1.30	0.04	-1.98	0.05	0.57
2.08	2.08	-1.26	0.04	-1.72	0.04	0.74
2.11	2.10	-1.31	0.04	-1.77	0.04	0.79
		-1.30	0.05	-1.86	0.27	0.67
2.24	2.24	-1.97	0.04	-2.83	0.03	1.02
2.27	2.27	-2.05	0.03	-2.98	0.03	1.03
2.28	2.25	-2.03	0.04	-2.97	0.04	1.00
2.25	2.27	-2.14	0.03	-3.09	0.03	1.08
		-2.05	0.14	-2.97	0.22	1.03

1.96	1.89	0.68	0.06	2.12	0.08	0.80
1.96	1.90	0.58	0.06	2.00	0.09	0.86
1.97	1.91	0.52	0.05	1.92	0.07	0.91
1.97	1.91	0.61	0.08	2.04	0.09	0.86
		0.60	0.13	2.02	0.17	0.86
1.90	1.87	1.05	0.07	2.83	0.07	0.78
1.95	1.87	0.99	0.04	2.72	0.06	0.79
		1.02	0.08	2.77	0.15	0.78
1.87	1.80	1.37	0.05	3.47	0.07	0.79
1.88	1.82	1.38	0.04	3.47	0.08	0.79
		1.38	0.003	3.47	0.003	0.79
0.68	0.66	0.37	0.08	1.51	0.11	0.79
0.66	0.64	0.45	0.08	1.66	0.10	0.77
		0.41	0.12	1.58	0.21	0.78
0.62	0.60	-0.72	0.09	-0.65	0.14	0.76
0.62	0.60	-0.77	0.10	-0.81	0.15	0.69
		-0.74	0.06	-0.73	0.22	0.72

2SE ‰	f_{25}*	2σ [a]	Corrected bias*$_{25(RM-SCOl)}$	2σ [b]	f_{26}*	2σ [a]
0.06	-1.80	0.10			-2.93	0.18
0.06	-1.89	0.10			-3.11	0.18
0.06	-1.87	0.10			-3.05	0.19
0.05	-1.90	0.10			-3.10	0.19
0.06	-1.90	0.10			-3.08	0.18
0.07	-1.92	0.10			-3.18	0.18
0.05	-1.86	0.10			-3.06	0.18
0.08	-1.86	0.12			-3.00	0.18
0.05	-1.87	0.08			-3.07	0.15
0.06	-2.31	0.10	-0.50	0.16	-3.79	0.20
0.05	-2.47	0.11	-0.67	0.16	-4.09	0.20
0.05	-2.32	0.10	-0.51	0.16	-3.86	0.20
0.08	-2.39	0.10	-0.58	0.16	-3.94	0.19
0.05	-2.30	0.10	-0.49	0.16	-3.73	0.20
0.05	-2.24	0.10	-0.44	0.16	-3.70	0.19
0.06	-2.24	0.10	-0.44	0.16	-3.71	0.19
0.05	-2.23	0.10	-0.43	0.16	-3.64	0.19
0.06	-2.31	0.17	-0.51	0.17	-3.81	0.30
0.06	-2.11	0.13	-0.30	0.16	-3.44	0.22
0.07	-2.08	0.14	-0.27	0.16	-3.46	0.22
0.05	-1.92	0.13	-0.11	0.16	-3.15	0.22
0.06	-1.89	0.13	-0.08	0.16	-3.11	0.22
0.08	-2.00	0.22	-0.19	0.22	-3.29	0.37
0.04	-2.20	0.14	-0.32	0.15	-3.65	0.23
0.06	-2.24	0.14	-0.36	0.15	-3.62	0.22
0.15	-2.22	0.06	-0.34	0.06	-3.64	0.03
0.05	-0.94	0.14	0.93	0.15	-1.39	0.16
0.06	-1.00	0.14	0.87	0.15	-1.42	0.16
0.13	-0.97	0.09	0.90	0.09	-1.41	0.04
0.05	-1.14	0.18	0.74	0.18	-1.59	0.30
0.05	-1.22	0.18	0.65	0.18	-1.78	0.30
0.04	-1.18	0.12	0.70	0.12	-1.69	0.27
0.06	-3.27	0.20	-1.35	0.21	-5.41	0.54

0.07	-3.21	0.21	-1.29	0.21	-5.36	0.54
0.05	-3.17	0.20	-1.25	0.21	-5.27	0.54
0.07	-3.19	0.20	-1.27	0.21	-5.27	0.54
0.06	-3.21	0.21	-1.29	0.21	-5.31	0.54
0.06	-3.23	0.21	-1.32	0.21	-5.38	0.54
0.05	-3.21	0.07	-1.30	0.07	-5.33	0.12
0.07	-0.87	0.07	0.93	0.11	-0.89	0.09
0.05	-0.71	0.06	1.09	0.11	-0.59	0.08
0.05	-0.90	0.06	0.90	0.11	-0.98	0.08
0.05	-0.96	0.06	0.84	0.11	-1.02	0.08
0.05	-0.95	0.06	0.85	0.11	-1.02	0.08
0.06	-0.91	0.06	0.89	0.11	-0.99	0.08
0.05	-0.71	0.06	1.09	0.11	-0.55	0.08
0.07	-0.87	0.06	0.93	0.11	-0.99	0.08
0.09	-0.86	0.19	0.94	0.19	-0.88	0.39
0.06	-0.86	0.07	0.94	0.11	-0.94	0.07
0.05	-1.01	0.07	0.79	0.11	-1.15	0.07
0.06	-0.88	0.07	0.92	0.11	-1.02	0.07
0.07	-1.11	0.07	0.69	0.11	-1.41	0.07
0.06	-0.94	0.07	0.86	0.11	-1.09	0.07
0.06	-0.91	0.07	0.89	0.11	-1.06	0.07
0.06	-0.93	0.08	0.87	0.11	-1.03	0.08
0.07	-0.89	0.07	0.91	0.11	-0.98	0.07
0.08	-0.94	0.16	0.86	0.16	-1.09	0.29
0.05	-1.39	0.06	0.45	0.14	-1.91	0.08
0.06	-1.31	0.06	0.53	0.14	-1.80	0.08
0.07	-1.33	0.06	0.52	0.14	-1.87	0.08
0.06	-1.28	0.06	0.56	0.14	-1.70	0.07
0.04	-1.30	0.06	0.54	0.14	-1.75	0.08
0.07	-1.37	0.06	0.47	0.14	-1.84	0.08
0.07	-1.20	0.06	0.64	0.14	-1.59	0.07
0.06	-1.34	0.06	0.51	0.14	-1.82	0.08
0.07	-1.31	0.12	0.53	0.12	-1.78	0.20
0.07	-1.97	0.10	-0.13	0.14	-3.05	0.18
0.05	-1.93	0.10	-0.08	0.14	-2.98	0.18
0.05	-1.96	0.10	-0.12	0.14	-3.00	0.17
0.06	-1.97	0.10	-0.13	0.14	-3.05	0.17
0.06	-1.97	0.10	-0.13	0.14	-3.04	0.17
0.06	-1.98	0.10	-0.13	0.14	-3.08	0.17
0.06	-2.01	0.11	-0.17	0.14	-3.13	0.18
0.07	-1.94	0.10	-0.10	0.14	-3.04	0.17
0.04	-1.96	0.05	-0.12	0.05	-3.05	0.09
0.06	-0.81	0.14	1.00	0.16	-0.88	0.13
0.06	-0.87	0.14	0.94	0.16	-1.00	0.13
0.04	-0.60	0.14	1.22	0.18	-0.30	0.13

0.06	-0.64	0.14	1.19	0.18	-0.27	0.13
0.07	-0.65	0.15	1.17	0.18	-0.33	0.14
0.06	-0.72	0.14	1.11	0.18	-0.46	0.13
0.26	-0.72	0.21	1.10	0.23	-0.54	0.64
0.06	-3.45	0.09	-1.58	0.13	-6.08	0.15
0.06	-3.45	0.09	-1.57	0.13	-6.09	0.16
0.08	-3.59	0.09	-1.67	0.11	-6.09	0.15
0.06	-3.56	0.09	-1.64	0.11	-6.03	0.15
0.06	-3.45	0.09	-1.63	0.18	-5.83	0.15
0.06	-3.45	0.09	-1.63	0.18	-5.81	0.15
0.28	-3.49	0.13	-1.62	0.08	-5.99	0.27
0.07	-1.89	0.11	-0.01	0.13	-3.10	0.22
0.08	-1.91	0.11	-0.03	0.13	-3.14	0.22
0.06	-1.99	0.11	-0.07	0.11	-3.01	0.22
0.07	-1.94	0.11	-0.02	0.12	-2.92	0.21
0.07	-2.09	0.11	-0.19	0.11	-3.27	0.22
0.06	-2.07	0.11	-0.16	0.11	-3.23	0.22
0.06	-2.11	0.11	-0.20	0.12	-3.31	0.22
0.06	-2.06	0.12	-0.15	0.12	-3.25	0.22
0.05	-2.09	0.11	-0.18	0.11	-3.23	0.22
0.05	-2.10	0.11	-0.20	0.12	-3.28	0.22
0.06	-2.09	0.11	-0.18	0.12	-3.23	0.22
0.05	-2.10	0.11	-0.19	0.11	-3.24	0.22
0.06	-2.04	0.11	-0.13	0.11	-3.18	0.21
0.07	-1.85	0.11	-0.02	0.18	-2.77	0.21
0.05	-1.85	0.11	-0.03	0.18	-2.79	0.21
0.18	-2.01	0.20	-0.12	0.15	-3.13	0.36
0.07	-1.50	0.08	0.38	0.13	-2.38	0.14
0.07	-1.49	0.08	0.39	0.13	-2.34	0.14
0.08	-1.43	0.07	0.45	0.13	-2.20	0.14
0.06	-1.43	0.08	0.45	0.13	-2.22	0.14
0.07	-1.41	0.08	0.42	0.18	-2.01	0.14
0.10	-1.41	0.09	0.42	0.18	-2.04	0.14
0.16	-1.44	0.08	0.42	0.06	-2.20	0.30
0.06	-1.24	0.20	0.64	0.20	-1.88	0.30
0.04	-1.23	0.20	0.64	0.20	-1.88	0.30
0.06	-1.19	0.20	0.63	0.21	-1.62	0.30
0.05	-1.24	0.20	0.58	0.21	-1.67	0.30
0.23	-1.23	0.05	0.62	0.06	-1.76	0.27
0.07	-1.90	0.15	-0.14	0.17	-2.77	0.10
0.06	-1.98	0.14	-0.22	0.17	-2.92	0.10
0.06	-1.96	0.14	-0.20	0.17	-2.91	0.10
0.07	-2.07	0.14	-0.28	0.15	-3.04	0.10
0.07	-1.98	0.14	-0.21	0.12	-2.91	0.22

0.06	0.73	0.08	2.54	0.12	2.23	0.14
0.06	0.64	0.08	2.45	0.12	2.10	0.14
0.05	0.58	0.07	2.39	0.12	2.02	0.13
0.08	0.67	0.10	2.48	0.12	2.15	0.14
0.09	0.65	0.13	2.46	0.13	2.13	0.17
0.10	1.31	0.09	3.12	0.12	3.33	0.13
0.08	1.25	0.07	3.06	0.12	3.23	0.13
0.01	1.28	0.08	3.09	0.08	3.28	0.15
0.08	1.41	0.09	3.22	0.12	3.54	0.15
0.06	1.41	0.09	3.23	0.12	3.54	0.15
0.002	1.41	0.003	3.22	0.003	3.54	0.003
0.12	0.51	0.12	2.32	0.13	1.79	0.22
0.13	0.59	0.12	2.40	0.13	1.93	0.22
0.03	0.55	0.12	2.36	0.12	1.86	0.21
0.11	0.02	0.10	1.83	0.12	0.78	0.18
0.15	-0.03	0.12	1.78	0.12	0.62	0.19
0.10	0.00	0.06	1.81	0.06	0.70	0.22

bias* $_{26(RM-SCOI)}$	2σ [b]
-0.80	0.26
-1.11	0.26
-0.87	0.26
-0.95	0.26
-0.74	0.26
-0.71	0.26
-0.72	0.26
-0.65	0.26
-0.82	0.30
-0.45	0.26
-0.47	0.26
-0.16	0.26
-0.12	0.26
-0.30	0.37
-0.58	0.24
-0.56	0.24
-0.57	0.03
1.68	0.23
1.65	0.23
1.66	0.04
1.48	0.31
1.29	0.31
1.38	0.27
-2.54	0.54

-2.49	0.54
-2.39	0.54
-2.39	0.54
-2.43	0.54
-2.50	0.54
-2.46	0.12
1.80	0.19
2.10	0.19
1.71	0.19
1.67	0.19
1.67	0.19
1.70	0.19
2.14	0.19
1.69	0.19
1.81	0.39
1.74	0.19
1.54	0.19
1.66	0.19
1.28	0.19
1.60	0.19
1.62	0.19
1.66	0.19
1.71	0.19
1.60	0.29
0.86	0.27
0.96	0.27
0.90	0.27
1.06	0.27
1.01	0.27
0.92	0.27
1.17	0.27
0.94	0.27
0.98	0.20
-0.29	0.27
-0.22	0.27
-0.24	0.27
-0.29	0.27
-0.28	0.27
-0.32	0.27
-0.37	0.27
-0.28	0.27
-0.29	0.09
2.12	0.26
1.99	0.26
2.46	0.32

2.50	0.32
2.43	0.32
2.30	0.32
2.30	0.41
-3.03	0.23
-3.03	0.23
-3.21	0.20
-3.15	0.20
-3.08	0.32
-3.06	0.32
-3.09	0.15
-0.03	0.23
-0.08	0.23
-0.13	0.23
-0.04	0.22
-0.39	0.23
-0.36	0.23
-0.44	0.23
-0.38	0.23
-0.36	0.23
-0.41	0.23
-0.36	0.23
-0.37	0.23
-0.31	0.22
-0.01	0.32
-0.03	0.32
-0.25	0.34
0.69	0.23
0.73	0.23
0.87	0.23
0.85	0.23
0.75	0.32
0.71	0.32
0.77	0.15
1.19	0.31
1.19	0.31
1.14	0.32
1.09	0.32
1.15	0.10
-0.21	0.27
-0.37	0.27
-0.35	0.27
-0.19	0.24
-0.28	0.18

5.00	0.20
4.87	0.20
4.79	0.20
4.92	0.20
4.90	0.17
6.11	0.20
6.00	0.20
6.05	0.15
6.32	0.20
6.32	0.20
6.32	0.003
4.55	0.23
4.70	0.23
4.63	0.21
3.55	0.20
3.39	0.20
3.47	0.22

Appendix EA6-4: SIMS Mg isotope data (session FI4, 2.6nA, O^- prima

[a] 2σ error (A) = $\sqrt{(2SE_{SIMS})^2+(2SD_{ICPMS})^2}$

[b] 2σ error = $\sqrt{(A)^2+(2SD_{SIMS\_bracket})^2}$

Erros of averaged values are 2SD.

File	Analysis spot	Cycle# (measured)	Cycle# (used)
20190425@31.asc	WI-STD-91 SCOL	30	30
20190425@32.asc	WI-STD-91 SCOL	30	30
20190425@33.asc	WI-STD-91 SCOL	30	30
20190425@34.asc	WI-STD-91 SCOL	30	30
20190425@47.asc	WI-STD-91 SCOL	30	30
20190425@48.asc	WI-STD-91 SCOL	30	30
20190425@49.asc	WI-STD-91 SCOL	30	30
20190425@50.asc	WI-STD-91 SCOL	30	30
	Average (SC-Ol)		
20190425@21.asc	WI-STD-91 UWOL1-42_1	30	30
20190425@22.asc	WI-STD-91 UWOL1-42_2	30	30
20190425@66.asc	WI-STD-15 UWOL1 g1_1	30	30
20190425@67.asc	WI-STD-15 UWOL1 g1_2	30	30
	Average (UW-Ol)		
20190425@23.asc	WI-STD-91 SWOL15_1	30	30
20190425@24.asc	WI-STD-91 SWOL15_2	30	30
20190425@25.asc	WI-STD-91 SWOL8_1	30	30
20190425@26.asc	WI-STD-91 SWOL8_2	30	30
20190425@27.asc	WI-STD-91 SWOL3_1	30	30
20190425@28.asc	WI-STD-91 SWOL3_2	30	30
20190425@29.asc	WI-STD-91 SWOL1_1	30	30
20190425@30.asc	WI-STD-91 SWOL1_2	30	30
	Average (SW-Ol)		
20190425@35.asc	WI-STD-91 OROL17_1	30	30
20190425@36.asc	WI-STD-91 OROL17_2	30	30
20190425@37.asc	WI-STD-91 OROL5_1	30	30
20190425@38.asc	WI-STD-91 OROL5_2	30	30
	Average (OR-Ol)		
20190425@43.asc	WI-STD-91 WKOL1_1	30	30
20190425@44.asc	WI-STD-91 WKOL1_2	30	30
20190425@45.asc	WI-STD-91 WKOL8_1	30	30
20190425@46.asc	WI-STD-91 WKOL8_2	30	30
	Average (WK-Ol)		
20190425@51.asc	WI-STD-91 WNOL1E_1	30	30
20190425@61.asc	WI-STD-91 WNOL1E_3	30	30

20190425@53.asc	WI-STD-91 WNOL1C_1	30	30
20190425@54.asc	WI-STD-91 WNOL1C_2	30	30
20190425@55.asc	WI-STD-91 WNOL4C_1	30	30
20190425@56.asc	WI-STD-91 WNOL4C_2	30	30
20190425@57.asc	WI-STD-91 WNOL4A_1	30	30
20190425@58.asc	WI-STD-91 WNOL4A_2	30	30
	Average (WN-Ol)		
20190425@59.asc	WI-STD-91 A77257-5_1	30	30
20190425@60.asc	WI-STD-91 A77257-5_2	30	30
20190425@114.asc	WI-STD-92 A77257-4_1	30	30
20190425@115.asc	WI-STD-92 A77257-4_2	150	30
	Average (A77257-Ol)		
20190425@68.asc	WI-STD-15 SKOL-W_1	30	30
20190425@69.asc	WI-STD-15 SKOL-W_2	30	30
20190425@70.asc	WI-STD-15 SKOL-V_1	30	30
20190425@71.asc	WI-STD-15 SKOL-V_2	30	30
20190425@72.asc	WI-STD-15 SKOL-X_1	30	30
20190425@73.asc	WI-STD-15 SKOL-X_2	30	30
20190425@74.asc	WI-STD-92 SKOL-X_3	150	30
	Average (SK-Ol)		
20190425@17.asc	WI-STD-91 HNOL	30	30
20190425@18.asc	WI-STD-91 HNOL	30	30
	Average (HN-Ol)		
20190425@19.asc	WI-STD-91 HaKOL g1-2_1	30	30
20190425@20.asc	WI-STD-91 HaKOL g1-2_2	30	30
	Average (HaK-Ol)		
20190425@39.asc	WI-STD-91 KNOL1-2_1	30	30
20190425@40.asc	WI-STD-91 KNOL1-2_2	30	30
	Average (KN-Ol)		
20190425@41.asc	WI-STD-91 FJOL2_1	30	30
20190425@42.asc	WI-STD-91 FJOL2_2	30	30
	Average (FJ-Ol)		
20190425@101.asc	N7325 OL7_1	30	30
20190425@102.asc	N7325 OL7_2	150	30
	Average (N7325-Ol)		
20190425@116.asc	WI-STD-92 IGOL1_1	150	30
20190425@117.asc	WI-STD-92 IGOL1_2	30	30
	Average (IG-Ol)		
20190425@111.asc	WI-STD-92 CL0908-1_1	30	30
20190425@118.asc	WI-STD-92 CL0908-1_2	150	30
	Average (CL0908-Ol)		
20190425@112.asc	WI-STD-92 CL0919-1_1	30	30
20190425@119.asc	WI-STD-92 CL0919-1_2	150	30
	Average (CL0919-Ol)		
20190425@113.asc	WI-STD-92 CL0933-4_1	30	30

20190425@120.asc	WI-STD-92 CL0933-4_2	150	30
	Average (CL0933-Ol)		

ary ion beam)

24Mg (100M cps)	Yield (10^8 cps/nA)	Measured d25Mg-m ‰	2SE ‰	d26Mg-m ‰	2SE ‰	d26Mg*-m ‰
2.36	0.88	-2.42	0.12	-4.32	0.21	0.39
2.37	0.88	-2.46	0.12	-4.37	0.21	0.43
2.37	0.88	-2.52	0.10	-4.39	0.21	0.51
2.37	0.88	-2.50	0.12	-4.43	0.21	0.44
2.36	0.88	-2.46	0.11	-4.34	0.22	0.46
2.37	0.88	-2.49	0.11	-4.39	0.21	0.46
2.37	0.88	-2.50	0.11	-4.41	0.22	0.45
2.37	0.89	-2.51	0.10	-4.44	0.22	0.46
		-2.48	0.07	-4.39	0.09	0.45
2.34	0.88	-2.52	0.12	-4.51	0.23	0.41
2.35	0.88	-2.48	0.12	-4.46	0.22	0.37
2.34	0.88	-2.55	0.12	-4.51	0.23	0.45
2.36	0.88	-2.55	0.12	-4.49	0.23	0.48
		-2.52	0.07	-4.49	0.05	0.43
2.32	0.87	-1.66	0.07	-2.94	0.11	0.29
2.33	0.87	-1.74	0.06	-3.01	0.11	0.38
2.32	0.86	-1.63	0.06	-2.82	0.10	0.37
2.33	0.87	-1.61	0.06	-2.80	0.11	0.34
2.32	0.86	-1.60	0.06	-2.77	0.10	0.35
2.34	0.87	-1.61	0.06	-2.79	0.11	0.35
2.32	0.87	-1.56	0.06	-2.68	0.11	0.36
2.34	0.87	-1.60	0.06	-2.77	0.10	0.35
		-1.63	0.11	-2.82	0.21	0.35
2.07	0.77	-0.54	0.03	-0.75	0.03	0.31
2.07	0.77	-0.57	0.04	-0.78	0.03	0.34
2.12	0.79	-0.45	0.04	-0.57	0.02	0.30
2.12	0.79	-0.43	0.03	-0.54	0.02	0.30
		-0.50	0.14	-0.66	0.25	0.31
2.41	0.90	-2.54	0.10	-4.51	0.19	0.45
2.41	0.90	-2.42	0.09	-4.24	0.19	0.47
2.41	0.90	-2.49	0.10	-4.39	0.19	0.46
2.42	0.90	-2.43	0.09	-4.30	0.19	0.43
		-2.47	0.12	-4.36	0.24	0.45
2.43	0.91	-2.69	0.10	-4.80	0.18	0.45
2.42	0.90	-2.79	0.10	-4.93	0.18	0.51

