ANALYSIS OF MODERATELY SIDEROPHILE ELEMENTS IN ANGRITES: IMPLICATIONS FOR
CORE FORMATION OF THE ANGRITE PARENT BODY. N. Shirai1, M. Humayun1, K. Righter2 and A. J.
Irving1 1National High Magnetic Field Laboratory and Department of Geological Sciences, Florida State University,
1800 E. Paul Dirac Drive, Tallahassee, FL, 32310, USA (shirai@magnet.fsu.edu, humayun@magnet.fsu.edu),
2Astromaterials Research and Exploration Science, NASA Johnson Space Center, 2101 NASA Parkway, Houston,
TX 77058, USA (kevin.righter-1@nasa.gov), 3Department of Earth & Space Sciences, University of Washington,
Seattle, WA 98195, USA (irving@ess.washington.edu).

Introduction: Angrites are an enigmatic group of achondrites, that constitute the largest group of basalts
not affiliated with the Moon, Mars or Vesta (HEDs). Chemically, angrites are exceptionally refractory ele-
ment-enriched (e.g., Al, Ca) and volatile element-depleted (e.g., Na and K) achondrites [1]. Highly volatile
 siderophile and chalcophile elements (Zn, Ge and Se) may be less depleted than alkalis and Ga taken to
 imply a fractionation of plagiophile elements [1]. Core formation on the angrite parent body (APB) is not
well understood due to the dearth of moderately siderophile element (Ga, Ge, Mo, Sb, W) data for angrites, with
the exception of Ni and Co [2]. In particular, there are no data for Mo abundances of angrites, while Sb and
W abundances are reported for only 3 angrites, and have not always been determined on the same sample
[1, 3-7].

The recent increase in angrite numbers (13) has greatly increased our knowledge of the compositional
 diversity of the angrite parent body (APB). In this study, we report new Co, Ni, Ga, Mo, Sb and W abun-
dances for angrites by laser ablation ICP-MS in order to place constraints on core formation of the APB.

Analytical methods: Determination of elemental abundances for D’Orbigny [8], Angra dos Reis, NWA
4801, NWA 4590 and NWA 4590 (fusion crust) were performed on a New Wave UP213 laser ablation sys-
tem coupled to a Finnigan Element™ ICP-MS. A portion of the sample was rastered using a 100 µm beam
spot, at 10µm/s, 20 Hz, 1.6 mJ laser energy on the UP
213. The peaks 27Na, 25Mg, 27Al, 29Si, 44Ca, 45Sc, 47Ti,
51V, 52Cr, 55Mn, 56Fe, 59Co, 60Ni, 69Ga, 73Ge, 74Ge, 95Mo,
97Mo, 121Sb, 123Sb, 139La, 144Nd, 182W and 193Ir were
monitored in medium resolution mode (R = 4300). A
detailed analytical procedure for fusion crust of NWA
4590 is reported separately [9]. Individual rasters on
NWA 4801 and NWA 4590 exhibited a rather large
degree of scatter, relative to data obtained from
D’Orbigny, Angra dos Reis, and NWA 4590 fusion
crust, so that not all ratios determined were used in the
final averages reported here.

Results and Discussions: Co and Ni. Cobalt and
Ni data are reported more often than other MSEs in the
literature. Iron and Co abundances for angrites are
shown in Fig. 1. There can be seen a positive correla-
tion between Fe and Co abundances among angrites.
However, a systematic deviation for Angra dos Reis to
higher values of Co at a given value of Fe should be
noted (indicated by open circles in Fig. 1). Based on
spot analysis of pyroxene in Angra dos Reis, we found
that Fe, Co and Ni abundances positively correlated
with that of S, indicating that Fe, Co and Ni are affect-
ed by sulfide contribution. From these correlations, Fe,
Co and Ni abundances for the silicate portion of Angra
dos Reis were obtained. The elemental abundances for
the parent magma of Angra dos Reis were calculated
by using partition coefficients from [10]. The estima-
ed Co/Fe and Ni/Mg ratios for parent magma of Angra
dos Reis are then consistent with those for other an-
grites. As shown in Fig. 1, deviations of literature val-
ues from regression line is due to heterogeneous dis-
tribution of sulfide. CI-normalized Co/Fe and Ni/Mg ratios for APB are then obtained as 0.067± 20% and
0.0096± 55%, respectively.

Ga. Angrites have good correlations between Ga
and Al abundances. The (Ga/Al)CI ratio obtained for
the APB is 0.0055± 26%.

Mo. It is known that Mo and Nd have similar de-
grees of incompatibility during terrestrial igneous
processes [11]. Our data for Mo/Nd ratios of angrites
have a range of 0.015-0.043. The (Mo/Nd)CI ratios
obtained in this study is 0.014 ± 48%.
Sb. Jochum and Hofmann [12] found that Sb/Pr ratios for MORB and OIB were constant, indicating that Sb behaves like the incompatible element Pr during terrestrial igneous processes. Neodymium abundances for angrites are plotted against their Sb abundances in Fig. 2, where literature values are also shown for comparison. For Angra dos Reis, our Sb values are in good agreement with literature values obtained by RNAA [1]. Angra dos Reis exhibits a Sb/Nd ratio identical to that of other angrites (Fig. 2), implying that incompatibility of Sb is similar to that of Nd during igneous processes in APB, as found for terrestrial rocks [12]. The (Sb/Nd)$_{CI}$ ratio obtained for APB is 0.017 ± 14%.

W. There is a considerable spread in W/La ratios among angrites due to variation of W abundances. This variation of W/La ratios for angrites is higher than that of previous studies [2]. D’Orbigny and NWA 4590 have similar W/La ratios of 0.064 and 0.060, respectively, three times higher that of our Angra dos Reis value (0.023). As Angra dos Reis is a pyroxene-cumulate rock, its W/La ratio requires a correction for selective partitioning by pyroxene, for which suitable experimental data is not currently available.

Conditions of Metal-Silicate Equilibrium in the APB. MSE abundances of the APB mantle were calculated from the observed correlations with refractory lithophile elements, using estimates of the LREE content of the APB mantle. Our new data for Mo imply that the angrite parent body mantle contained ~ 40 ppb Mo. When this result is combined with new and existing data for Ni, Co, and W [2], depletions for all four elements can be estimated. Using these new estimates of APB mantle concentrations, the metal/silicate partition coefficient expressions of [13], and assuming a CV chondrite bulk composition of the APB [14], we can test whether the new Mo data is consistent with the presence of a small core in the APB, as suggested by [2]. Figure 3 compares the observed depletions with calculated depletions of MSE. Consideration of a simple model shows that if the core size is fixed at 8 mass%, the Ni, Co, Mo and W abundances can be explained by metal-silicate equilibrium between peridotite mantle and a FeNi metallic liquid core at 2073 K, 1 kb, and IW-1 (Fig. 3). This pressure is consistent with a core near the center of a body a few hundred km in radius. Since angrites record oxygen fugacity near IW+1 [10], angrite basalts would have to be oxidized upon degassing and eruption. This is consistent with the presence of vesicles in several angrites [15] possibly indicating the presence of a C-bearing gas derived from carbon (graphite) in the APB mantle source that underwent oxidation during melting.