ASTEROIDAL DIFFERENTIATION PROCESSES DEDUCED FROM ULTRAMAFIC ACHONDRITE UREILITE METEORITES.

Hilary Downes[1,2], David W Mittlefehldt[3], Pierre Hudon[4], Christopher S. Romanek[5] and Ian Franchi[6] [1]Lunar and Planetary Institute, Houston, Texas, USA (Downes@lpi.usra.edu); [2]School of Earth Sciences, Birkbeck, University of London, London, UK; [3]NASA/Johnson Space Centre, Houston, Texas, USA; [4]Dept. of Earth and Planetary Sciences, McGill University, Montreal, Quebec, Canada; [5] Savannah River Ecology Laboratory, University of Georgia, Aiken, SC, USA; [6]Planetary Sciences Research Institute, Open University, Milton Keynes, UK.

Introduction: Ureilites are the second largest achondrite group. They are ultramafic achondrites that have experienced igneous processing whilst retaining some degree of nebula-derived chemical heterogeneity [1, 2]. They differ from other achondrites in that they contain abundant carbon and their oxygen isotope compositions are very heterogeneous and similar to those of the carbonaceous chondrite anhydrous mineral line. Their carbonaceous nature and some compositional characteristics indicative of nebular origin suggest that they are primitive materials that form a link between nebular processes and early periods of planetesimal accretion. However, despite numerous studies, the exact origin of ureilites remains unclear. Current opinion is that they represent the residual mantle of an asteroid that underwent silicate and Fe-Ni-S partial melting and melt removal. Recent studies of short-lived chronometers [3,4] indicate that the parent asteroid of the ureilites differentiated very early in the history of the Solar System. Therefore, they contain important information about processes that formed small rocky planetesimals in the early Solar System. In effect, they form a bridge between nebula processes and differentiation in small planetesimals prior to accretion into larger planets and so a correct interpretation of ureilite petrogenesis is essential for understanding this critical step.

Sampling the ureilite parent asteroid: Polymict ureilites contain olivine and pyroxene clasts that cover an identical range of compositions to that shown by all known monomict ureilites [5,6], indicating derivation from a single parent asteroid. Each thin-section of a polymict ureilite may contain hundreds of clasts of ureilitic material, and multiple thin-sections greatly increase the number of clasts available for analysis. Therefore the potential for studying the parent asteroid of ureilites is much greater if polymict samples are analysed. We have analysed over 500 mineral or lithic clasts from polymict ureilites in order to compare the distribution of mineral compositions within samples and to shed light on ureilite petrogenesis. Although the basaltic material formed by partial melting is largely missing from the present-day meteorite collection, numerous melt clasts are present within polymict ureilites, indicating that such material was present on the surface of the asteroid [7]. Furthermore, our study shows that many individual mineral clasts in polymict ureilites have identical compositions to the unusual olivine and pyroxene grains from the Hughes 009 augite-bearing ureilite, considered to have undergone interaction between melt and residue [8]. We have also done petrologic, bulk chemical and isotopic study of a suite of monomict ureilites.

Two types of ureilite: Our study has confirmed the observation that ureilitic olivine grains with mg#s < 85 are more common than those with mg# > 85 [9]. Recognition of the existence of two groups of ureilites (**Fig. 1**) may be of major significance. The ferroan group comprises a coherent suite of olivine compositions with a strong negative correlation between Fe and Mn, whereas the magnesian group shows much more scatter and possibly even a positive correlation. There are also differences between the two groups in bulk C and siderophile element contents of monomict ureilites (**Figs. 2, 3**). Note that while there are two distinct groups, the actual boundary criterion that distinguishes the groups is uncertain. The two groups merge at mg# 85 for olivine compositions (**Fig.1**), but mg# 83-84 works better for C and Ir (**Figs. 2, 3**). The two groups represent the products of contrasting processes or, more likely, the disruption of a single process by impact.

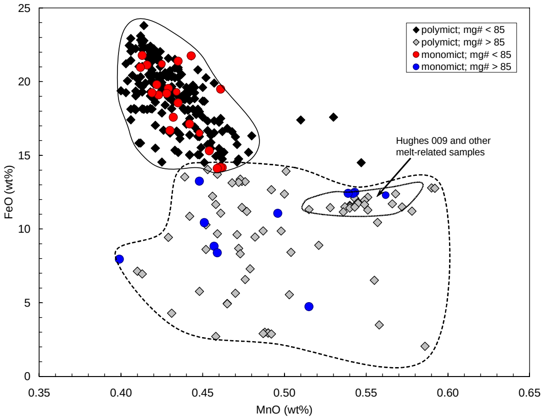

Figure 1. FeO vs MnO in ureilitic olivine grains from monomict ureilites and clasts within polymict ureilites. The coherent trend shown by samples with mg# < 85 is largely nebula-derived but overprinted by small degrees of melt extraction. Samples with mg#s > 85 were

undergoing partial melting at the instant of disruption of the parent ureilite asteroid.