2.43	0.91	-2.68	0.09	-4.82	0.18	0.40
2.44	0.91	-2.72	0.09	-4.81	0.18	0.48
2.44	0.91	-2.62	0.10	-4.60	0.19	0.50
2.44	0.91	-2.59	0.08	-4.63	0.16	0.42
2.42	0.90	-2.61	0.09	-4.63	0.18	0.46
2.44	0.91	-2.52	0.08	-4.42	0.15	0.49
		-2.65	0.17	-4.70	0.33	0.46
2.39	0.89	-0.78	0.03	-1.13	0.03	0.39
2.42	0.91	-0.66	0.03	-0.82	0.04	0.47
2.47	0.92	-0.68	0.03	-0.69	0.03	0.64
2.45	0.91	-0.69	0.03	-0.73	0.04	0.62
		-0.70	0.11	-0.84	0.40	0.53
2.29	0.86	-4.13	0.05	-7.62	0.11	0.43
2.30	0.86	-4.23	0.07	-7.70	0.12	0.53
2.30	0.86	-4.27	0.05	-7.85	0.10	0.46
2.30	0.86	-4.25	0.06	-7.79	0.12	0.48
2.31	0.87	-4.26	0.07	-7.84	0.11	0.46
2.31	0.87	-4.27	0.07	-7.81	0.11	0.51
2.31	0.86	-4.28	0.05	-7.83	0.11	0.49
		-4.24	0.10	-7.78	0.17	0.48
2.28	0.86	-3.89	0.06	-7.20	0.11	0.39
2.30	0.86	-3.92	0.06	-7.24	0.10	0.39
		-3.91	0.04	-7.22	0.07	0.39
2.37	0.89	-2.68	0.13	-4.77	0.24	0.44
2.37	0.89	-2.66	0.13	-4.74	0.23	0.44
		-2.67	0.02	-4.76	0.04	0.44
2.45	0.91	-0.25	0.03	-0.15	0.03	0.34
2.43	0.90	-0.21	0.03	-0.08	0.03	0.33
		-0.23	0.06	-0.12	0.09	0.34
2.40	0.89	-0.34	0.03	-0.33	0.03	0.33
2.40	0.89	-0.34	0.03	-0.32	0.03	0.33
		-0.34	0.002	-0.32	0.01	0.33
2.44	0.91	-2.13	0.05	-3.43	0.10	0.73
2.47	0.92	-2.16	0.04	-3.48	0.09	0.72
		-2.15	0.03	-3.45	0.07	0.73
2.39	0.89	-2.70	0.12	-4.59	0.23	0.68
2.39	0.89	-2.69	0.12	-4.49	0.24	0.74
		-2.69	0.02	-4.54	0.13	0.71
2.34	0.87	-1.71	0.06	-2.75	0.11	0.57
2.35	0.88	-1.77	0.07	-2.77	0.10	0.69
		-1.74	0.10	-2.76	0.03	0.63
2.36	0.88	-1.46	0.04	-2.24	0.09	0.61
2.36	0.88	-1.47	0.05	-2.24	0.08	0.63
		-1.47	0.02	-2.24	0.004	0.62
2.37	0.88	-2.41	0.09	-3.98	0.19	0.72

2.37	0.88	-2.41	0.08	-4.04	0.17	0.66
		-2.41	0.002	-4.01	0.08	0.69

2SE ‰	f_{25}*	2σ [a]	bias*$_{25(RM\text{-}SCOl)}$	Corrected 2σ [b]	f_{26}*	2σ [a]
0.06	-2.34	0.15			-4.16	0.27
0.06	-2.39	0.15			-4.22	0.27
0.05	-2.44	0.14			-4.24	0.26
0.05	-2.43	0.15			-4.28	0.26
0.05	-2.39	0.15			-4.19	0.27
0.05	-2.41	0.14			-4.23	0.27
0.04	-2.42	0.14			-4.26	0.27
0.05	-2.44	0.14			-4.29	0.27
0.06	-2.41	0.07			-4.23	0.09
0.04	-2.39	0.15	-0.01	0.20	-4.26	0.30
0.06	-2.34	0.15	0.04	0.20	-4.21	0.30
0.04	-2.41	0.15	-0.06	0.16	-4.27	0.30
0.05	-2.42	0.16	-0.07	0.16	-4.25	0.30
0.10	-2.39	0.07	-0.03	0.10	-4.25	0.05
0.05	-1.64	0.16	0.74	0.20	-2.91	0.19
0.05	-1.72	0.15	0.66	0.20	-2.98	0.19
0.06	-1.61	0.15	0.77	0.20	-2.79	0.19
0.05	-1.59	0.15	0.79	0.20	-2.77	0.19
0.05	-1.58	0.15	0.80	0.20	-2.74	0.19
0.05	-1.59	0.15	0.79	0.20	-2.76	0.19
0.05	-1.54	0.15	0.84	0.20	-2.65	0.19
0.05	-1.58	0.15	0.80	0.20	-2.74	0.18
0.05	-1.60	0.11	0.77	0.11	-2.79	0.21
0.04	-0.53	0.07	1.88	0.12	-0.73	0.13
0.06	-0.56	0.07	1.85	0.12	-0.76	0.13
0.07	-0.43	0.07	1.98	0.12	-0.55	0.13
0.05	-0.42	0.07	2.00	0.12	-0.51	0.13
0.03	-0.49	0.14	1.93	0.14	-0.64	0.25
0.05	-2.46	0.16	-0.05	0.16	-4.34	0.27
0.05	-2.33	0.16	0.08	0.16	-4.07	0.27
0.06	-2.40	0.16	0.01	0.17	-4.22	0.27
0.05	-2.34	0.16	0.07	0.16	-4.13	0.27
0.04	-2.38	0.12	0.03	0.12	-4.19	0.24
0.05	-2.65	0.13	-0.26	0.14	-4.65	0.24
0.05	-2.76	0.13	-0.36	0.13	-4.79	0.24

0.05	-2.64	0.12	-0.25	0.12	-4.67	0.24
0.05	-2.68	0.12	-0.29	0.13	-4.67	0.24
0.04	-2.58	0.13	-0.19	0.13	-4.46	0.25
0.05	-2.56	0.12	-0.16	0.12	-4.49	0.23
0.05	-2.57	0.12	-0.18	0.12	-4.48	0.24
0.05	-2.49	0.11	-0.09	0.12	-4.28	0.22
0.08	-2.62	0.17	-0.22	0.17	-4.56	0.33
0.05	-0.71	0.14	1.69	0.15	-0.85	0.13
0.06	-0.59	0.14	1.81	0.15	-0.53	0.13
0.05	-0.61	0.14	2.00	0.16	-0.40	0.13
0.07	-0.62	0.14	1.99	0.16	-0.44	0.14
0.24	-0.63	0.11	1.87	0.30	-0.56	0.40
0.07	-3.24	0.21	-0.90	0.21	-5.91	0.55
0.05	-3.34	0.21	-0.99	0.22	-5.99	0.55
0.04	-3.38	0.21	-1.03	0.21	-6.14	0.55
0.05	-3.36	0.21	-1.01	0.21	-6.08	0.55
0.06	-3.37	0.21	-1.03	0.22	-6.13	0.55
0.05	-3.38	0.21	-1.04	0.22	-6.10	0.55
0.06	-3.39	0.21	-1.04	0.21	-6.13	0.55
0.07	-3.35	0.10	-1.01	0.10	-6.07	0.17
0.05	-3.53	0.10	-1.15	0.20	-6.50	0.18
0.05	-3.56	0.11	-1.18	0.20	-6.55	0.17
0.005	-3.54	0.04	-1.17	0.04	-6.53	0.07
0.05	-2.62	0.18	-0.24	0.20	-4.61	0.30
0.05	-2.60	0.18	-0.22	0.20	-4.58	0.30
0.001	-2.61	0.02	-0.23	0.02	-4.60	0.04
0.05	-0.29	0.18	2.12	0.18	-0.14	0.30
0.06	-0.25	0.18	2.16	0.18	-0.07	0.30
0.02	-0.27	0.06	2.14	0.06	-0.10	0.09
0.05	-0.27	0.20	2.15	0.20	-0.23	0.30
0.05	-0.27	0.20	2.15	0.20	-0.22	0.30
0.01	-0.27	0.002	2.15	0.002	-0.23	0.01
0.05	-2.06	0.15	0.26	0.16	-3.37	0.13
0.06	-2.08	0.15	0.24	0.15	-3.42	0.13
0.01	-2.07	0.03	0.25	0.03	-3.40	0.07
0.04	-2.67	0.15	-0.07	0.16	-4.54	0.27
0.06	-2.66	0.15	-0.06	0.16	-4.44	0.28
0.09	-2.67	0.02	-0.07	0.02	-4.49	0.13
0.06	-1.50	0.07	1.11	0.16	-2.34	0.13
0.05	-1.56	0.09	1.04	0.16	-2.36	0.13
0.16	-1.53	0.10	1.07	0.10	-2.35	0.03
0.03	-1.25	0.07	1.36	0.16	-1.87	0.10
0.05	-1.26	0.08	1.34	0.16	-1.87	0.10
0.04	-1.26	0.02	1.35	0.02	-1.87	0.004
0.06	-2.16	0.10	0.44	0.16	-3.51	0.20

0.05	-2.16	0.10	0.44	0.16	-3.57	0.18
0.09	-2.16	0.002	0.44	0.002	-3.54	0.08

bias*$_{26(RM-SCOI)}$	2σ [b]
-0.04	0.36
0.01	0.36
-0.17	0.31
-0.15	0.31
-0.09	0.18
1.32	0.36
1.25	0.36
1.45	0.36
1.46	0.36
1.49	0.36
1.48	0.36
1.59	0.36
1.50	0.36
1.44	0.21
3.52	0.19
3.49	0.19
3.70	0.19
3.74	0.19
3.61	0.25
-0.11	0.28
0.16	0.28
0.01	0.28
0.10	0.28
0.04	0.24
-0.46	0.25
-0.59	0.25

-0.48	0.25
-0.48	0.25
-0.26	0.26
-0.29	0.24
-0.29	0.25
-0.08	0.23
-0.37	0.33
3.37	0.21
3.68	0.21
3.99	0.30
3.95	0.30
3.75	0.58
-1.82	0.55
-1.90	0.56
-2.05	0.55
-1.99	0.55
-2.05	0.55
-2.01	0.55
-2.04	0.55
-1.98	0.17
-2.28	0.36
-2.33	0.36
-2.31	0.07
-0.39	0.36
-0.36	0.36
-0.37	0.04
4.11	0.31
4.18	0.30
4.15	0.09
4.02	0.31
4.03	0.31
4.02	0.01
0.49	0.25
0.44	0.25
0.47	0.07
-0.16	0.30
-0.07	0.30
-0.12	0.13
2.04	0.30
2.02	0.30
2.03	0.03
2.52	0.30
2.52	0.30
2.52	0.004
0.86	0.30

	0.81	0.30
	0.83	0.08

Appendix EA6-5: Comparison of the relationship between IMF an

[a] 2σ error (‰) = $\sqrt{(2SD_{SIMS})^2+(2SD_{ICPMS})^2}$, where $2SD_{SIMS}$ represents either δ^{25}Mg hom

		O2-		
		Session FI1		Sessio
RM name	Fo#	bias*$_{25(RM\text{-}SCOl)}$	2 σ[a]	bias*$_{25(RM\text{-}SCOl)}$
OR-Ol	59.27	0.70	0.14	0.42
FJ-Ol	73.36	0.89	0.24	0.62
KN-Ol	77.97	0.95	0.22	0.70
CL09-19-Ol	79.44			0.86
CL09-08-Ol	80.53			0.94
SW-Ol	81.81	1.23	0.19	0.90
A77257-Ol	85.70	1.49	0.27	1.10
CL09-33-Ol	86.63			0.53
SC-Ol	88.82	0.00	0.17	0.00
UWOL-1	89.23	0.01	0.18	-0.12
IG-Ol	89.58			-0.12
HaK-Ol	91.85	-0.36	0.19	-0.34
WK-Ol	94.30	-0.07	0.18	-0.19
WN-Ol	95.52	-0.46	0.19	-0.51
N7325-Ol	97.42			-0.21
SK-Ol	99.81			-1.30
HN-Ol	100.00	-1.41	0.16	-1.62

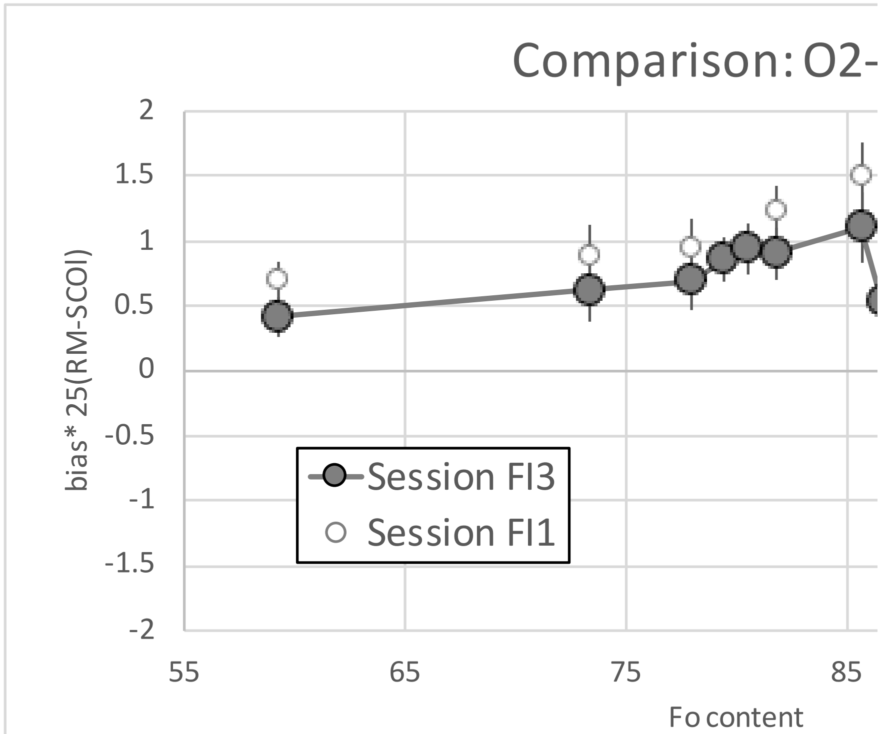
		O-		
		Session FI2		Sessio
RM name	Fo#	bias*$_{25(RM\text{-}SCOl)}$	2 σ[a]	bias*$_{25(RM\text{-}SCOl)}$
OR-Ol	59.27	1.87	0.14	1.93
FJ-Ol	73.36	2.12	0.23	2.15
KN-Ol	77.97	2.08	0.22	2.14
CL09-19-Ol	79.44			1.35
CL09-08-Ol	80.53			1.07
SW-Ol	81.81	0.84	0.19	0.77
A77257-Ol	85.70	2.04	0.27	1.87
CL09-33-Ol	86.63			0.44
SC-Ol	88.82	0.00	0.17	0.00
UWOL-1	89.23	-0.01	0.18	-0.03
IG-Ol	89.58			-0.07
HaK-Ol	91.85	-0.13	0.18	-0.23
WK-Ol	94.30	0.13	0.18	0.03
WN-Ol	95.52	-0.07		-0.22
N7325-Ol	97.42		0.00	0.25
SK-Ol	99.81			-1.01

HN-OI	100.00	-1.00	0.15	-1.17

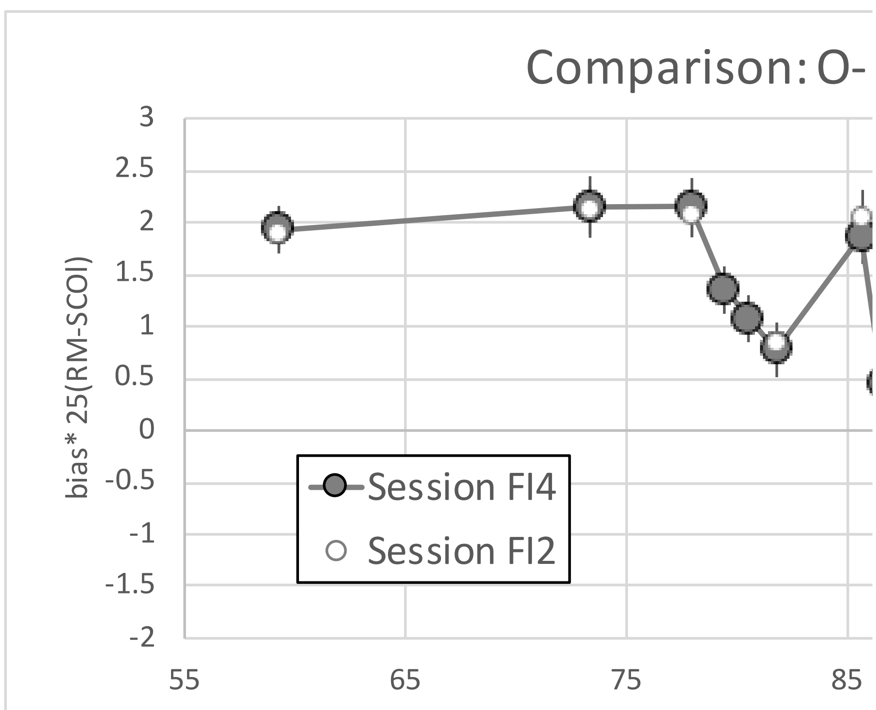
d Fo content obtained by multiple sessions

ogeneity of each RM or long-term reproducibility of the running standard (SC-Ol) durin

n FI3
2 σ[a]
0.15
0.24
0.23
0.17
0.20
0.20
0.27
0.15
0.17
0.18
0.17
0.19
0.19
0.19
0.20
0.25
0.16



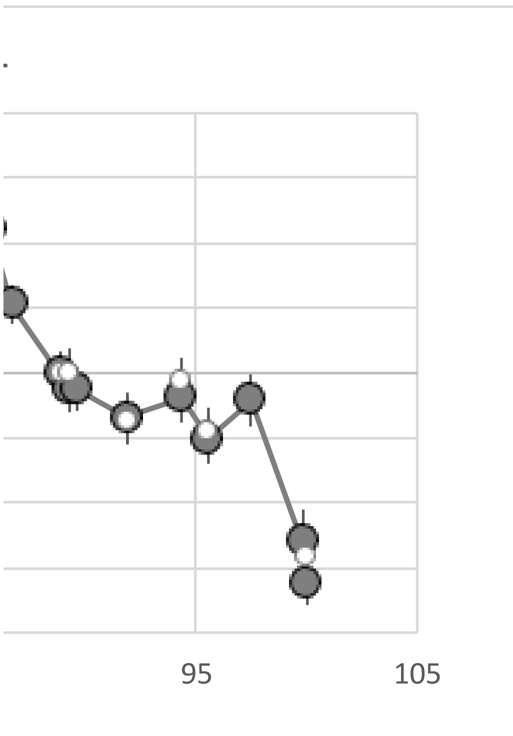
n FI4
2 σ[a]
0.23
0.30
0.28
0.23
0.23
0.26
0.27
0.23
0.24
0.24
0.24
0.26
0.25
0.24
0.26
0.30

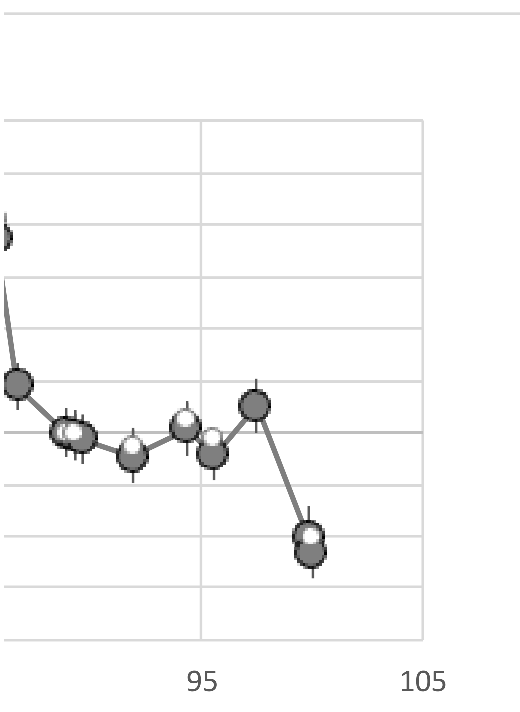


0.24

Fo content

g each session, whichever is larger.





Appendix EA6-6: SIMS Mg isotope data (session UI1, 4.5nA, O^- pr

Data reported in Ushikubo et al. (2013).GCA

[a] 2σ error (A) = $\sqrt{(2SE_{SIMS})^2+(2SD_{ICPMS})^2}$

[b] 2σ error = $\sqrt{(A)^2+(2SD_{SIMS\_bracket})^2}$

Erros of averaged values are 2SD.

