Chromium Oxidation State in Planetary Basalts: Oxygen Fugacity Indicator and Critical Variable for Cr-Spinel Stability

A.S. Bell¹ (asbell@unm.edu), P.V. Burger¹, Loan Le², J.J. Papike¹, J. Jones², and C.K. Shearer¹. ¹Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque New Mexico 87131, ²ESCG, Houston, TX 77058, ³KR, NASA/ JSC, Houston, TX 77058

Introduction: Cr is a ubiquitous and relatively abundant minor element in basaltic, planetary magmas. At the reduced oxidation states (<FMQ) of many planetary basalts Cr is present in melts as both divalent and trivalent forms. The ratio of trivalent to divalent Cr present in the melt has many consequences for the stability and Cr concentration of magmatic phases such as spinel, clinopyroxene, and olivine. However, understanding the Cr valence in quenched melts has historically been plagued with analytical issues, and only recently has reliable methodology for quantifying Cr valence in quenched melts been developed. Despite this substantial difficulty, the pioneering works of Hanson and Jones and Berry and O’Neill provided important insights into the oxidation state of Cr in in silicate melts [1,2]. Here we present a series of 1-bar gas mixing experiments performed with a Fe-rich basaltic melt in which have determined the Cr redox ratio of the melt at over a range of fO₂ values by measuring this quantity in olivine with X-ray Absorption Near Edge Spectroscopy (XANES). The measured Cr redox ratio of the olivine phenocrysts can be readily converted to the ratio present in the conjugate melt via the ratio of crystal-liquid partition coefficients for Cr³⁺ and Cr²⁺. We have applied these results to modeling Cr spinel stability and Cr redox ratios in a primitive, iron-rich martian basalt.

The Petrologic Importance of Cr-Spinel: Cr-spinel plays many significant roles in modulating the concentrations of important trace elements. Cr spinel has been demonstrated to be a potentially important sink of highly siderophile elements (HSEs) such as Rh, Re and Ir [3,4]. Cr-Spinel is also an important host for transition metals such as Ni, Co, and V. Additionally the composition of Cr-spinels are highly sensitive to changing melt compositions and fO₂ during magmatic differentiation; these relationships render Cr-spinel crystals a sensitive petrologic indicator [5]. Within this work we attempt to lay a framework with which fundamental questions about the link between magmatic Cr-spinels and their conditions of formation can be addressed. In broad terms the data and modeling presented in this abstract will ultimately help answer outstanding questions such as: 1) How much Cr³⁺ required to meet the threshold for a melt to attain Cr-Spinel saturation, and what implications does this have for the fO₂ and bulk Cr contents of planetary magmas? 2) How is the Cr redox ratio in the melt (changing as a function of fO₂) manifested in the equilibrium composition of Cr-spinel? 3) What can the composition of early formed Cr-spinel in SNC meteorites reveal about the undifferentiated melt composition, redox state, and chemistry of its mantle source?

Experiments: Wire loop experiments were conducted in the one-bar gas mixing laboratory at NASA Johnson Space Center (JSC). The experiments were performed using Re loops to prevent Fe-loss with the exception of experiments run at oxygen fugacity values near the FMQ buffer, which employed Pt-Rh loops. The starting materials consisted of a composition patterned after the whole rock composition of Martian meteorite Yamato 980459. Experiments were performed at temperatures of 1300°C, 1320°C and 1380°C. Experimental fO₂ was controlled with CO-CO₂ mixtures that were calibrated with a Y-stabilized zirconia electrochemical oxygen sensor.

X-ray Absorption Near Edge Spectroscopy (XANES) Data Acquisition and Reduction: Chromium K-edge XANES data were acquired with the x-ray microprobe of GSECARS beamline 13-ID-E at the Advanced Photon Source (APS), Argonne National Laboratory, Illinois. The x-ray source at APS beamline 13-ID-E was a 72-pole, 33 mm period undulator. Cr valence ratios measured with XANES in olivine have been re-calculated to reflect the liquid from which they grew (using the ratio of DCr³⁺/DCr²⁺ and the mole fractions of Cr³⁺ and Cr²⁺ in the olivine).

