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1	The case for the angrite parent body as the archetypal first-generation planetesimal:
2	Large, reduced and Mg-enriched.
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4	François L.H. Tissot ^{1,2} , Max Collinet ^{1,3} , Olivier Namur ^{4,5} , Timothy L. Grove ¹
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7	¹ Department of the Earth, Atmospheric and Planetary Sciences, Massachusetts
8	Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, 02139, USA.
9	² The Isotoparium, Division of Geological and Planetary Sciences, California
10	Institute of Technology, Pasadena, CA 91125, USA.
11	³ Institute of planetary research, German Aerospace Center (DLR),
12	Rutherfordstaße 2, 12489 Berlin, Germany.
13	⁴ Institute of Mineralogy, Leibniz University Hannover, Callinstrasse 3, 30167
14	Hannover, Germany
15	⁵ Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan
16	200e, 3001 Heverlee, Belgium
17	
18	
19	
20	
21	
22	*Corresponding author. E-mail: tissot@caltech.edu
23	
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32 Abstract (363 words)

33 Angrites are silica-undersaturated achondrites formed very early in the history of 34 the Solar System, and the most volatile-depleted known meteorites. As such, the study of 35 angrites can provide critical insights into the early stages of planetary formation, melting 36 and differentiation. Yet, understanding the origins of angrites and the nature of their 37 parent body has long been hindered by the initially small number of specimens available. 38 Here, we leverage (i) the rapidly growing number of known angrites, and (ii) equilibrium 39 crystallization experiments at various pressure, temperature and oxygen fugacity 40 conditions (P-T- fO_2), to revisit the petrogenesis of angrites and constrain key features of 41 the angrite parent body (APB), such as its composition and size.

42 We observe that quenched (*i.e.*, volcanic) angrites define two compositional 43 groups, which we show are readily related by fractional crystallization. This 44 crystallization trend converges on an olivine-clinopyroxene-plagioclase (Ol + Cpx + 45 Plag) multiple saturation boundary, whose composition is sampled by D'Orbigny, Sahara 46 99555 and NWA 1296. Using the observation that some quenched specimens represent 47 primitive angritic melts, we derive a self-consistent bulk composition for the APB. We 48 find that this composition matches the proposed Mg/Si ratio of 1.3 derived from the 49 angrite δ^{30} Si values, and yields a core size (18 ± 6 wt%) in agreement with the 50 siderophile elements depletion in the APB mantle. Our results support a primary control 51 of nebular fractionation (*i.e.*, partial condensation) on the composition of the APB. To 52 establish the liquid phase equilibria of angrites, a series of 1 atmosphere and high-53 pressure crystallization experiments (piston cylinder and internally heated pressure 54 vessel) was performed on a synthetic powder of D'Orbigny. The results suggest that the 55 APB was a large (possibly Moon-sized) body, formed from materials condensed at 56 relatively high-temperature (~1300-1400 K), and whose fO_2 changed from mildly 57 reducing (\sim IW-1.5) to relatively oxidizing (\sim IW+1±1) in the \sim 3 Myr between its core 58 formation and the crystallization of D'Orbigny-like (Group 2) angrites. Based on its 59 timing of accretion and differentiation, its composition, redox, and size, we argue that the 60 APB represents the archetype of the first-generation of refractory-enriched planetesimals 61 and embryos formed in the *innermost* part of the inner Solar System (<1 AU), and which 62 accreted in the telluric planets.

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1. Introduction

64 Named after the type specimen that fell in 1869 in the bay of Angra dos Reis (Brazil), angrites are a series of differentiated meteorites (achondrites) of basaltic 65 66 composition, which owing to their ancient and pristine nature, have become key samples 67 in the study of the Early Solar System. Indeed, angrites display minimal post-68 crystallization alteration, metamorphism, shock or impact brecciation (e.g., Keil, 2012 69 and references therein), and the quenched specimens are some of the earliest known 70 volcanic rocks, with crystallization ages only ~4 Myr after the formation of Calcium, 71 Aluminum-rich inclusions (CAIs, the oldest known solids in the Solar System) (e.g., 72 Tissot et al., 2017 and references therein). Furthermore, the angrite parent body (APB) 73 itself is thought to have accreted within the first ~0.5-1 Myr of the Solar System (e.g., 74 Kleine et al., 2012). As such, angrites both act as key anchors for Early Solar System 75 chronology and provide critical insights into the early stages of planetary formation, 76 melting, and differentiation.

77 For a long time, the limited number of angrite specimens hindered our ability to 78 understand the details of their petrogenesis and the characteristics of the APB. For 79 instance, the seminal work of Longhi (1999) used all of the 4 specimens then available, 80 which included two very similar fine-grained, rapidly-cooled volcanic (*i.e.*, quenched) 81 angrites (Asuka 881371, LEW 87051), one plutonic angrite (LEW 86010) and the very 82 atypical plutonic angrite Angra dos Reis (hereafter, AdoR), a 98% pyroxene cumulate. 83 Although D'Orbigny had been discovered in 1979, it was not recognized as a meteorite 84 until 1999 (see Keil, 2012), the same year that Sahara 99555 was discovered. These two 85 new meteorites, both quenched in texture, formed the first set of compositionally 86 identical angrites, and seemed to have crystallized from a parental magma similar to that 87 of the previously known two quenched angrites. Yet no simple petrogenetic sequence 88 seemed to be able to explain the entire angrite suite, and multiple source magmas were 89 posited to explain the plutonic LEW 86010 and AdoR (Mittlefehldt et al., 2002; Floss et 90 al., 2003).

Over the last two decades, new meteorite finds, predominantly in the hot deserts
of Northern Africa, have steadily increased the size of the angrite suite. Today, this
collection counts 37 angrite specimens representing 24 different angrites (Table 1) and

94 including 7 plutonic angrites (AdoR, LEW 86010, NWA 2999, NWA 4590, NWA 4801, 95 NWA 5379, NWA 14758 and their paired specimens), 10 volcanic/quenched angrites (Asuka 881371, Asuka 12209, D'Orbigny, LEW 87051, NWA 1296, NWA 1670, NWA 96 97 7203, NWA 7812, NWA 12774 and Sahara 99555), 5 diabasic angrites (NWA 12004, 98 NWA 12320, NWA 12879, NWA 12934 and NWA 13363), 1 dunitic angrite (NWA 99 8535) and 1 angrite that might represent an intermediate stage between volcanic and 100 plutonic angrites (NWA 10463 and paired specimens, Santos et al., 2016). While 101 numerous studies (mainly conference abstracts) have reported detailed mineralogical, 102 petrological and geochemical characterization for each of these new specimens (e.g., Jambon et al., 2005, 2008; Gellissen et al., 2007; Shirai et al., 2009a; Baghdadi et al., 103 104 2013, 2015; Irving et al., 2013, 2019, 2020; Santos et al., 2016; Shearer et al., 2016), 105 comparatively little effort has been dedicated to understanding the angrite suite as a 106 whole, and the constraints this augmented family of meteorite places on the nature of the 107 APB (Mikouchi et al., 2004; Riches et al., 2012; McKibbin and O'Neill, 2018; Sanborn 108 and Wadhwa, 2021).

109 In this paper, we first examine the relationships between angrites, which reveals 110 the existence of two groups of quenched angrites. We show that these two groups are 111 readily related by a fractional crystallization trend, which converges on an olivine-112 clinopyroxene-plagioclase (Ol + Cpx + Plag) multiple saturation boundary whose 113 composition is sampled by D'Orbigny, Sahara 99555 and NWA 1296. Leveraging the 114 recognition that the least differentiated quenched angrites represent primitive angritic 115 melts, we place novel constraints on the APB's bulk composition, and show that it is 116 primarily controlled by nebular fractionation processes (*i.e.*, partial condensation) rather 117 parent body processing. Through a series of equilibrium crystallization experiments of a 118 synthetic D'Orbigny composition at various pressure, temperature and oxygen fugacity 119 conditions $(P-T-fO_2)$, we then establish the liquid phase equilibria of angrites. These 120 results provide novel constraints on the size and fO_2 of the APB, confirming its reduced 121 nature, while also indicating that the size of the APB has historically been significantly 122 underestimated. Based on these results, we argue that the APB represents the archetype 123 of an important group of early formed, refractory-enriched, planetesimals from which the 124 terrestrial planets accreted.

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2. The composition of angrites and previous experimental works

129 When the compositions (Table 2) of the full suite of known angrites are projected 130 in pseudoquaternary Ol-Cpx-Plag-Qtz diagrams, two groups appear amongst quenched 131 angrites (Fig. 1). Group 1 contains angrites Asuka 881371, LEW 87051, NWA 1670, 132 NWA 5167, NWA 7812 and NWA 12774. It is somewhat diffuse, with ~ 10-15 % 133 compositional variability in any given mineral component between specimens. In 134 contrast, Group 2 is a tightly clustered set of three angrites – D'Orbigny, Sahara 99555 135 and NWA 1296 – whose compositions are nearly identical. Ouenched angrite NWA 7203 136 plots close to the Group 2 specimens in the Ol-Cpx-Plag projection but not in the Ol-137 Cpx-Qtz projection, due to its more silica-undersaturated nature. The two diabasic 138 specimens for which bulk compositions have been reported (NWA 12004 and NWA 139 12320) plot tightly with the Group 2 angrites suggesting they formed by the same 140 process.

141 The invariant position of the Group 2 specimen compositions in the Ol-Cpx-Plag 142 diagram, and their small spread in the Ol-Cpx-Qtz diagram is similar to the systematic 143 observed during fractional crystallization of mid-ocean ridge basalts (MORBs) (Grove et al., 1992). In fact, the quenched Group 2 specimens plot near the Ol-Cpx-Plag-melt 144 145 saturation boundary calculated at 1 atm for a D'Orbigny-like melt (Mg # 0.32, NaK # = 146 0, and TiO₂ = 0.9 wt %) (Fig. 1). These observations, along with the presence and 147 textural relationships of Ol, Cpx and Plag in quenched Group 2 angrites (e.g., Floss et al., 148 2003), suggest that these specimens might have crystallized in shallow magma 149 chamber(s) in equilibrium with Ol-Cpx-Plag, before being erupted and cooled in 150 subsurface conditions. Group 1 angrites, on the other hand, plot in the olivine primary 151 phase space, and could therefore represent samples of a more primitive magma from 152 which the Group 2 specimens were later derived. While too few angrites were available 153 at the time to reveal such a clear systematic between Group 1 and Group 2 quenched 154 angrites, previous work, using major and minor element abundance trends in Ol, Cpx and 155 Plag minerals and cooling rates experiments (Mikouchi et al., 2000, 2004; Floss et al.,

2003; Sanborn and Wadhwa, 2010) have proposed an evolutionary relationship between
some Group 1 (Asuka 881371, LEW 87051 and/or NWA 1670) and Group 2 specimens
(Sahara 99555, D'Orbigny and/or NWA 1296). In Section 5.1, we will show that
fractional crystallization from Group 1 liquids converges on the composition of the
quenched Group 2 specimens, at the expected Ol-Cpx-Plag saturation boundary.

161 Equilibration of a given liquid composition with multiple phases only occurs at 162 restricted fO₂-P-T conditions, often indicative of the melting conditions of a particular 163 mineral assemblage (*i.e.*, mantle source) or the conditions at which a liquid stalled in a 164 magma chamber or multi-phase crystal mush (Wyllie et al., 1981). The primary goal of 165 this work is thus to investigate the phase equilibrium of a natural angrite from the 166 quenched Group 2 to place novel constraints on the P-T- fO_2 conditions relevant to the 167 APB early in its magmatic evolution. To date, most angrite experimental studies have 168 aimed to (i) produce angritic melt by partial melting of chondrites (e.g., Allende CV3, 169 Murchison CM2, St. Severin LL, Lost City H, Jurewicz et al., 1991, 1993, 1995, 2004), 170 (ii) determine the trace element equilibrium partition coefficients relevant to silicate 171 minerals in plutonic angrites (McKay et al., 1988a, 1994; Fittipaldo et al., 2005), or (iii) 172 constrain the cooling rates of the quenched angrites via crystallization experiments 173 (Mikouchi et al., 2000, 2001). An early attempt to constraint the phase equilibrium of 174 angrite using synthetic compositions of the plutonic LEW 86010 specimen was done by 175 McKay et al. (1988b), but the authors concluded that their experiments failed to achieve 176 complete equilibrium thus strongly limiting their usefulness. Using liquid boundaries and 177 solid solution parameterizations in the CMAS+Fe system (from Shi, 1992), Longhi 178 (1999) performed a theoretical investigation but was limited by the small number (four) 179 of specimens known then. More recently, McKibbin and O'Neill (2018) reported a series 180 of 1 atm reversal crystallization experiments using synthetic D'Orbigny and Sahara 181 99555 compositions under both reduced (1.2 log unit below the iron-wüstite buffer: IW-182 1.2) and oxidized conditions (IW+2.0), to investigate the role of spinel as a sink of Al in 183 the angrite source region and potential cause of the elevated Ca/Al ratios in angritic 184 melts.

