THERMODYNAMIC CONSTRAINTS ON THE FORMATION CONDITIONS OF SILICATE-BEARING IAB IRON METEORITES.

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Introduction: The majority of iron meteorite groups exhibit geochemical trends that likely originated during fractional crystallization of a common metallic body for each parent body and provide strong evidence for core formation [1,2]. In contrast, there are a number of iron meteorite groups (e.g., IAB, IIE, IIICD) that exhibit much wider ranges in Ni and certain siderophile trace elements than the other groups. In addition, they contain silicate inclusions that are broadly similar in chemical composition to the chondritic material from which their parent bodies must have formed [1,3]. These features indicate a formation by one or more mechanisms that may not have operated on the parent bodies of the more common "magmatic" iron meteorites [2]. We proposed a scenario for IAB-IIICD iron formation that explains these apparently contradictory features by invoking incomplete melting and separation of the Fe,Ni-FeS cotectic and basaltic partial melts from the chondritic to ultramafic residues, followed by catastrophic impact, to produce these silicate-metal mixtures [4]. This model provides a broad framework for interpreting the genesis of these meteorites, particularly their textural features, but leaves a number of questions unanswered. In this work, we are attempting to constrain the temperature-oxygen fugacity conditions under which these silicate inclusions formed and equilibrated and to use these constraints to examine their physical formation environment.

The motivation for this study comes from the variety of contrasting geochemical signatures in the IAB silicate inclusions. Notably, Cr occurs within single inclusions in iron meteorites, in daubreélite ($FeCr_2S_4$), chromite and chromian diopside [4]. Similarly, P can coexist as the phosphide schreibersite, and a vast array of Fe, Mg, Mn, Ca, Na and K phosphates [3,5]. Many of the inclusions in IAB irons also contain graphite and are hosted in an Fe,Ni matrix while having FeO in the mafic silicates. Thus, these elements can occur as siderophile, chalcophile and lithophile elements. Although bulk chemical composition must be a strong control on the occurrence of these elements, temperature and oxygen fugacity also play a role in their distribution amongst minerals.

Samples: Silicate minerals in the IAB irons are characterized by relatively reduced compositions with olivine ranging from $Fa_{1.0}$(Pine River) to $Fa_{8.0}$(Udei Station) and low-Ca pyroxene ranging from $Fs_{1.0}$(Kendall County) to $Fs_{8.7}$(Udei Station). Our initial study was conducted on the Udei Station IAB iron meteorite and we have added Copiapo and Campo del Cielo, since all 3 meteorites contain both the oxidized and reduced phases of Cr and P (i.e. chromian diopside-chromite-daubreélite and phosphate-phosphide minerals). We also studied Caddo County because it has an extremely coarse-grained texture and contains the reduced silicate mineral phases and troilite. Chromite, however, was not evident in the thin section we examined (see discussion below).

Methods: For this work, we concentrated on the oxidized and reduced forms of Cr. Using mineral relationships in Udei Station, we determined reactions (eqns 1-4) to calculate temperature, oxygen and sulfur fugacity, and silica activity.

$$2\ Fe + SiO_2 + O_2(g) = Fe_2SiO_4 \quad (1)$$
$$Fe + SiO_2 + 0.5\ O_2(g) = FeSiO_3 \quad (2)$$
$$2\ CrS + FeS + 2\ O_2(g) = FeCr_2O_4 + 1.5\ S_2(g) \quad (3)$$
$$2\ Fe + S_2(g) = 2\ FeS \quad (4)$$

We chose these reactions because they involved oxidized and reduced phases of Cr, all of which are present in the Udei Station thin section. A thermodynamic model was constructed to determine the conditions under which the silicate inclusions in IAB iron meteorites equilibrated. The model uses three observed parameters: the Fe-content of olivine, the Fe-content of orthopyroxene and the Cr abundance in troilite. The activity coefficients for fayalite (Fa) and ferrosilite (Fs) are related to the mole fractions of these compounds and were calculated using the solid solution model of [6]. The activity of Fe in the metallic phase is equal to its concentration. The temperature dependence of a_{SiO2} and f_{O2} are determined from log K equations derived from eqn. (1) and (2) using the measured values for a_{Fa}, a_{Fs}, and a_{Fe}. Thermodynamic data are from [7].

The closure temperature (T) and sulfur fugacity (f_{S2}) of the system are determined using reactions (3) and (4). The value for the activity of chromite (a_{Chr}) is assumed to be unity. Values for the activity of CrS in FeS (a_{CrS}) were determined from the microprobe data, assuming an ideal solid solution. All thermodynamic data are from [7], except that for CrS, which were taken from [8]. Uncertainties in the final values were determined from those on the analytical measurements as well as those associated with the thermodynamic parameters.

