HIGHLY SIDEROPHILE ELEMENTS AND ^{187}Re-^{187}Os ISOTOPIC SYSTEMATICS OF THE ALLENDE METEORITE RECORD BOTH PRIMARY NEBULAR AND LATE-STAGE PARENT BODY ALTERATION PROCESSES. G. J. Archer[1], R. D. Ash[1], E. S. Bullock[2], and R. J. Walker[1]. [1]Department of Geology, University of Maryland, College Park, MD 20742 (garcher@umd.edu). [2]Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560.

Introduction: Chondritic components, including refractory inclusions, chondrules, and matrix, formed early in Solar System history [1]. Secondary processes, including thermal and aqueous alteration, variably modified these components after formation [2].

Conditions of primary component formation, as well as the nature and timing of secondary processing are still debated. Highly siderophile elements (HSE), including Re, Os, Ir, Ru, Pt, and Pd are useful for exploring primary nebular processes, as their range of condensation temperatures overlaps with those of the major chondritic components. Further, the Re-Os isotopic system ($^{187}Re \rightarrow {}^{187}Os + \beta^-$; λ=1.67 x $10^{-11}a^{-1}$) is useful for constraining the timing of secondary processes that acted on chondritic components [3].

The most refractory components present in chondrites are calcium-aluminum-rich inclusions (CAIs), the first known condensates from the solar nebula [4-5]. Chondrules may have formed during or shortly after CAI formation [6-7]. Matrix is composed primarily of fine-grained silicates, and is less refractory than other materials in chondrites [8]. Prior studies have examined the HSE abundances and Os isotopic systematics of some chondritic components [e.g, 9, 10], but none have analyzed all three major components from the same meteorite.

If chondritic components formed from a uniform $^{187}Os/^{188}Os$ reservoir, and remained closed systems subsequent to formation, they should plot within uncertainties of a primordial isochron [11]. Becker et al. [3], however, investigated the Re-Os isotopic systematics of a suite of Allende CAIs, and found that many plotted beyond analytical uncertainties of a primordial isochron. They reported a secondary isochron age of 1614±39 Ma for a single CAI. This age may reflect the timing of open-system behavior.

Here we present the first combined dataset of HSE abundances, and Re-Os isotopic systematics for all three major chondritic components taken from the carbonaceous chondrite Allende. For comparison, we also examine chondrules from ordinary chondrite Chainpur (LL 3.4).

Methods: Chondritic components were separated from Allende, made into powders, then combined with isotopic spikes enriched in ^{190}Os, ^{185}Re, ^{99}Ru, ^{194}Pt, ^{191}Ir, and ^{105}Pd. Samples, spikes, and ~3 mL 2:1 concentrated HNO_3 + HCl were combined in Pyrex Carius tubes [12] and heated to 260°C for three days. Osmium was then removed via solvent extraction using CCl_4 and back extraction into HBr [13], and then purified by microdistillation [14]. All other HSE were purified using anion exchange chromatography. Purified Os was then analyzed by negative thermal ionization using a *VG Sector 54* mass spectrometer. Rhenium, Ru, Pt, Ir, and Pd were analyzed using a *Nu Plasma* multi-collector-ICP-MS. To investigate possible nucleosynthetic effects and cosmic ray interactions, unspiked portions of two CAIs were processed in the same manner. Their Os and Re isotopic compositions were measured to high precision by N-TIMS using a *Thermo-Fisher Triton* and MC-ICP-MS using a *Nu Plasma*, respectively.

Results: Group I and III CAIs have suprachondritic abundances of the measured refractory HSE, and depletions in Pd (Fig. 1a). Allende group II CAIs are depleted in all measured HSE, relative to CI chondrites (Fig. 1a). Allende chondrules have near chondritic abundances of the refractory HSE, and all but two are depleted in Pd (Fig. 1b). Chainpur (LL3.4) chondrules have very similar HSE abundance patterns. Allende matrix fractions are characterized by HSE patterns that are generally similar to bulk Allende (Fig. 1c).