Here, we will demonstrate that the more magnesian quenched angrites (Group 1),represent more primitive melts and that the quenched Group 2 angrites are more evolved

187 lavas (Section 5.1), whose invariant position in the pseudo-ternary Ol-Cpx-Plag diagram 188 is due to multiple saturation of their source magma. Because the position of the saturation boundary, as well as the nature of the saturating phases depend on the P-T-fO₂ conditions 189 190 (e.g., Ol + Cpx + Plag at 1 atm vs. Ol + Cpx + Sp above 5-6 kbar), we used equilibrium 191 crystallization experiments to determine the specific P-T-fO₂ relevant to formation of 192 quenched Group 2 angrites. We performed both 1 atm and high-pressure (up to 13 kbar) 193 experiments, under various temperature (from 1106 to 1295 °C) and oxygen fugacity 194 conditions (from the Iron-Quartz-Fayalite (IQF; ~IW-0.6) buffer to the Quartz-Fayalite-195 Magnetite (QFM; ~IW+3.6) buffer.

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3. Experimental methods

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3.1 Synthetic powder preparation

199 A synthetic powder of D'Orbigny composition (Table 3) was prepared from high-200 purity oxide powders (Specpure), following the methods of Grove and Bence (1977). To 201 avoid issues arising from hydration of some oxide powders (P2O5, CaO, Na2O, K2O, 202 FeO), phosphorus was added as Ca₅(PO₄)₃.F, calcium as CaSiO₃, nickel as NiO, and iron 203 as a mixture of Fe and Fe_2O_3 . Sodium and potassium were not added given their 204 extremely low abundance in quenched Group 2 angrites. All oxides except NiO and Fe 205 were initially mixed together in a clean agate mortar, covered with ethanol and ground in 206 an automatic grinder for 4 hr. Iron and nickel were then added to the oxide mix and 207 ground for another 40 min. The ethanol + oxide mixture was left to evaporate under a 208 gentle flow of compressed air until dried. The powder was then scraped from the surface 209 of the mortar using weighing paper, and further ground by hand in ethanol with an agate 210 pestle for another 30 min to ensure full homogenization, and dried again.

Using polyvinyl alcohol (Elvanol®), the dried powder was made into a cohesive paste, shaped into small pellets using a clean metal cylinder and rod, and dried under a heat lamp for 1 hr. Dried pellets were suspended using Pt wires in a 1 atm Deltech VT-31 gas mixing furnace, and conditioned for 3 days at 1050°C at the QFM buffer to react the oxides to more stable minerals. After conditioning, the pellets were finally ground in ethanol in a clean agate mortar and the powder was dried under a heat lamp.

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218 *3.2. One atmosphere experiments*

219 A first set of 11 experiments were conducted in the MIT experimental petrology laboratory using a 1 atm Deltech VT-31 vertical furnace to determine the stable mineral 220 221 assemblage at low-pressure at the liquidus (Table 4). As angrites are thought to have 222 formed under reducing conditions, around the IW buffer (Brett et al., 1977; Mckay et al., 223 1994; Shearer et al., 2016; Steenstra et al., 2017), five initial experiments were carried 224 out in iron capsules in evacuated silica tubes (Grove and Bence, 1977). Inside the vacuum 225 of the evacuated tube, the combination of Fe (from the capsule) and FeO+SiO₂ (from the 226 sample) maintains the fO_2 at the Iron-Quartz-Favalite buffer (IQF ~ IW-0.6). As the Ol-227 Cpx-Plag equilibrium assemblage present in D'Orbigny was not observed at the liquidus 228 under such reducing conditions, two series of runs were carried out at higher fO_2 : IW+0.5 229 and QFM. For these 6 additional experiments, the sample powder was loaded on Fe+Pt 230 loops using Elvanol and the fO_2 was fixed using a mixture of CO_2 and H_2 gases inside the 231 furnace. The Fe+Pt loops, used to avoid problem of Fe-loss, were pre-saturated in Fe 232 following Grove (1982). The samples were loaded in the furnace at $\sim 980^{\circ}$ C and the 233 temperature was increased to the run temperature over the next 60-90 min. The run 234 temperatures were measured using a calibrated thermocouple placed in close proximity to 235 the sample and are precise to within $\pm 1^{\circ}$ C. The oxygen fugacity was measured using an 236 electrolyte solid cell inside the gas mixing furnace. At the end of the run (after 3 to 6 237 days, depending on the run), the experimental charges were quenched by being dropped 238 in water. None of these 1 atm experiments yielded the Ol-Cpx-Plag equilibrium 239 assemblage present in D'Orbigny. Therefore, a series of high-pressure experiments were 240 undertaken to explore the effect of changing pressure on Ol-Cpx-Plag saturation.

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3.3. Piston-cylinder experiments: 5 to 13 kbar

Ten piston-cylinder experiments (Table 4) were conducted in the MIT experimental petrology laboratory using a 12.7 mm end-loaded, solid medium, pistoncylinder device (Boyd and England, 1960). Following Medard et al. (2008), ~ 10 mg of the sample powder was loaded in a graphite crucible, which imposes an upper limit on oxygen fugacity at the graphite-carbon dioxide (CCO) buffer, above which graphite is not stable. Calibration of the exact fO_2 during such experiments yielded a value of CCO-

 $0.8(\pm 0.3)$ (Medard et al., 2008), which translates here to fO_2 values between IW+1.13 and 249 250 IW+1.63 depending on the experimental P-T conditions (Table 4). The sample loaded 251 graphite crucible, closed with a graphite lid, was placed inside of a platinum (Pt) capsule, 252 and dried overnight at 300–330 °C in a pot furnace. The Pt capsule was then welded shut, 253 inserted in an alumina (Al₂O₃) sleeve, and positioned in the center of a straight-walled 254 graphite furnace using MgO spacers. The furnace itself was surrounded by a BaCO₃ 255 pressure medium, which has been found to require no friction correction through 256 calibration against the reaction Ca-Tschermak pyroxene = anorthite + gehlenite + 257 corundum (Hays, 1966). The assembly was placed inside the piston-cylinder device, on 258 top of a thin sealing graphite disk, and capped with a steel plug. A Tungsten-Rhenium 259 thermocouple was inserted in the hollow portion of the steel plug and MgO spacer, and 260 positioned on top of the graphite furnace to monitor the sample's temperature. 261 Experiments were first pressurized to 10 kbar (or to the desired pressure, for experiments 262 below 10 kbar) at room temperature, then heated to 865 °C at 100 °C/min, at which point 263 the T was held constant for 3–5 min while the pressure was increased to the experimental 264 pressure. The temperature was then increased to the experimental T at a rate of 50 265 °C/min. The samples were held at their final run conditions for 24–67 h, and the 266 experiments were terminated by turning off the heating components while maintaining 267 the cooling system on. In all runs, temperature readings remained stable within 1 °C. A 268 temperature correction of +20 °C is applied to account for the difference in temperature 269 between the hotspot and the thermocouple location. The temperature reproducibility 270 inside the capsule is estimated at $\pm 10^{\circ}$ C. The pressure is thought to be accurate to within 271 ± 0.5 kbar down to 8 kbar (Medard et al., 2008). The uncertainty on the pressure at 5 kbar 272 has not been previously investigated.

In these high-pressure experiments, spinel replaces plagioclase as the stable Alrich phase, and the 8 kbar experiments showed saturation in Ol + Cpx + Sp close to the liquidus. To complement the upper limit of 8–9 kbar thus obtained for the multiple saturation of a D'Orbigny-like melt, and to validate the results of the 5 kbar piston cylinder experiment, a series of experiments were also conducted using an IHPV (internally heated pressure vessels) setup, in which the pressure has been shown to be accurate to within \pm 0.01 kbar with no correction (Berndt et al., 2002). 280

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3.4. IHPV experiments: 3 to 5 kbar

282 Four IHPV experiments (Table 4) were conducted in large volume IHPV at the 283 Institute of Mineralogy of the Leibniz University Hannover (Germany), using argon as 284 the pressure medium. The ground starting material was packed into 3 mm inner diameter 285 graphite capsule with top lid, and dried for 24 hr at 120-150 °C. The graphite capsule 286 was placed into an outer 4 mm inner diameter Pt jacket welded shut with bottom and top 287 Pt lids, before being fixed to a Pt-wire in the hot spot of the double-wire element furnace. 288 Temperature was controlled using two S-type thermocouples while two additional S-type 289 thermocouples were used to monitor the sample temperature. Temperature gradient 290 across the sample is generally less than 5°C. The vessel was pressurized cold to $\sim 80\%$ of 291 final pressure and then heated to the final temperature while pressure was slowly 292 increased. Temperature was increased with a ramp of 0.8°C/s to a temperature 30°C 293 lower than the final temperature and then 0.3° C/s to the final temperature. Quenching 294 was performed by fusing the Pt-wire and dropping the capsules onto a cold (~ 25° C) 295 copper block. Quench rate was ~ 150° C/s.

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3.5. Electron Probe X-ray Microanalyzer (EMPA)

298 Silicate phases in the experimental charges were analyzed using the JEOL JXA-299 8200 electron microprobe at MIT, with a 10 nA beam current and a 15 kV accelerating 300 potential. Beam diameter was set to 1 µm for minerals and highly crystalline runs in 301 which only small pocket melts remained (e.g., Dorb-8, B1398, B1407), and 10 µm for 302 silicate glasses in low crystallinity runs. The CITZAF correction package of Armstrong 303 (1995) was used to reduce the data. The atomic number correction of Duncumb and 304 Reed, Heinrich's tabulation of absorption coefficients, and the fluorescence correction of 305 Reed were used to obtain a quantitative analysis as outlined in of Armstrong (1995). 306 Analytical precisions were estimated during each analytical session through replicate 307 analyses of well-characterized mineral standards, both synthetic (fayalite, forsterite, 308 anorthite) and natural (olivine, orthopyroxene, clinopyroxene, hematite and spinel), as 309 well as a basalt glass working standard (e.g., Grove et al., 1992; Médard and Grove, 310 2008).

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4. Results

For all experiments, a summary of the run conditions, duration, and the phase proportions is presented in Table 4. The target fO_2 values are calculated relative to the IW buffer using the parameterization of Huebner (1971), O'Neill (1987), O'Neill and Pownceby (1993), and Jakobsson and Oskarsson (1994). Electron microprobe analyses of the phases in each run are reported in Table 5.

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4.1. One atmosphere experiments

320 Representative backscattered electron (BSE) images of the 1 atm runs are shown 321 in Figure 2, while the temperature and phase assemblages are shown in Figure 3. 322 Regardless of fO_2 conditions, near the liquidus, the experimental charges all present 323 olivine (Fo 36.9–46.6) and anorthite (An 98.9–100), but no pyroxene is observed. In the 324 reducing (silica-evacuated glass) experiments (IOF buffer, *i.e.*, IW-0.6) a hercynite-spinel 325 (Fe# = 56) is present near the liquidus (1173 °C) but reacts away at lower T (below 326 ~1150 °C). In contrast, in the most oxidized experiments (QFM buffer, *i.e.*, IW+3.5), the 327 more hercynitic spinel (Fe# = 75) initially present near the liquidus (1163 $^{\circ}$ C) is replaced 328 by magnetite at lower T (below ~1150 °C). In all experiments, a fassaitic pyroxene only 329 appears far from the liquidus, after $\sim 40-50\%$ of crystallization. The Ol-melt equilibrium exchange coefficients between Fe and Mg, $K_{D_{OI-liq}^{Fe-Mg}}$, calculated from the composition of 330 331 equilibrium olivine cores and the glass, are 0.289-0.317, 0.336-0.368, and 0.313-0.328 332 respectively, for experiments performed under IQF, IW+0.5 and QFM fO2 conditions.

