

Vaporization and Thermodynamics of Forsterite-Rich Olivine. G. C. C. Costa¹, N. S. Jacobson¹ and B. Fegley², ¹NASA Glenn Research Center, 21000 Brookpark Road, MS 106-1, Cleveland, OH, 44135(gustavo.costa@nasa.gov), ²Planetary Chemistry Laboratory, McDonnell Center for the Space Sciences & Department of Earth and Planetary Sciences, Washington University in St. Louis, Campus Box 1169, 1 Brookings Dr, Saint Louis, MO, 63130-4899.

Summary: We studied near-equilibrium vaporization of carefully characterized olivine ($\text{Fo}_{93}\text{Fa}_{0.07}$) samples in iridium cells with Knudsen effusion mass spectrometry (KEMS). We report the partial pressure of the major gases evolved (Fe, Mg, SiO, O_2 , O) as a function of temperature. Our results confirm preferential evaporation of fayalite (Fa) relative to forsterite (Fo) reported by [1], constrain the pressure and composition of silicate vapor atmospheres on hot rocky exoplanets like Kepler 10-b and CoRoT-7b [2,3], constrain the silicate vapor pressure in the Moon-forming disk [4,5], and give basic thermodynamic data for the “FeO” – MgO – SiO_2 system, which we compare to literature data [6,7], which we focus on here.

Background: We studied vaporization of Fo-rich olivine because of its importance for the silicate vapor atmosphere on the early Earth, the Moon-forming disk, and hot rocky exoplanets. Astronomers have discovered over 100 hot rocky exoplanets (HRE) with substellar equilibrium surface temperatures hot enough to melt peridotite rock (solidus $T \geq 1473$ K) and produce silicate vapor atmospheres. Many of these planets orbit stars with solar or near-solar composition. Fo-rich olivine (approximately $(\text{Mg}_{0.9}\text{Fe}_{0.1})_2\text{SiO}_4$, $\text{Fo}_{90}\text{Fa}_{10}$) is a major constituent of peridotite rock, which comprises Earth’s upper mantle and is plausibly the major rock on hot rocky exoplanets such as Kepler-10b. Olivine is also one of the most abundant silicate minerals in the solar system. Its ubiquity is due to its high thermodynamic stability and the large solar elemental abundances of its constituent elements (O, Mg, Si, Fe) [1,2].

Experimental methods: Sample studied in this scientific work was mined from the west coast of Norway by Nor Mineral and provided by Miller & Co., Chicago, IL. The phase evolution and composition of the samples before and after KEMS experiments were characterized using X-ray diffraction (XRD), inductively coupled plasma optical emission spectroscopy (ICP-OES) and electron microprobe analysis. The vapor composition and partial pressure of the vapor species were measured in a Nuclide/MAAS/PATCO 12-90-HT single-focus 90° magnetic-sector mass spectrometer.

The vaporization of olivine of composition $\text{Fa}_{0.07}\text{Fo}_{0.93}$ has been studied from 1750-2250 K. It was found that impurities in the mineral could be removed by heating in a vacuum at 1853 K for 10 h. The vapor-

ization behavior was studied with Knudsen Effusion Mass Spectrometry to obtain partial pressures as a function of inverse temperature. An iridium cell was fairly inert to olivine below the melting point; however there was some reaction above the melting point. The onset of melting was observed at ~ 2050 K, consistent with the literature. It was also observed that significant losses of FeO occurred at the melting point.

Results: Vapor pressure measurements below the melting point are shown in Fig. 1. Comparing the measured partial pressure over olivine to those over pure materials lead to thermodynamic activities as a function of inverse temperature. These are shown in Fig. 2. Partial molar enthalpies are determined from the slope of this plot and listed in Table 1.