File	Analysis spot	24Mg (100M cps)	Yield (10^8 cps/nA)
Olivine (Ushikubo et al., 2013.GCA)			
20090910-17	STD18_SC-OL	2.32	0.75
20090910-18	STD18_SC-OL	2.30	0.73
20090910-19	STD18_SC-OL	2.32	0.73
20090910-20	STD18_SC-OL	2.34	0.73
20090910-36	STD18_SC-OL	2.75	0.74
20090910-37	STD18_SC-OL	2.72	0.73
20090910-38	STD18_SC-OL	2.74	0.73
20090910-39	STD18_SC-OL	2.80	0.74
	Average (SC-Ol)		
20090910-21	STD18_Fo100-4	2.42	0.75
20090910-22	STD18_Fo100-4	2.42	0.75
20090910-23	STD18_Fo100-4	2.44	0.74
20090910-24	STD18_Fo100-4	2.47	0.75
20090910-25	STD18_Fo100-4	2.49	0.75
20090910-26	STD18_Fo100-4	2.50	0.74
20090910-27	STD18_Fo100-4	2.53	0.75
	Average (HN-Ol)		
20090910-28	STD18_Fo90-75	2.57	0.75
20090910-29	STD18_Fo90-75	2.56	0.74
20090910-30	STD18_Fo90-75	2.59	0.74
20090910-31	STD18_Fo90-75	2.64	0.75
	Average (IG-Ol)		
20090910-32	STD18_Fo60-37	2.60	0.73
20090910-33	STD18_Fo60-37	2.61	0.73
20090910-34	STD18_Fo60-37	2.62	0.73
20090910-35	STD18_Fo60-34	2.66	0.73
	Average (OR-Ol)		
Pyroxene (Ushikubo et al., 2013.GCA)			
20090910-42	STD19_SC-OL	2.96	0.77
20090910-43	STD19_SC-OL	2.99	0.77

20090910-44	STD19_SC-OL	3.00	0.77
20090910-45	STD19_SC-OL	3.03	0.77
20090910-65	STD19_SC-OL	3.45	0.74
20090910-66	STD19_SC-OL	3.40	0.72
20090910-67	STD19_SC-OL	3.40	0.72
20090910-68	STD19_SC-OL	3.42	0.72
	Average (SC-Ol)		
20090910-46	STD19_SP79-11-G3	2.56	0.65
20090910-47	STD19_SP79-11-G3	2.60	0.65
20090910-48	STD19_SP79-11-G3	2.63	0.65
20090910-49	STD19_SP79-11-G3	2.65	0.65
20090910-50	STD19_SP79-11-G3	2.69	0.66
20090910-51	STD19_SP79-11-G3	2.61	0.63
20090910-52	STD19_SP79-11-G3	2.69	0.64
20090910-61	STD19_SP79-11-G5	2.89	0.64
20090910-62	STD19_SP79-11-G6	2.90	0.64
20090910-63	STD19_SP79-11-G4	2.94	0.64
20090910-64	STD19_SP79-11-G3	2.97	0.64
	Average (Sp79-11 En)		
20090910-53	STD19_IGOPX-G5	2.54	0.60
20090910-54	STD19_IGOPX-G4	2.59	0.61
20090910-55	STD19_IGOPX-G3	2.55	0.60
20090910-56	STD19_IGOPX-G1	2.59	0.60
	Average (IG-Opx)		
20090910-57	STD19_JE-En-G2	2.66	0.61
20090910-58	STD19_JE-En-G1	2.71	0.62
20090910-59	STD19_JE-En-G5	2.72	0.61
20090910-60	STD19_JE-En-G4	2.75	0.61
	Average (JE En)		

imary ion beam)

d25Mg-m ‰	2SE ‰	d26Mg-m ‰	2SE ‰	d26Mg*-m ‰	2SE ‰	f_{25}*
-2.98	0.04	-5.47	0.07	0.33	0.05	-2.91
-2.85	0.04	-5.21	0.06	0.34	0.05	-2.78
-2.88	0.04	-5.24	0.05	0.37	0.05	-2.81
-2.91	0.04	-5.35	0.07	0.32	0.05	-2.84
-2.96	0.04	-5.45	0.07	0.31	0.05	-2.89
-2.91	0.03	-5.31	0.05	0.36	0.06	-2.84
-2.91	0.03	-5.31	0.05	0.37	0.05	-2.84
-2.88	0.03	-5.24	0.06	0.37	0.05	-2.81
-2.91	0.08	-5.32	0.19	0.35	0.04	-2.84
-4.22	0.06	-7.79	0.10	0.41	0.04	-3.85
-4.15	0.05	-7.68	0.10	0.40	0.04	-3.79
-4.15	0.05	-7.70	0.09	0.38	0.06	-3.78
-4.19	0.05	-7.82	0.09	0.33	0.06	-3.82
-4.19	0.05	-7.83	0.09	0.32	0.06	-3.82
-4.13	0.04	-7.69	0.08	0.35	0.05	-3.76
-4.15	0.05	-7.69	0.09	0.38	0.04	-3.78
-4.17	0.06	-7.74	0.14	0.37	0.07	-3.80
-3.07	0.04	-5.64	0.05	0.34	0.06	-3.05
-3.12	0.03	-5.73	0.06	0.34	0.04	-3.09
-3.14	0.04	-5.77	0.06	0.35	0.04	-3.11
-3.14	0.04	-5.72	0.06	0.39	0.04	-3.11
-3.12	0.06	-5.71	0.10	0.36	0.05	-3.09
-0.66	0.02	-0.97	0.03	0.31	0.05	-0.65
-0.50	0.02	-0.69	0.02	0.28	0.04	-0.48
-0.47	0.02	-0.64	0.02	0.27	0.04	-0.45
-0.58	0.03	-0.87	0.02	0.26	0.06	-0.56
-0.55	0.17	-0.79	0.31	0.28	0.05	-0.54
-3.05	0.04	-5.60	0.07	0.34	0.05	-2.98
-3.09	0.05	-5.71	0.08	0.31	0.04	-3.02

-3.03	0.05	-5.56	0.08	0.34	0.04	-2.96
-3.09	0.04	-5.67	0.07	0.35	0.04	-3.02
-3.15	0.04	-5.79	0.07	0.34	0.04	-3.07
-3.04	0.04	-5.61	0.06	0.31	0.04	-2.97
-2.97	0.03	-5.50	0.06	0.28	0.04	-2.90
-3.01	0.03	-5.51	0.06	0.35	0.04	-2.94
-3.05	0.11	-5.62	0.20	0.33	0.05	-2.98
-0.21	0.05	-0.10	0.10	0.32	0.05	-0.16
-0.25	0.05	-0.15	0.09	0.35	0.05	-0.20
-0.28	0.05	-0.20	0.09	0.36	0.04	-0.23
-0.30	0.05	-0.22	0.09	0.36	0.04	-0.24
-0.38	0.05	-0.31	0.09	0.43	0.04	-0.32
-0.45	0.04	-0.53	0.09	0.35	0.05	-0.40
-0.35	0.05	-0.33	0.09	0.36	0.05	-0.30
-0.31	0.05	-0.31	0.09	0.30	0.06	-0.25
-0.36	0.04	-0.39	0.07	0.32	0.05	-0.30
-0.30	0.04	-0.30	0.07	0.27	0.05	-0.24
-0.41	0.05	-0.45	0.08	0.35	0.04	-0.35
-0.33	0.14	-0.30	0.26	0.34	0.08	-0.27
0.40	0.06	1.18	0.10	0.39	0.04	0.44
0.18	0.05	0.77	0.08	0.43	0.04	0.22
0.40	0.05	1.19	0.09	0.42	0.06	0.44
0.41	0.05	1.12	0.09	0.32	0.04	0.45
0.35	0.23	1.07	0.40	0.39	0.10	0.39
0.17	0.05	0.70	0.08	0.37	0.05	0.43
0.22	0.04	0.76	0.08	0.33	0.05	0.48
0.16	0.04	0.70	0.08	0.39	0.05	0.42
0.15	0.04	0.66	0.08	0.38	0.04	0.40
0.17	0.06	0.70	0.08	0.37	0.05	0.43

			Corrected			
2σ [a]	$bias^*_{25(RM\text{-}SCOI)}$	2σ [b]	f_{26} *	2σ [a]	$bias^*_{26(RM\text{-}SCOI)}$	2σ [b]
0.10			-5.31	0.18		
0.10			-5.06	0.17		
0.10			-5.09	0.17		
0.10			-5.20	0.17		
0.10			-5.30	0.17		
0.09			-5.15	0.17		
0.09			-5.15	0.17		
0.09			-5.09	0.17		
0.08			-5.17	0.19		
0.11	-1.02	0.13	-7.10	0.17	-1.64	0.26
0.10	-0.95	0.13	-6.99	0.17	-1.53	0.26
0.10	-0.95	0.13	-7.00	0.17	-1.55	0.26
0.10	-0.99	0.13	-7.13	0.16	-1.67	0.26
0.10	-0.99	0.13	-7.14	0.17	-1.68	0.26
0.10	-0.93	0.13	-6.99	0.16	-1.54	0.26
0.10	-0.95	0.13	-7.00	0.17	-1.54	0.26
0.06	-0.97	0.06	-7.05	0.14	-1.59	0.14
0.10	-0.21	0.13	-5.59	0.16	-0.13	0.26
0.10	-0.25	0.13	-5.68	0.16	-0.22	0.26
0.10	-0.28	0.13	-5.72	0.16	-0.25	0.26
0.10	-0.27	0.13	-5.67	0.16	-0.20	0.26
0.06	-0.25	0.06	-5.66	0.10	-0.20	0.11
0.07	2.20	0.13	-0.95	0.13	4.54	0.26
0.07	2.36	0.13	-0.67	0.13	4.83	0.26
0.06	2.39	0.13	-0.61	0.13	4.88	0.26
0.07	2.28	0.13	-0.85	0.13	4.64	0.26
0.17	2.31	0.17	-0.77	0.31	4.72	0.32
0.10			-5.45	0.17		
0.10			-5.56	0.18		

0.10			-5.41	0.18		
0.10			-5.52	0.18		
0.10			-5.64	0.17		
0.10			-5.46	0.17		
0.09			-5.35	0.17		
0.09			-5.35	0.17		
0.11			-5.47	0.20		
0.08	2.83	0.15	0.01	0.15	5.50	0.27
0.07	2.79	0.15	-0.04	0.14	5.45	0.27
0.07	2.76	0.15	-0.09	0.14	5.40	0.27
0.07	2.75	0.15	-0.12	0.15	5.38	0.27
0.08	2.67	0.15	-0.21	0.14	5.29	0.27
0.07	2.59	0.15	-0.42	0.14	5.07	0.27
0.07	2.69	0.15	-0.22	0.14	5.27	0.27
0.07	2.73	0.15	-0.20	0.14	5.29	0.27
0.07	2.68	0.15	-0.28	0.13	5.21	0.27
0.07	2.75	0.15	-0.20	0.13	5.30	0.27
0.07	2.64	0.15	-0.34	0.14	5.15	0.27
0.14	2.72	0.14	-0.19	0.26	5.30	0.26
0.10	3.43	0.15	1.25	0.17	6.75	0.27
0.09	3.21	0.15	0.84	0.15	6.34	0.27
0.10	3.43	0.15	1.26	0.16	6.76	0.27
0.09	3.44	0.15	1.19	0.16	6.69	0.27
0.23	3.38	0.23	1.14	0.40	6.64	0.40
0.07	3.42	0.15	1.21	0.14	6.71	0.27
0.07	3.47	0.15	1.26	0.14	6.77	0.27
0.07	3.41	0.15	1.20	0.14	6.70	0.27
0.07	3.39	0.15	1.17	0.14	6.67	0.27
0.06	3.42	0.06	1.21	0.08	6.71	0.08

Appendix EA6-7: SIMS Mg isotope data (session UI2, 2.2nA, O^- pr

Data reported in Ushikubo et al. (2017).GCA

[a] 2σ error (A) = $\sqrt{(2SE_{SIMS})^2+(2SD_{ICPMS})^2}$

[b] 2σ error = $\sqrt{(A)^2+(2SD_{SIMS\_bracket})^2}$

Erros of averaged values are 2SD.

File	Analysis spot	24Mg (100M cps)	Yield (10^8 cps/nA)
Pyroxene (Ushikubo et al., 2017.GCA)			
20130430-25	WI-STD19_SCOl#1	1.60	0.69
20130430-26	WI-STD19_SCOl#2	1.59	0.69
20130430-27	WI-STD19_SCOl#3	1.61	0.69
20130430-28	WI-STD19_SCOl#4	1.60	0.69
20130430-37	WI-STD19_SCOl#5	1.61	0.69
20130430-38	WI-STD19_SCOl#6	1.62	0.69
20130430-39	WI-STD19_SCOl#7	1.61	0.68
20130430-40	WI-STD19_SCOl#8	1.58	0.67
	Average (SC-Ol)		
20130430-29	WI-STD19_95AK-6-G1#1	0.48	0.21
20130430-30	WI-STD19_95AK-6-G2#1	0.48	0.21
20130430-31	WI-STD19_95AK-6-G4#1	0.48	0.21
20130430-32	WI-STD19_95AK-6-G5#1	0.48	0.21
	Average (95AK-6 Di)		
20130430-33	WI-STD19_IG-CPx-G3#1	0.52	0.22
20130430-34	WI-STD19_IG-CPx-G2#1	0.52	0.22
20130430-35	WI-STD19_IG-CPx-G4#1	0.52	0.22
20130430-36	WI-STD19_IG-CPx-G5#1	0.51	0.22
	Average (IG Cpx)		

imary ion beam)

d25Mg-m ‰	2SE ‰	d26Mg-m ‰	2SE ‰	d26Mg*-m ‰	2SE ‰	f_{25}*
-2.90	0.08	-5.67	0.14	-0.01	0.06	-2.83
-2.83	0.07	-5.53	0.13	-0.01	0.06	-2.76
-2.91	0.07	-5.73	0.13	-0.07	0.07	-2.83
-2.94	0.06	-5.66	0.13	0.07	0.07	-2.87
-2.99	0.06	-5.77	0.12	0.05	0.08	-2.92
-3.04	0.07	-5.84	0.13	0.08	0.07	-2.97
-2.99	0.06	-5.84	0.11	-0.01	0.07	-2.92
-3.02	0.07	-5.87	0.12	0.01	0.06	-2.95
-2.95	0.14	-5.74	0.23	0.01	0.10	-2.88
0.09	0.09	0.08	0.11	-0.09	0.19	0.83
0.17	0.08	0.20	0.10	-0.14	0.15	0.91
0.13	0.11	0.20	0.09	-0.05	0.21	0.87
-0.03	0.09	-0.20	0.11	-0.14	0.16	0.71
0.09	0.18	0.07	0.38	-0.10	0.08	0.83
1.13	0.08	2.29	0.10	0.09	0.15	1.27
1.23	0.06	2.39	0.10	-0.01	0.15	1.37
1.22	0.07	2.50	0.08	0.11	0.12	1.36
1.20	0.07	2.49	0.07	0.15	0.13	1.34
1.19	0.09	2.42	0.19	0.09	0.14	1.33

Appendix EA7-1: SIMS major and minor element analyses data (sessio

[a] 2σ errors represent either 2SE of each RM or 2SD of the runnning standard (SC-Ol), whiche

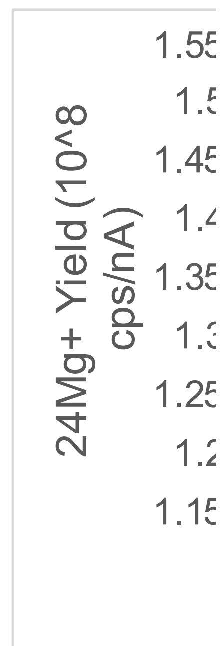
[b] 2SD errors were deduced from 5 analyses of each grain.

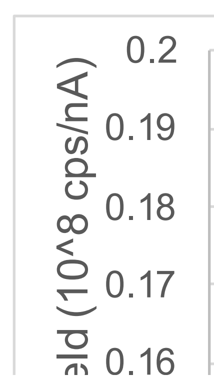
File	Analysis spot	Fo#	Cycle#
20190124@1.asc	WI-STD-92 SCOL	88.8	5
20190124@5.asc	WI-STD-91 SCOL	88.8	5
20190124@13.asc	WI-STD-91 SCOL	88.8	5
20190124@22.asc	WI-STD-91 SCOL	88.8	5
	Average (SC-Ol)		
	2SD		
	2SD %		
20190124@21.asc	WI-STD-91 OROL17_1	57.9	5
20190124@20.asc	WI-STD-91 OROL5_1	60.3	5
20190124@19.asc	WI-STD-91 FJOL2_1	73.2	5
20190124@18.asc	WI-STD-91 KNOL1-2_1	77.9	5
20190124@3.asc	WI-STD-92 CL0919-1_1	79.5	5
20190124@2.asc	WI-STD-92 CL0908-1_1	80.8	5
20190124@17.asc	WI-STD-91 SWOL15_1	81.8	5
20190124@24.asc	WI-STD-92 A77257-4_1	85.6	5
20190124@6.asc	WI-STD-91 A77257-5_1	85.8	5
20190124@4.asc	WI-STD-92 CL0933-4_1	86.5	5
	Average (SC-Ol)_Errors are 2SD	88.8	
20190124@16.asc	WI-STD-91 UWOL1-42_1	89.3	5
20190124@23.asc	WI-STD-92 IGOL1_1	89.6	5
20190124@15.asc	WI-STD-91 HaKOL g1-2_1	91.9	5
20190124@12.asc	WI-STD-91 WKOL8_1	93.7	5
20190124@11.asc	WI-STD-91 WKOL1_1	94.7	5
20190124@7.asc	WI-STD-91 WNOL1E_1	94.9	5
20190124@8.asc	WI-STD-91 WNOL1C_1	95.5	5
20190124@9.asc	WI-STD-91 WNOL4A_1	96.0	5
20190124@10.asc	WI-STD-91 WNOL4C_1	96.1	5
20190124@25.asc	WI-STD-92 NWA7325 OL7_1	97.4	5
20190124@26.asc	WI-STD-15 Skye-X_1	99.8	5
20190124@28.asc	WI-STD-15 Skye-V_1_5 cycle	99.8	5
20190124@27.asc	WI-STD-15 Skye-W_1_5 cycle	99.8	5
20190124@14.asc	WI-STD-91 HNOL	100.0	5

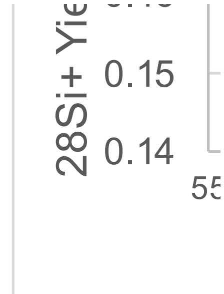
Averaged values of each olivien RMs

1	OR-Ol	59.1
2	FJ-Ol	73.2

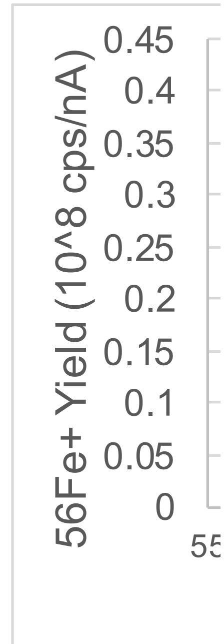
3	KN-Ol	77.9
4	CL09-19	79.5
5	CL09-08	80.8
6	SW-Ol	81.8
7	A77257-Ol	85.7
8	CL09-33	86.5
9	Average (SC-Ol)_Errors are 2SD	88.8
10	UWOL-1	89.3
11	IG-Ol	89.6
12	HaK-Ol	91.9
13	WK-Ol	94.2
14	WN-Ol	95.6
15	N7325-Ol	97.4
16	SK-Ol	99.8
17	HN-Ol	100.0







28Si+ Yie
0.15
0.14
55



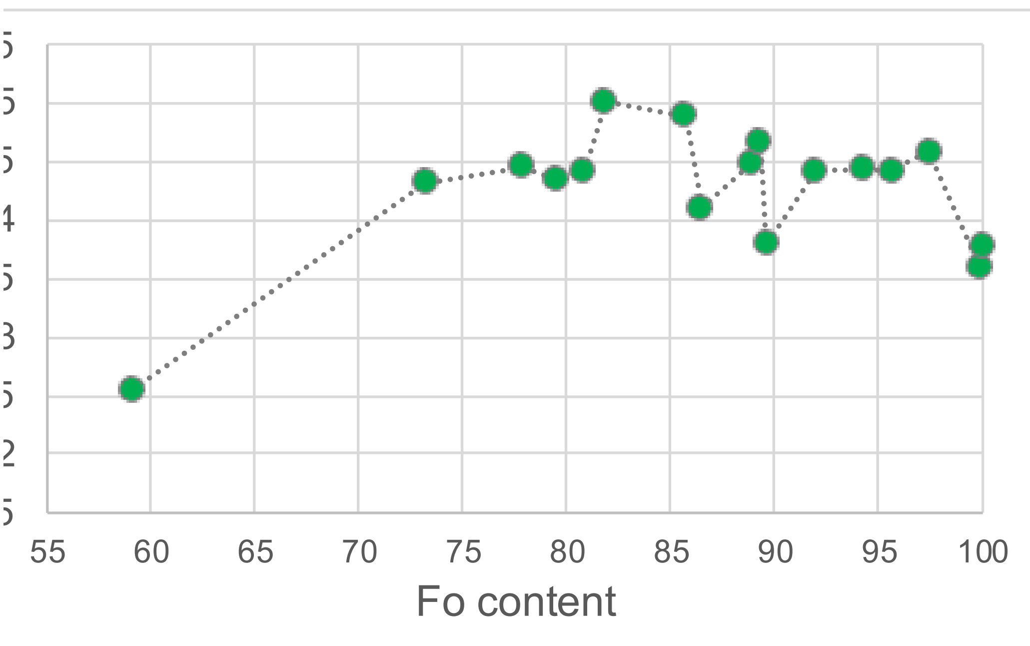
56Fe+ Yield (10^8 cps/nA)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
55