333 When the positions of the saturation boundaries observed in the 1 atm 334 experiments are plotted in the pseudoquaternary Ol-Cpx-Plag-Qtz diagrams, the 335 dependency on oxygen fugacity is clearly visible (Fig. 4a). As fO₂ increases, the 336 saturation boundary moves away from the Cpx corner and towards the quenched Group 2 337 cluster. Nevertheless, even under the most oxidizing conditions tested (QFM), none of 338 the 1 atm experiments fully reproduce the quenched Group 2 cluster position. Such 339 oxidizing conditions are unrealistic for the APB as magnetite would become a major 340 stable phase, similar in abundance to olivine (Table 4), a feature that is not observed in 341 quenched angrite specimens, indicating that more reducing conditions prevailed on the

APB, and as pointed out by previous work (e.g., Brett et al., 1977; Mckay et al., 1994;
Shearer et al., 2016; Steenstra et al., 2017).

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4.2. High-pressure experiments

346 Representative BSE images of the IHPV and piston-cylinder runs are shown in 347 Figure 5. The temperature, pressure and phase assemblages are summarized in the phase 348 diagram shown in Figure 6. In most experiments, FeO loss/gain is minimal (< 0.5%), 349 indicating that the charges behaved as closed systems. The three main exceptions are the 350 5 kbar IHPV experiments (IHPV-2, -3 and -4; Table 4) in which significant FeO loss is 351 observed (from 2.4 to 12.3 %), and pure FeO is visible in the charge (Fig. 5). We suspect 352 that for these experiments, the Pt capsules were not correctly sealed and/or opened during 353 the experiment, allowing the fO_2 to deviate from the ~IW+2 target and reach significantly 354 more reducing conditions at which Fe metal is stable.

355 As best seen in Figure 6, at low pressures (from 1 atm to 5 kbar) the Ol + Cpx + 356 Plag saturation occurs increasingly closer to the liquidus as pressure increases. At 5 kbar, 357 all three phases are present ~ $20-30^{\circ}$ C below the liquidus (~29 % crystallization). At this 358 same pressure, however, the Ol + Cpx + Plag saturation is still not yet achieved near the 359 liquidus, and only olivine (and trace amounts of spinel) is observed in the experimental 360 charge. While piston-cylinder experiments are rarely calibrated at such low pressures, 361 and therefore seldom used, we find that the IHPV and piston-cylinder experiments 362 performed under similar conditions (5 kbar, 1170 C, IW+~1.5) present similar textures, 363 and their mineral assemblages have virtually identical compositions (see experiments 364 IHPV-3, IHPV-4 and B1412; Table 5), indicating that the piston-cylinder experiments at 365 5 kbar are reliable and equivalent to the IHPV experiments. However, because 366 experiments IHPV-3 and -4 suffered large FeO losses (12.3 and 8.6 % respectively) 367 compared to piston-cylinder experiment B1412 (0.3 % loss), the latter will be favored in 368 the discussion.

As P increases above 5 kbar, the melts pass through a four-phase equilibrium saturation Ol + Cpx + Plag + Sp, starting at ~ 6 kbar with the appearance of spinel and ending at ~ 7.5 kbar with the disappearance of plagioclase. The experiment performed at 7 kbar showed saturation in Ol + Cpx + Plag + Sp and a high degree of crystallization 373 (53%) despite being only 20°C below the liquidus, which is consistent with multiple 374 saturation near the liquidus in those P-T conditions (*i.e.*, large amount of crystallization over a short temperature interval). Similarly, the experiment performed at 8 kbar and 375 376 within 10° C of the liquidus is highly crystallized (13 %) and multiply saturated in Ol + 377 Cpx + Sp (plagioclase is no longer stable in those conditions). In both cases, Ol + Cpx +378 Sp $(\pm$ Plag) saturation at the liquidus seems to have been achieved. At higher pressures 379 (10 and 13 kbar), experimental runs are no longer multiply saturated in Ol + Cpx + Sp380 near the liquidus, as the melt moves from the Liq + Ol + Cpx + Sp field to the Liq + Cpx381 + Sp field with increasing temperature.

382 When the composition of the glasses measured in these experiments are plotted in 383 the pseudoquaternary Ol-Cpx-Plag-Qtz diagrams, a match with the quenched Group 2 384 cluster (i.e., D'Orbigny-like composition) is only obtained for the 7-8 kbar runs (Fig. 4b). 385 Experiments at 5 kbar (and below) are offset towards the Cpx corner, while experiments 386 at 10 kbar and above are offset towards the Ol corner. Collectively, our experiments 387 indicate that a pressure of $\sim 6-9$ kbar is necessary for saturation in Ol + Cpx + Sp (\pm Plag) 388 for a melt of D'Orbigny composition crystallizing under redox conditions close to the IW buffer. 389

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5. Discussion

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5.1. Two related groups of quenched angrites

393 As discussed in Section 2, the growing number of angrite specimens reveals that 394 quenched angrites define two compositionally distinct groups (Fig. 1). Based on the tight 395 clustering of quenched Group 2 specimens in the pseudoquaternary Ol-Cpx-Plag-Qtz 396 diagrams, we initially hypothesized (i) that the quenched Group 2 angrites sit on an Ol + 397 $Cpx + Sp (\pm Plag at low pressure)$ multiple saturation boundary, and (ii) that quenched 398 Group 1 angrites might represent the primitive melts from which Group 2 specimens 399 formed, for instance, through fractional crystallization. Under these assumptions, the 400 sequence of crystallization going from the Group 1 to Group 2 angrites would be Ol, 401 followed by Ol + Plag, and finally, once the melts have reached the multiple saturation 402 boundary, Ol + Plag + Cpx.

403 To test this hypothesis, we performed forward and reverse equilibrium fractional 404 crystallization calculations, in 2 % liquid mass increment, and assuming no 405 reequilibration between the solid and melt. At each step, the composition of the 406 equilibrium solid phase(s) is calculated using the models of Grove et al. (1992), Yang et 407 al. (1996), and Till et al. (2012), and the results are shown graphically in Fig. 7 (see 408 Supplementary Table S1 for more details). Forward crystallization calculations, starting 409 from the average composition of LEW 87051 and NWA 1670, on the one hand, and 410 Asuka 881371 and LEW 87051 on the other hand, provide decent matches to the average 411 composition of quenched Group 2 specimens (Fig. 7a-b). The reverse fractional 412 crystallization calculation yields a composition nearly identical to that of angrite LEW 413 87051 and the average of guenched Group 1 angrites (Fig. 7c-d). These illustrative 414 calculations clearly demonstrate that the two groups of quenched angrites can be related 415 through fractional crystallization and originated from similar source magmas.

416 While the major element composition of quenched Group 1 and 2 angrites 417 indicate that they evolved from similar parental melts, trace elements abundances, in 418 particular REEs, allow us to rule out direct linkages between known specimens in the two 419 groups. That is, they did not evolve from the *exact same* magma. Indeed, using REE 420 mineral-melt equilibrium partition coefficients relevant to angrite for olivine, plagioclase 421 and clinopyroxene (see Supplementary Table S2), in combination with the degree of 422 fractional crystallization between quenched Group 1 and 2 angrites derived above (Table 423 S1), we can model the REE pattern and enrichment levels in guenched Group 2 angrites. 424 We find that, while the modeled REE patterns remain flat (*i.e.*, chondritic), the modeled 425 enrichment levels are about 30% higher than those in the natural samples ($\sim 20 \times CI$, 426 instead of $14 \times CI$ (Fig. 8a). This observation indicates that quenched Group 1 and 2 427 angrites originated from similar, yet distinct, reservoirs on the APB.

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5.2. Relationship between quenched and plutonic angrites

430 Despite their partial cumulate textures, some of the plutonic angrites have bulk
431 compositions relatively close to those of quenched angrites (Fig. 1). For instance,
432 LEW86010 and NWA 10463 could represent quenched Group 2 melts with excess Cpx
433 (±Plag). On the other hand, NWA 2999 and NWA 4931 could represent primitive

(quenched Group 1) compositions with excess olivine. Similarly, and after subtraction of
an exogenous metal component (Baghdadi et al., 2015), NWA 3164 and NWA 5167 have
bulk compositions within the field of primitive (quenched Group 1) angrites.

437 Here, we integrate petrological observations on plutonic angrites and the results of 438 our fractional crystallization modeling to test whether some of the plutonic angrites 439 originated from parental melts similar to those of quenched angrites. Specifically, we 440 consider angrites LEW 86010, NWA 4801 and NWA 4950, for which mineral modes 441 (Crozaz and McKay, 1990; Sanborn, 2012), as well as REE abundances in whole rock 442 (Table 6) and individual mineral phases (Crozaz and McKay, 1990; Sanborn and 443 Wadhwa, 2021) are available. We assume that the primitive melt from which these 444 samples evolved had an REE pattern and enrichment similar to quenched Group 1 445 angrites (we use Asuka 881371, for which the whole REE pattern is available). For each sample, we use the Mg# of the most magnesian cpx (~73.6 to 74.4) and a $K_{D_{cpx-liq}^{Fe-Mg}}$ of 446 447 0.24 to calculate the Mg# of the equilibrium melt from which the first Cpx in the rock 448 crystallized (~40.1 to 41.1). Varying the K_D value to cover the range observed in our high 449 pressure experiments (0.18-0.24), has only a small impact on the modeled pattern 450 enrichment level. Using the fractional crystallization models shown in Table S1, we find

451 the step along the crystallization path that matches the melt Mg# and, using the REE K_D 452 values in Table S2 and the REE content in Asuka 881371, we calculate the REE pattern 453 and enrichment of the residual melt. At this point, the patterns are chondritic, at $\sim 16 \times CI$, 454 and the residual melts are plotting on the multiple saturation boundary, where closed-455 system crystallization would yield Ol/Cpx/Plag modal abundances of ~30/38/32 %. We 456 then compare these values to the Ol-Cpx-Plag modal abundances of the three plutonic 457 angrites, and using the average REE abundances in the relevant mineral phases, attempt 458 to account for the cumulate nature of these rocks by simply adding the extra amount of 459 each mineral phase needed.

To first-order, LEW 86010 and NWA 4801 contain, respectively, ~25% and ~60% excess Cpx compared to the residual melt matching their magnesian Cpx Mg#, while NWA 4590 contains both 12% excess Ol and 9 % excess Cpx. Adding the corresponding REE content to the modeled residual melt yields the modeled REE patterns shown in Figure 8b-d. We find very good agreement between the measured and

465 modeled whole rock REE patterns, both in terms of pattern and enrichment level: within 466 10% for NWA 4801 and 30 % for LEW 86010. For the NWA 4590, the average enrichment is well matched, but a lower LREE abundance is not captured by our 467 468 modeling, suggesting a more complex cumulate evolution for this sample. Nevertheless, 469 this exercise indicates that to first-order, some plutonic angrites share the same general 470 magmatic evolution as quenched Group 2 angrites, and their compositional offset from 471 the multiple saturation boundary only reflects their slight cumulate nature. In this context, 472 the trend in Lu concentrations (used as a proxy for REE enrichments and by extension, 473 magmatic evolution) vs ages in plutonic angrites revealed by our compilation work (Fig. 474 9), could reflect a combination of crystallization of a main silicate reservoir on the APB 475 (*i.e.*, magma ocean crystallization), and accumulation of olivine (NWA 2999 and paired 476 specimen, such as NWA 6291) or clinopyroxene (± plag) (LEW 86010, NWA 4801, 477 NWA 4590, and AdoR), in agreement with the cumulate nature of these samples.