Only 4 of 14 Allende CAIs, 2 of 6 Allende chondrules, and 0 of 4 Allende matrix fractions plot within uncertainties of a primordial isochron. Remarkably, 10 of 24 Allende components plot within uncertainties of the linear array described by [3] that defines an age of ~1600 Myr (Fig. 2).

Discussion: The refractory HSE enrichment of group I and III CAIs is consistent with high temperature condensation, as previously suggested by [9]. The characterisitic Pd depletions in group I and III CAIs reflects either the separation of CAIs, or their precursors, from nebular gas above the 50% condensation temperature of Pd (1324 K at 10^{-4} bar), or evaporative loss during heating. Due to the required efficiency of evaporation to produce Pd depletions, and the lack of CAIs without Pd depletions, we favor the interpretation of a condensation effect. The low abundances of all measured HSE in group II CAIs are consistent with fractional condensation, a mechanism which as been suggested by prior studies [e.g., 15].

One possible mechanism for generating chondrule HSE abundances that are broadly similar to those of

group I and III CAIs, would be inheriting HSE abundances from CAI-like refractory condensate precursors. Concentration variations among chondrules could then reflect different proportions of these precursors. Another possible explanation for the HSE abundances in chondrules is the formation of a fractionated (Pd-depleted), HSE carrier phase during chondrule formation, and mixing of that carrier phase with an unfractionated HSE carrier phase. Such phases have been suggested for ordinary chondrite chondrules [10]. Ordinary and carbonaceous chondrite chondrules have similar HSE patterns (Fig. 1b). Thus, it is likely that their HSE patterns were established by similar processes, and that mixing of the two carrier phases could have resulted in the observed HSE abundances.

There are several possible explanations as to why some chondritic components do not plot on a primordial Re-Os isochron. These include early Solar System processes, such as intense interactions with cosmic rays or inefficient mixing of Os from different stellar sources. However, the measured stable isotopic compositions of Re and Os are not consistent with such processes. The most likely explanation is that the Re-Os system in Allende was disturbed by a late-stage open-system event around 1600 Ma. This event was most likely caused by impact-generated fluid mobilization of Re.

References: [1] Wadhwa M. and Russell S.S. (2000) In *Protostars and Planets* **IV**, 995-1018 [2] Zolensky M.E. and McSween H.Y. Jr. (1988) In *Meteorites and the Early Solar System*, 114-143 [3] Becker H. et al. (2001) *Geochim. Cosmochim. Acta* **65**, 3379–3390 [4] Bouvier A. and Wadhwa M. (2010) *Nature Geoscience* **3**, 637-641 [5] Grossman L. (1972) *Geochem. Cosmochim. Acta* **36**, 597-619 [6] Amelin Y. et al. (2010) *Earth Planet. Sci. Lett.* **300**, 343-350 [7] Connelly J. et al. (2012) *Science* **338**, 651-655 [8] Scott E.R.D. et al. (1988) In *Meteorites and the Early Solar System* 718-745 [9] Mason B. and Taylor S.R. (1982) *Smithson. Contrib. Earth Sci.* **25**, 1-30. [10] Horan M.F. et al. (2009) *Geochim. Cosmochim. Acta* **73**, 6984-6997. [11] Smoliar M.I. et al. (1996) *Science* **271,** 1099–1102 [12] Shirey S.B. and Walker R.J. (1995) *Anal. Chem.* **67**, 2136-2141 [13] Cohen A.S. and Waters F.G. (1996) *Anal. Chim. Acta* **332,** 269–275 [14] Birck J.L. et al. (1997) *Geostand. Newsl.* **21**, 19–27 [15] MacPherson G.J. (2003) *Meteorites, Planets, and Comets* **Vol. 1** 201-246.

