THE ANGRITE PARENT BODY AS THE ARCHETYPAL FIRST-GENERATION PLANETESIMAL: LARGE, REDUCED AND MG-ENRICHED.

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Introduction: Angrites are silica-undersaturated achondrites formed very early in the history of the Solar System, and the most volatile-depleted known meteorites [1]. As such, their study can provide critical insights into the early stages of planetary formation, melting and differentiation. Yet, understanding the origins of angrites and the nature of their parent body has long been hindered by the initially small number of specimens available. Here [2], we leverage (i) the rapidly growing number of known angrites, and (ii) equilibrium crystallization experiments at various pressure, temperature and oxygen fugacity conditions (P-T-fO_2), to revisit the petrogenesis of angrites and constrain key features of the angrite parent body (APB), such as its size and composition.

Composition of Angrites: Since 2001, the number of known angrites has more than quintupled. The collection now counts 37 specimens from 24 different angrites including plutonic (n=7), volcanic/ quenched (n=10), diabasic (n=5), dunitic (n=1) and intermediate (n=1) angrites. When their compositions are projected in pseudoquaternary Ol-Cpx-Plag-Qtz diagrams, two groups appear amongst quenched angrites. Group 1 contains Asuka 881371, Lewis Cliff 87051, Northwest Africa 1670, Northwest Africa 7812 and Northwest Africa 12774. It is somewhat diffuse, with ~10–15 % compositional variability in any given mineral component between specimens. In contrast, Group 2 is a tightly clustered set of three angrites (D'Orbigny, Sahara 99555 and Northwest Africa 1296) with nearly identical compositions.

The tight clustering of quenched Group 2 angrites suggest (i) that they sit on an Ol + Cpx + Sp (±Plag at low pressure) multiple saturation boundary, and (ii) that quenched Group 1 angrites might represent the primitive melts from which Group 2 specimens formed. Equilibrium fractional crystallization calculations performed to test these hypotheses (Fig. 1) confirm that the two group of quenched angrites can readily be related through fractional crystallization.

Materials and Methods: To establish the liquid phase equilibria of angrites and determine the P-T-fO_2 conditions relevant to formation of quenched Group 2 angrites, a series of 1 atm and high-pressure (up to 13 kbar) crystallization experiments were performed on a synthetic powder of D'Orbigny composition (see [2]).

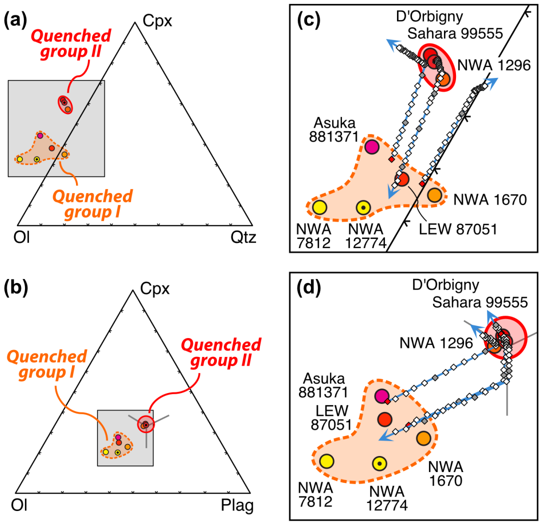

Fig. 1: *Ol-Cpx-Qtz/Plag pseudoternary projections (a,b) and close up views (c, d) showing that quenched Group 1 & 2 angrites can be related by fractional crystallization.*

Results: Near the liquidus, the 1 atm experimental charges all present olivine (Fo 36.9–46.6) and anorthite (An 98.9–100). Regardless of the fO_2 conditions, however, a fassaitic pyroxene only appears far from the liquidus, after ~40–50 % of crystallization, and the Ol + Cpx + Plag assemblage observed in the natural D'Orbigny sample is not observed near the liquidus. As pressure increases (Fig. 2), Ol + Cpx + Plag saturation occurs increasingly closer to the liquidus. In the 7 and 8 kbar experiments, Ol + Cpx + Sp (±Plag) saturation at the liquidus seems to have been achieved, and the mineral compositions match those observed in the natural D'Orbigny sample. At higher pressures (10–13 kbar), experimental runs are no longer multiply saturated in Ol + Cpx + Sp near the liquidus, indicating that a pressure of ~6–9 kbar is needed for Ol + Cpx + Sp (±Plag) saturation of a melt of D'Orbigny composition crystallizing under the mildly reducing conditions (~IW) relevant to the APB (review in [2]).