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5.3. The APB's bulk composition and core size

5.3.1. The nebular vs. parent body processing debate

481 We now consider the major outstanding question of the APB's bulk composition, 482 and by extension, the size of its core. Angrites are silica-undersaturated basalts and the 483 most volatile-depleted (and refractory-enriched) meteorites known to date, displaying 484 K/U and Rb/Sr ratios $100 \times$ lower than the Bulk Silicate Earth and $500 \times$ lower than CI 485 chondrites (Halliday and Porcelli, 2001; Dauphas et al., 2022). Whether this volatile 486 depletion is a primitive feature or the result of processing of the APB remains highly 487 debated. Initial studies proposed that the APB consisted in a mixture of components 488 observed in meteorites: CAI-type materials and Fe-bearing silicates (Delaney and Sutton, 489 1988) or opaque matrix from chondrites (Prinz et al., 1988). Similarly, Longhi (1999) 490 observed that the APB could have formed by incomplete mixing between an 491 (hypothetical) alkali-depleted primitive chondrite from which metal had been removed, 492 with a low-SiO₂ high-T condensate (e.g., CAI, amoeboid olivine aggregates: AOAs). A 493 nebular control was also invoked by Papike et al. (2017), who observed, based on Mn-Fe 494 trends in olivines, that the APB volatile depletion could reflect formation from partial 495 condensates from a hot vapor cloud.

496 Instead of such nebular origin, Crozaz and McKay (1990) argued that volatile 497 depletion associated with extensive igneous processing (e.g., parent-body formation, 498 magmatic activity) of a chondrite-like parent body (possibly enriched in refractory 499 elements), better explained the major features of angrites, including the presence of FeO 500 in plutonic angrites AdoR and LEW 86010. Similarly, Mittlefehldt and Lindstrom (1990) 501 proposed that the high FeO/MnO ratios of angrites and their low Na (volatile) content 502 reflected outgassing during differentiation of an APB of bulk composition akin to 503 carbonaceous chondrites (CI, CM, or CO). In this model, the superchondritic Ca/Al ratio 504 of angrites (*i.e.*, refractory enrichment) would simply reflect residual aluminous spinel in 505 the source regions of angrites (Mittlefehldt and Lindstrom, 1990; Mittlefehldt et al., 506 2002: McKibbin and O'Neill 2018). This hypothesis has been the subject of a series of 507 experiments aimed at producing angritic melt by partial melting of chondrites (e.g., 508 Jurewicz et al., 1991, 1993, 1995, 2004). These showed that partial melting of Allende 509 powder at 1200°C under oxidizing conditions (IW+2) can produce a melt with major 510 element composition closely matching that of quenched Group 2 angrites (D'Orbigny, 511 Sahara 99555). Significant differences remained in the minor element, in particular, a 512 higher Mn and lower Na content in D'Orbigny relative to the partial melts produced from 513 Allende, which the authors suggested reflect actual features of the APB (Jurewicz et al., 514 2004). More recently, McKibbin and O'Neill (2018) pointed out that the distinct isotopic 515 anomalies in the angrites and CV chondrites (e.g., Warren, 2011; Charlier et al., 2017; 516 Budde et al., 2019) precluded a direct genetic link between the two materials, and 517 proposed that the APB composition was made of CV-like materials (i.e., refractory 518 enriched) via processing in early high-T nebular, magma ocean, or impact environments. 519 By observing that the large majority of early formed meteorite parent bodies from the 520 "non-carbonaceous" group were alkali-rich, Collinet and Grove (2020) suggested that 521 angrites became alkali-depleted following igneous differentiation or impacts.

522 Two alternative, and more controversial, scenarios have also been proposed to 523 explain the unique compositional and textural features of angrites. The first model 524 proposes a non-magmatic origin whereby D'Orbigny, and other angrites, would have 525 formed by direct condensation from a vapor phase with solar composition. This would 526 explain the high Ca/Al ratio and low SiO₂ content of angrites, as well as the presence of vesicles, open druses and abundant glass in D'Orbigny, and proponents of this model argue that angrites "*can be seen as CAIs, which grew larger than the ones we know from carbonaceous chondrites*" (Kurat et al., 2004; Varela et al., 2003, 2005, 2017). The second model posits, based on the puzzling presence of magmatic carbonate in NWA 1296, that the elevated Ca/Al ratio in angrites is the results of melting in the presence of a carbonates (Jambon et al., 2005, 2008).

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5.3.2. Support for the nebular hypothesis

534 Here, we argue that two key observations provide strong support for a nebular 535 control on the bulk composition and volatile depletion of angrites, and in fact provide 536 novel constraints on the composition of the APB. First is the fact that the ratios of major 537 (refractory, non-siderophile) elements in chondrites define a nebular trend (see dashed 538 lines and grey envelops in Fig. 10a-c), whereby the enrichment in refractory elements 539 increases from enstatite to ordinary to carbonaceous chondrites (EC \leq OC \leq CC). 540 Importantly, while the fits and error envelops shown in Fig. 10 are defined using only the 541 chondrite data (see Supplementary Table S3), the high- and low-T components derived from equilibrium condensation calculations of a gas of solar composition at 10⁻³ bar 542 543 (Morbidelli et al., 2020) plot on this nebular trend in Mg/Si vs Al/Si, Ca/Si and Ti/Si 544 spaces, reinforcing the interpretation that this trend testifies to a first-order nebular 545 control on the composition of Solar System materials. In Fig. 10, both the 1400 K and 546 1280 K "first condensates" and corresponding "residual condensates" are shown. In each 547 case, the "first condensates" integrate the matter condensed all the way down to the 548 threshold T (1400 K or 1280 K), with the matter condensing below this threshold T and 549 down to 830 K forming the corresponding "residual condensate". For the refractory 550 elements shown in Fig. 10, both the 1400 K and 1280 K condensates and residues fall on 551 the nebular trend. The composition of AOAs - which are high-T condensates formed 552 early in the history of the Solar System (Ruzicka et al., 2012) – and most types of 553 chondrules also plot on (or close to) the nebular trend defined by chondrites, and further 554 support the idea that this trend captures a first-order control on the composition of Solar 555 System materials. As such, it is reasonable to assume that a nebular origin for the APB 556 would require the APB to plot on that same nebular trend.

557 Second is the fact that, while plutonic angrites tend to have cumulate textures and 558 will see their bulk composition controlled by the amount of cumulate phases they incorporated, quenched angrites with minimal xenocryts content will preserve the 559 560 composition of their parental melt. Specifically, we here leverage the recognition that 561 quenched Group 1 angrites represent such primitive angritic melts (Section 5.1). During 562 equilibrium melting, and assuming the source melted to a large extent, the parental melt 563 of these quenched Group 1 angrites would leave behind a residual mantle mainly made of 564 olivine, the composition of which can be calculated using well-documented equilibrium 565 partitioning coefficients (e.g., Toplis 2005, Spandler and O'Neill, 2010; Blundy et al., 566 2020). This implies that, to first-order, the ratios of major lithophile elements in the APB 567 corresponds to a mixture between those in a primitive melt of quenched Group 1 568 composition and its corresponding equilibrium olivine (yellow symbols in Fig. 10). 569 Combining these two observations implies that, under the assumption of a nebular origin, 570 the composition of the APB will lie at the intersection of the nebular trend defined by 571 chondrites and the tie-lines between angritic primitive melts and their equilibrium olivine.

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5.3.3. Implications for the APB's bulk composition and core size

573 We first consider the ratios of refractory and moderately refractory elements (*i.e.*, 574 with 50% condensation temperatures, Tc, above 1350 K, Lodders, 2003): Mg/Si, Al/Si, 575 Ca/Si and Ti/Si. In these ratio spaces, the intercepts of the nebular trend and the primitive 576 angrite Ol-melt tie-lines define tight domains (red contours in Fig. 10). Furthermore, in 577 all three spaces, a unique Mg/Si atomic ratio, of ~ 1.3 , is retrieved. This feature 578 demonstrates the self-consistency of the APB composition thus obtained. Interestingly, a 579 similar APB Mg/Si ratio of 1.31±0.09 has been proposed based on a nebular trend 580 between Mg/Si ratios and δ^{30} Si in chondrites (Dauphas et al., 2015). The remarkable 581 agreement between these two values, one derived using only the major element 582 composition and the other combining elemental and isotopic compositions, further 583 strengthens the hypothesis of a nebular control on the abundance of refractory to 584 moderately refractory elements in the APB. Indeed, the Mg/Si ratio of ~1.3 derived for the APB is significantly higher than those of chondrites (between 0.75-1.08) and 585 586 displaced toward the high Mg/Si ratio (~1.52 to 1.60) of high-T condensates, both 587 theoretical (Morbidelli et al., 2020) and natural (AOAs).

588 Of the moderately volatile elements present in minor abundance in most 589 meteorites (Cr, K, P, Na), only Cr defines a (broad) nebular trend with refractory and 590 moderately refractory elements (Fig. 11a). Unlike for refractory elements, where both the 591 1400 K and 1280 K first and residual condensates fall on the nebular trend defined by 592 chondrites, in Mg/Si vs Cr/Si space only the 1280 K condensate and residue fall on this 593 trend. In stark contrast, the 1400 K condensates and residues define a separate, and 594 orthogonal trend. This is partly because Cr is both moderately volatile (Tc \sim 1300 K) and 595 moderately siderophile, and partly because the 1280 K condensates and residues are 596 calculated under more reducing conditions (C/O ~ 0.9) than the 1400 K condensates and 597 residues (which assume a solar C/O ratio of ~0.54, ; Asplund et al. 2009). Therefore, 598 while no Cr has condensed in the first condensate at 1400 K, it is quantitatively removed 599 from the gas phase into the first condensate (silicate and iron) at 1280 K under more 600 reducing conditions (Morbidelli et al., 2020). As seen in Fig. 11a, in the Mg/Si vs Cr/Si 601 space, the angrite Ol-melt tie-lines do not intersect the chondritic nebular trend at Mg/Si 602 \sim 1.3. Instead, the angrite Ol-melt tie-lines intersect the theoretical nebular trend defined 603 by the 1400 K condensate and residue at Mg/Si ratios of ~ 1.4–1.6. This indicates that the 604 composition of the APB is dominated by material condensed before quantitative 605 condensation of Cr: *i.e.*, at T > ~1300 K. The slightly elevated Mg/Si ratio (1.4–1.6) 606 obtained in the Mg/Si vs Cr/Si space compared to the ~1.3 value obtained when 607 considering lithophile refractory elements (Fig. 10) could be explained by the moderately 608 siderophile nature of Cr during core formation, which will move the Ol-melt tie-lines 609 towards lower Cr/Si values (Fig 11a). To first-order, the bulk APB Cr/Si ratio can thus be 610 retrieved by projecting the Mg/Si of ~1.3 onto the 1400 K condensate-residue tie-line, 611 vielding a Cr/Si ratio of ~0.007–0.008.

We now consider the Fe/Si ratio of the APB, and by extension, the size of the APB core. While the Fe/Si ratios in primitive angrites (quenched Group 1) and their equilibrium olivine are virtually identical, and cluster around a value of ~ 0.36 to 0.54, this value only provides an estimate of the Fe/Si of the APB mantle (*i.e.*, silicate portion) (see Fig. 11b). Like for Cr, a first-order estimate of the Fe/Si ratio of the bulk APB can be obtained by projecting the Mg/Si ratio of ~ 1.3 onto the 1400 K condensate-residue tie618 line, which yields a value of ~ 1. This corresponds to ~46 to 64% of Fe removal into the 619 APB core, or a core representing ~17–23 wt % of the APB.

620 The above values are, of course, dependent on the APB Mg/Si ratio assumed 621 (~ 1.3) and the projection of this ratio on the tie-line between the 1400 K first and residual 622 condensates. We recognize that the later assumption might be too stringent. To more 623 conservatively estimate the Fe/Si ratio and core size of the APB, we therefore relaxed this 624 assumption and allowed the APB composition to be represented by 2-component 625 mixtures between some high-T components (1400 K condensate, 1280 K condensate, 626 AOAs) and low-T components (EH, EL, H, and LL chondrites, Type IB and Type III 627 chondrules, as well as 1400 K and 1280 K residual condensates) (see Table S3). 628 Carbonaceous chondrites and CAIs are not considered as they are both enriched in 629 neutron-rich nuclides (⁴⁸Ca, ⁵⁰Ti, ⁵⁴Cr) relative to angrites (*e.g.*, Dauphas, 2017), which 630 precludes a direct genetic link with the APB. For each 2-component mixture, between 0 631 and 100 % of the Fe was allowed to be removed into the core. A least-square 632 minimization was then performed to find how closely the resulting hypothetical APB 633 composition could be matched by some mixture between the average quenched Group 1 634 melt and its equilibrium olivine (i.e., LEW 87051 and Olivine Fo 80.5).