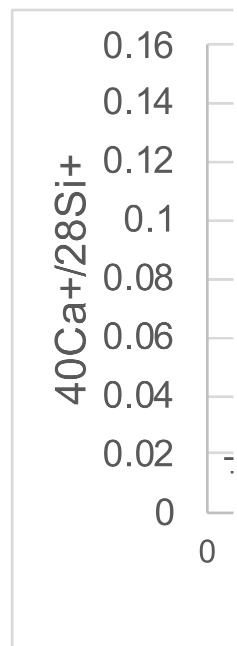
n FE1, 6pA, O_2^- primary ion beam)

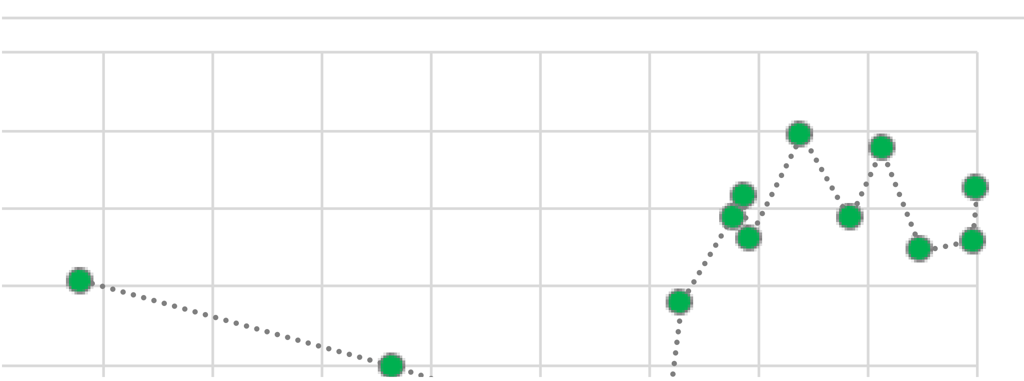
ver is larger

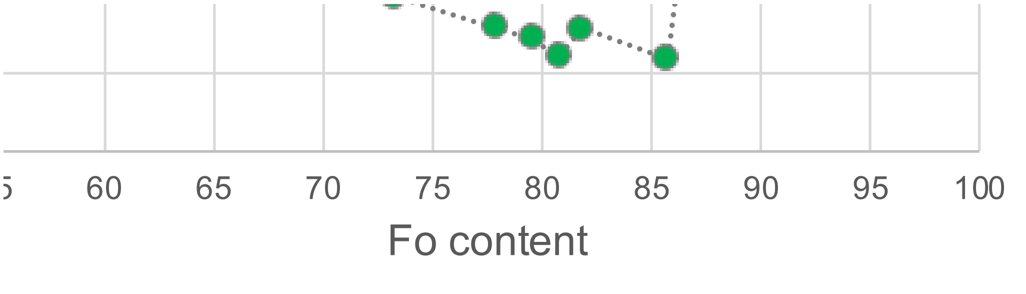
					Yield (× 10^8 cps n/
^{24}Mg (10^5 cps)	23Na	24Mg	27Al	28Si	40Ca
8.31	1.6.E-03	1.4.E+00	7.5.E-04	1.8.E-01	4.5.E-03
8.60	9.5.E-04	1.5.E+00	6.9.E-04	1.8.E-01	3.8.E-03
8.62	9.3.E-04	1.5.E+00	7.0.E-04	1.8.E-01	3.8.E-03
8.59	9.5.E-04	1.5.E+00	7.4.E-04	1.8.E-01	3.8.E-03
8.53	1.1.E-03	1.4.E+00	7.2.E-04	1.8.E-01	4.0.E-03
0.29	6.3.E-04	5.5.E-02	5.4.E-05	2.1.E-03	7.1.E-04
3%	57%	4%	8%	1%	18%
7.26	2.5.E-04	1.2.E+00	4.2.E-04	1.7.E-01	4.5.E-03
7.50	3.1.E-04	1.3.E+00	4.2.E-04	1.7.E-01	2.4.E-03
8.47	2.0.E-04	1.4.E+00	6.9.E-04	1.6.E-01	3.0.E-03
8.54	8.0.E-04	1.4.E+00	1.3.E-03	1.6.E-01	1.8.E-02
8.42	1.4.E-03	1.4.E+00	8.2.E-04	1.5.E-01	4.2.E-03
8.51	1.0.E-03	1.4.E+00	5.5.E-04	1.5.E-01	3.5.E-03
8.88	9.2.E-05	1.5.E+00	4.0.E-04	1.6.E-01	5.3.E-04
8.56	1.3.E-03	1.5.E+00	1.0.E-03	1.5.E-01	1.4.E-02
8.93	7.2.E-04	1.5.E+00	1.1.E-03	1.5.E-01	1.5.E-02
8.31	1.5.E-03	1.4.E+00	6.9.E-04	1.7.E-01	2.9.E-03
8.53	1.1.E-03	1.4.E+00	7.2.E-04	1.8.E-01	4.0.E-03
8.68	9.5.E-04	1.5.E+00	8.5.E-04	1.8.E-01	3.1.E-03
8.07	9.2.E-04	1.4.E+00	5.8.E-04	1.8.E-01	3.4.E-03
8.49	9.5.E-04	1.4.E+00	3.5.E-04	1.9.E-01	3.5.E-03
8.52	4.5.E-04	1.4.E+00	1.6.E-03	1.8.E-01	6.0.E-03
8.54	5.4.E-04	1.4.E+00	1.6.E-03	1.8.E-01	7.2.E-03
8.51	1.0.E-04	1.4.E+00	7.2.E-04	1.9.E-01	3.3.E-04
8.42	8.1.E-05	1.4.E+00	5.7.E-04	1.9.E-01	3.0.E-04
8.65	8.6.E-05	1.5.E+00	3.5.E-04	1.9.E-01	2.4.E-04
8.47	9.6.E-05	1.4.E+00	4.4.E-04	1.9.E-01	3.1.E-04
8.53	5.3.E-04	1.5.E+00	1.5.E-03	1.7.E-01	1.5.E-02
8.04	3.5.E-05	1.3.E+00	6.0.E-05	1.7.E-01	1.8.E-03
8.14	4.1.E-05	1.4.E+00	4.9.E-05	1.8.E-01	1.4.E-03
8.06	4.5.E-05	1.4.E+00	7.9.E-05	1.8.E-01	1.0.E-03
8.09	4.8.E-05	1.4.E+00	1.7.E-04	1.8.E-01	1.2.E-04
7.38	2.8.E-04	1.3.E+00	4.2.E-04	1.7.E-01	3.4.E-03
8.47	2.0.E-04	1.4.E+00	6.9.E-04	1.6.E-01	3.0.E-03

8.54	8.0.E-04	1.4.E+00	1.3.E-03	1.6.E-01	1.8.E-02
8.42	1.4.E-03	1.4.E+00	8.2.E-04	1.5.E-01	4.2.E-03
8.51	1.0.E-03	1.4.E+00	5.5.E-04	1.5.E-01	3.5.E-03
8.88	9.2.E-05	1.5.E+00	4.0.E-04	1.6.E-01	5.3.E-04
8.75	9.9.E-04	1.5.E+00	1.0.E-03	1.5.E-01	1.4.E-02
8.31	1.5.E-03	1.4.E+00	6.9.E-04	1.7.E-01	2.9.E-03
8.53	1.1.E-03	1.4.E+00	7.2.E-04	1.8.E-01	4.0.E-03
8.68	9.5.E-04	1.5.E+00	8.5.E-04	1.8.E-01	3.1.E-03
8.07	9.2.E-04	1.4.E+00	5.8.E-04	1.8.E-01	3.4.E-03
8.49	9.5.E-04	1.4.E+00	3.5.E-04	1.9.E-01	3.5.E-03
8.53	5.0.E-04	1.4.E+00	1.6.E-03	1.8.E-01	6.6.E-03
8.51	9.2.E-05	1.4.E+00	5.2.E-04	1.9.E-01	2.9.E-04
8.53	5.3.E-04	1.5.E+00	1.5.E-03	1.7.E-01	1.5.E-02
8.08	4.0.E-05	1.4.E+00	6.3.E-05	1.8.E-01	1.4.E-03
8.09	4.8.E-05	1.4.E+00	1.7.E-04	1.8.E-01	1.2.E-04

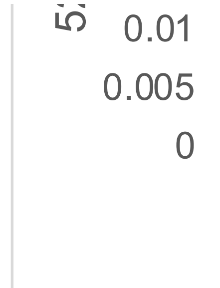




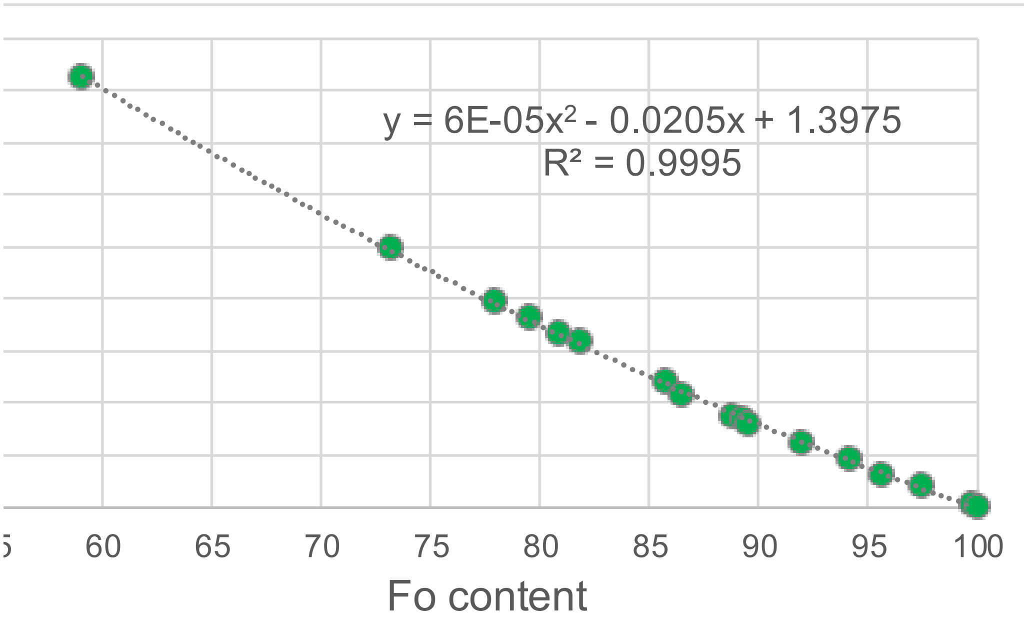




5
60
65
70
75
80
85
90
95
100
Fo content



0.01
0.005
0
0



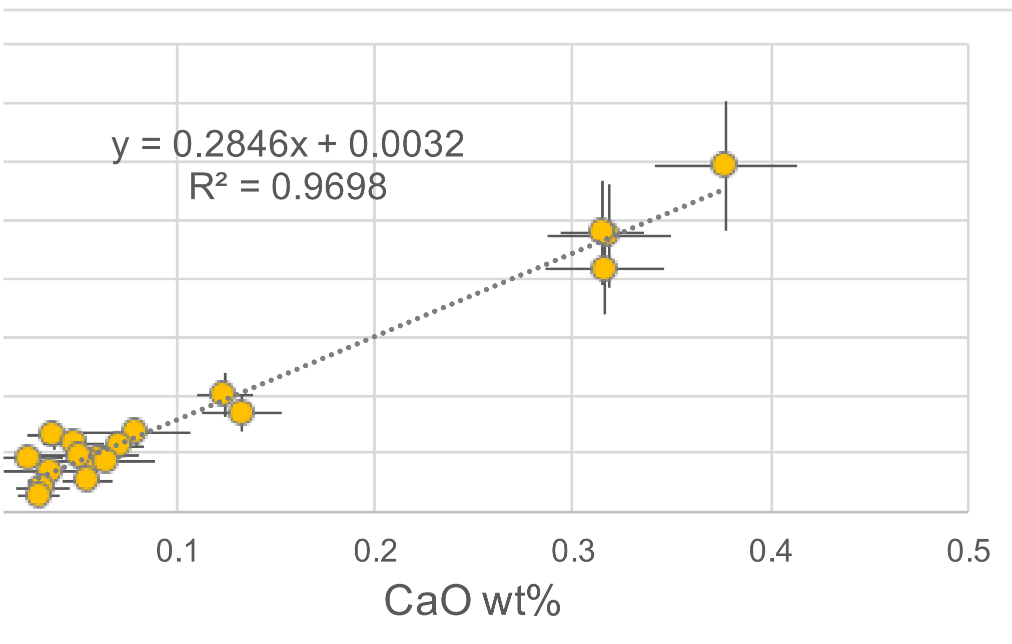
y = 6E-05x² - 0.0205x + 1.3975
R² = 0.9995
5
60
65
70
75
80
85
90
95
100
Fo content

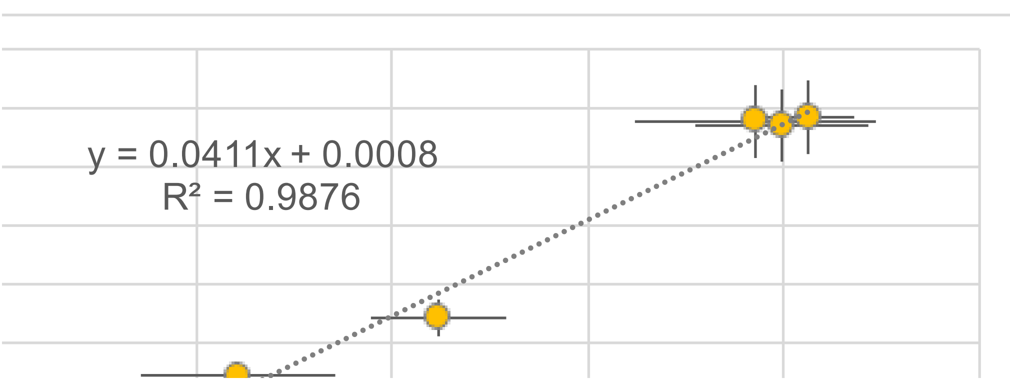
A^{-1})

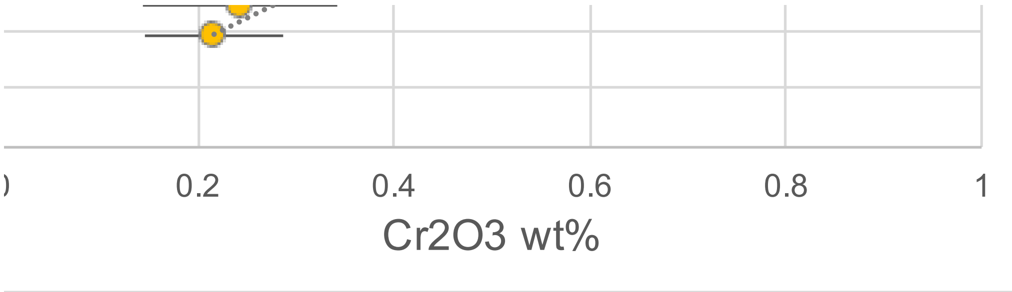
52Cr	55Mn	56Fe	60Ni	23Na+/ 28Si+
1.5.E-04	1.9.E-03	8.7.E-02	5.3.E-04	8.8.E-03
1.6.E-04	2.0.E-03	8.9.E-02	5.3.E-04	5.3.E-03
1.7.E-04	2.0.E-03	8.9.E-02	5.6.E-04	5.2.E-03
1.7.E-04	1.9.E-03	8.8.E-02	5.3.E-04	5.3.E-03
1.6.E-04	1.9.E-03	8.8.E-02	5.4.E-04	6.2.E-03
1.6.E-05	5.2.E-05	1.5.E-03	2.8.E-05	3.6.E-03
10%	3%	2%	5%	58%
7.1.E-07	1.2.E-02	4.3.E-01	6.3.E-05	1.5.E-03
1.1.E-06	1.2.E-02	4.0.E-01	7.5.E-05	1.8.E-03
1.1.E-06	6.4.E-03	2.5.E-01	2.7.E-04	1.2.E-03
5.2.E-03	6.3.E-03	2.0.E-01	1.9.E-05	5.1.E-03
3.3.E-05	3.1.E-03	1.8.E-01	3.3.E-04	9.1.E-03
3.0.E-05	2.9.E-03	1.7.E-01	4.6.E-04	6.8.E-03
1.7.E-04	4.4.E-03	1.6.E-01	5.3.E-06	5.9.E-04
5.2.E-03	5.8.E-03	1.2.E-01	1.1.E-05	8.4.E-03
5.2.E-03	5.9.E-03	1.2.E-01	9.2.E-06	4.7.E-03
5.9.E-05	2.2.E-03	1.1.E-01	6.4.E-04	9.0.E-03
1.6.E-04	1.9.E-03	8.8.E-02	5.4.E-04	6.2.E-03
7.6.E-05	1.8.E-03	8.4.E-02	5.5.E-04	5.2.E-03
4.8.E-05	1.8.E-03	7.9.E-02	5.4.E-04	5.2.E-03
5.2.E-05	1.3.E-03	6.2.E-02	5.9.E-04	5.0.E-03
2.1.E-03	1.2.E-03	5.0.E-02	5.6.E-04	2.6.E-03
1.7.E-03	1.0.E-03	4.1.E-02	5.7.E-04	3.0.E-03
1.5.E-04	3.8.E-03	3.4.E-02	1.1.E-06	5.6.E-04
1.4.E-04	3.9.E-03	3.1.E-02	7.1.E-07	4.4.E-04
1.4.E-04	3.8.E-03	2.9.E-02	0.0.E+00	4.5.E-04
1.1.E-04	3.6.E-03	2.6.E-02	7.1.E-07	5.2.E-04
3.0.E-03	9.4.E-04	2.0.E-02	1.1.E-06	3.0.E-03
2.1.E-06	5.3.E-04	2.0.E-03	0.0.E+00	2.0.E-04
1.1.E-06	4.7.E-04	2.0.E-03	0.0.E+00	2.3.E-04
2.1.E-06	4.2.E-04	1.8.E-03	3.5.E-07	2.5.E-04
1.1.E-06	2.5.E-06	3.4.E-05	0.0.E+00	2.6.E-04

8.9.E-07	1.2.E-02	4.1.E-01	6.9.E-05	1.6.E-03
1.1.E-06	6.4.E-03	2.5.E-01	2.7.E-04	1.2.E-03

5.2.E-03	6.3.E-03	2.0.E-01	1.9.E-05	5.1.E-03
3.3.E-05	3.1.E-03	1.8.E-01	3.3.E-04	9.1.E-03
3.0.E-05	2.9.E-03	1.7.E-01	4.6.E-04	6.8.E-03
1.7.E-04	4.4.E-03	1.6.E-01	5.3.E-06	5.9.E-04
5.2.E-03	5.8.E-03	1.2.E-01	9.9.E-06	6.5.E-03
5.9.E-05	2.2.E-03	1.1.E-01	6.4.E-04	9.0.E-03
1.6.E-04	1.9.E-03	8.8.E-02	5.4.E-04	6.2.E-03
7.6.E-05	1.8.E-03	8.4.E-02	5.5.E-04	5.2.E-03
4.8.E-05	1.8.E-03	7.9.E-02	5.4.E-04	5.2.E-03
5.2.E-05	1.3.E-03	6.2.E-02	5.9.E-04	5.0.E-03
1.9.E-03	1.1.E-03	4.5.E-02	5.7.E-04	2.8.E-03
1.4.E-04	3.8.E-03	3.0.E-02	6.2.E-07	4.9.E-04
3.0.E-03	9.4.E-04	2.0.E-02	1.1.E-06	3.0.E-03
1.8.E-06	4.7.E-04	1.9.E-03	1.2.E-07	2.3.E-04
1.1.E-06	2.5.E-06	3.4.E-05	0.0.E+00	2.6.E-04