We acquired microprobe data and used the data in these equations to calculate T, fO_2, and fS_2 in silicate inclusions from Udei Station, Caddo County, Campo del Cielo, and Copiapo.

Results: We presented the result for Udei Station earlier this year [9]. These previous and our new results are illustrated in Fig. 1. On this plot are the buffer curves for Cr-Cr_2O_3, C-CO, and Fe-FeO. The most important results of these data are: (A) Udei Station falls on the C-CO buffer, while Caddo County, Copiapo and Campo del Cielo fall below the C-CO buffer; (B) The data for all the meteorites lie on a line with an R^2 of 0.99. (C) There is variation within a single inclusion. Data from three occurrences of a specific mineral assemblage (i.e. olivine, pyroxene, troilite, and chromite) in contact in Campo del Cielo lie on a line with the average composition of Campo del Cielo and span a range of temperatures and $fO2$. (D) The slope of the line connecting all data points is steeper than the C-CO buffer curve, but parallels the Fe-FeO buffer curve.

Discussion and Conclusions: The most interesting result presented here is the variation in temperature and oxygen fugacity both between inclusions from different meteorites and within a single inclusion. In the Campo del Cielo inclusion we measured the compositions of co-existing olivine, pyroxene, and troilite in 3 different areas of the inclusion. The calculated closure temperature ranges from ~980 to ~1140˚C within the inclusion. We also randomly measured several olivine, orthopyroxene, and troilite grains throughout the entire inclusion to determine the extent of equilibration in the inclusion. This data is labeled on the figure as Campo del Cielo – avg. These data lie on a line with an R^2 of 0.99. What is more interesting is that all the data from the other inclusions also lie along this line, indicating that the system is buffered. However, the C-CO buffer plotted on the figure is for a specific pressure. Hence, the data do not lie on any particular buffer on this plot because they equilibrated under slightly different pressures. It may also indicate that a simple two-component buffer may not be sufficient to explain the data. The calculated temperature is a closure temperature for the equilibration between the three mineral phases. The data from the single inclusion in Campo del Cielo appears to indicate that the closure temperature varied throughout the inclusion. Variation in closure temperature could be due to local differences in grain size or composition, causing equilibration at slightly different temperatures.

Although chromite was not found in the thin section of Caddo County we studied, the fact that the data from troilite (Cr = 0.4 wt%), olivine and pyroxene gives a point that falls on the trend formed by the other data indicates a relationship. It is also interesting to note that Caddo County has the lowest closure temperature which is consistent with the slow cooling evidenced by its coarse-grained texture. Clearly, more data are required to fully determine and understand the range of temperature and oxygen fugacities of these enigmatic meteorites.

Future Work: For this project, the goals are: 1) Continue to calculate temperature and oxygen fugacity for inclusions in IAB irons. In particular, we will to investigate the range of properties within a single meteorite (i.e. Campo del Cielo). In addition to measurements on IAB irons, we would like to calculate the thermodynamic properties of the related winonaite, Pontlyfni. 2). Determine the C-CO buffer curve in 3-dimensional space, i.e. in log fO_2-T-P space. 3) Undertake melting experiments of chondritic starting materials to determine if the mineral assemblages found in the IAB silicate inclusions can be reproduced.

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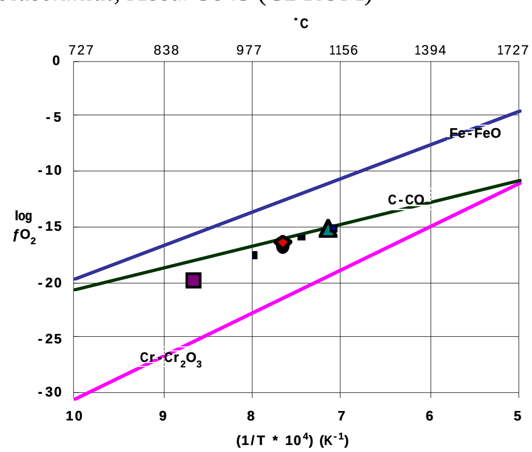

Figure 1. Plot of log fO_2vs 1/T for silicate inclusions in Udei Station (diamond), Caddo County (large square), Copiapo (triangle), and Campo del Cielo (avg = circle, points = small squares). Buffer curves for Fe-FeO, C-CO, and Cr-Cr_2O_3 are also shown in the figure. The C-CO buffer on this curve is for a CO pressure of ~0.01 atm. The data lie on a line with R^2 =0.99. The small squares are data from three different areas of the inclusion in Campo del Cielo where the minerals, olivine, pyroxene, troilite, and chromite are in contact. Udei Station slightly overlaps the data point for Campo del Cielo average.