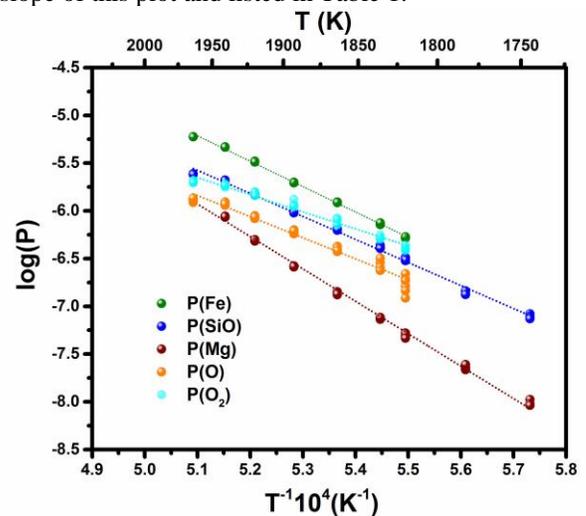


Figure 1. Dependence of the partial pressures of the species above olivine with inverse temperature for olivine ($\text{Fo}_{0.93}\text{Fa}_{0.07}$). Energy of ionizing electron 16.5 eV.

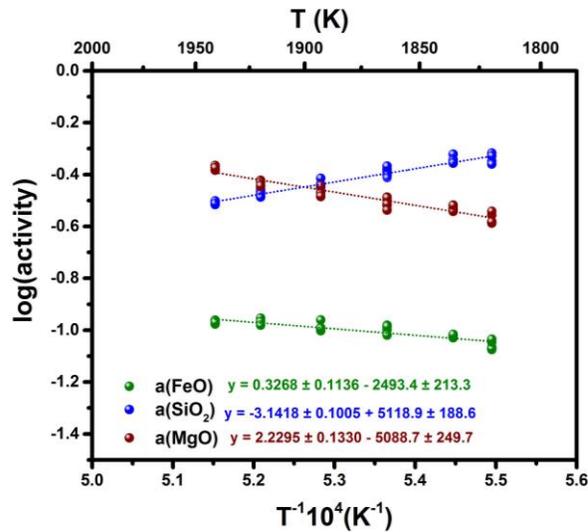


Figure 9. Thermodynamic activities for FeO, MgO, and SiO₂ in olivine as a function of temperature.

Discussion: As noted, there are several assessment of the MgO-‘FeO’-SiO₂ system in the literature. [6,7] These are constructed with all available thermodynamic and phase data at the time of the assessment and provide a self-consistent thermodynamic description of this system. A comparison of the data from this study to the assessments indicates that the data is consistent with previous measurements and allows inferences about the exact phase composition of the olivine. It also suggests improvements for future assessments.

Table 1 compares the measured partial molar enthalpies of each component to those calculated from the two databases discussed above. Agreement between our measurements and the database of Fabrichnaya [6] is reasonable. The relatively low partial enthalpy of MgO and high partial enthalpy of SiO₂ are important and need to be included in future assessments.

Table 1. Partial molar enthalpies of MgO, ‘FeO’, and SiO₂ as determined from activity dependence on inverse temperature.

Component	This Study	Calculated from Fabrichnaya Database	Calculated from Pelton Database
MgO	-97.4 ± 4.8	-74.29	-26.21
‘FeO’	-47.7 ± 4.1	-44.92	-22.44
SiO ₂	98.0 ± 3.6	89.07	6.15

Summary: Thermodynamic data was taken on this composition below the melting point. The equilibrium constant for each component’s (MgO, Fe/FeO, and SiO₂) were compared to the equilibrium constant for the pure material. Thermodynamic activities and partial molar enthalpies were derived for these components in olivine. Our data were compared to activities

calculated from two thermodynamic databases in the literature.

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References: [1] Ozawa, K. & Nagahara, H. (2000) GCA 64, 939-955. [2] Schaefer, L. & Fegley, B., Jr. (2009) ApJ 703, L113-L118. [3] Ito, Y. et al (2015) ApJ 801:144 (15pp). [4] Canup, R. et al. (2015) Nat Geo 8, 918. [5] Visscher, C. & Fegley, B., Jr. (2013) ApJ 767:L12 (6 pp). [6] Fabrichnaya O. (1998) *Calphad*, 22, 85-125. [7] Jung I.-H. (2004) *Metall. Mater. Trans. B*, 35, 877-889.