635 The results of this exercise are presented in Fig. 12 (see also Supplementary Fig 636 S2), as density maps of the residual between the hypothetical APB composition and the 637 best fit using the quenched Group 1 compositions and equilibrium olivine. For each 2-638 component mixture, the composition that can be best reproduced by a mixture of 639 primitive angritic melt + equilibrium olivine is given in Supplementary Table S4. We 640 find that 2-component mixtures with AOAs produce generally poor fits (residual up to 641 ~ 16 wt%), which makes sense as AOAs are too Ti rich and plot off the nebular trend in 642 Fig. 10c. Furthermore, their low Fe content mainly precludes the formation of a core (see 643 Supplementary Fig S2), which is an important feature to match. Both the high Ti and low 644 Fe of AOAs testify to their very high temperature of formation, and suggest that the APB 645 formed from material condensed at somewhat lower temperatures.

In contrast to AOAs, most 2-component mixtures involving the 1400 K and 1280
K first condensates provide decent fits (residuals below 1.91 wt %). In details, the closest
fits are obtained when the 1400 K first condensates (Fig. 12) are considered as the high-T

649 component, and mixtures involving enstatite or ordinary chondrites, Type IB chondrules 650 and the 1280 K residual condensate all produce remarkable matches, with residuals 651 below 1 wt % and r^2 values ≥ 0.9997 (Supplementary Table S4). The average of these 652 specific 2-component mixtures is used to define the best estimate APB composition, and 653 core size, from this minimization exercise.

654 Estimates of the bulk composition, mantle Fe/Si and core size derived using the 655 various methods described above are summarized in Table 7. Collectively, these point to 656 a conservative best estimate APB with Mg/Si of 1.29 ± 0.11 , Al/Si of 0.117 ± 0.027 , 657 Ca/Si of 0.101±0.025, Ti/Si of 0.0039 ± 0.0008, Fe/Si of 0.875 ± 0.182 and Cr/Si of 658 0.0062 ± 0.0038 (see Table 7 for oxide abundances, in wt%). The recommended core size 659 thus obtained is 18 ± 6 wt% of the APB, in remarkable agreement with the 18 ± 11 % 660 estimate from Steenstra et al. (2017), while the mantle Fe/Si ratio derived from the 661 composition of primitive angritic melts (quenched Group 1) is 0.452 ± 0.089 . To our 662 knowledge, this is the first self-consistent estimate of the major elements composition of 663 the APB.

664 Notably, our estimate has a much higher Mg/Si and much lower Al/Si (as well as 665 Ca/Si, and Ti/Si) than the one from Longhi (1999), who also derived an APB bulk 666 composition based on 2-component mixing between chondrites from which metal had 667 been removed (Allende- 40% Fe) and some high-T component. The reason for this 668 difference is that Longhi (1999) considered a high-T component formed at 1440 K, when 669 only 10% of the Mg and 15 % of the Si present in the nebula have condensed, while we 670 considered a high-T component formed at 1400 K, when more than 70 % of the Mg and 671 50 % of the Si have condensed (Grossman, 1972). This small difference in temperature 672 results in drastic changes in major element ratios in the total condensed material, and the 673 resulting bulk composition of the APB. Future experiments will be necessary to further 674 test our proposed composition for the APB and its Mg-enriched nature.

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5.4. Oxygen fugacity of the APB

677 We now discuss the constraints that our 1 atm and high-pressure experiments 678 place on the fO_2 during crystallization of D'Orbigny-like angrites. Because our 1 atm 679 experiments were performed over a range of redox conditions, we use the Mg# in the 680 core of the clinopyroxene as an empirical tracer of fO_2 conditions. In Figure 13, we plot 681 the Mg# measured in the core of Cpx when they first appear in the 1 atm experimental charges as a function of fO_2 (filled circles). Because (i) Mg contents in the melt decrease 682 683 as crystallization proceeds, and (ii) the Cpx appears slightly later in the crystallization 684 sequence at lower fO_2 (Fig. 3), a negative trend is observed in Figure 13. In natural 685 angrites, pyroxenes in equilibrium with the most primitive melt(s) will have the highest 686 core Mg#. Previous studies have reported high Mg# in the cores of Cpx from natural 687 quenched Group 2 angrites, with values typically between 55.5-57.9 in D'Orbigny and 688 NWA 1296 (Mittlefehldt et al., 2002; Kurat et al., 2004; Jambon et al., 2005), and the 689 highest value of 60.5 measured in D'Orbigny (Floss et al., 2003). Based on the trend 690 defined by our 1 atm experiments, these values indicate crystallization from a melt under 691 fO_2 conditions as oxidizing as ~ IW+0.4 to IW+2 (Fig. 13).

692 On the other hand, some of our high-pressure experiments provide constraints on 693 the fO_2 relevant to the source magma of quenched angrites. Indeed, at 8 kbar (B1402 and 694 B1403; Table 4) we obtain multi-saturation surfaces that matches the mineralogy of 695 quenched Group 2 angrites (Table 5). The fO_2 of these experiments is ~IW+1.2, a value 696 consistent with those derived from our 1 atm experiments. Such oxidizing conditions are 697 in excellent agreement with previous independent estimates of fO_2 during the 698 crystallization of both quenched and plutonic angrites, which collectively point to values 699 between ~IW-0.7 and IW+2 (Table 8).

700 Reconciling these oxidizing conditions with the differentiation of a core on the 701 APB – as evidenced by paleomagnetic data (Weiss et al., 2008), W isotope systematics 702 (Markowski et al., 2007; Kleine et al., 2009, 2012), and the depletions of siderophile 703 elements relative to chondrites (Righter, 2008; Shirai et al., 2009b; Riches et al., 2012; 704 Steenstra et al., 2017) – is a well-known conundrum. Indeed, under conditions as 705 oxidizing as IW+1 or +2, Fe metal is, by definition, unstable, which would prevent core 706 formation from taking place. At the same time, the metal-silicate partition coefficient of 707 siderophile elements decreases with increasing fO_2 , which would requires a large (~60 % 708 by mass) core to explain the siderophile element depletion in the APB mantle (Righter, 709 2008). Because (i) core formation on the APB did happen, and (ii) formation of a large 710 core under oxidizing conditions is highly unlikely, previous studies have proposed that the APB formed and differentiated a core under mildly reducing conditions (~IW-1.4 \pm 0.5, Table 8), so as to explain the siderophile element depletion in the APB mantle. This scenario requires that the higher *f*O₂ conditions during crystallization recorded in angrite specimens testify to either (i) a subsequent oxidation of the APB mantle, or (ii) oxidation of the basaltic angrite melts upon degassing and eruption (Righter, 2008; Shirai et al., 2009b). The latter would be consistent with the presence of vesicles in some quenched angrites (McCoy et al., 2006).

Our data, pointing to relatively oxidized conditions during crystallization of D'Orbigny-like angrites, further strengthen the conclusion that a change in fO_2 occurred on the APB between core formation, at ~IW-1.4±0.5, and magma crystallization, at ~IW+1±1. Sanborn and Wadhwa (2021) observed that this change could be related to the addition of water/volatiles to the APB during this time interval (Sarafian et al., 2017a, b).

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5.5. Minimum size of the APB

725 Since the APB is currently unknown (*i.e.*, has not been observed), its size can 726 only be constrained indirectly. While it is clear that the APB must have been larger than 727 100 km in radius, or else angrite melts would have been lost to space during eruption, and 728 no basaltic plutonic or quenched angrites would be observed (Wilson and Keil, 1991), 729 accurately estimating the size of the APB remains an important point of debate (e.g., 730 Scott and Bottke, 2011; Keil, 2012). Traditionally, the APB has been assumed to be a 731 small body, similar in size to asteroid 4 Vesta (r ~ 260km), the presumed parent body of 732 HED meteorites. Multiple lines of evidence, however, support the idea of a larger APB. 733 For instance, the presence of solar-like gases trapped in D'Orbigny glass is consistent 734 with a parent body large enough to retain a nebular atmosphere (Busemann et al., 2006). 735 Furthermore, the large and uniform spread in cosmic-ray exposure ages in angrites (~ 0.6 -736 60 Ma) points to an APB large enough for prolonged impact/ejection events (Nakashima 737 et al., 2018). Metamorphic coronas in NWA 3164 point to contact metamorphism on the 738 APB, at P conditions < 9 kbar, suggesting that the APB must have been a large asteroid 739 or a planetary-size body (Baghdadi et al., 2013). Quantitatively, estimates on the size of 740 the APB have recently been proposed based on (i) the volatile (H, C) content of melt 741 inclusions within angrite specimens, which point to an APB radius of at least 270 km,

and probably \geq 340 km (Sarafian et al., 2017a), and (ii) the presence of a sustained core dynamo on the APB up to 11 Myr after CAI formation (Weiss et al., 2008; Wang et al., 2017), whose paleo-intensity combined with chronometric data and thermal modelling indicate a rapid accretion to a minimum APB radius of 420 km only 1.8 Myr after CAI formation (Bryson et al., 2019; Dodds et al., 2021).

Our pressure experiments indicate that a pressure of 6 to 9 kbar is necessary for multiple saturation in Ol + Cpx + Sp (\pm Plag) in the source magma of quenched Group 2 angrites (Fig. 6), which allows us to independently determine a lower limit on the size of the APB. Assuming a spherical APB under hydrostatic conditions (*i.e.*, the only force at play is the APB gravitational force), the pressure profile inside the APB can be calculated as:

753 $P(z) = \int_{0}^{z} \rho(z)g(z) \, dz, \qquad (1)$

754 where z is depth (downward from the surface), $\rho(z)$ is the density at depth z (in 755 kg/m³), and g(z) is the acceleration of gravity at depth z (in m/s²), defined as:

756 $g(z) = -\frac{G \times M(z)}{(R_{APB} - z)^2}$. (2)

In Eq. (2), *G* is the gravitational constant $(6.674 \times 10^{-11} \text{ N.m}^2/\text{kg}^2)$, M(z) is the mass of the APB material below depth *z*, and $(R_{APB} - z)$ is the distance between the center of the APB and depth *z*. For a given density profile, M(z) can be easily calculated, yielding through Eq. (2) and (1), the depth profiles for the local gravity and pressure in the APB.

762 Figure 14 shows the APB pressure profiles calculated (see code in Supplementary 763 Materials) for three scenarii: a pure silicate APB (*i.e.*, no core) of constant density, $\rho_{silicate}$ = 3300 kg/m³ (Fig 14a), an APB with a 14 wt % core composed of 80% Fe and 20% Ni, 764 ρ_{core} = 8080 kg/m³ (Fig. 14b), and an APB with a 21 wt % core composed of 70% Fe, 765 20% Ni, 5% S, and 5% C, $\rho_{core} = 7500 \text{ kg/m}^3$ (Fig. 14c). The core masses and 766 767 compositions are taken from Steenstra et al. (2017). While the core compositions simply 768 illustrate possible compositions assuming a volatile-poor (only Fe-Ni) and volatile-rich 769 (with significant C and S) APB, the corresponding core masses are the ones that best 770 explain the metal depletion in the APB mantle based on metal-silicate partition 771 coefficients (from Steenstra et al. 2017). To reach a pressure of 6 kbar in the silicate portion of the APB translates to a minimum APB radius of ~594–628 km, while a pressure of 9 kbar requires a radius of ~728–769 km (Fig. 14, red envelopes). The presence, size and compositions of the APB core have little influence on these values, as the higher density of the metallic core results in a higher local acceleration of gravity (and thus a higher pressure) at lower depth compared to a pure silicate APB.