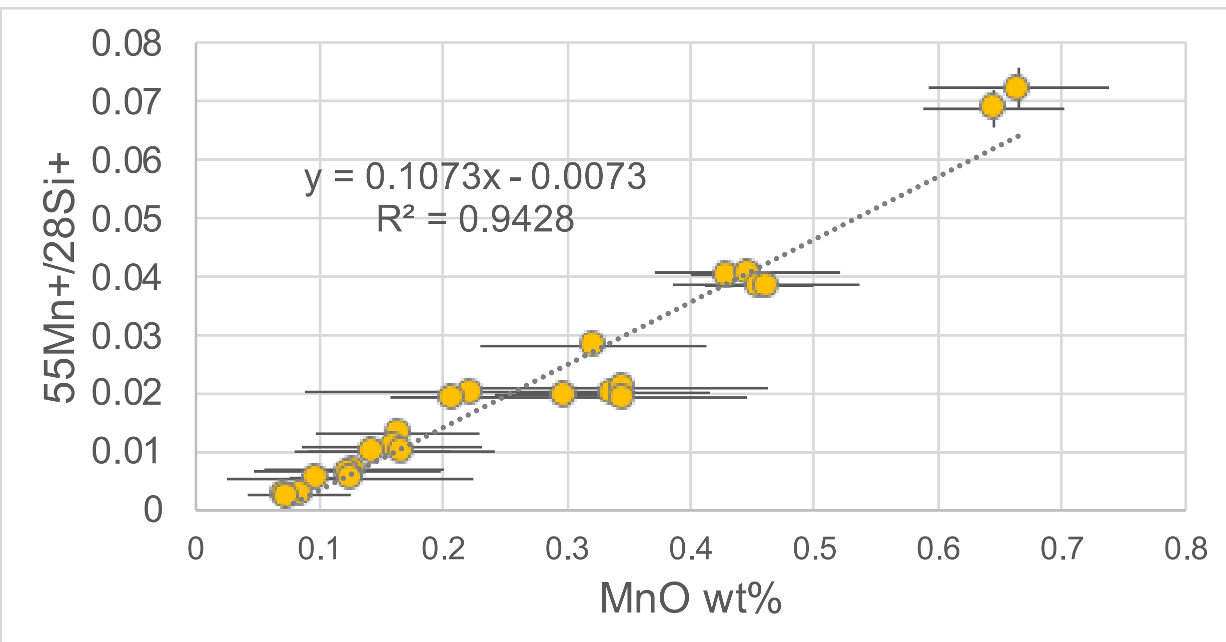


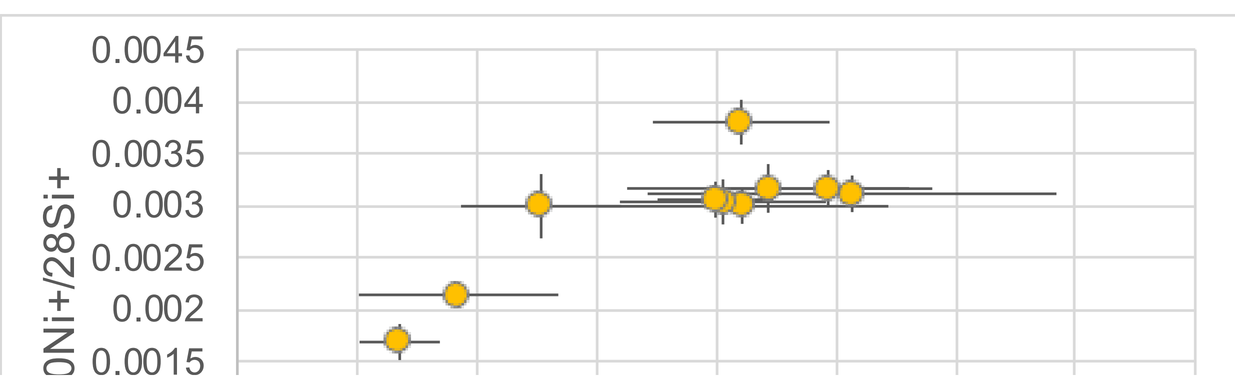


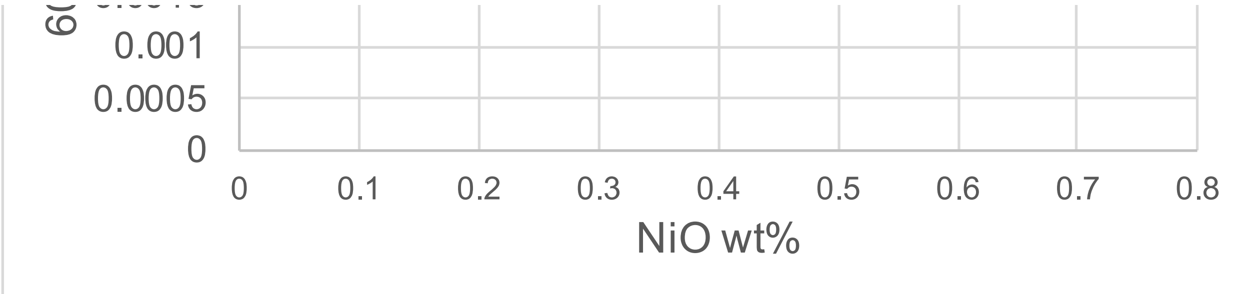

0
0.2
0.4
0.6
0.8
1
Cr2O3 wt%

24Mg+/ 28Si+	27Al+/ 28Si+	40Ca+/ 28Si+	52Cr+/ 28Si+	55Mn+/ 28Si+
7.9.E+00	4.2.E-03	2.5.E-02	8.7.E-04	1.1.E-02
8.1.E+00	3.9.E-03	2.1.E-02	9.1.E-04	1.1.E-02
8.2.E+00	3.9.E-03	2.2.E-02	9.3.E-04	1.1.E-02
8.1.E+00	4.1.E-03	2.1.E-02	9.7.E-04	1.1.E-02
8.1.E+00	4.0.E-03	2.2.E-02	9.2.E-04	1.1.E-02
2.6.E-01	3.2.E-04	4.2.E-03	8.5.E-05	2.9.E-04
3%	8%	19%	9%	3%
7.2.E+00	2.4.E-03	2.6.E-02	4.1.E-06	7.2.E-02
7.5.E+00	2.5.E-03	1.4.E-02	6.2.E-06	6.9.E-02
9.0.E+00	4.3.E-03	1.9.E-02	6.6.E-06	4.0.E-02
9.3.E+00	8.5.E-03	1.2.E-01	3.3.E-02	4.1.E-02
9.3.E+00	5.3.E-03	2.7.E-02	2.1.E-04	2.0.E-02
9.5.E+00	3.6.E-03	2.3.E-02	2.0.E-04	1.9.E-02
9.6.E+00	2.5.E-03	3.4.E-03	1.1.E-03	2.8.E-02
9.7.E+00	6.6.E-03	9.4.E-02	3.4.E-02	3.8.E-02
9.9.E+00	7.1.E-03	9.5.E-02	3.4.E-02	3.9.E-02
8.4.E+00	4.1.E-03	1.7.E-02	3.5.E-04	1.3.E-02
8.1.E+00	4.0.E-03	2.2.E-02	9.2.E-04	1.1.E-02
8.1.E+00	4.7.E-03	1.7.E-02	4.2.E-04	1.0.E-02
7.8.E+00	3.3.E-03	1.9.E-02	2.8.E-04	1.0.E-02
7.6.E+00	1.8.E-03	1.9.E-02	2.8.E-04	7.0.E-03
8.1.E+00	8.9.E-03	3.4.E-02	1.2.E-02	6.7.E-03
8.0.E+00	8.9.E-03	4.0.E-02	9.5.E-03	5.6.E-03
7.6.E+00	3.8.E-03	1.7.E-03	8.1.E-04	2.0.E-02
7.7.E+00	3.1.E-03	1.6.E-03	7.6.E-04	2.1.E-02
7.7.E+00	1.8.E-03	1.2.E-03	7.2.E-04	2.0.E-02
7.7.E+00	2.4.E-03	1.7.E-03	6.0.E-04	1.9.E-02
8.4.E+00	8.7.E-03	8.3.E-02	1.7.E-02	5.4.E-03
7.8.E+00	3.5.E-04	1.1.E-02	1.2.E-05	3.0.E-03
7.8.E+00	2.8.E-04	8.1.E-03	6.0.E-06	2.6.E-03
7.6.E+00	4.4.E-04	5.6.E-03	1.2.E-05	2.3.E-03
7.5.E+00	9.2.E-04	6.5.E-04	5.9.E-06	1.3.E-05
7.4.E+00	2.4.E-03	2.0.E-02	5.1.E-06	7.0.E-02
9.0.E+00	4.3.E-03	1.9.E-02	6.6.E-06	4.0.E-02

9.3.E+00	8.5.E-03	1.2.E-01	3.3.E-02	4.1.E-02
9.3.E+00	5.3.E-03	2.7.E-02	2.1.E-04	2.0.E-02
9.5.E+00	3.6.E-03	2.3.E-02	2.0.E-04	1.9.E-02
9.6.E+00	2.5.E-03	3.4.E-03	1.1.E-03	2.8.E-02
9.8.E+00	6.9.E-03	9.5.E-02	3.4.E-02	3.8.E-02
8.4.E+00	4.1.E-03	1.7.E-02	3.5.E-04	1.3.E-02
8.1.E+00	4.0.E-03	2.2.E-02	9.2.E-04	1.1.E-02
8.1.E+00	4.7.E-03	1.7.E-02	4.2.E-04	1.0.E-02
7.8.E+00	3.3.E-03	1.9.E-02	2.8.E-04	1.0.E-02
7.6.E+00	1.8.E-03	1.9.E-02	2.8.E-04	7.0.E-03
8.1.E+00	8.9.E-03	3.7.E-02	1.1.E-02	6.1.E-03
7.7.E+00	2.8.E-03	1.6.E-03	7.2.E-04	2.0.E-02
8.4.E+00	8.7.E-03	8.3.E-02	1.7.E-02	5.4.E-03
7.7.E+00	3.6.E-04	8.1.E-03	1.0.E-05	2.7.E-03
7.5.E+00	9.2.E-04	6.5.E-04	5.9.E-06	1.3.E-05






0.001
0.0005
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
NiO wt%

56Fe+/ 28Si+	60Ni+/ 28Si+	23Na/ 28Si 2SE%	24Mg/ 28Si 2SE%	27Al/ 28Si 2SE%	Error (2 40Ca/ 28Si 2SE%
4.9.E-01	3.0.E-03	3.37	3.32	5.03	1.68
4.9.E-01	3.0.E-03	4.87	3.17	11.10	3.61
5.0.E-01	3.1.E-03	5.96	2.86	11.97	3.62
4.9.E-01	2.9.E-03	4.48	3.56	8.24	6.00
4.9.E-01	3.0.E-03				
6.9.E-03	1.7.E-04				
1%	6%				
2.5.E+00	3.7.E-04	17.10	4.43	13.17	9.09
2.3.E+00	4.5.E-04	13.09	4.68	25.42	3.95
1.6.E+00	1.7.E-03	7.30	3.91	6.97	3.69
1.3.E+00	1.2.E-04	9.95	4.29	2.94	3.76
1.2.E+00	2.1.E-03	12.27	3.92	4.66	2.01
1.1.E+00	3.0.E-03	16.70	4.13	15.33	7.93
1.0.E+00	3.4.E-05	15.55	3.82	13.47	7.02
7.9.E-01	7.1.E-05	9.13	3.83	6.86	3.67
7.9.E-01	6.0.E-05	5.37	4.46	8.98	4.38
6.4.E-01	3.8.E-03	14.25	4.40	9.70	2.93
4.9.E-01	3.0.E-03	57.83	3.19	8.02	18.71
4.6.E-01	3.0.E-03	3.11	2.72	7.09	3.04
4.5.E-01	3.1.E-03	19.57	3.61	9.37	3.13
3.3.E-01	3.1.E-03	14.62	2.54	12.81	13.18
2.8.E-01	3.2.E-03	4.53	3.33	5.66	4.22
2.2.E-01	3.2.E-03	5.30	3.86	3.29	2.84
1.8.E-01	5.6.E-06	12.75	3.24	19.80	6.22
1.7.E-01	3.7.E-06	24.61	2.73	20.78	7.78
1.5.E-01	0.0.E+00	12.23	2.45	21.60	6.35
1.4.E-01	3.8.E-06	13.18	2.01	14.89	9.58
1.1.E-01	6.2.E-06	7.09	2.93	7.14	3.41
1.2.E-02	0.0.E+00	12.13	2.15	19.43	3.60
1.1.E-02	0.0.E+00	19.23	1.60	16.83	2.14
1.0.E-02	2.0.E-06	30.55	2.93	27.14	5.63
1.9.E-04	0.0.E+00	38.97	2.65	21.09	5.73
2.4.E+00	4.1.E-04	15.09	4.56	19.30	6.52
1.6.E+00	1.7.E-03	7.30	3.91	6.97	3.69

1.3.E+00	1.2.E-04	9.95	4.29	2.94	3.76
1.2.E+00	2.1.E-03	12.27	3.92	4.66	2.01
1.1.E+00	3.0.E-03	16.70	4.13	15.33	7.93
1.0.E+00	3.4.E-05	15.55	3.82	13.47	7.02
7.9.E-01	6.5.E-05	7.25	4.14	7.92	4.03
6.4.E-01	3.8.E-03	14.25	4.40	9.70	2.93
4.9.E-01	3.0.E-03	28.92	1.60	4.01	9.36
4.6.E-01	3.0.E-03	3.11	2.72	7.09	3.04
4.5.E-01	3.1.E-03	19.57	3.61	9.37	3.13
3.3.E-01	3.1.E-03	14.62	2.54	12.81	13.18
2.5.E-01	3.2.E-03	4.91	3.59	4.48	3.53
1.6.E-01	3.3.E-06	15.69	2.61	19.27	7.48
1.1.E-01	6.2.E-06	7.09	2.93	7.14	3.41
1.1.E-02	6.6.E-07	20.64	2.22	21.13	3.79
1.9.E-04	0.0.E+00	38.97	2.65	21.09	5.73

2SE%)

52Cr/ 28Si 2SE%	55Mn/ 28Si 2SE%	56Fe/ 28Si 2SE%	60Ni/ 28Si 2SE%	23Na/ 28Si 2σ	24Mg/ 28Si 2σ	27Al/ 28Si 2σ
8.69	3.62	3.71	11.81			
9.66	4.05	3.08	4.58			
5.48	3.05	2.96	8.04			
6.88	4.26	3.88	6.16			
122.48	4.73	4.85	13.86	8.6.E-04	3.2.E-01	3.2.E-04
131.66	4.66	5.09	24.17	1.0.E-03	3.5.E-01	6.2.E-04
200.00	4.73	4.60	10.26	7.1.E-04	3.5.E-01	3.5.E-04
1.98	5.08	4.30	28.75	3.0.E-03	4.0.E-01	6.8.E-04
18.24	5.04	4.30	1.82	5.3.E-03	3.6.E-01	4.2.E-04
17.21	3.70	4.35	10.32	3.9.E-03	3.9.E-01	5.5.E-04
7.93	3.66	4.06	21.31	3.4.E-04	3.7.E-01	3.4.E-04
2.83	4.62	4.07	43.56	4.8.E-03	3.7.E-01	5.3.E-04
3.79	5.12	3.90	46.11	2.7.E-03	4.4.E-01	6.4.E-04
24.83	4.31	4.39	3.46	5.2.E-03	3.7.E-01	4.0.E-04
9.21	2.71	1.39	5.65	3.6.E-03	2.6.E-01	3.2.E-04
25.66	3.07	2.27	7.13	3.0.E-03	2.6.E-01	3.8.E-04
26.45	4.18	3.83	5.22	3.0.E-03	2.8.E-01	3.1.E-04
18.25	1.69	1.84	4.92	2.9.E-03	2.4.E-01	2.4.E-04
3.98	3.98	3.28	7.40	1.5.E-03	2.7.E-01	7.2.E-04
4.49	6.85	3.25	3.81	1.7.E-03	3.1.E-01	7.1.E-04
12.67	4.22	3.63	131.60	3.2.E-04	2.5.E-01	7.6.E-04
14.71	2.46	3.58	200.00	2.5.E-04	2.4.E-01	6.4.E-04
11.28	3.05	2.72		2.6.E-04	2.5.E-01	4.0.E-04
7.26	2.31	2.54	122.48	3.0.E-04	2.5.E-01	3.6.E-04
4.58	4.83	2.26	81.66	1.7.E-03	2.7.E-01	7.0.E-04
96.58	2.90	0.68		1.2.E-04	2.5.E-01	6.8.E-05
81.67	3.93	3.01		1.3.E-04	2.5.E-01	4.7.E-05
97.83	7.35	3.92	200.00	1.5.E-04	2.4.E-01	1.2.E-04
133.84	71.55	18.73		1.5.E-04	2.4.E-01	1.9.E-04
127.07	4.69	4.97	19.01			
200.00	4.73	4.60	10.26			

1.98	5.08	4.30	28.75
18.24	5.04	4.30	1.82
17.21	3.70	4.35	10.32
7.93	3.66	4.06	21.31
3.31	4.87	3.99	44.83
24.83	4.31	4.39	3.46
4.61	1.36	0.70	2.83
25.66	3.07	2.27	7.13
26.45	4.18	3.83	5.22
18.25	1.69	1.84	4.92
4.24	5.42	3.26	5.60
11.48	3.01	3.12	
4.58	4.83	2.26	81.66
92.03	4.73	2.54	
133.84	71.55	18.73	

Error (2σ)[a]						
40Ca/ 28Si 2σ	52Cr/ 28Si 2σ	55Mn/ 28Si 2σ	56Fe/ 28Si 2σ	60Ni/ 28Si 2σ	MgO	2SD[b]
4.9.E-03	5.0.E-06	3.4.E-03	1.2.E-01	5.1.E-05	27.55	0.13
2.6.E-03	8.1.E-06	3.2.E-03	1.2.E-01	1.1.E-04	29.07	0.27
3.5.E-03	1.3.E-05	1.9.E-03	7.2.E-02	1.7.E-04	37.13	0.19
2.2.E-02	3.1.E-03	2.1.E-03	5.4.E-02	3.5.E-05	39.67	0.16
5.1.E-03	3.9.E-05	1.0.E-03	5.1.E-02	1.2.E-04	41.41	0.37
4.4.E-03	3.4.E-05	7.1.E-04	4.8.E-02	3.1.E-04	42.35	0.28
6.4.E-04	1.0.E-04	1.0.E-03	4.1.E-02	7.2.E-06	42.86	0.28
1.8.E-02	3.1.E-03	1.8.E-03	3.2.E-02	3.1.E-05	44.96	0.28
1.8.E-02	3.1.E-03	2.0.E-03	3.1.E-02	2.8.E-05	44.95	0.41
3.2.E-03	8.8.E-05	5.7.E-04	2.8.E-02	2.1.E-04	46.14	0.34
4.2.E-03	8.5.E-05	2.9.E-04	6.9.E-03	1.7.E-04	48.22	0.25
3.2.E-03	1.1.E-04	3.1.E-04	1.1.E-02	2.2.E-04	48.30	0.30
3.6.E-03	7.3.E-05	4.2.E-04	1.7.E-02	1.7.E-04	48.50	0.16
3.5.E-03	5.1.E-05	1.9.E-04	6.0.E-03	1.8.E-04	49.94	0.17
6.3.E-03	1.1.E-03	2.7.E-04	9.2.E-03	2.3.E-04	51.35	0.43
7.5.E-03	8.8.E-04	3.8.E-04	7.3.E-03	1.8.E-04	52.04	0.33
3.3.E-04	1.0.E-04	8.5.E-04	6.5.E-03	7.4.E-06	53.52	0.43
3.1.E-04	1.1.E-04	5.7.E-04	6.0.E-03	7.5.E-06	53.69	0.14
2.3.E-04	8.1.E-05	6.0.E-04	4.2.E-03		53.99	0.63
3.1.E-04	5.5.E-05	5.2.E-04	3.6.E-03	4.6.E-06	54.38	0.36
1.6.E-02	1.6.E-03	2.6.E-04	2.5.E-03	5.0.E-06	54.69	0.25
2.0.E-03	1.2.E-05	8.8.E-05	1.6.E-04		56.58	0.33
1.5.E-03	4.9.E-06	1.0.E-04	3.4.E-04		56.91	0.10
1.0.E-03	1.2.E-05	1.7.E-04	4.0.E-04	4.0.E-06	56.84	0.26
1.2.E-04	7.9.E-06	9.6.E-06	3.5.E-05		57.31	0.22

Oxide wt% (EPMA) Data were obtained by the sess

SiO2	2SD[b]	CaO	2SD[b]	Cr2O3	2SD[b]	FeO
34.94	0.08	0.037	0.014			35.77
35.53	0.21	0.036	0.024			34.16
37.08	0.18	0.059	0.004			24.21
38.07	0.39	0.377	0.036	0.80	0.09	20.07
38.26	0.27	0.079	0.027			18.98
38.22	0.36	0.047	0.015			17.93
38.40	0.49					16.95
39.03	0.29	0.318	0.031	0.82	0.05	13.45
39.12	0.33	0.315	0.021	0.77	0.12	13.29
39.31	0.40	0.054	0.024			12.86
40.01	0.42	0.070	0.012			10.82
39.75	0.30	0.064	0.024			10.32
39.91	0.16	0.050	0.030			10.08
39.92	0.28	0.025	0.017			7.81
40.57	0.58	0.132	0.020	0.24	0.10	6.13
40.60	0.09	0.124	0.014	0.22	0.07	5.22
41.22	0.47					5.16
41.04	0.28					4.49
41.34	0.22					4.01
41.27	0.24					3.89
41.61	0.22	0.316	0.030	0.45	0.07	2.58
41.27	0.18	0.054	0.013			0.23
41.72	0.46	0.032	0.014			0.19
41.73	0.28	0.030	0.011			0.16
42.04	0.48					

sion_2019Jan.

2SD[b]	NiO	2SD[b]	MnO	2SD[b]	Total
0.10			0.665	0.073	98.96
0.31			0.645	0.057	99.44
0.26	0.14	0.03	0.429	0.030	99.05
0.25			0.446	0.075	99.43
0.38	0.18	0.08	0.222	0.134	99.13
0.27	0.25	0.07	0.207	0.050	99.01
0.34			0.321	0.091	98.53
0.27			0.455	0.044	99.03
0.44			0.461	0.075	98.90
0.27	0.42	0.07	0.163	0.066	98.94
0.27	0.42	0.12	0.159	0.073	99.69
0.27	0.41	0.09	0.166	0.075	99.01
0.21	0.40	0.05	0.143	0.063	99.07
0.13	0.51	0.17	0.128	0.073	98.34
0.69	0.44	0.12	0.122	0.075	98.99
0.27	0.49	0.09	0.097	0.021	98.80
0.56			0.337	0.078	100.36
0.16			0.346	0.116	99.56
0.18			0.297	0.055	99.65
0.23			0.345	0.101	99.88
0.16			0.125	0.100	99.77
0.09			0.072	0.002	98.20
0.06			0.083	0.042	98.93
0.03			0.072	0.002	98.83
					99.35

Appendix EA7-2: SIMS major and minor element analyses data (sessio

[a] 2σ errors represent either 2SE of each RM or 2SD of the runnning standard (SC-Ol), whiche

[b] 2SD errors were deduced from 5 analyses of each grain.