Size of the APB: A 6-9 kbar pressure in the source region of quenched Group 2 angrites places a stringent lower limit on the size of the APB, whose radius must therefore have been >~ 600–770 km. The presence, size and compositions of the APB core have little influence on these values [2]. Our results are fully compatible with previous minimum radius estimates of

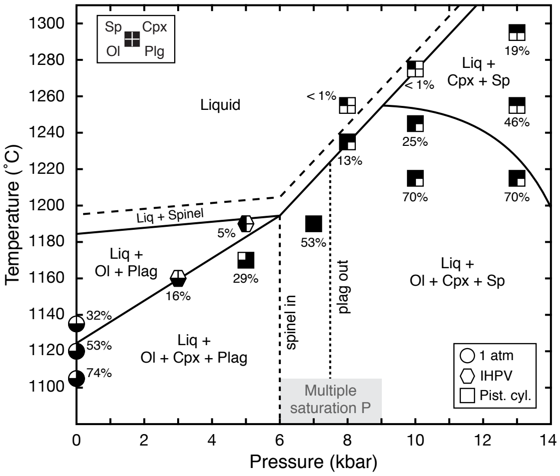

Fig. 2: *D'Orbigny phase equilibria. Filled (open) quadrant denotes a phase's presence (absence).*

270 km [3] and 420 km [4] based on volatile content and paleomagnetic field intensities of angrites and their melt inclusions but imply a significantly larger APB than previously thought. The above estimates are very conservative lower limits as they assume that the parental magma of quenched Group 2 angrites formed in the deepest silicate portion of the APB. If Group 2 angrites are indeed evolved lavas derived from a parental magma with quenched Group 1 composition, assuming multiple phase saturation on the liquidus (see modeling details in [2]) suggests that the APB must have been large enough for pressures of ~20–30 kbar to exist in the source region of quenched angrites. This translates to an APB radius > 1085–1405 km, raising the possibility of a Moon-sized APB.

Composition of the APB: Angrites are the most volatile-depleted meteorites known to date [5-6], but whether this depletion is a primitive feature (*i.e.*, nebular origin) or the result of processing of the APB remains highly debated. Using the fact that (i) the ratios of major (refractory, non-siderophile) elements in chondrites define a nebular trend (Fig. 3), and (ii) quenched Group 1 specimens represent primitive angritic melts, we test the self-consistency of the nebular origin of the APB. Assuming the source of Group 1 angrites melted to a large extent, the parental melt of these angrites would leave behind a residual mantle mainly made of olivine. As such, in major element ratio spaces, the composition of the APB will lie at the intersection of the nebular trend defined by chondrites and the tie-lines between angritic primitive melts and their equilibrium olivine (Fig. 3).

We find that the intercepts of the nebular trend and the primitive angrite Ol-melt tie-lines define tight domains in Mg/Si vs Al/Si, Ca/Si and Ti/Si spaces. In all three spaces, a unique Mg/Si (atomic) ratio of ~ 1.3 is retrieved (*i.e.*, this result is self-consistent), which is identical to the value derived from the angrite δ^{30}Si values [7]. Our results thus suggests that the refractory-enriched (and volatile-depleted) nature of the APB is a primitive feature resulting from nebular fractionation at high-T (~1300–1400 K), rather than the result of parent body processing. Our results also place a constraint on the APB's core size, yielding a value of 18 ± 6 wt%, in agreement with the siderophile elements depletion in the APB mantle [8].

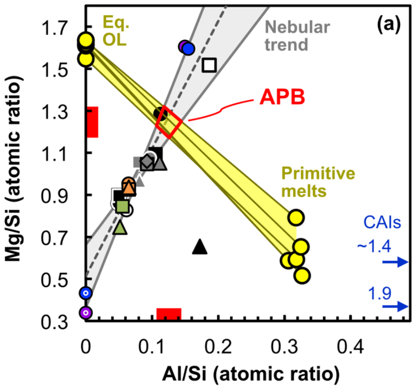

Fig. 3: *Mg/Si vs Al/Si ratio of angritic primitive melt and their equilibrium olivine (yellow), theoretical high-T condensates and residues (purple/blue symbols, from [11]), chondrites and chondritic components (black: chondrules; white: AOAs). Nebular trend (grey dashed lines & 95CI envelop) defined using ordinary (orange), enstatite (green), and most carbonaceous (grey) chondrites.*

The Archetypal First-Generation Planetesimal: Combined with its early accretion (~0.5–1 Myr after CAIs) and differentiation (< 2 Myr after CAIs) [9-10], the large size and refractory-enriched nature of the APB suggests that it was an important body in the inner Early Solar System. We propose that the APB is archetypal of the first-generation of refractory-enriched planetesimals and embryos formed in the *innermost* part of the inner Solar System (<1 AU), and which accreted in the telluric planets. In this framework, the terrestrial planets would grow dry, at least during the early stages of their accretion, and their volatile inventory would be delivered later in their history, through accretion of more volatile rich materials, such as chondrites and/or comets.

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