777 The above lower limits are fully compatible with the minimum radii of 270 km 778 (Sarafian et al., 2017a) and 420 km (Bryson et al., 2019; Dodds et al., 2021) based on 779 volatile content and paleomagnetic field intensities of angrites and their melt inclusions, 780 but imply a significantly larger APB than previously thought. Indeed, the ~ 600 to 770 km 781 estimates shown in Figure 14 (red envelopes) are very conservative lower limits, as they 782 assume that the parental magma of angrites formed in a source located in the deepest 783 silicate portion of the APB (near the center of the APB in the core-free case, or otherwise 784 at the core-mantle boundary). Under these conditions, the extraction and eruption of such 785 melts onto the surface of the APB would be physically hard to explain. For the angrite 786 parental melt to be able to equilibrate at $\sim 6-9$ kbar before eruption and quenching at or 787 near the surface, therefore requires that the APB was much larger than the lower limit of 788 ~600 to 770 km derived above.

789 Assuming D'Orbigny and other quenched Group 2 angrites are evolved lavas 790 derived from a parental magma with quenched Group 1 composition (e.g., Asuka 881371, 791 LEW 87051, NWA 7812), a first-order estimate on the pressure at which these parental 792 melts were formed can be obtained by identifying the conditions under which their bulk 793 compositions are saturated with multiple phases on the liquidus. The parameterization of 794 Grove et al. (2013) yields pressures between 26 and 32 kbar. Similar values are obtained 795 using the Perple X model (Connolly, 2009) with the Holland et al. (2018) database (23 to 796 31 kbar, accounting for a small pressure correction based on Barr and Grove (2013) 797 experiments, see Supplementary Material), or the PETROGEN model (24-29 kbar, Krein 798 et al., 2020). While additional experiments would allow to constrain more precisely the 799 pressure of the source of Group 1 angrites, the convergence of independent models is 800 informative and indicate that the APB must have been large enough for pressures of ~20-801 30 kbar to be reached in the source region of quenched angrites. This translates to an 802 APB radius of at least 1085–1405 km (Fig. 14, orange envelopes).

803 In summary (Fig. 15), our pressure experiments indicate that the APB had a 804 radius of at least ~600–770 km (about 3 times larger than Vesta, the parent body of HED 805 meteorites). When the fractional crystallization relationship between the two groups of 806 quenched angrites is considered, this lower limit is increased to $\sim 1085-1405$ km, raising 807 the possibility of a Moon-sized (if not larger) APB. The latter would naturally explain the 808 relatively elevated abundance of Highly Siderophile Element (HSE) in the angritic 809 mantle (10 ng/g), which has been proposed to be controlled by the parent-body size (Dale 810 et al., 2012). In Figure 16, we show that 9 and 30 kbar lower limits derived above 811 confirm that the APB plots on the HSE content vs parent body mass trend defined by Earth, Mars and Vesta, and point to an APB mass of ~ 10^{26} g. 812

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5.6. Where is the APB?

815 The rare asteroids with reflectance spectra matching those of angrites are small (r 816 < 34 km, McCord et al., 1970; Burbine et al., 2001; Rivkin et al., 2007), which implies 817 that the APB either (i) has not been observed yet, (ii) was extremely small, or (iii) got 818 disrupted or destroyed early in its history (Scott and Bottke, 2011). The large size of the 819 APB inferred from our experiments supports the proposal that the APB was a major body 820 in the early inner Solar System (Baghdadi et al., 2013; Sarafian et al., 2017a; Bryson et 821 al., 2019; Dodds et al., 2021), and thus favors the latter hypothesis. Based on elemental 822 and isotopic mass balance considerations, Fitoussi et al. (2016) even proposed that the 823 APB (or an APB-like material) was a major building block of the terrestrial planets, that 824 could account for up to 50-60% of Earth's and Mars' mass, with the remainder mass 825 coming from ordinary chondrites (~30%) and CI/CV carbonaceous chondrites (~10-826 20%). Using a similar approach, but not limiting the number of possible components to 827 four, Liebske and Khan (2019) found a smaller but still significant APB contribution to 828 Earth/Mars.

The idea that the APB was accreted into one (or several) of the terrestrial planets is consistent with models of terrestrial planet formation by collision between early formed planetary embryos from the inner Solar System (*e.g.*, Chambers and Wetherill, 1998). The status of the APB as a true planetary embryo is supported by (i) the early accretion (~0.5 to 1 Myr after CAIs) and differentiation (within ~ 2 Myr after CAI

834 formation) of the APB (Markowski et al., 2007; Kleine et al., 2009, 2012), (ii) the very 835 old crystallization ages of angrites, ranging from 4 to 11 Myr after CAIs (see Tissot et al., 2017 and references therein), and (iii) the reduced and volatile-depleted nature of the 836 837 APB, as well as its non-carbonaceous isotope composition (Budde et al., 2019), which 838 both suggest a formation in the inner Solar System. The large size and bulk APB 839 composition derived in this study, consistent with a nebular origin at relatively high 840 temperatures ($\sim 1300-1400$ K), further strengthen the case that the APB was indeed a 841 planetary embryo. As such, it seems most likely that the APB was disrupted early in the 842 history of the Solar System and accreted into the terrestrial planets.

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6. Conclusions

845 Taking advantage of the rapidly growing number of known angrite meteorites 846 (which has more than quintupled in 20 years), we attempted here to revisit their 847 petrogenesis and place novel constraints on key features of the APB. We found that 848 quenched (*i.e.*, volcanic) specimens define two distinct compositional groups: Group 1, 849 which currently includes Asuka 881371, LEW 87051, NWA 1670, NWA 5167, NWA 850 7812 and NWA 12774, and Group 2, which currently includes D'Orbigny, Sahara 99555 851 and NWA 1296 (Fig. 1). We showed that these two groups can be readily related by 852 fractional crystallization (Fig. 7), with Group 1 specimens representing more primitive 853 angritic melts, and Group 2 specimens representing more evolved lavas, whose 854 composition sits on an Ol + Cpx + Sp (\pm Plag at low pressure) multiple saturation 855 boundary.

856 Recognizing that quenched Group 1 specimens likely capture the composition of primitive angritic melts, we derived a self-consistent estimate of the major elements 857 858 abundances in the APB (Table 7), which suggests that the refractory-enriched (and 859 volatile-depleted) nature of the APB is a primitive feature resulting from nebular 860 fractionation at high-T (~ 1300–1400 K), rather than the result of parent body processing. 861 Importantly, our APB bulk composition estimate matches the proposed Mg/Si ratio of 1.3 862 derived from the angrite δ^{30} Si values, and yields a core size (18 ± 6 wt%) in agreement 863 with the siderophile elements depletion in the APB mantle.

Through a series of 1 atm and high-pressure crystallization experiments, we 864 865 established the liquid phase equilibria of angrites (Fig. 6). Our data indicate that 866 crystallization of D'Orbigny-like (Group 2) angrites occurred under relatively oxidized 867 conditions ($-IW+1\pm 1$), in contrast with the more reducing conditions ($IW-1.4\pm 0.5$) 868 thought to prevail during core formation, implying a change in fO_2 in the APB over its 869 evolution. Furthermore, our results place a stringent lower limit on the size of the APB, 870 whose radius must have been at least ~600-770 km (3 times larger than Vesta), and more 871 likely greater than 1085–1405 km, raising the possibility of a Moon-sized APB (Fig 14-872 15).

873 When combined with its extremely early accretion (~0.5-1 Myr after CAIs) and 874 differentiation (within 2 Myr after CAIs), the large size and refractory-enriched nature of 875 the APB (this work) suggests that it was an important body in the inner Early Solar 876 System. In fact, in light of the above observations, we propose that the APB represents 877 the archetype of the first-generation of refractory-enriched planetesimals and embryos 878 formed in the innermost part of the inner Solar System (<1 AU), and which accreted in 879 the telluric planets. In this framework, the terrestrial planets would grow dry (*i.e.*, devoid of volatiles), at least during the early stages of their accretion, and their volatile inventory 880 881 would be delivered later in their history, through accretion of more volatile rich materials, 882 such as chondrites and/or comets.

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- 1283
- 1284

1285 Figure legends

Figure 1: Pseudoternary Ol-Cpx-Qtz (left) and Ol-Cpx-Plag (center and right) projections showing the bulk composition of angrites. Warm colors are for volcanic angrites, and cold colors for plutonic angrites. The illustrative saturation boundaries are calculated at 1 atm, for a D'Orbigny-like melt (Mg # 0.32, NaK # = 0, and TiO₂ = 0.9 wt %) using the MORB model from Grove et al. (1992). The goal of this work is to establish the actual position of these boundaries and the P-T- fO_2 conditions relevant to the angrites.

1292

Figure 2: Representative BSE images of selected 1 atm experiments. Temperature decreases towards the right and oxygen fugacity increases towards the bottom. The 10micron scale bar shown in the top left panel applies to all images. From left to right, top row: Dorb-3, -1, -2 and -11; center row: Dorb-9, -10, and -8; bottom row: Dorb-6 and -5. Note the large abundance of magnetite in Dorb-5 (bottom right panel); a phase not present in the natural D'Orbigny angrite.

1299

Figure 3: Temperature and phase assemblages in the 1 atm experiments. Top labels refer to the oxygen fugacity of the experiments and percent values to crystallinity of the run. While the synthetic powder used has the composition of the D'Orbigny angrite, the Ol+Cpx+Plag assemblage observed in the natural specimen is not observed near the liquidus, regardless of the fO_2 conditions.

1305

Figure 4: Pseudoternary Ol-Cpx-Qtz and Ol-Cpx-Plag projections showing the position of the Ol-Cpx-Plag saturation boundary at (a) different oxygen fugacities, and (b) different pressures, as established by the glass composition of the experiments when all three phases are first present. The dependency on oxygen fugacity (a) is clearly visible but regardless of fO_2 , none of the experiments fully reproduce the quenched Group 2 cluster position. In contrast, at 7–8 kbar (b), the pressure experiments perfectly match the quenched Group 2 composition.

1313

Figure 5: Representative BSE images of selected IHPV (3 to 5 kbar) and piston cylinder
(5 to 13 kbar) experiments. Temperature decreases towards the right and pressure

increases towards the bottom. The 10-micron scale bar shown in the top left panel applies
to all images, except B1421 (middle row, left column), which is magnified by a factor ~2
(see 10-micron scale bar in that panel).

1319

1320 Figure 6: P-T conditions of the experiments conducted on the synthetic D'Orbigny 1321 composition. Piston cylinder experiments are shown as squares, IHPV experiments as 1322 hexagons and 1 atm experiments conducted in similar fO_2 conditions (~IW +0.5) as 1323 circles. In each symbol, a filled (open) quadrant denotes the presence (absence) of the 1324 corresponding phase. The slopes of the phase boundaries are from the experimental 1325 literature on MORB compositions (Tormey et al., 1987; Grove and Bryan, 1983; Grove et 1326 al., 1992) and correspond to: $\sim 10^{\circ}$ C / 6 kbar for the liquidus over the 0 to 6 kbar range; 1327 10-11°C / kbar for the Liq + Ol + Plag to Liq + Ol + Plag + Cpx boundary over the 0 to 6 1328 kbar range; ~20°C / kbar for the liquidus over the 6 to 12 kbar range. As too few 1329 constraints exist on the plagioclase to spinel transition in natural systems (Obata, 1976), 1330 this boundary is shown as a dashed vertical line.

1331

Figure 7: Close up view of the pseudoternary Ol-Cpx-Qtz (a and c) and Ol-Cpx-Plag (b and d) projections showing the compositions of quenched Group 1 and 2 angrites, and the fractional crystallization models. Forward models are shown in panel (a) and (b) and reverse models in panels (c) and (d). The two group of quenched angrites can easily be related by fractional crystallization.

1337

1338 Figure 8: Whole rock REE abundances in angrites, and calculated equilibrium melts. (a) 1339 Ouenched Group 1 abundances, $\sim 10 \times CI$, are shown in orange (open circle: Asuka 1340 881371; filled circle NWA 1670; open square: LEW 87051). Quenched Group 2 1341 abundances, ~14×CI, are shown in red (solid line: NWA 1296; dashed line: D'Orbigny; 1342 dotted line: Sahara 99555). Theoretical melts, evolved from quenched Group 1 1343 compositions using the steps shown in Table S1, are shown in black. (b-d) Whole-rock 1344 and modeled REE pattern for plutonic angrites LEW 86010, NWA 4801 and NWA 4590. 1345 Good agreement is observed between the measured and modeled patterns, except for the

1346 light REEs for NWA 4590, indicating a more complex evolution history than that1347 assumed by our modeling.