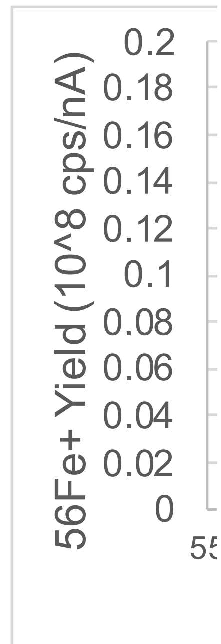
File	Analysis spot	Fo content	Cycle#
20190427@5.asc	WI-STD-92 SCOL	88.8	5
20190427@6.asc	WI-STD-92 SCOL	88.8	5
20190427@14.asc	WI-STD-92 SCOL	88.8	5
20190427@15.asc	WI-STD-92 SCOL	88.8	5
20190427@21.asc	WI-STD-91 SCOL	88.8	5
20190427@27.asc	WI-STD-91 SCOL	88.8	5
20190427@33.asc	WI-STD-91 SCOL	88.8	5
20190427@43.asc	WI-STD-91 SCOL	88.8	5
20190427@44.asc	WI-STD-91 SCOL	88.8	5
20190427@45.asc	WI-STD-91 SCOL	88.8	5
	Average (SC-Ol)		
	2SD		
	2SD %		
20190124@21.asc	WI-STD-91 OROL17_1	57.9	5
20190124@20.asc	WI-STD-91 OROL5_1	60.3	5
20190124@19.asc	WI-STD-91 FJOL2_1	73.2	5
20190124@18.asc	WI-STD-91 KNOL1-2_1	77.9	5
20190124@3.asc	WI-STD-92 CL0919-1_1	79.5	5
20190124@2.asc	WI-STD-92 CL0908-1_1	80.8	5
20190124@17.asc	WI-STD-91 SWOL15_1	81.8	5
20190124@24.asc	WI-STD-92 A77257-4_1	85.6	5
20190124@6.asc	WI-STD-91 A77257-5_1	85.8	5
20190124@4.asc	WI-STD-92 CL0933-4_1	86.5	5
	Average (SC-Ol)_Errors are 2SD	88.8	
20190124@16.asc	WI-STD-91 UWOL1-42_1	89.3	5
20190124@23.asc	WI-STD-92 IGOL1_1	89.6	5
20190124@15.asc	WI-STD-91 HaKOL g1-2_1	91.9	5
20190124@12.asc	WI-STD-91 WKOL8_1	93.7	5
20190124@11.asc	WI-STD-91 WKOL1_1	94.7	5
20190124@7.asc	WI-STD-91 WNOL1E_1	94.9	5
20190124@8.asc	WI-STD-91 WNOL1C_1	95.5	5
20190124@9.asc	WI-STD-91 WNOL4A_1	96.0	5
20190124@10.asc	WI-STD-91 WNOL4C_1	96.1	5
20190124@25.asc	WI-STD-92 NWA7325 OL7_1	97.4	5
20190124@26.asc	WI-STD-15 Skye-X_1	99.8	5
20190124@28.asc	WI-STD-15 Skye-V_1_5 cycle	99.8	5

20190124@27.asc	WI-STD-15 Skye-W_1_5 cycle	99.8	5
20190124@14.asc	WI-STD-91 HNOL	100.0	5

Averaged values of each olivien RMs

1	OR-Ol	59.1
2	FJ-Ol	73.2
3	KN-Ol	77.9
4	CL09-19	79.5
5	CL09-08	80.8
6	SW-Ol	81.8
7	A77257-Ol	85.7
8	CL09-33	86.5
9	Average (SC-Ol)_Errors are 2SD	88.8
10	UWOL-1	89.3
11	IG-Ol	89.6
12	HaK-Ol	91.9
13	WK-Ol	94.2
14	WN-Ol	95.6
15	N7325-Ol	97.4
16	SK-Ol	99.8
17	HN-Ol	100.0


28Si+ Yield (10^8 c
0.105
0.1
0.095
0.09
0.085
0.08

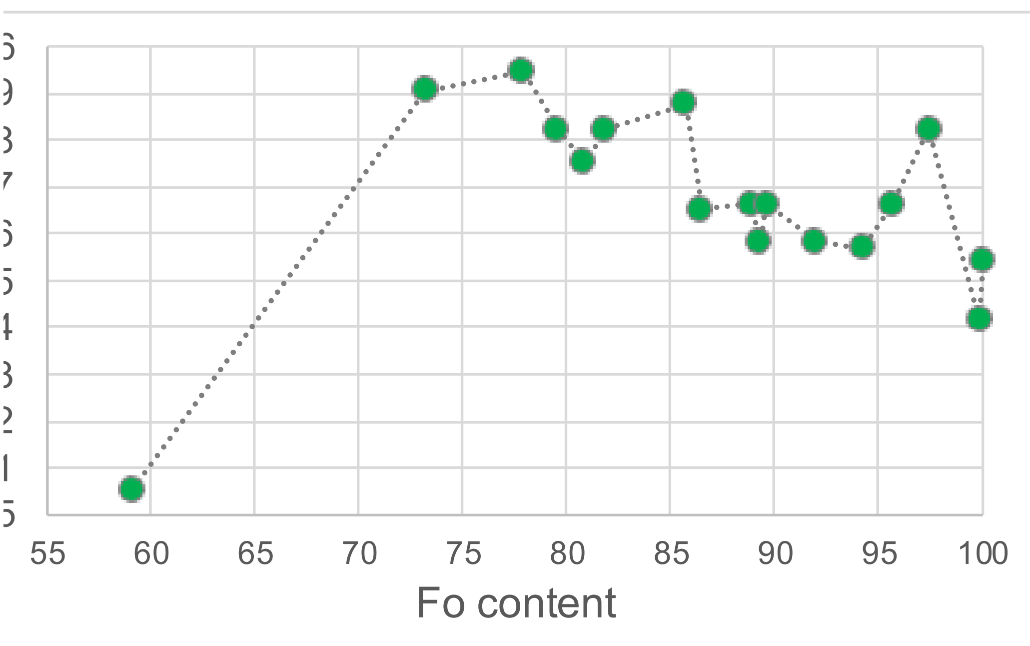

56Fe+ Yield (10^8 cps/nA)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0

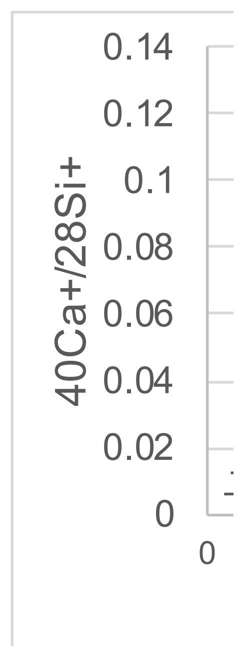
n FE2, 16pA, O^- primary ion beam)

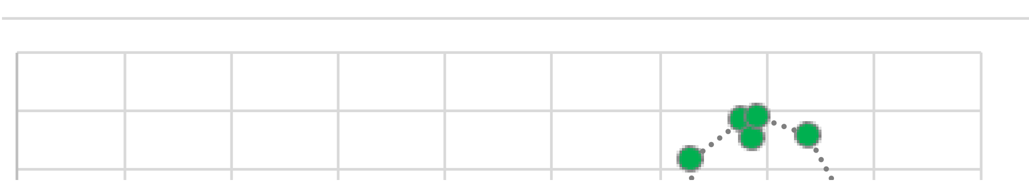
ver is larger

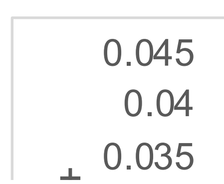
					Yield (× 10^8 cps n/
^{24}Mg (10^5 cps)	23Na	24Mg	27Al	28Si	40Ca
8.44	4.5.E-04	5.6.E-01	4.7.E-04	1.1.E-01	1.6.E-03
8.51	4.4.E-04	5.6.E-01	4.4.E-04	1.1.E-01	1.5.E-03
8.72	4.5.E-04	5.8.E-01	4.7.E-04	1.2.E-01	1.6.E-03
8.46	4.4.E-04	5.6.E-01	4.6.E-04	1.1.E-01	1.5.E-03
8.44	4.4.E-04	5.6.E-01	6.5.E-04	1.1.E-01	1.9.E-03
8.71	4.6.E-04	5.7.E-01	6.8.E-04	1.2.E-01	2.0.E-03
8.70	4.6.E-04	5.7.E-01	6.6.E-04	1.1.E-01	1.9.E-03
8.68	4.6.E-04	5.6.E-01	6.5.E-04	1.1.E-01	1.9.E-03
8.91	4.4.E-04	5.7.E-01	8.4.E-04	1.1.E-01	2.1.E-03
8.85	4.7.E-04	5.7.E-01	6.4.E-04	1.2.E-01	1.9.E-03
8.64	4.5.E-04	5.7.E-01	6.0.E-04	1.1.E-01	1.8.E-03
0.34	2.2.E-05	1.5.E-02	2.6.E-04	3.3.E-03	4.2.E-04
4%	5%	3%	44%	3%	23%
7.71	7.3.E-05	5.0.E-01	1.2.E-03	1.0.E-01	1.3.E-03
7.73	9.1.E-05	5.1.E-01	1.1.E-03	9.7.E-02	1.2.E-03
8.99	1.2.E-04	5.9.E-01	9.1.E-04	9.1.E-02	1.5.E-03
9.05	3.4.E-04	5.9.E-01	1.3.E-03	8.6.E-02	8.0.E-03
8.76	4.6.E-04	5.8.E-01	4.5.E-04	9.6.E-02	1.6.E-03
8.66	2.2.E-04	5.8.E-01	3.2.E-04	1.0.E-01	9.0.E-04
8.85	5.9.E-05	5.8.E-01	7.5.E-04	1.1.E-01	4.8.E-04
8.87	3.5.E-04	5.9.E-01	5.0.E-04	8.9.E-02	6.4.E-03
9.06	3.1.E-04	5.9.E-01	2.6.E-03	8.9.E-02	6.1.E-03
8.53	4.5.E-04	5.7.E-01	3.7.E-04	1.1.E-01	1.8.E-03
8.64	0.00	0.57	0.00	0.11	0.00
8.50	4.4.E-04	5.6.E-01	7.1.E-04	1.1.E-01	1.5.E-03
8.55	1.3.E-04	5.7.E-01	3.8.E-04	1.1.E-01	1.0.E-03
8.47	1.1.E-04	5.6.E-01	7.6.E-04	1.1.E-01	7.1.E-04
8.46	2.3.E-04	5.6.E-01	1.1.E-03	1.1.E-01	2.5.E-03
8.48	2.2.E-04	5.6.E-01	1.2.E-03	1.0.E-01	2.5.E-03
8.73	7.4.E-05	5.8.E-01	8.4.E-04	1.1.E-01	3.0.E-04
8.54	7.2.E-05	5.6.E-01	7.5.E-04	1.1.E-01	3.4.E-04
8.50	7.1.E-05	5.6.E-01	6.9.E-04	1.1.E-01	3.7.E-04
8.55	8.6.E-05	5.6.E-01	6.9.E-04	1.1.E-01	4.2.E-04
8.92	2.4.E-04	5.8.E-01	9.3.E-04	1.0.E-01	5.6.E-03
8.22	8.4.E-05	5.4.E-01	6.2.E-04	9.7.E-02	9.6.E-04
8.53	5.0.E-05	5.5.E-01	3.1.E-04	1.0.E-01	4.6.E-04

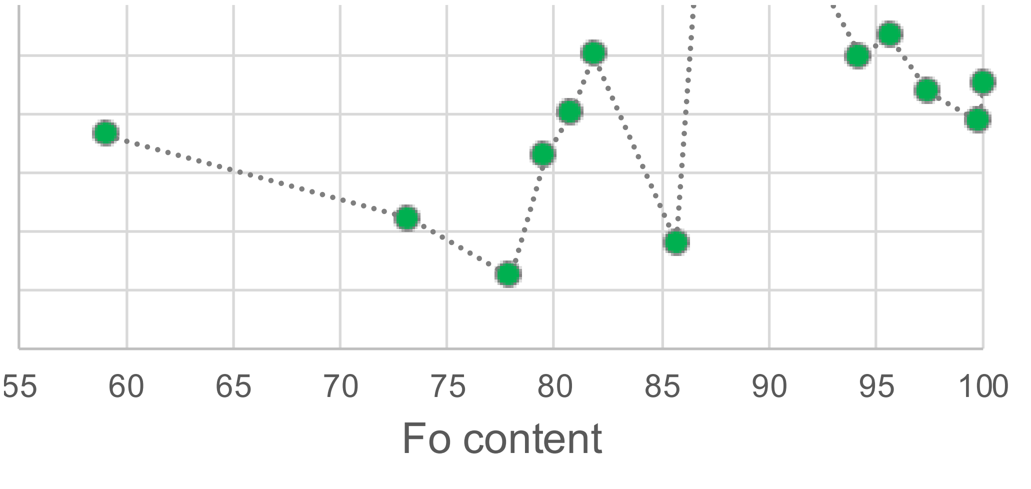
8.29	5.2.E-05	5.4.E-01	3.6.E-04	9.8.E-02	5.4.E-04
8.43	5.7.E-05	5.5.E-01	5.3.E-04	1.0.E-01	2.7.E-04
7.72	8.2.E-05	5.1.E-01	1.2.E-03	9.8.E-02	1.3.E-03
8.99	1.2.E-04	5.9.E-01	9.1.E-04	9.1.E-02	1.5.E-03
9.05	3.4.E-04	5.9.E-01	1.3.E-03	8.6.E-02	8.0.E-03
8.76	4.6.E-04	5.8.E-01	4.5.E-04	9.6.E-02	1.6.E-03
8.66	2.2.E-04	5.8.E-01	3.2.E-04	1.0.E-01	9.0.E-04
8.85	5.9.E-05	5.8.E-01	7.5.E-04	1.1.E-01	4.8.E-04
8.97	3.3.E-04	5.9.E-01	1.5.E-03	8.9.E-02	6.2.E-03
8.53	4.5.E-04	5.7.E-01	3.7.E-04	1.1.E-01	1.8.E-03
8.64	4.5.E-04	5.7.E-01	6.0.E-04	1.1.E-01	1.8.E-03
8.50	4.4.E-04	5.6.E-01	7.1.E-04	1.1.E-01	1.5.E-03
8.55	1.3.E-04	5.7.E-01	3.8.E-04	1.1.E-01	1.0.E-03
8.47	1.1.E-04	5.6.E-01	7.6.E-04	1.1.E-01	7.1.E-04
8.47	2.2.E-04	5.6.E-01	1.2.E-03	1.0.E-01	2.5.E-03
8.58	7.6.E-05	5.7.E-01	7.4.E-04	1.1.E-01	3.5.E-04
8.92	2.4.E-04	5.8.E-01	9.3.E-04	1.0.E-01	5.6.E-03
8.35	6.2.E-05	5.4.E-01	4.3.E-04	9.9.E-02	6.5.E-04
8.43	5.7.E-05	5.5.E-01	5.3.E-04	1.0.E-01	2.7.E-04



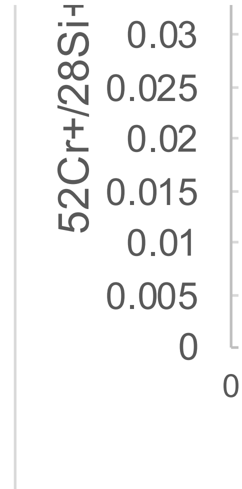




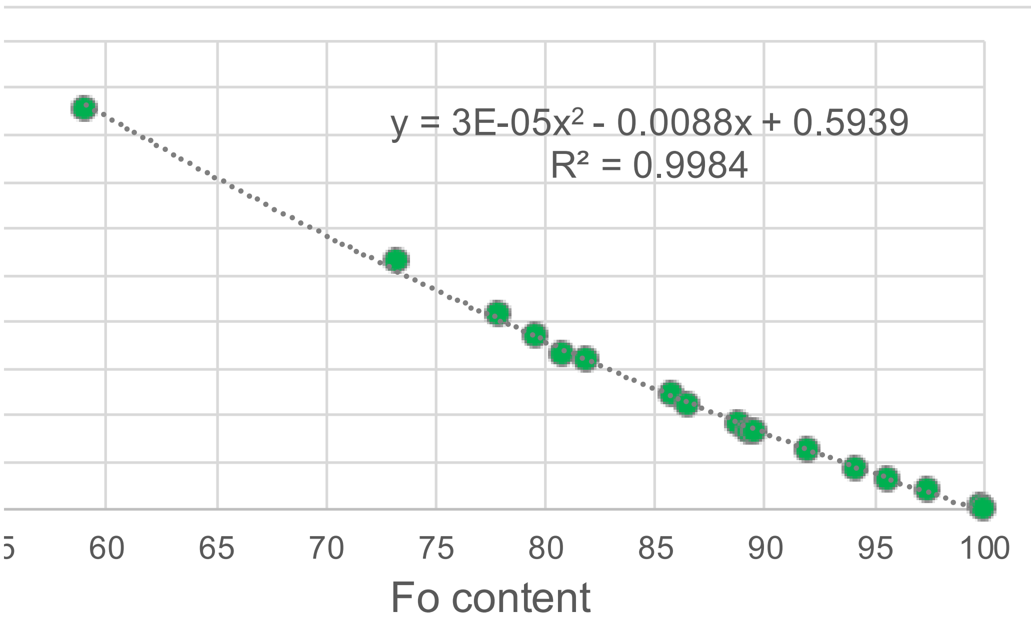




55
60
65
70
75
80
85
90
95
100
Fo content



0.03
0.025
0.02
0.015
0.01
0.005
0
0



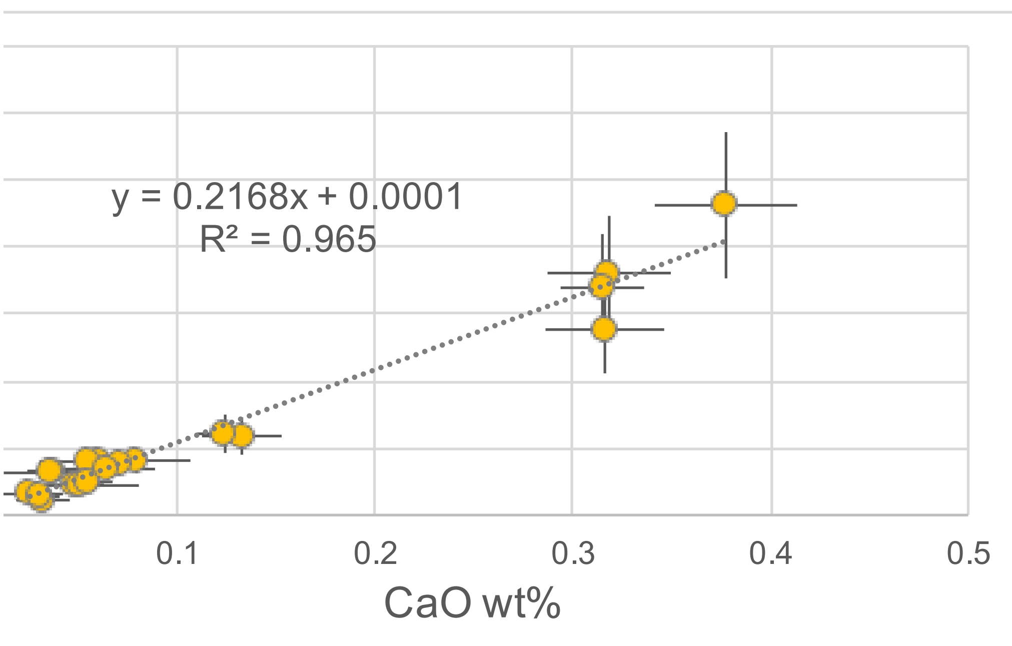
y = 3E-05x² - 0.0088x + 0.5939
R² = 0.9984
60
65
70
75
80
85
90
95
100
Fo content

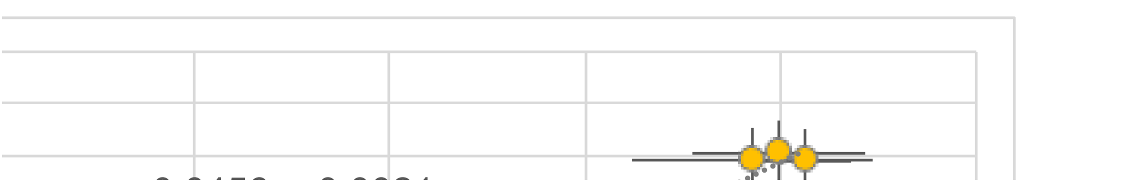
A^{-1})

