PETROLOGY, GEOCHEMISTRY AND GENESIS OF UREILITES. D. W. Mittlefehldt[1], Pierre Hudon[1] and Charles Galindo Jr.[2], [1]NASA/Johnson Space Center , Houston, TX, USA (david.w.mittlefehldt@nasa.gov), [2]Hernandez Engineering Inc., Houston, TX, USA.

Introduction: Ureilites are enigmatic achondrites that have some characteristics resulting from high temperature igneous processing, yet retain other characteristics inherited from the solar nebula. They are basalt-depleted ultramafic rocks containing 7-66 mg/g elemental C. They are rich in noble gases and display a correlation between mg# and $\Delta^{17}O$ [1]. This mishmash of properties has engendered various models for ureilite genesis, from those in which nebular processes dominate to those in which parent body igneous processes dominate. Characterization of new ureilites, especially of new subtypes, is an important part of attempts to unravel the history of the ureilite parent body or bodies. Here we report on the petrology and geochemistry of a suite of ureilites, mostly from Antarctica, and use these data to discuss ureilite petrogenesis.

Petrology and Geochemistry: The ureilites studied here span the range in olivine core mg# from 76 to 95, nearly the entire range of the ureilite suite. They show the positive correlation between Fe/Mn and Fe/Mg characteristic of ureilites [2]. Ureilites have been divided into three groups based on Fe/Mg [3]. A histogram of olivine mg# shows minima at ~83 and ~90. We will divide ureilites into olivine mg# groups ≤82, 83-89, ≥90; groups 1 through 3. These divisions correspond to molar Fe/Mn of ≥38, 37-21, ≤20.

Lithophile elements have different distributions among the groups. In group 1, there are general decreases in the incompatible elements Ca, Sc and Sm and an increase in compatible element Cr with decreasing Fe/Mn and increasing mg#. In contrast, groups 2 and 3 show the opposite; general increases Ca, Sc and Sm and a decrease in Cr with decreasing Fe/Mn and increasing mg#. The trends are somewhat diffuse, possibly a result of heterogeneous distribution of pyroxene. The ratios Sc/Cr and Sm/Cr show more well defined trends; they decrease in group 1 and increase in groups 2 and 3 with decreasing Fe/Mn.

Siderophile element distributions in group 1 samples show no correlations with olivine Fe/Mn or mg#. When combined, groups 2 and 3 show increases in siderophile elements with increasing mg# and decreasing Fe/Mn. The ranges in siderophile elements in the individual olivine groups are similar, with the exception of Ir. None of the samples in groups 2 or 3 have Ir abundances greater than ~0.7× CI, while half of those in group 1 do. Group 1 ureilites have Ir abundances ranging from 0.044 to 1.28× CI.

Discussion: Widely different models for ureilite genesis have been proposed, from differential grain settling in the nebula, to impact melting of chondritic precursors, to accumulation of crystals from magma (see [4] for a review). Current consensus is that ureilites are magmatic rocks. Most are believed to be melting residues; some augite-bearing ureilites are considered to be cumulates [5]. One subset of partial melting models holds that reduction of FeO via graphite oxidation occurred during melting, producing the observed variations in mg# and Fe/Mn [6]. We will start by examining this smelting model.

The smelting model posits that the final mg# of ureilites was imposed by pressure-sensitive graphite oxidation. Thus, high mg# ureilites were originally more ferroan and lost FeO during smelting. Figure 1 compares bulk rock Fe vs. olivine core mg# for the ureilites studied here; a strong negative correlation in bulk Fe with olivine mg# is observed. **If the smelting model is correct, then Fe metal produced during reduction must have drained out of the bulk rock silicates.** Iron metal formed via smelting would have scavenged siderophile elements from the rocks, but this is not attested to by our data. Neither Ni nor Ir shows the predicted decrease with increasing mg# (Figs. 2a, 2b). Indeed, groups 2 and 3 ureilites, taken together, show increases in Ni and Ir with increasing mg#, opposite that expected from smelting reactions. **There is no evidence that smelting reactions played any part in defining silicate mineral or bulk rock mg# and Fe/Mn.** Rather, ureilite mg# variations were largely inherited from the chondritic protolith, with some modification caused by igneous processes.
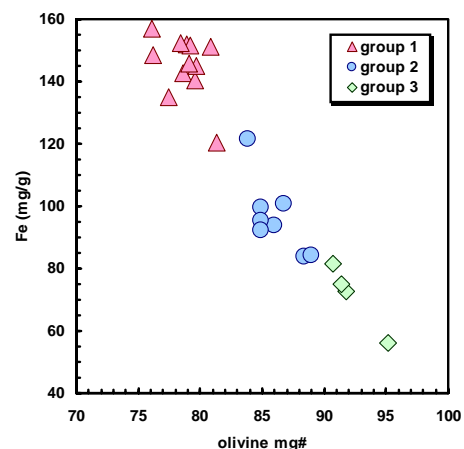

