

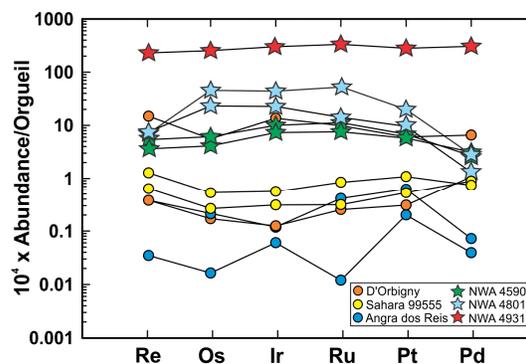
## HIGHLY-SIDEROPHILE-ELEMENT AND OSMIUM ISOTOPE CONSTRAINTS ON THE EVOLUTION OF ANGRITES

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**Introduction:** The highly-siderophile-elements (HSE: including Os, Ir, Ru, Pt, Pd, Re) can be used to place important constraints on planetary differentiation processes including metal-silicate equilibration during core formation, and post-core formation late-accretion (e.g., [1-4]). We report new HSE abundance and Re-Os isotope data for texturally diverse angrites [5], and use this information to explore differentiation processes acting on the parent body to angrite meteorites (hereafter referred to as APB).

Angrites are among the oldest differentiated achondrites and are pivotal reference points for Solar System chronology [6-9]. Oxygen isotope compositions [10] and trace element data [e.g., 5] for these meteorites are consistent with derivation from a parent body that experienced wide-spread melting associated with the formation of a magma-ocean. Hafnium-W isotope data and magnetic studies of angrites suggest that the APB formed a metallic core within ~2 Myr of CAI formation [11-13]. In detail, angrites define two texturally distinct groups that may be chronologically linked [6-9,11,14-16]; 1) quenched-angrites represent the oldest group with Pb-Pb ages of  $4564.18 \pm 0.14$  Ma to  $4563.8 \pm 0.4$  Ma; and 2) slowly-cooled angrites that may be younger with Pb-Pb ages of  $4558.86 \pm 0.30$  Ma to  $4557.65 \pm 0.13$  Ma. Further, the angrite NWA 4931 is texturally anomalous and has been paired with NWA 2999 ( $4561.79 \pm 0.42$  Ma; [15]), and may contain impact derived metals [17]. In addition, Angra dos Reis (AdoR;  $4557.65 \pm 0.13$  Ma; [15]) differs in texture when compared to other angrites, and is dominated by coarse-grained and equilibrated fassaitic pyroxene [5].

**Whole-rock HSE abundances & Re-Os isotope systematics:** Abundances of the HSE and  $^{187}\text{Os}/^{188}\text{Os}$  values were measured in powder aliquots of 6 angrites using methods outlined in [3]. Like diogenites [18], angrites cover approximately five orders of magnitude variation in CI-normalized HSE abundances (Fig. 1). Comparison of multiple aliquots for individual samples shows that slowly-cooled angrites have relatively uniform within sample abundances of HSE ( $\text{HSE}_{\text{total}} = 17.1$  to  $22.0$  and  $39.0$  to  $72.0$  ng/g for NWA 4590 and NWA 4801, respectively) that are commonly in excess of those observed in quenched-angrites ( $\text{HSE}_{\text{total}} = 1.18$  to  $24.5$  ng/g) and AdoR ( $\text{HSE}_{\text{total}} = 0.24$  to  $1.01$  ng/g). Rhenium-Os systematics of angrites delineate three sample types; 1) several powder aliquots of slowly-cooled angrites and NWA 4931 have  $^{187}\text{Os}/^{188}\text{Os}$  and

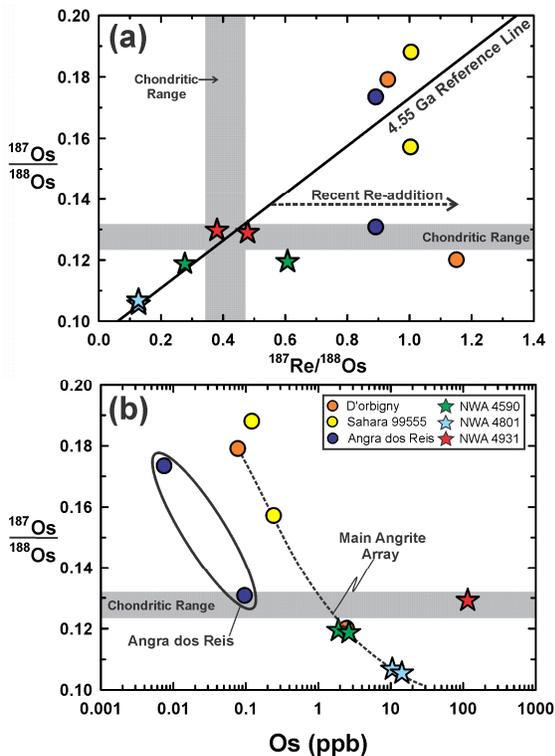


**Figure 1:** Highly-siderophile element abundances of bulk-rock angrites. Measured values are plotted in order of increasing elemental volatility from left to right, and are normalized to the composition of the CI-chondrite Orgueil [30].