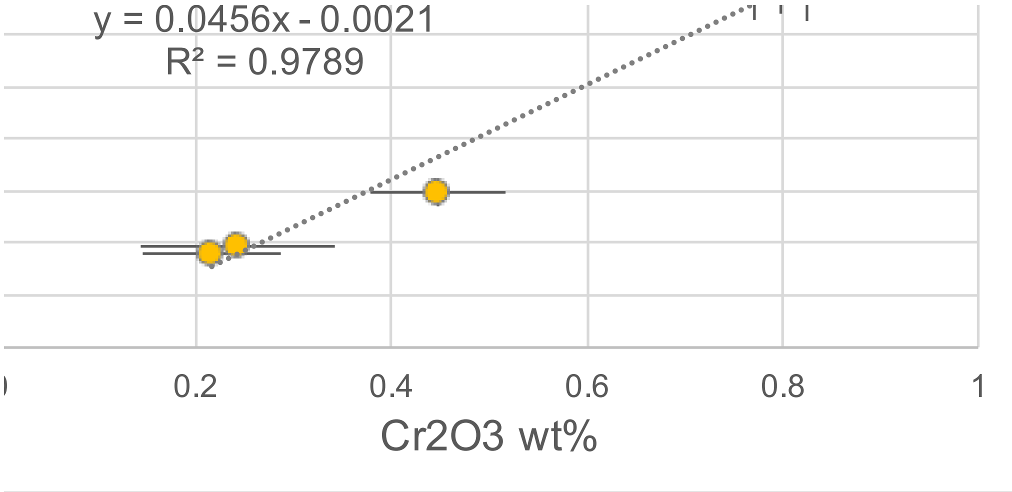
52Cr	55Mn	56Fe	60Ni	23Na+/ 28Si+
8.9.E-05	7.8.E-04	3.5.E-02	1.7.E-04	4.1.E-03
9.1.E-05	8.0.E-04	3.5.E-02	1.6.E-04	3.9.E-03
9.9.E-05	8.3.E-04	3.6.E-02	1.7.E-04	3.9.E-03
9.5.E-05	7.9.E-04	3.6.E-02	1.7.E-04	3.8.E-03
8.7.E-05	8.0.E-04	3.6.E-02	1.7.E-04	3.9.E-03
8.8.E-05	8.3.E-04	3.7.E-02	1.9.E-04	4.0.E-03
8.9.E-05	8.0.E-04	3.6.E-02	1.7.E-04	4.0.E-03
8.6.E-05	8.1.E-04	3.6.E-02	1.6.E-04	4.0.E-03
9.5.E-05	8.4.E-04	3.7.E-02	1.7.E-04	3.9.E-03
9.7.E-05	8.4.E-04	3.6.E-02	1.8.E-04	4.1.E-03
9.2.E-05	8.1.E-04	3.6.E-02	1.7.E-04	4.0.E-03
8.9.E-06	4.2.E-05	1.3.E-03	1.7.E-05	1.6.E-04
10%	5%	4%	10%	4%
2.3.E-06	5.3.E-03	1.8.E-01	2.6.E-05	7.3.E-04
1.6.E-06	4.8.E-03	1.6.E-01	2.6.E-05	9.4.E-04
1.8.E-06	2.8.E-03	1.1.E-01	1.0.E-04	1.3.E-03
3.0.E-03	2.7.E-03	8.4.E-02	7.3.E-06	4.0.E-03
2.0.E-05	1.3.E-03	7.4.E-02	1.1.E-04	4.8.E-03
2.3.E-05	1.2.E-03	6.6.E-02	1.5.E-04	2.2.E-03
1.1.E-04	1.9.E-03	6.3.E-02	2.1.E-06	5.7.E-04
3.1.E-03	2.4.E-03	4.9.E-02	4.1.E-06	4.0.E-03
3.1.E-03	2.5.E-03	4.9.E-02	2.6.E-06	3.5.E-03
3.1.E-05	9.3.E-04	4.4.E-02	2.1.E-04	4.1.E-03
0.00	0.00	0.04	0.00	0.00
4.1.E-05	7.5.E-04	3.3.E-02	1.7.E-04	3.9.E-03
2.5.E-05	7.6.E-04	3.3.E-02	1.8.E-04	1.2.E-03
2.9.E-05	5.5.E-04	2.5.E-02	1.8.E-04	9.9.E-04
1.0.E-03	4.6.E-04	1.8.E-02	1.7.E-04	2.2.E-03
9.5.E-04	3.9.E-04	1.7.E-02	1.7.E-04	2.1.E-03
6.4.E-05	1.6.E-03	1.4.E-02	1.4.E-07	6.9.E-04
6.8.E-05	1.6.E-03	1.2.E-02	2.7.E-07	6.8.E-04
6.5.E-05	1.5.E-03	1.1.E-02	4.1.E-07	6.7.E-04
5.5.E-05	1.5.E-03	1.1.E-02	1.4.E-07	8.2.E-04
1.5.E-03	4.0.E-04	7.9.E-03	1.4.E-07	2.3.E-03
1.6.E-06	2.0.E-04	8.6.E-04	0.0.E+00	8.7.E-04
1.3.E-06	1.7.E-04	7.3.E-04	1.3.E-07	4.9.E-04

1.3.E-06	1.9.E-04	8.2.E-04	0.0.E+00	5.3.E-04
1.8.E-06	9.6.E-07	1.7.E-05	0.0.E+00	5.6.E-04

2.0.E-06	5.1.E-03	1.7.E-01	2.6.E-05	8.3.E-04
1.8.E-06	2.8.E-03	1.1.E-01	1.0.E-04	1.3.E-03
3.0.E-03	2.7.E-03	8.4.E-02	7.3.E-06	4.0.E-03
2.0.E-05	1.3.E-03	7.4.E-02	1.1.E-04	4.8.E-03
2.3.E-05	1.2.E-03	6.6.E-02	1.5.E-04	2.2.E-03
1.1.E-04	1.9.E-03	6.3.E-02	2.1.E-06	5.7.E-04
3.1.E-03	2.5.E-03	4.9.E-02	3.4.E-06	3.7.E-03
3.1.E-05	9.3.E-04	4.4.E-02	2.1.E-04	4.1.E-03
9.2.E-05	8.1.E-04	3.6.E-02	1.7.E-04	4.0.E-03
4.1.E-05	7.5.E-04	3.3.E-02	1.7.E-04	3.9.E-03
2.5.E-05	7.6.E-04	3.3.E-02	1.8.E-04	1.2.E-03
2.9.E-05	5.5.E-04	2.5.E-02	1.8.E-04	9.9.E-04
9.8.E-04	4.3.E-04	1.8.E-02	1.7.E-04	2.1.E-03
6.3.E-05	1.6.E-03	1.2.E-02	2.4.E-07	7.1.E-04
1.5.E-03	4.0.E-04	7.9.E-03	1.4.E-07	2.3.E-03
1.4.E-06	1.9.E-04	8.0.E-04	4.5.E-08	6.3.E-04
1.8.E-06	9.6.E-07	1.7.E-05	0.0.E+00	5.6.E-04





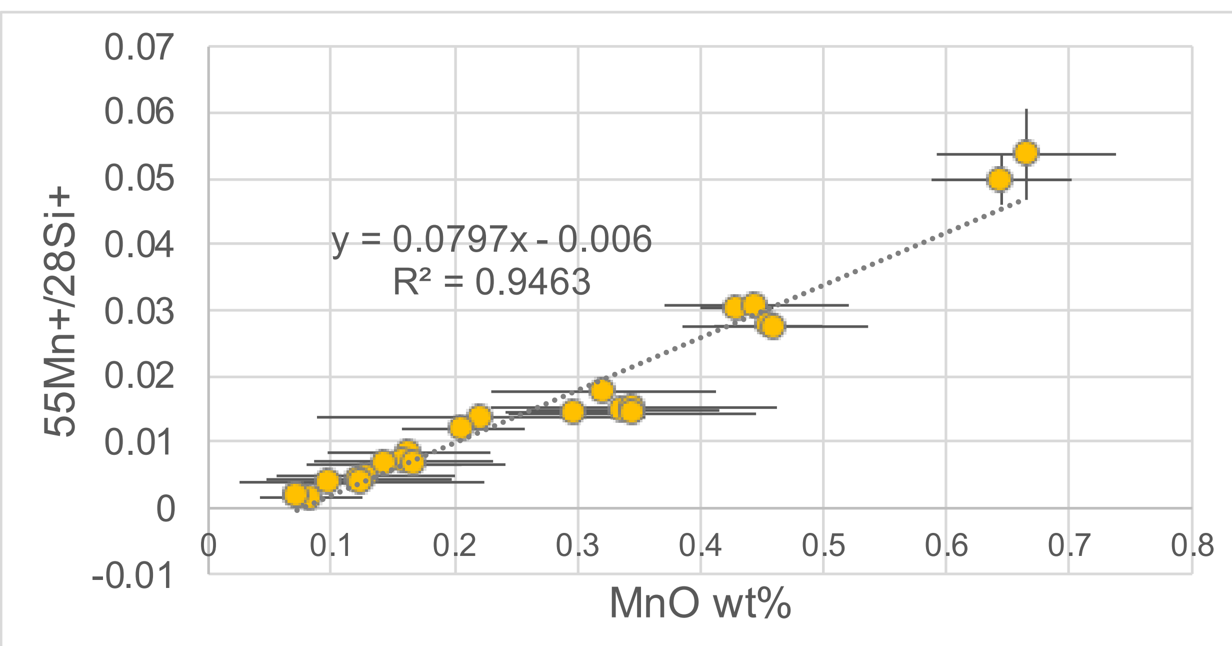


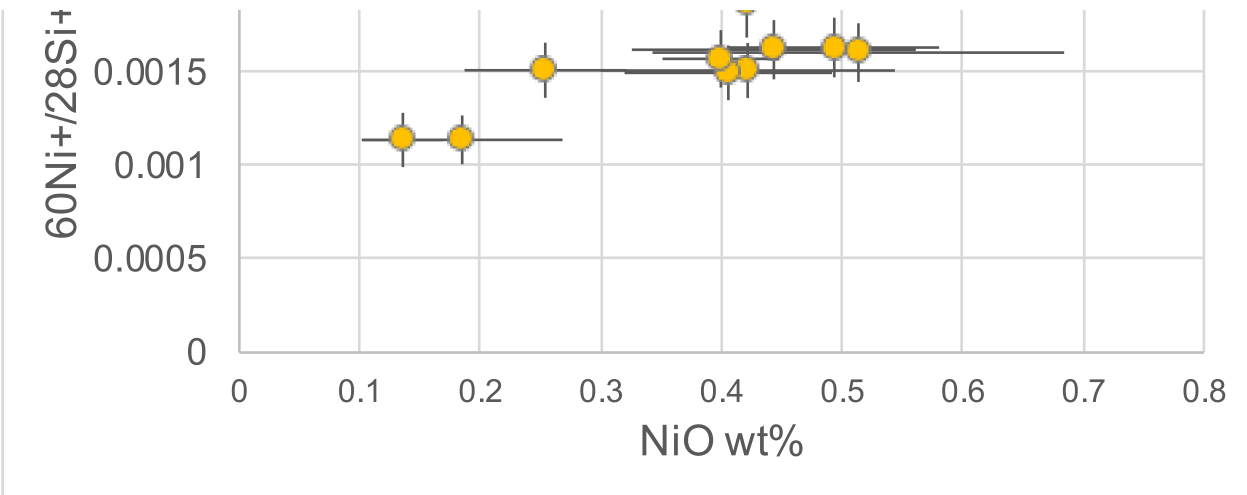
y = 0.0456x - 0.0021
R² = 0.9789
0.2
0.4
0.6
0.8
1
Cr2O3 wt%

24Mg+/ 28Si+	27Al+/ 28Si+	40Ca+/ 28Si+	52Cr+/ 28Si+	55Mn+/ 28Si+
5.0.E+00	4.2.E-03	1.4.E-02	8.0.E-04	7.0.E-03
5.0.E+00	3.9.E-03	1.4.E-02	8.0.E-04	7.1.E-03
4.9.E+00	4.0.E-03	1.4.E-02	8.4.E-04	7.2.E-03
4.9.E+00	4.0.E-03	1.3.E-02	8.2.E-04	6.9.E-03
4.9.E+00	5.8.E-03	1.7.E-02	7.7.E-04	7.1.E-03
5.0.E+00	5.9.E-03	1.7.E-02	7.6.E-04	7.1.E-03
5.0.E+00	5.8.E-03	1.6.E-02	7.8.E-04	7.0.E-03
4.9.E+00	5.7.E-03	1.6.E-02	7.5.E-04	7.0.E-03
5.1.E+00	7.5.E-03	1.9.E-02	8.4.E-04	7.5.E-03
4.9.E+00	5.6.E-03	1.6.E-02	8.4.E-04	7.2.E-03
5.0.E+00	5.3.E-03	1.6.E-02	8.0.E-04	7.1.E-03
1.4.E-01	2.3.E-03	3.7.E-03	7.2.E-05	3.2.E-04
3%	44%	24%	9%	5%
5.1.E+00	1.2.E-02	1.3.E-02	2.3.E-05	5.4.E-02
5.2.E+00	1.2.E-02	1.3.E-02	1.7.E-05	5.0.E-02
6.5.E+00	1.0.E-02	1.6.E-02	2.0.E-05	3.0.E-02
6.9.E+00	1.5.E-02	9.3.E-02	3.5.E-02	3.1.E-02
6.0.E+00	4.7.E-03	1.6.E-02	2.0.E-04	1.4.E-02
5.7.E+00	3.2.E-03	9.0.E-03	2.3.E-04	1.2.E-02
5.5.E+00	7.1.E-03	4.6.E-03	1.1.E-03	1.8.E-02
6.6.E+00	5.6.E-03	7.2.E-02	3.4.E-02	2.8.E-02
6.6.E+00	2.9.E-02	6.8.E-02	3.5.E-02	2.8.E-02
5.1.E+00	3.4.E-03	1.6.E-02	2.8.E-04	8.4.E-03
4.96	0.01	0.02	0.00	0.01
5.0.E+00	6.4.E-03	1.4.E-02	3.6.E-04	6.6.E-03
4.9.E+00	3.3.E-03	8.8.E-03	2.2.E-04	6.6.E-03
4.9.E+00	6.8.E-03	6.3.E-03	2.6.E-04	4.9.E-03
5.3.E+00	1.1.E-02	2.4.E-02	9.7.E-03	4.4.E-03
5.3.E+00	1.2.E-02	2.4.E-02	9.0.E-03	3.8.E-03
5.3.E+00	7.8.E-03	2.8.E-03	5.9.E-04	1.5.E-02
5.3.E+00	7.1.E-03	3.1.E-03	6.3.E-04	1.5.E-02
5.3.E+00	6.5.E-03	3.5.E-03	6.2.E-04	1.5.E-02
5.3.E+00	6.6.E-03	4.0.E-03	5.2.E-04	1.4.E-02
5.7.E+00	9.2.E-03	5.5.E-02	1.5.E-02	3.9.E-03
5.5.E+00	6.4.E-03	9.9.E-03	1.7.E-05	2.1.E-03
5.4.E+00	3.1.E-03	4.5.E-03	1.3.E-05	1.6.E-03

5.4.E+00	3.7.E-03	5.5.E-03	1.4.E-05	2.0.E-03
5.4.E+00	5.2.E-03	2.6.E-03	1.7.E-05	9.3.E-06

5.2.E+00	1.2.E-02	1.3.E-02	2.0.E-05	5.2.E-02
6.5.E+00	1.0.E-02	1.6.E-02	2.0.E-05	3.0.E-02
6.9.E+00	1.5.E-02	9.3.E-02	3.5.E-02	3.1.E-02
6.0.E+00	4.7.E-03	1.6.E-02	2.0.E-04	1.4.E-02
5.7.E+00	3.2.E-03	9.0.E-03	2.3.E-04	1.2.E-02
5.5.E+00	7.1.E-03	4.6.E-03	1.1.E-03	1.8.E-02
6.6.E+00	1.7.E-02	7.0.E-02	3.5.E-02	2.8.E-02
5.1.E+00	3.4.E-03	1.6.E-02	2.8.E-04	8.4.E-03
5.0.E+00	5.3.E-03	1.6.E-02	8.0.E-04	7.1.E-03
5.0.E+00	6.4.E-03	1.4.E-02	3.6.E-04	6.6.E-03
4.9.E+00	3.3.E-03	8.8.E-03	2.2.E-04	6.6.E-03
4.9.E+00	6.8.E-03	6.3.E-03	2.6.E-04	4.9.E-03
5.3.E+00	1.1.E-02	2.4.E-02	9.4.E-03	4.1.E-03
5.3.E+00	7.0.E-03	3.3.E-03	5.9.E-04	1.5.E-02
5.7.E+00	9.2.E-03	5.5.E-02	1.5.E-02	3.9.E-03
5.4.E+00	4.4.E-03	6.6.E-03	1.5.E-05	1.9.E-03
5.4.E+00	5.2.E-03	2.6.E-03	1.7.E-05	9.3.E-06





60Ni+/28Si+
0.0015
0.001
0.0005
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
NiO wt%

		Error (2			
56Fe+/ 28Si+	60Ni+/ 28Si+	23Na/ 28Si 2SE%	24Mg/ 28Si 2SE%	27Al/ 28Si 2SE%	40Ca/ 28Si 2SE%
3.1.E-01	1.5.E-03	1.71	3.93	17.07	6.55
3.1.E-01	1.4.E-03	3.60	2.63	8.60	2.87
3.1.E-01	1.4.E-03	4.69	3.38	9.48	4.50
3.1.E-01	1.5.E-03	6.77	3.91	13.54	5.00
3.2.E-01	1.5.E-03	5.97	4.20	14.60	4.60
3.2.E-01	1.7.E-03	6.85	4.20	15.65	4.09
3.2.E-01	1.5.E-03	2.40	4.51	11.55	3.11
3.2.E-01	1.4.E-03	7.75	2.31	11.84	1.55
3.3.E-01	1.5.E-03	3.89	2.58	15.01	1.45
3.2.E-01	1.6.E-03	3.07	2.17	11.65	1.02
3.2.E-01	1.5.E-03				
9.7.E-03	1.5.E-04				
3%	10%				
1.8.E+00	2.6.E-04	19.47	10.27	16.44	4.57
1.7.E+00	2.6.E-04	10.83	7.54	13.20	4.74
1.2.E+00	1.1.E-03	9.11	3.33	12.04	2.99
9.7.E-01	8.4.E-05	5.96	4.42	7.53	2.72
7.7.E-01	1.1.E-03	8.57	4.68	7.76	3.99
6.6.E-01	1.5.E-03	7.86	4.89	8.85	6.05
6.0.E-01	2.0.E-05	12.73	2.44	15.31	11.50
5.5.E-01	4.7.E-05	13.20	4.30	4.84	2.64
5.5.E-01	2.9.E-05	9.48	1.90	15.12	2.28
4.0.E-01	1.9.E-03	8.51	2.53	8.40	9.89
0.32	0.00	4.15	2.73	44.18	23.62
3.0.E-01	1.5.E-03	6.72	5.03	14.99	3.67
2.9.E-01	1.6.E-03	12.31	2.86	12.66	5.19
2.2.E-01	1.6.E-03	10.82	1.68	17.97	4.09
1.7.E-01	1.6.E-03	11.71	2.92	6.38	2.35
1.6.E-01	1.6.E-03	5.04	2.11	8.36	1.69
1.3.E-01	1.2.E-06	20.63	2.20	14.23	13.03
1.2.E-01	2.6.E-06	17.06	5.47	16.41	10.24
1.1.E-01	3.9.E-06	28.13	3.72	22.52	14.09
1.1.E-01	1.3.E-06	14.35	2.40	20.04	10.07
7.8.E-02	1.3.E-06	7.98	4.65	10.10	4.09
8.8.E-03	0.0.E+00	24.14	3.17	15.30	5.20
7.1.E-03	1.3.E-06	26.21	5.74	15.76	4.75

8.3.E-03	0.0.E+00	22.48	4.43	10.89	5.10
1.6.E-04	0.0.E+00	36.59	4.33	18.20	11.96

1.7.E+00	2.6.E-04	15.15	8.90	14.82	4.65
1.2.E+00	1.1.E-03	9.11	3.33	12.04	2.99
9.7.E-01	8.4.E-05	5.96	4.42	7.53	2.72
7.7.E-01	1.1.E-03	8.57	4.68	7.76	3.99
6.6.E-01	1.5.E-03	7.86	4.89	8.85	6.05
6.0.E-01	2.0.E-05	12.73	2.44	15.31	11.50
5.5.E-01	3.8.E-05	11.34	3.10	9.98	2.46
4.0.E-01	1.9.E-03	8.51	2.53	8.40	9.89
3.2.E-01	1.5.E-03	2.08	1.36	22.09	11.81
3.0.E-01	1.5.E-03	6.72	5.03	14.99	3.67
2.9.E-01	1.6.E-03	12.31	2.86	12.66	5.19
2.2.E-01	1.6.E-03	10.82	1.68	17.97	4.09
1.7.E-01	1.6.E-03	8.38	2.52	7.37	2.02
1.1.E-01	2.2.E-06	20.04	3.45	18.30	11.86
7.8.E-02	1.3.E-06	7.98	4.65	10.10	4.09
8.1.E-03	4.5.E-07	24.28	4.44	13.99	5.02
1.6.E-04	0.0.E+00	36.59	4.33	18.20	11.96

2SE%)

52Cr/ 28Si 2SE%	55Mn/ 28Si 2SE%	56Fe/ 28Si 2SE%	60Ni/ 28Si 2SE%	23Na/ 28Si 2σ	24Mg/ 28Si 2σ	27Al/ 28Si 2σ
9.43	2.61	4.06	5.61			
5.85	6.86	2.69	9.71			
7.75	5.52	3.99	7.23			
6.16	4.69	3.61	8.40			
10.87	6.41	3.95	7.60			
11.56	6.40	4.07	8.27			
8.77	5.22	4.89	8.51			
5.46	3.20	1.71	5.42			
7.48	6.24	2.65	4.17			
6.46	4.23	2.27	4.81			
51.76	12.88	10.68	30.04	1.4.E-04	5.2.E-01	5.5.E-03
42.17	7.60	6.65	17.50	1.0.E-04	3.9.E-01	5.2.E-03
18.25	3.59	3.43	12.77	1.2.E-04	2.2.E-01	4.4.E-03
1.30	5.21	4.21	8.81	2.4.E-04	3.0.E-01	6.7.E-03
18.12	6.43	3.47	11.49	4.1.E-04	2.8.E-01	2.1.E-03
6.96	5.50	4.38	6.26	1.7.E-04	2.8.E-01	1.4.E-03
9.63	4.04	2.01	65.99	7.2.E-05	1.5.E-01	3.2.E-03
6.41	6.29	4.78	29.05	5.2.E-04	2.8.E-01	2.5.E-03
4.82	3.45	1.82	27.48	3.3.E-04	1.8.E-01	1.3.E-02
10.69	3.17	2.19	4.70	3.5.E-04	1.4.E-01	1.5.E-03
8.97	4.52	3.07	9.79	1.6.E-04	1.4.E-01	2.3.E-03
5.53	7.30	4.39	4.13	2.7.E-04	2.5.E-01	2.8.E-03
17.09	4.06	3.83	6.44	1.4.E-04	1.4.E-01	1.5.E-03
12.76	2.65	1.97	6.06	1.1.E-04	1.3.E-01	3.0.E-03
3.13	4.08	2.42	9.01	2.5.E-04	1.5.E-01	4.7.E-03
3.17	3.19	1.49	4.70	1.1.E-04	1.5.E-01	5.2.E-03
10.56	1.72	1.69	200.00	1.4.E-04	1.5.E-01	3.4.E-03
16.78	3.87	4.24	200.00	1.2.E-04	2.9.E-01	3.1.E-03
6.88	7.94	3.79	81.77	1.9.E-04	2.0.E-01	2.9.E-03
10.07	3.68	1.94	200.00	1.2.E-04	1.5.E-01	2.9.E-03
4.65	4.20	3.81	200.00	1.8.E-04	2.7.E-01	4.0.E-03
55.73	8.69	2.73		2.1.E-04	1.7.E-01	2.8.E-03
70.66	3.60	4.52	200.00	1.3.E-04	3.1.E-01	1.3.E-03