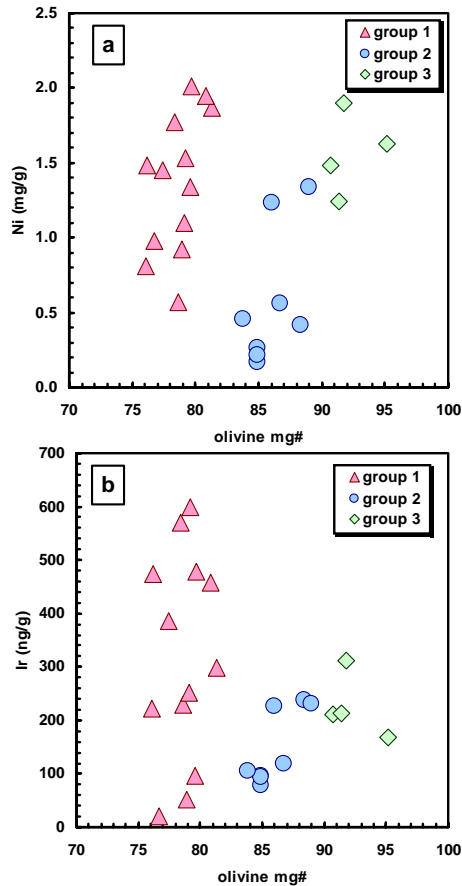Figure 1. Ureilite bulk rock Fe vs. olivine core mg#.

Figure 2. Ureilite bulk rock Ni and Ir vs. olivine core mg#.

Lithophile element distributions do not allow an easy choice between partial melting and cumulate models for genesis. For example, the general decrease in Sc with increasing olivine mg# observed in group 1 (Fig. 3) could result in a suite of partial melt residues (increasing melting, increasing mg# and decreasing Sc) or cumulates (early cumulates with high mg#, low Sc).
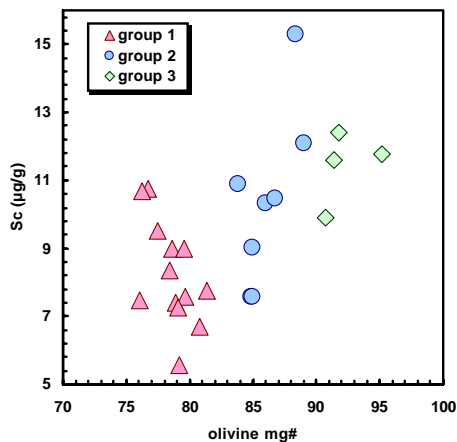

Figure 3. Ureilite bulk rock Sc vs. olivine core mg#.

Neither of these mechanisms can explain the variation in Fe/Mn within group 1; igneous processes will leave this ratio relatively unchanged [7].

Siderophile element abundances indicate, however, that most, if not all, group 1 ureilites are melt residues. Most group 1 ureilites have Ir abundances $\geq 0.5\times$ CI. A silicate melt/liquid metal partition coefficient for Ir is $\sim 10^{-5}$ [8], and a magma in equilibrium with molten metal of chondritic composition will contain $\sim 10^{-4}\times$ CI Ir. Olivine-dominated cumulates from this magma will have roughly the same Ir content; the olivine/melt partition coefficient is ~ 1 [9]. Thus, most group 1 ureilites have $\geq 5000\times$ the Ir expected for ultramafic cumulates. Even the group 1 ureilite with the lowest Ir content has $\sim 400\times$ the Ir expected for ultramafic cumulates. (This is the lowest Ir content we measured; Fig. 2b.)

The high siderophile element content can be explained by the melting residue model as arising from inefficient removal of metal from the partially molten source. The Ir/Au ratios for all samples are greater than CI, consistent with loss of low-melting-temperature metallic components and retention of residual solid metal.

Groups 2 and 3 together show diffuse trends of increasing Sc with increasing olivine mg# (Fig. 3). This cannot be explained by either partial melting or crystal accumulation models without recourse to ad hoc mechanisms. Original heterogeneity apparently obscures the imprint of igneous processes. The high Ir abundances and Ir/Au ratios in groups 2 and 3 ureilites are inconsistent with cumulate origin, but can be explained by a melt-residue origin (Fig. 2).

Groups 1-3 are artificial constructs of the human tendency to pigeonhole objects, although they are based on olivine mg# histogram minima. Nevertheless, lithophile and siderophile element patterns in group 1 and combined groups 2 and 3 are distinct, suggesting the possibility that group 1 represents some distinct ureilite lithology. Roughly 2/3 of ureilites belong to group 1. Further detailed comparison of group 1 with groups 2 and 3 could provide evidence regarding the petrogenetic reality of these groupings.

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