1348

1349 Figure 9: Lu concentrations vs Pb-Pb ages of angrites. Symbols as in Figure 1. 1350 Concentration data from Table 6. For D'Orbigny, NWA 4590, NWA 4801, NWA 6291, 1351 AdoR and Sahara 99555, ages are U-corrected Pb-Pb ages from Tissot et al. (2017). For 1352 the other samples, only uncorrected dates are available: LEW 86010 (Amelin, 2008), 1353 NWA 1296 and NWA 2999 (Amelin and Irving, 2007), and Asuka 881371 (Premo and 1354 Tatsumoto, 1995). For high-precision uncorrected Pb-Pb dates, a conservative uncertainty 1355 of \pm 1.25 Myr is shown (the largest age offset due to U isotope variations in angrites, 1356 Tissot et al. 2017).

1357

1358 Figure 10: Mg/Si ratio vs (a) Al/Si, (b) Ca/Si, and (c) Ti/Si showing the relationship 1359 between angritic primitive melt and their equilibrium olivine (vellow symbols) and 1360 chondrites and chondritic components (all other symbols, see legend). Nebular trends 1361 (grey dashed lines and 95 % CI envelops) are defined using ordinary, enstatite, and most carbonaceous chondrites. Some carbonaceous chondrites are omitted from the regressions 1362 1363 (CV for Al/Si; CV, CR, CH for Ca/Si; and CV, CK, CH for Ti/Si), as they clearly depart 1364 from the general trend defined by all other chondrites, testifying to secondary control on 1365 their composition (e.g., high CAI content in CVs, high-T reprocessing of CHs, Hezel et 1366 al., 2003). Component compositions are given in Table S3.

1367

Figure 11: Mg/Si ratio vs (a) Cr/Si, and (b) Fe/Si. Symbols as in Fig 13, and compositions from Table S3. In panel (a), the grey dashed line and 95 % CI envelop is a regression through all chondrite data.

1371

Figure 12: Density maps showing the difference (*i.e.*, residual) between hypothetical APB compositions (2-component mixtures) and the best fit composition obtained by mixing a primitive angritic melt and its equilibrium olivine. For each panel, the x-axis denotes the amount of Fe sequestered into the core, and the y-axis the % of low-T component in the 2-component mixture. The high-T component is taken as the 1400 K

first condensate (see Fig S2 in Supplementary Materials for maps using the 1280 K first condensate, and AOAs instead). The low-T component is labeled in the top left corner of each panel. White curves are lines of equal core mass (by 3% mass increment, from left to right). Dashed black curves are lines of equal Mg/Si ratio for the best fit composition obtained by mixing a primitive angritic melt and its equilibrium olivine (from 1.1 to 1.5, by 0.1 step increment). In each panel, the white circle denotes the optimal solution (*i.e.*, minimum residual), whose composition is reported in Table S4.

1384

1385 Figure 13: Mg# in the core of clinopyroxene as function of oxygen fugacity (log units, 1386 relative to the IW buffer). Filled circles represent the values measured in the 1 atm 1387 experimental charges (this study). Open symbols on the y-axis denote Mg# measured in 1388 natural specimen of quenched Group 2 angrites: the diamonds, square and circle are data 1389 from D'Orbigny reported in, respectively, Mittlefehldt et al., (2002), Kurat et al., (2004), 1390 and Floss et al., (2003), and the triangle shows data from NWA 1296 (Jambon et al., 1391 2005). The highest Mg# record the fO_2 relevant to the crystallization of the primitive 1392 basaltic angrite melts, at ~IW+0.4 to IW+2.

1393

1394 Figure 14: Hydrostatic pressure as a function of depth. Pressure profiles in hypothetical 1395 APBs are shown for (a) a core-free APB, (b) an APB with a 14 wt% by mass core, made 1396 of Fe-Ni (80:20), and (c) an APB with a 21 wt% by mass core, made of Fe-Ni-C-S 1397 (70:20:5:5). For the APB profiles, a grey filling denotes the core. Red (orange) envelopes 1398 are bound by the profiles of the smallest APBs reaching the 6 and 9 kbar (20 and 30kbar) 1399 threshold in the APB mantle. These constraints from quenched Group 2 (and Group 1) 1400 angrites point to a minimum radius of ~600-770 km (~1085-1405 km) for the APB, 1401 regardless of the presence, size and composition of a core. Profiles for the telluric planets, 1402 as well as the Moon and Vesta are also shown, and were calculated using literature 1403 density profiles: Mercury after Rivoldini et al. (2009), Venus after Aitta (2012), Earth after PREM, http://ds.iris.edu/ds/products/emc-prem/, Dziewonski and Anderson (1981), 1404 1405 Mars after Bertka and Fei (1998) assuming at core with 14 wt% S (Dreibus and Wanke, 1406 1985), Moon after the seismic VPREMOON model from Garcia et al. (2011, 2012); and 1407 Vesta after Ruzicka et al. (1997).

1408

Figure 15: Illustration of the temporal and compositional relationship between quenched Group 1 and Group 2 angrites. The values in kbar denote the pressure of multiple saturation derived from our high-pressure experiments (Group 2 angrites) and modeling (Group 1). The minimum APB radii implied by these pressures are also shown.

1413

Figure 16: Total mantle HSE concentration plotted against parent body mass for the Earth, Mars, Moon and Vesta (data from Dale et al., 2012). The range of HSE concentration in the APB mantle is shown as horizontal red dotted lines (Dale et al., 2012), while the constraints on the minimum APB size (this work) are shown as vertical lines. The lower limits of 9 and 30 kbar derived in Section 5.3 confirm that the APB plots on the trend defined by Earth, Mars and Vesta, and point to a Moon-sized (if not larger) APB.

1421



Decreasing temperature -

































Comp 1: First condensate (1400 K)







Depth (km)

Depth (km)

Depth (km)





Requires *r*_{АРВ} ≥ 1100-1400 km



6-9

kbar

Requires *r*_{АРВ} ≥ 660-770 km



List of all known a	ingrites, as of Augus	t 2022	
Sample	Date of find/fall	Location	Mass (g)
Plutonic angrites	3		
Angra dos Reis	January, 1869 (Fal	l) Bay of Angra dos Reis, Brazil	~1500
LEW 86010	1986	Lewis Cliff, Antarctica	6.9
NWA 2999	2004, 2005	Morocco or Algeria, purchased in Tagou	392, 2400
paired, NWA 315	82004	Northwest Africa, purchased in Tagounit	681
paired. NWA 316	42004	Morocco or Algeria, purchased in Rabat	928
paired. NWA 456	92005	Northwest Africa, purchased in Erfoud	484
paired, NWA 466	2 2006	Northwest Africa, purchased in Erfoud	60
paired. NWA 487	7 2007	Northwest Africa, purchased in Erfoud	1000
paired, NWA 493	12007	Northwest Africa, purchased in Tagounit	2140
paired NWA 516	72007	Morocco, purchased in Erfoud	859
paired, NWA 629	12010	Northwest Africa, purchased in Morocco	250
paired, NWA 620 paired NWA 670:	52011	Northwest Africa, purchased in Frfoud	1003
paired, NWA 107	52015	Northwest Africa, purchased in Paris	770
paired, NWA 128	22019	Northwest Africa, purchased in Morocco	172
NWA 4590	2006	Morocco/Algeria, purchased in Tagounit	212.8
NWA 4801	2000	Algeria, purchased in Erfoud	212.0
naired NW/A 840	52014	Northwest Africa, purchased in Erfoud	501
NWA 5379	2019	Northwest Africa, purchased in Erfoud	6.1
NWA 14758	2019	Northwest Africa, purchased in Guelmin	125.5
Intermediate ang NWA 10463 <i>paired, NWA 106</i> 4	jrites (contain both z 2015 42016	zoned olivines and olivine with exsolution la Northwest Africa, purchased in Erfoud Northwest Africa, purchased in Morocco	amellae) 202.5 14
Quenched angrit	tes		
Asuka 12209	2012	Antarctica	43.65
Asuka 881371	1988	Antarctica	11.3
D'Orbigny	.luly 1979	Argentina (farm field)	16550
LEW 87051	1987	Lewis Cliff. Antarctica	0.6
NWA 1296	Spring, 2001	Morocco, purchased in Bouarfa	810
NWA 1670	2003	Northwest Africa, purchased in Morocco	29
NWA 7203	2011	Morocco, purchased in Tucson (Arizona)	107
NWA 7812	2013	Northwest Africa, purchased in Erfoud	46.2
NWA 12774	2019	Northwest Africa, purchased in Mauritan	454
Sahara 99555	1999	Sahara	2710
Diabasic angrite	S		
NWA 12004	2018	Near Touignin, Morocco	183
NWA 12320	2018	Mauritania, purchased in Nouakchott	1946, 2379
NWA 12879	2019	Northwest Africa, purchased in Morocco	11
NWA 12934	2018	Northwest Africa	563
NWA 13363	2020	Algeria	54
Dunitic angrite			
		Northwest Africa, purchased in	
NWA 8535	2014	Guelmin	149

Data source: Keil (2012), Meteoritical Bulletin Database.

Table 1 List of all known angrites. as of August 2022

Table 2

Compilation of bulk composition of angrites (wt%). When multiple estimates available, preferred values in bold font.