30.57	2.88	2.18		1.2.E-04	2.4.E-01	1.6.E-03
70.89	96.63	18.76		2.1.E-04	2.3.E-01	2.3.E-03

46.96	10.24	8.66	23.77
18.25	3.59	3.43	12.77
1.30	5.21	4.21	8.81
18.12	6.43	3.47	11.49
6.96	5.50	4.38	6.26
9.63	4.04	2.01	65.99
5.61	4.87	3.30	28.26
10.69	3.17	2.19	4.70
4.48	2.26	1.54	4.89
5.53	7.30	4.39	4.13
17.09	4.06	3.83	6.44
12.76	2.65	1.97	6.06
3.15	3.63	1.96	6.85
11.07	4.30	2.92	170.44
4.65	4.20	3.81	200.00
52.32	5.06	3.14	
70.89	96.63	18.76	

Error (2σ)[a]						
40Ca/ 28Si 2σ	52Cr/ 28Si 2σ	55Mn/ 28Si 2σ	56Fe/ 28Si 2σ	60Ni/ 28Si 2σ	MgO	2SD[b]
3.1.E-03	1.2.E-05	6.9.E-03	1.9.E-01	7.8.E-05	27.55	0.13
3.0.E-03	7.1.E-06	3.8.E-03	1.1.E-01	4.6.E-05	29.07	0.27
3.8.E-03	3.6.E-06	1.4.E-03	4.0.E-02	1.4.E-04	37.13	0.19
2.2.E-02	3.2.E-03	1.6.E-03	4.1.E-02	8.2.E-06	39.67	0.16
3.8.E-03	3.7.E-05	8.9.E-04	2.7.E-02	1.3.E-04	41.41	0.37
2.1.E-03	2.0.E-05	6.6.E-04	2.9.E-02	1.5.E-04	42.35	0.28
1.1.E-03	1.1.E-04	8.0.E-04	1.8.E-02	1.3.E-05	42.86	0.28
1.7.E-02	3.1.E-03	1.7.E-03	2.6.E-02	1.4.E-05	44.96	0.28
1.6.E-02	3.1.E-03	1.2.E-03	1.7.E-02	7.9.E-06	44.95	0.41
3.8.E-03	3.0.E-05	3.8.E-04	1.2.E-02	1.8.E-04	46.14	0.34
3.7.E-03	7.2.E-05	3.2.E-04	9.7.E-03	1.5.E-04	48.22	0.25
3.2.E-03	3.3.E-05	4.8.E-04	1.3.E-02	1.5.E-04	48.30	0.30
2.1.E-03	3.7.E-05	3.0.E-04	1.1.E-02	1.5.E-04	48.50	0.16
1.5.E-03	3.3.E-05	2.2.E-04	6.7.E-03	1.6.E-04	49.94	0.17
5.6.E-03	8.7.E-04	2.0.E-04	5.4.E-03	1.6.E-04	51.35	0.43
5.7.E-03	8.1.E-04	1.7.E-04	4.9.E-03	1.6.E-04	52.04	0.33
6.5.E-04	6.3.E-05	6.7.E-04	4.0.E-03	2.5.E-06	53.52	0.43
7.4.E-04	1.1.E-04	6.9.E-04	4.9.E-03	5.2.E-06	53.69	0.14
8.3.E-04	5.5.E-05	1.2.E-03	4.0.E-03	3.2.E-06	53.99	0.63
9.4.E-04	5.3.E-05	6.5.E-04	3.2.E-03	2.5.E-06	54.38	0.36
1.3.E-02	1.3.E-03	1.8.E-04	3.0.E-03	2.6.E-06	54.69	0.25
2.3.E-03	9.3.E-06	1.8.E-04	2.7.E-04		56.58	0.33
1.1.E-03	9.4.E-06	7.3.E-05	3.2.E-04	2.7.E-06	56.91	0.10

1.3.E-03	4.2.E-06	8.9.E-05	2.6.E-04	56.84	0.26
6.3.E-04	1.2.E-05	9.0.E-06	3.1.E-05	57.31	0.22

Oxide wt% (EPMA) Data were obtained by the sess

SiO2	2SD[b]	CaO	2SD[b]	Cr2O3	2SD[b]	FeO
34.94	0.08	0.037	0.014			35.77
35.53	0.21	0.036	0.024			34.16
37.08	0.18	0.059	0.004			24.21
38.07	0.39	0.377	0.036	0.80	0.09	20.07
38.26	0.27	0.079	0.027			18.98
38.22	0.36	0.047	0.015			17.93
38.40	0.49					16.95
39.03	0.29	0.318	0.031	0.82	0.05	13.45
39.12	0.33	0.315	0.021	0.77	0.12	13.29
39.31	0.40	0.054	0.024			12.86
40.01	0.42	0.070	0.012			10.82
39.75	0.30	0.064	0.024			10.32
39.91	0.16	0.050	0.030			10.08
39.92	0.28	0.025	0.017			7.81
40.57	0.58	0.132	0.020	0.24	0.10	6.13
40.60	0.09	0.124	0.014	0.22	0.07	5.22
41.22	0.47					5.16
41.04	0.28					4.49
41.34	0.22					4.01
41.27	0.24					3.89
41.61	0.22	0.316	0.030	0.45	0.07	2.58
41.27	0.18	0.054	0.013			0.23
41.72	0.46	0.032	0.014			0.19

41.73	0.28	0.030	0.011			0.16
42.04	0.48					

sion_2019Jan.

2SD[b]	NiO	2SD[b]	MnO	2SD[b]	Total
0.10			0.665	0.073	98.96
0.31			0.645	0.057	99.44
0.26	0.14	0.03	0.429	0.030	99.05
0.25			0.446	0.075	99.43
0.38	0.18	0.08	0.222	0.134	99.13
0.27	0.25	0.07	0.207	0.050	99.01
0.34			0.321	0.091	98.53
0.27			0.455	0.044	99.03
0.44			0.461	0.075	98.90
0.27	0.42	0.07	0.163	0.066	98.94
0.27	0.42	0.12	0.159	0.073	99.69
0.27	0.41	0.09	0.166	0.075	99.01
0.21	0.40	0.05	0.143	0.063	99.07
0.13	0.51	0.17	0.128	0.073	98.34
0.69	0.44	0.12	0.122	0.075	98.99
0.27	0.49	0.09	0.097	0.021	98.80
0.56			0.337	0.078	100.36
0.16			0.346	0.116	99.56
0.18			0.297	0.055	99.65
0.23			0.345	0.101	99.88
0.16			0.125	0.100	99.77
0.09			0.072	0.002	98.20
0.06			0.083	0.042	98.93

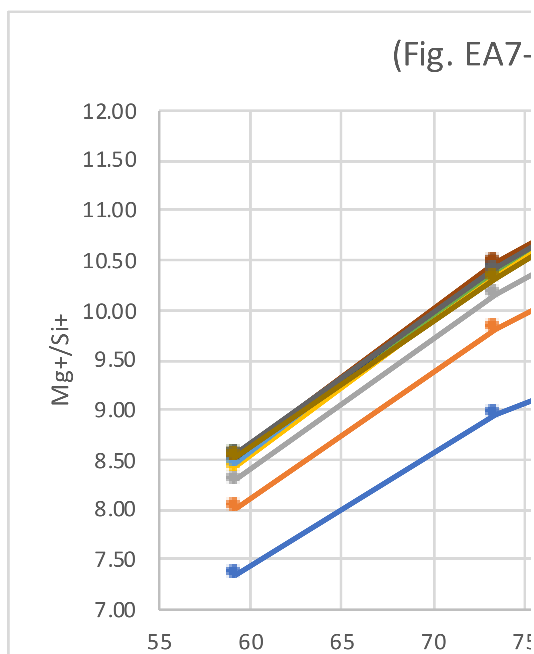
0.03			0.072	0.002	98.83
					99.35

Appendix EA7-3: depth dependence of Mg^+/Si^+ ratios

We conducted longer major and minor element analyses (50 cycle

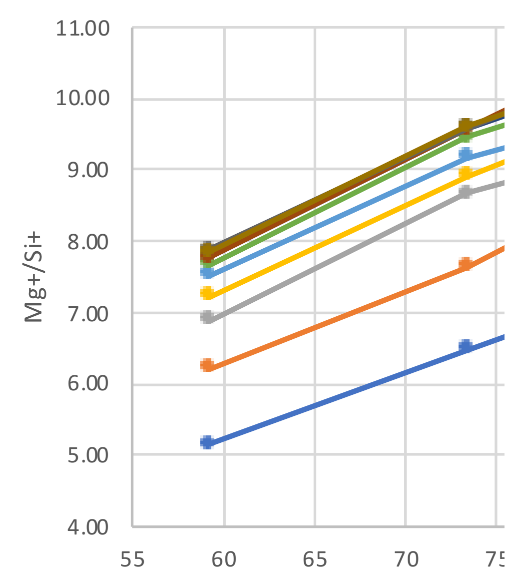
O^-). Present data are averaged by each 5 cycle to see depth deper

		Fo content	1-5 c	6-10 c	11-15 c
6pA, O_2^- primary ion beam					
1	OR-Ol	59	7.35	8.03	8.31
2	FJ-Ol	73	8.97	9.81	10.16
3	KN-Ol	78	9.28	10.24	10.60
4	CL09-19-Ol	79	9.28	10.24	10.60
5	CL09-08-Ol	81	9.48	10.26	10.62
6	SW-Ol	82	9.65	10.42	10.96
7	A77257-Ol	86	9.73	10.65	11.24
8	CL09-33-Ol	87	8.40	9.07	9.52
9	SC-Ol	89	8.13	8.80	9.10
10	UWOL-1	89	8.08	8.49	8.98
11	IG-Ol	90	7.84	8.43	8.75
12	HaK-Ol	92	7.61	8.16	8.42
13	WK-Ol	94	8.08	8.45	8.83
14	WN-Ol	96	7.69	8.21	8.43
15	N7325-Ol	97	8.35	8.73	8.90
16	SK-Ol	100	7.77	8.13	8.43
17	HN-Ol	100	7.55	7.92	8.25



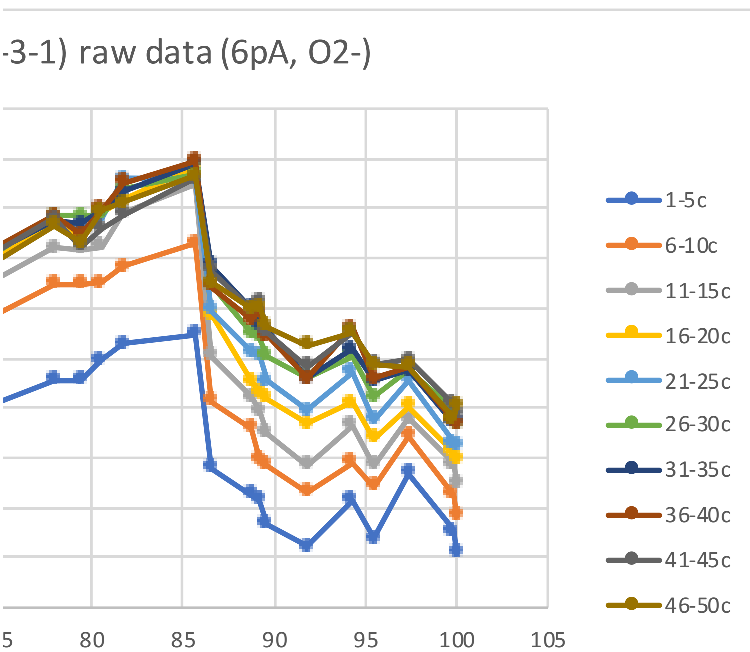
16pA, O⁻ primary ion beam					
1	OR-Ol	59	5.16	6.21	6.89
2	FJ-Ol	73	6.48	7.64	8.68
3	KN-Ol	78	6.90	8.25	9.00
4	CL09-19-Ol	79	6.04	6.25	6.80
5	CL09-08-Ol	81	5.74	6.11	6.67
6	SW-Ol	82	5.54	6.10	6.36
7	A77257-Ol	86	6.63	7.16	7.27
8	CL09-33-Ol	87	5.09	5.44	5.68
9	SC-Ol	89	4.96	5.33	5.63
10	UWOL-1	89	4.96	5.34	5.66
11	IG-Ol	90	4.95	5.44	5.54
12	HaK-Ol	92	4.95	5.56	5.57
13	WK-Ol	94	5.30	5.81	6.09
14	WN-Ol	96	5.30	5.91	6.14
15	N7325-Ol	97	5.72	6.27	6.64
16	SK-Ol	100	5.68	6.07	6.57
17	HN-Ol	100	5.40	6.18	6.54

(Fig. EA7-



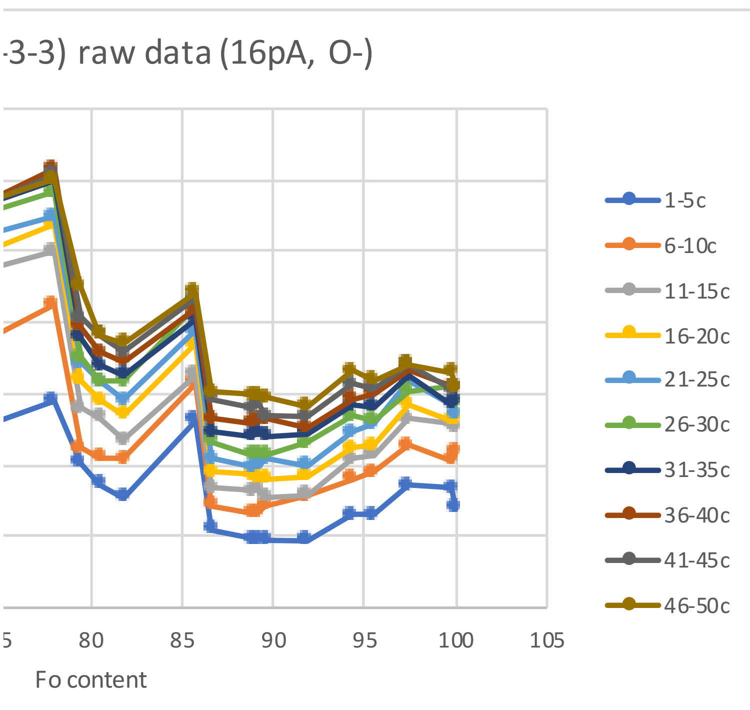
s) with two primary ion beam conditions (6 pA, O_2^- and 16 pA,
ndences on Mg^+/Si^+ ratios. Errors are not shown.

	raw 24Mg+/28Si+					
16-20 c	21-25 c	26-30 c	31-35 c	36-40 c	41-45 c	46-50 c
8.44	8.48	8.56	8.53	8.55	8.57	8.54
10.36	10.47	10.39	10.45	10.48	10.41	10.32
10.89	10.90	10.92	10.89	10.92	10.90	10.83
10.70	10.78	10.92	10.84	10.73	10.62	10.66
10.95	10.89	10.94	10.98	11.00	10.81	10.98
11.09	11.30	11.20	11.16	11.26	10.93	11.05
11.41	11.30	11.34	11.45	11.47	11.30	11.33
9.93	9.97	10.24	10.43	10.21	10.38	10.25
9.26	9.56	9.75	10.00	9.89	9.98	9.99
9.17	9.54	9.70	9.83	9.96	10.07	10.01
9.10	9.27	9.52	9.78	9.72	9.76	9.81
8.84	8.98	9.31	9.30	9.29	9.42	9.63
9.06	9.36	9.52	9.58	9.80	9.77	9.76
8.70	8.89	9.11	9.27	9.30	9.44	9.43
9.01	9.28	9.37	9.38	9.41	9.48	9.41
8.56	8.65	8.97	8.85	8.88	9.03	8.89
8.49	8.63	8.83	8.87	8.84	8.95	9.01



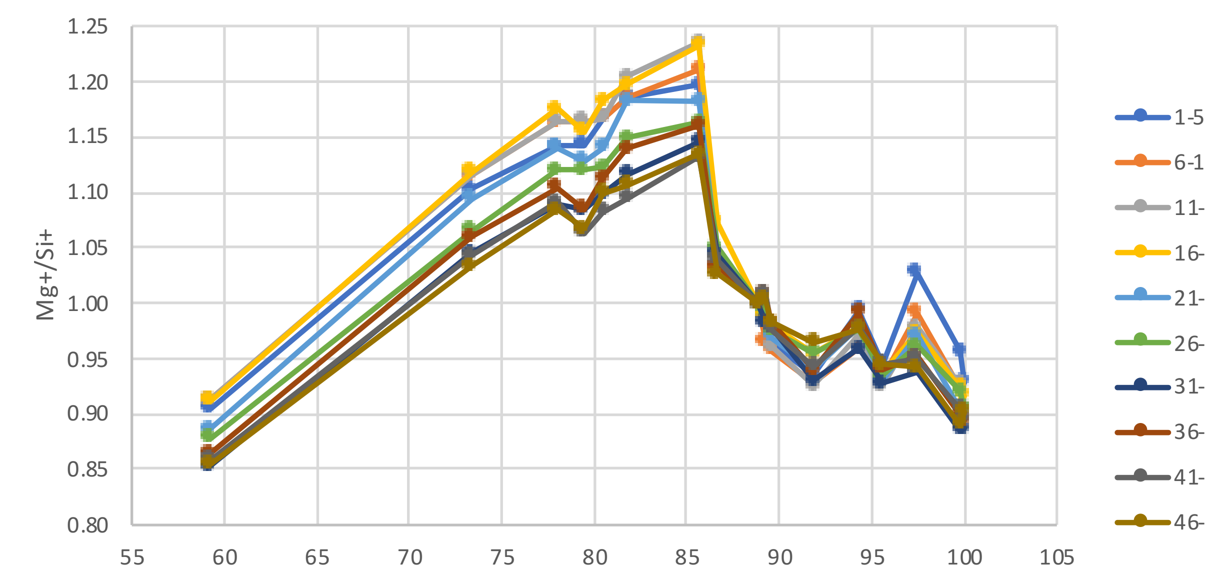
Fo content

7.23	7.52	7.68	7.78	7.78	7.88	7.85
8.91	9.17	9.45	9.58	9.57	9.59	9.61
9.38	9.49	9.84	9.99	10.16	10.07	10.01
7.19	7.44	7.52	7.80	7.94	8.08	8.50
6.91	7.18	7.17	7.40	7.58	7.82	7.83
6.71	6.91	7.18	7.27	7.45	7.58	7.72
7.70	7.88	8.25	8.05	8.18	8.32	8.43
5.91	6.08	6.32	6.46	6.65	6.92	7.02
5.86	5.98	6.14	6.40	6.59	6.80	6.99
5.80	6.00	6.17	6.46	6.63	6.85	6.99
5.82	6.10	6.15	6.41	6.65	6.69	6.95
5.85	6.00	6.31	6.44	6.52	6.68	6.82
6.24	6.46	6.69	6.83	6.93	7.13	7.31
6.28	6.57	6.63	6.82	7.00	7.08	7.19
6.85	7.18	7.05	7.25	7.34	7.42	7.41
6.62	6.85	7.09	6.86	7.10	7.07	7.31
6.62	6.70	6.87	6.89	7.07	7.10	7.09



24Mg+/28Si+ normalized to SC-Ol						
1-5 c	6-10 c	11-15 c	16-20 c	21-25 c	26-30 c	31-35 c
0.90	0.91	0.91	0.91	0.89	0.88	0.85
1.10	1.11	1.12	1.12	1.10	1.07	1.04
1.14	1.16	1.16	1.18	1.14	1.12	1.09
1.14	1.16	1.16	1.15	1.13	1.12	1.08
1.17	1.17	1.17	1.18	1.14	1.12	1.10
1.19	1.18	1.20	1.20	1.18	1.15	1.12
1.20	1.21	1.24	1.23	1.18	1.16	1.15
1.03	1.03	1.05	1.07	1.04	1.05	1.04
1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.99	0.97	0.99	0.99	1.00	1.00	0.98
0.96	0.96	0.96	0.98	0.97	0.98	0.98
0.94	0.93	0.93	0.95	0.94	0.95	0.93
0.99	0.96	0.97	0.98	0.98	0.98	0.96
0.95	0.93	0.93	0.94	0.93	0.93	0.93
1.03	0.99	0.98	0.97	0.97	0.96	0.94
0.96	0.92	0.93	0.92	0.90	0.92	0.89
0.93	0.90	0.91	0.92	0.90	0.91	0.89

(Fig. EA7-3-2) normalized to SC-Ol (6pA, O2-)



Appendix EA8: Calculation of residual biases for Cr-bearing olivine RMs

The modelled value ($bias^*_{25\ (RM\text{-}SCOl)\_calc}$) is calculated by assuming linear correlation between $bias^*_{25\ (RM\text{-}SCOl)}$ value and Fo content among olivine RMs with similar Fo contents.

$$bias^*_{25\ (RM-SCOl)\_calc} = \frac{(Fo_{high}) \times bias^*_{25\ (RM-SCOl)\_low} + (Fo_{low}) \times bias^*_{25\ (RM-SCOl)\_high}}{(Fo_{high}) - (Fo_{low})}$$

where Fo_{high} and Fo_{low} are Fo contents of each of two olivine RMs with higher and lower Fo contents relative to an olivine RM to be modelled. For example, if we estimate the $bias^*_{25\ (RM\text{-}SCOl)\_calc}$ value for KN-Ol ($Fo_{78.0}$), Fo_{high} and Fo_{low} are 73.4 (FJ-Ol) and 79.4 (CL09-19-Ol), respectively. Likewise, $bias^*_{25\ (RM\text{-}SCOl)\_high}$ and $bias^*_{25\ (RM\text{-}SCOl)\_low}$ are $bias^*_{25\ (RM\text{-}SCOl)}$ values of each of two olivine RMs.