Cr Valence in the Experimental Melts: As a first order observation, the calculated Cr³⁺/ΣCr values for the melt show a distinct trend as a function of the experimental fO₂ values. The trend in the data suggests that the Cr valence ratio in the olivine is indeed sensitive to the
oxidation state of the experimental charges, and, by extension the oxidation state of the melt from which the crystals in question, nucleated and grew. Additionally, plots of the ln[Cr^3+/Cr^2+] values of the melts vs. ln/O₂ yields a linear array of points for the of the average corrected ln[Cr^3+/Cr^2+] vs. ln/O₂ yields a linear array of points. Fitting the data via linear regression yields a line with a slope of 0.24 and a correlation coefficient of R² = 0.97. The observed relationship between ln[Cr^3+/Cr^2+] and ln/O₂ is in excellent agreement with the stoichiometry of the homogenous Cr²⁺-Cr³⁺ oxidation equilibrium. Using the calculated Cr³⁺/Cr²⁺ of the experimental melts it is possible to model curves for the. Figure 1 presents a plot of the modeled Cr³⁺/ΣCr values vs. f/O₂ for the experimental Y-98 melts.

![Figure 1](image1.png)

**Figure 1.** Modeled Cr³⁺/ΣCr for experimental Y-98 liquids at 1300°C and 1380°C; model curves constructed with equilibrium constants derived from XANES based measurements of Cr³⁺ and Cr²⁺ contents of the melts.

**How Much Cr³⁺ is Required in the Melt to Attain Cr-Spinel Saturation?** Cr-spinel a stable phase in nearly all of the experimental charges, with the notable exception of experiments conducted at f/O₂ values below the IW buffer. Using the XANES measured Cr redox ratios of the melt, we have calculated the concentration of Cr³⁺ in the experimental melts. Figure 2 shows the calculated Cr³⁺ contents of the experimental melts as well as model curves for the Cr³⁺, Cr²⁺, and Fe³⁺ content of the experimental melts. Our measurements indicate that the elemental Cr³⁺ concentration in the liquid must exceed 1450ppm to achieve Cr-spinel saturation. The most reduced experiments (IW-1) contained only 750ppm Cr³⁺, and therefore did not contain any spinel. As the f/O₂ of the experimental charges the Cr³⁺ content concurrently increased until reaching the level required for spinel saturation. From this point the presence of Cr-Spinel buffers the concentration of Cr³⁺ in the liquid at a constant value (at a fixed Cr-spinel composition). Curiously in the oxidized experiments appear to have required less Cr³⁺ in the liquid to maintain Cr-spinel saturation. This observation can be readily be explained considering the precipitous increase of Fe³⁺ present in both the melt and the spinel. The Cr-spinels in the most oxidized experiments (FMQ) have a much larger magnetite component than do the other spinels. The fact that the spinels from the oxidized experiments have a lower mole fraction of the chromite component, is consistent with the lower abundances of Cr³⁺ required to maintain Cr-spinel saturation in these experiments. This observation suggests that the stability field of Cr-spinel can be greatly expanded (in f/O₂ space) when a small quantity (~1-2 wt. %) of ferric iron is present in the liquid.

**Conclusions:** Assuming that the effects of pressure on the Cr redox equilibrium are minimal, results from this work suggest that the primitive, Y-98 melt may have contained significant quantities of both trivalent and divalent chromium at temperatures below 1380°C. Results from our modeling also suggest that a substantial quantity of Cr³⁺ is required in the melt to attain Cr-spinel saturation in iron rich martian basalts. One implication that falls out of this observation is that Cr-spinel may not be a liquidus phase but rather a late crystallizing phase in relatively Cr poor liquids, even at moderately oxidizing f/O₂ values.

**References:**

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