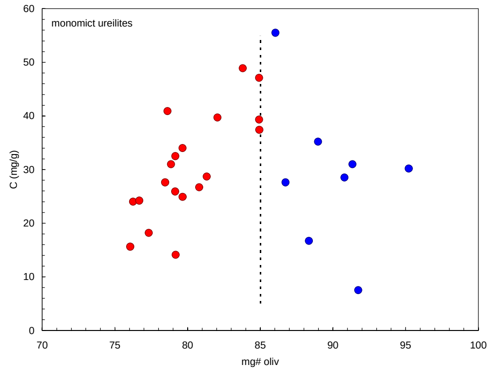

Figure 2. Bulk C vs olivine mg# in monomict ureilites. Samples with olivine mg# < 85 exhibit a positive correlation. Samples with olivine mg#s > 85 exhibit no coherent trend.

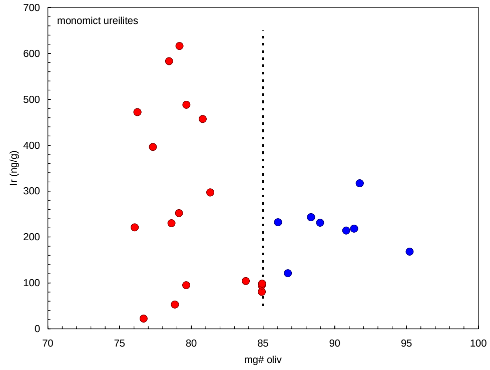

Figure 3. Bulk Ir vs olivine mg# in monomict ureilites. Samples with olivine mg# < 85 exhibit a wide range in Ir and no correlation. Samples with olivine mg#s > 85 have lower Ir contents on average, and possibly show a positive correlation.

Interpretation: We conclude that the proto-ureilite asteroid accreted from the solar nebula, probably as aggregates of olivine, orthopyroxene, diopside, plagioclase, metal, sulfide and carbonaceous material, with a range in mg# from ~74 to ~90 and wide $\Delta^{17}O$ variation. Ureilitic olivine compositions start abruptly at Fo74-75, the reason for which must relate to the minimum mg# of material in that part of the solar nebula from which the parent asteroid accreted. For comparison, the mantle of Mars also appears to have an mg# of ~75 [10]. The asteroid was heated by decay of radioactive ^{26}Al [11], causing metamorphism, and transformation of carbonaceous material to graphite. Siderophile contents of bulk ureilites indicate that removal of Fe-Ni-S melt may have occurred at this stage [12], perhaps forming a primitive core, but the high siderophile contents of some ureilites indicates that this process was incomplete (**Fig. 3**). As the inhomogeneous asteroid heated up, silicate melting would have commenced at the peritectic associated with the most iron-rich composition (mg# = 74-75), assuming a homogeneous Al distribution. Melting of each increment ceased when one (plagioclase) or more likely two (plagioclase + high-Ca pyroxene) of the original silicate phases had been consumed in the melting reaction and the melt expelled. This process explains the depletion of incompatible lithophile elements in ureilites [1]. It left behind a tri-mineralic olivine-pigeonite-graphite ureilite, essentially equivalent to a harzburgite in a more Mg-rich system (such as the Earth's mantle; mg# = 89). Thus the more abundant and more coherent group of ferroan ureilites probably represents residues from partial melting. However, this partial melting had occurred in a series of events in regions of the asteroid with different bulk mg#, so there was no planetesimal-wide magma ocean stage, and hence oxygen isotopes did not become homogenised. High precision oxygen isotope data for monomict ureilites can be interpreted as a series of small fractionation trends caused by partial melting [13].

One possible scenario is that the parent asteroid was disrupted by a major impact when melting reached silicate compositions with mg#s of approximately 85, giving rise to the two types of ureilites: (a) those that were already residual after melting and (b) those that were still partially molten when disruption occurred. In several samples with mg# > 85, melt impregnation of the mantle of the asteroid occurred, forming a suite of augite-bearing ureilites including Hughes 009 [8]. The impact event formed the highly shocked ureilite clasts found in polymict ureilites and represented in the monomict samples. It also formed the unusual highly magnesian rims around silicate minerals by a short-lived process akin to smelting. A daughter asteroid re-accreted from the remnants of the proto-ureilite asteroid; regolith formed on the daughter asteroid is represented by polymict ureilites. One problem with this scenario is that there is no quench-textured melt phase in mg# > 85 ureilites as might be expected from rapid cooling following disruption.

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