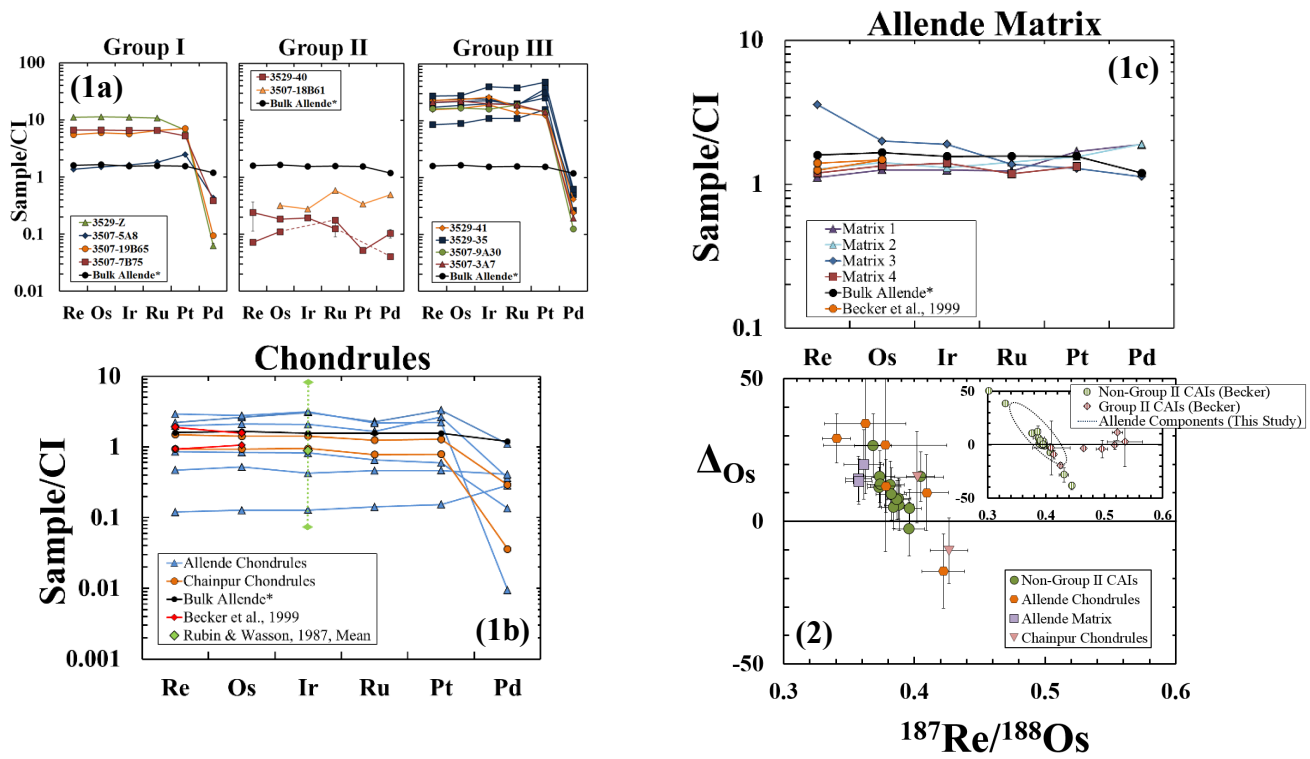

Figure 1: HSE abundances of (a) CAIs, (b) chondrules, and (c) matrix normalized to CI chondrites. Roman numerals indicate the REE group classification of CAIs. HSE abundances of fractions of the same CAIs have the same symbols. Most samples are from Allende, but two chondrules are from Chainpur.

Figure 2: Δ_{Os} vs. $^{187}Re/^{188}Os$ plot for Allende chondritic components analyzed by this study. Δ_{Os} is the absolute deviation from a primordial 4568 Ma primordial reference isochron. Data from [3] are included in insert.