$^{187}\text{Re}/^{188}\text{Os}$  compositions that are within uncertainties of the 4.55 Ga reference line (Fig. 2a); 2) some powder fractions of D'Orbigny, AdoR, and NWA 4590 have chondritic to sub-chondritic  $^{187}\text{Os}/^{188}\text{Os}$  compositions but supra-chondritic  $^{187}\text{Re}/^{188}\text{Os}$  values that plot to the right of the 4.55 Ga reference line; and 3) aliquots of D'Orbigny, Sahara 99555, and AdoR with relatively low Os abundances (Fig. 2b) have supra-chondritic  $^{187}\text{Os}/^{188}\text{Os}$  and  $^{187}\text{Re}/^{188}\text{Os}$  compositions. The Os-isotope compositions of each of these groups likely reflects ancient fractionation processes, whereas the  $^{187}\text{Re}/^{188}\text{Os}$  compositions of groups 2 and 3 have experienced recent Re addition/loss during alteration in a desert environment (*c.f.*, [19]). In detail, intra-sample Os-isotope heterogeneity observed for D'Orbigny, Sahara 99555, and AdoR, corresponds to variations in HSE-abundances (Figs. 1 and 2) thought to be related to the 'nugget effect'. Thus, heterogeneously distributed HSE-carrier phases within these samples may have distinct Os-isotope compositions.

**Discussion:** In contrast to terrestrial magmas and martian samples, angrites contain a wide-range of HSE concentrations that reach Os-abundances in excess of those observed for peridotites of Earth [20]. Further, angrites generally lack pronounced inter-element fractionation between Ir-group (IPGE; Ir, Os, Ru), Pt-group (PPGE; Pt and Pd) elements and Re, and require relatively unusual magmatic processing to limit inter-element fractionation over a range of HSE contents.

The nearly chondritic Os-isotope compositions of NWA 4590 and a portion of D'Orbigny testify to ancient processes that little fractionated Re/Os. Further,



**Figure 2:** Rhenium-Os isotope compositions (a) and osmium abundances (b) determined for two bulk-rock powder aliquots of each studied angrite. Internal precision ( $2\sigma$ ) is smaller than symbol size.  $^{187}\text{Re}/^{188}\text{Os}$  values were calculated from measured Re-Os concentrations assuming natural isotopic abundances. The 4.5 Ga reference line was calculated assuming chondritic Re/Os and a Solar System initial  $^{187}\text{Os}/^{188}\text{Os} = 0.0952 \pm 11$  (95% confidence interval [31]). The range of Re-Os isotope compositions observed in chondritic meteorites was taken from [30,32].

the Os-isotope composition of NWA 4801 ( $^{187}\text{Os}/^{188}\text{Os} = 0.10556 \pm 6$  to  $0.10686 \pm 6$ ) is among the lowest  $^{187}\text{Os}/^{188}\text{Os}$  values yet measured in meteorites and requires evolution with low Re-Os. Like eucrites and lunar basalts, the low Re/Os of NWA 4801 may suggest that Re behaved as a compatible trace-element during magmatic fractionation (e.g. [1,3,21]), and this contrasts to Re-behaviour observed in most terrestrial systems. In addition, the HSE-characteristics of NWA 4801 differ from most other planetary magma products studied to date as this sample is characterized by a sub-chondritic Pt/Os value (Pt/Os = 0.79 to 0.82 compared to  $\sim 2$  in chondrites).

The supra-chondritic  $^{187}\text{Os}/^{188}\text{Os}$  compositions of Sahara 99555, and portions of AdoR and D'Orbigny, may reflect evolution with high Re/Os. Experimental studies of HSE-partitioning (e.g., [22-23]) suggest that during magma generation under oxidizing conditions the  $\text{Re}^{6+}/\text{Re}^{4+}$  value may be high and that Re behaves

as an incompatible-element (e.g., [22-23]). Thus the high Re/Os values observed in quenched-angrite fractions and AdoR is consistent with experimental studies of silicate assemblages that suggest that many angrites were produced under relatively oxidizing conditions ( $\sim \text{IW} + 1$ ; [24-25]).

In detail, AdoR, with low HSE contents and chondritic to supra-chondritic  $^{187}\text{Os}/^{188}\text{Os}$ , does not coincide with the main array of angrite HSE-data (Fig. 2b). On the basis of major- and trace-element characteristics [26-29] suggested that AdoR may be derived from a magma distinct from that which generated other angrites, and this interpretation may be supported by the HSE systematics of the studied angrites. However, the chondritic Os-isotope composition and high HSE abundances of one powder fraction of AdoR may be accounted for by the addition of impact material at the time this meteorite was separated from its parent body.

The HSE characteristics of NWA 4931 are consistent with the suggestion given by [17] that, like its pair NWA 2999, NWA 4931 contains relatively high proportions of metals ( $\geq 6$  vol. %) with chondritic HSE characteristics that may have been imparted during impact processing.

The range of HSE abundances and Re-Os isotope compositions determined for angrites provides important evidence indicating that quenched- and slowly-cooled angrites represent distinct magmas, and suggests that these temporally resolved groups may have been produced under different oxidation conditions.

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