Sampla	Mass (mg)	SiO	TiO		Eo O	$C_{r2}O_{2}$	E-O	MaQ	Mao	6-0	No O	PO	КO		c	Total	Ma#	Dof
	(119)	5102	1102	$A_{12}O_3$	16203	01203	FeO	WINO	lvigO	CaO	Na ₂ O	F ₂ O ₅	N ₂ O	NIO	3	TOLAI	wg#	Rel.
Plutonic angrites	660	44 74	2 00	0.00		0.00	10 5	0.40	11.0	00.0	0.02		.0.01	.0.01		404 7	00 F	[4]
Angra dos Reis	~660	44.71	2.09	9.26		0.22	10.5	0.12	11.8	23.0	0.03	0.40	<0.01	<0.01		101.7	66.5	[1]
Angra dos Reis	< 57	43.7	2.05	9.30	2.05	0.21	9.4	0.10	10.0	22.9	0.06	0.13	~0.02	0.01	0.53	90.7	67.Z	[2]
Aligia dos iteis		43.22	2.33	0.92	2.03	0.20	0.07 0.57	0.13	11 0/	23.00	0.00	0.09		0.03	0.55	100.52	63.3	[J] [1_3]
1 EW 86010	100	43.00	1 57	9.10	2.05	0.21	20.3	0.12	7 30	175	0.04	0.11	0.02	-0.02	0.55	102.04	30.0	[1-3]
LEW 86010		39.0	1.57	14.0		0.13	18 5	0.22	7.30	17.5	0.03	0 13	0.04	<0.01		00.7	10 3	[י] [2]
LEW 86010	~900	40.32	1.13	14.1		0.11	18 24	0.20	7.0	18 20		0.13			0 40	100.02	40.3	[2] [4]
LEW 86010		43.3	0.42	12 1		0.12	15.9	0.30	94	15.20	<0.01	0.21	<0.01		0.10	96.99	51.3	[5]
LEW 86010		43	0.9	12		0.23	18	0.2	8.7	18	\$0.01		20.01			101.03	46.3	[6]
LEW 86010 avg		39.83	1.27	14.06		0.12	19.02	0.21	7.15	17.73	0.03	0.17	0.04	<0.01	0.40	100.03	40.1	[1-2,4]
NWA 2999	120	33.4	0.42	4.71		0.36	31.2	0.24	19.0	7.37		<0.1		0.59		97.30	52.1	[7]
NWA 2999	20-40	(35.4)	0.53	7.0		0.31	29.8	0.21	16.0	10.1				0.67		(100)	48.9	[8]
NWA 2999		37.67	0.23	3.34		0.12	23.46	0.12	21.10	8.58		0.03				94.64	61.6	[9]
paired, NWA 3158																		
paired, NWA 3164	100	(39.32)	0.57	8.35		0.29	22.73	0.26	18.28	9.86	0.01	0.09	0.04			(100)	58.9	[10]
paired, NWA 3164	450	35.37	0.52	7.58		0.26	29.29	0.24	16.60	8.95	0.01	0.08	0.04	0.56		99.50	50.3	[11]
paired, NWA 3164		38.91	0.51	8.62		0.30	21.21	0.10	19.13	10.87				0.02		99.66	61.7	[11]
paired, NWA 4509																		
paired, NWA 4002																		
paired, NWA 4077	20-40	(31.6)	0 44	10 55		0 37	26.7	0.24	20.7	9.05				0 32		(100)	58 0	[8]
paired, NWA 5167	500	34.68	0.49	10.30		0.31	26.52	0.24	15.12	11.55	0.01	0.02	0.01	0.29		99.50	50.4	[0]
paired, NWA 5167*	000	39.79	0.51	11.58		0.29	17.79	0.22	16.44	12.6	0.01	0.02	0.01	0.02		99.24	62.2	[11]
paired, NWA 6291																		
paired, NWA 6705																		
paired, NWA 10754																		
paired, NWA 12822																		
NWA 4590		37.49	1.46	8.50		0.09	27.16	0.31	6.80	17.84	0.11	0.18	0.18	<0.01	0.18	100.30	30.9	[12]
NWA 4590		38.25	0.31	10.56		0.10	16.59	0.12	6.19	21.32		0.12				93.55	39.9	[9]
NVVA 4801 naired NIM/A 8405		42.08	1.51	13.75		0.12	10.92	0.11	11.15	19.45		0.12				99.20	64.5	[9]
NWA 5379																		
NWA 14758																		
Intermediate angrit	es (cont	tain botl	h zoned	l olivine	s and c	livine wi	th exso	lution la	amellae)								
NWA 10463	20-40	(38.6)	1.17	11.0		0.16	24.1	0.26	8.19	, 16.5				0.02		(100)	37.7	[8]
paired, NWA 10646		, , ,														. ,		
Quenched angrites	5																	
Asuka 881371	700	37.30	0.88	10.07	0.63	0.13	23.43	0.20	14.81	12.51	0.03	0.17	0.02	0.03	0.59	100.80	52.4	[3]
Asuka 12209	100			10.0					o 1=			o 1 =						
D'Orbigny	120	36.9	0.85	12.3		0.05	24.9	0.25	6.45	15.2		0.17		0.000		97.07	31.6	[7]
D'Orbigny	20-40	(42.2) 38 /	0.77	14.3		0.04	21.1	0.22	5.90 6.40	15.4	0 0172	0.16		0.003		(100) 08 30	33.5 31 Q	[0] [13]
D'Orbiany ava	20/200	37 65	0.03	12.4		0.0419	24.7 24 80	0.20	6 47	15 10	0.0172	0.10		0.01		90.33 97 74	31 7	[7] [7] 13]
LEW 87051	27	41.1	0.07	10.8		0.16	21.1	0.24	14.9	12.0	0.03	0.17	<0.03	< 0.01		100.3	55.8	[1]
LEW 87051	22	40.4	0.73	9.19		0.17	19.0	0.24	19.4	10.8	0.00	0.08				100.0	64.5	[2]
LEW 87051		38.9	0.6	11.3		0.1	22.1	0.3	13.1	12.7	<0.1	0.1				99.6	51.4	[14]
LEW 87051 avg		40.12	0.67	10.42		0.144	20.73	0.261	15.81	11.85	0.03	0.09	<0.03	<0.01		100.12	57.6	[1-2,14]
NWA 1296	20-40	(36.2)	0.87	14.3		0.08	25.2	0.29	7.25	15.8				0.002		(100)	33.9	[8]
NWA 1296	500	(39)	0.93	12.18		0.068	25.00	0.28	6.71	14.65	0.028	0.17	<0.03			(100)	32.4	[15]
NWA 1670	500	(42.18)	0.67	11.70		0.14	18.52	0.22	14.60	11.95	0.01	0.12	0.03			(100.14)	58.4	[16]
NWA 7203	20-40	(34.2)	0.99	14.7		0.07	25.4	0.28	7.34	17.1				0.003		(100)	34.0	[8]
NWA 7812		(34.07)	0.54	9.18		0.22	22.04	0.24	18.09	10.03	0.07	0.13	0.01			94.62	59.4	[17]
NWA 12774		39.38	0.59	10.86			20.63	0.23	17.25	10.90	0.32	0.17	0.0			100.33	59.8	[18]
Sahara 99555	120	38.6	0.88	12.9		0.04	25.6	0.27	6.79	15.4		0.18				100.62	32.1	[7]
Sahara 99555	20-40	(39.0)	0.93	12.3		0.04	25.2	0.27	6.43	15.8				0.007		(100)	31.3	[8]
Sahara 99555	20-40	(42.7)	0.90	10.8		0.04	24.9	0.27	0.06	14.3	0.0464	045		0.006		(100)	30.2 25 0	[0] [12]
Saliala 99000 Sahara 00555 ave	~200	30.0 30 EU	0.91	12.5 12 70		0.0403	∠3.1 24 2E	0.20	7.04 6.02	15.1 15.25	0.0164	0.15		<0.01		91.12	ວວ.2 22 ຄ	[13] [7 12]
Diabasic anarites		30.00	0.093	12.70		0.0420	24.33	0.203	0.92	13.23	0.0104	0.103		~0.01		33.20	22.0	[7,13]
NWA 12004		(40.1)	0.89	11.74		0.05	24.89	0.27	6.32	14.96	0.03	0.18	0.01		0.43	(100)	31.2	[19]
NWA 12320		(40.4)	0.81	11.83		0.05	24.27	0.26	6.65	15.15	0.02	0.17	0.01		0.42	(100)	32.8	[19]
NWA 12879		. /				-		_	_	·						. /	-	
NWA 12934																		
NWA 13363																		
INVVA 8535																		

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* Denotes composition where extraneous metal has been substracted (see Baghdadi et al. (2015) for details). **Powder split (numerator) from an homogeneized mass (denominator).

Table 3	
Major element composition of D'Orbigny (i.e.,	Quenched Group 2) and the synthetic powder used in this work

Major element com	position of D'Or	bigny (i.e., C	Quenched G	Group 2) and	d the synthe	etic powder	used in this	s work.					
	SiO ₂	TiO ₂	AI_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P_2O_5	NiO	Total
Average*	37.65	0.87	12.35	0.044	24.80	0.265	6.47	15.10	0.0172		0.165	0.0116	97.74
Normalized	38.52	0.89	12.64	0.045	25.37	0.27	6.62	15.45	0.0176	0	0.169	0.0118	100.00
Synthetic powder	38.49	0.89	12.63	0.036	25.45	0.27	6.61	15.45	0	0	0.160	0.0145	100.00

*Average from this study (see Table 2).

Table 4			
Summary of experimental run conditions	, results and mass	balance calculat	tions

Run	Р	Т	Charge ^a	fO ₂ buffer		Log fO ₂	Dur. ^b	Crystal.	Phase	es					FeO
		(°C)	-	Target	Target	Exp.	(hrs)	-	liq	ol	срх	plag	sp	Other	loss(-)/gain(+)
Dorb-3	1 atm	1173	Fe	IQF (IW-0.57)	-12.85		73.0	17%	83.5	6.8		9.9	*		+3.5%
Dorb-1	1 atm	1153	Fe	IQF (IW-0.59)	-13.14		67.0	27%	72.5	12.0		15.8	*		+3.3%
Dorb-2	1 atm	1133	Fe	IQF (IW-0.61)	-13.43		94.5	38%	62.4	16.9		20.6		Ca-Ol*	+2.7%
Dorb-4	1 atm	1113	Fe	IQF (IW-0.63)	-13.73		120.3	46%	53.6	21.6		24.2			+3.6%
Dorb-11	1 atm	1094	Fe	IQF (IW-0.65)	-14.03		115.5	68%	32.0	29.6	13.5	24.4			+0.01%
Dorb-9	1 atm	1136	30-35% Fe-Pt	IW+0.5	-12.28	-12.18 (IW+0.60)	114.8	32%	68.3	11.2		16.5			-3.8%
Dorb-10	1 atm	1120	30-35% Fe-Pt	IW+0.5	-12.51	-12.29 (IW+0.72)	120.6	53%	46.6	20.2	10.8	22.0			-0.4%
Dorb-8	1 atm	1106	30-35% Fe-Pt	IW+0.5	-12.71	-12.72 (IW+0.49)	137.5	74%	26.4	28.9	18.3	25.8			-0.1%
Dorb-6	1 atm	1163	13-25% Fe-Pt	QFM (IW+3.56)	-8.86	-8.92 (IW+3.50)	46.3	8%	91.9	1.0		5.7	*		-1.5%
Dorb-7 ^c	1 atm	1151	13-25% Fe-Pt	QFM (IW+3.57)	-9.00	-8.89 (IW+3.69)	>68.5	N/A	liq, ol,	срх, р	lag, sj	o (mag	netit	te)	N/A
Dorb-5 ^d	1 atm	1132	13-25% Fe-Pt	QFM (IW+3.59)	-9.25	-9.08 (IW+3.76)	183.3	48%	52.2	7.8	17.1	17.4	7.1		-0.1%
IHPV-1	3 kbar	1160	IHPV	CCO (IW+1.81)	-10.53		48	16%	83.8	8.3		8.4			-0.3%
IHPV-2	5 kbar	1190	IHPV	CCO (IW+1.88)	-9.99		48	5%	94.8	3.8			1.0	Fe metal	-2.4%
B1412	5 kbar	1170	С	IW+1.14	-10.99		28.9	29%	70.8	11.8	3.8	12.7			-0.3%
IHPV-3 ^e	5 kbar	1170	IHPV	CCO (IW+1.94)	-10.19		48	81%	18.8	6.4	40.7	21.2		Fe meta	-12.3%
IHPV-4 ^e	5 kbar	1170	IHPV	CCO (IW+1.94)	-10.19		48	63%	37.4	6.0	34.4	12.4	0.8	B Fe metal	-8.6%
B1421	7 kbar	1190	С	IW+1.24	-10.56		30.9	53%	47.4	11.8	30.3	7.6	2.6	5	-0.02%
B1402	8 kbar	1255	С	IW+1.13	-9.85		28.3	<1%	99.1				0.5	5	+1.4%
B1403	8 kbar	1235	С	IW+1.19	-10.02		25.8	13%	87.4	0.9	9.4		2.2	2	-0.5%
B1400	10 kbar	1275	С	IW+1.22	-9.45		23.8	<1%	99.9				1.0)	+1.1%
B1399	10 kbar	1245	С	IW+1.31	-9.71		23.5	25%	74.6	*	22.4		3.2	2	+0.17%
B1398	10 kbar	1215	С	IW+1.40	-9.98		41.5	70%	29.9	8.0	54.7		6.2	2	-0.2%
B1401	13 kbar	1295	С	IW+1.39	-8.96		25.8	19%	80.7		19.1		2.3	3	+0.1%
B1404	13 kbar	1255	С	IW+1.51	-9.29		27.9	46%	53.6		42.8		5.4	Ļ	-0.4%
B1407	13 kbar	1215	С	IW+1.63	-9.63		66.7	70%	29.5	4.1	59.0		7.2	2	-0.5%

*Trace amounts (a few crystals)

^aFe = Fe capsule in evacuated SiO₂ tube; Fe-Pt = Fe-Pt loops + CO₂/H₂ mix for oxygen fugacity control; C = Graphite capsules. IHPV = Internally Heated Pressure Vessel. ^bDoes not include T±P ramp up time (typically 40 min to 1.5 hr for 1 atm experiments, 20 to 30 min for piston-cylinder experiments).

^cFurnace failure sometime after >68.5hr. Despite slow cooling (relative to quench), mineral assemblages and core compositions similar to Dorb-5 (1132°C) experiment. ^dSpinel in Dorb-5 and -7 is magnetite (not observed in natural angrite specimen).

^eGraphite capsule cracked and the melt touched the Pt capsule. With the exception of pure metal, the same mineral assemblages and compositions are observed in the piston cylinder experiment performed at similar P and T (B1412).

Table 5 Analyses of the experimental charges AI_2O_3 Cr_2O_3 FeO MnO MgO CaO P_2O_5 SiO₂ TiO₂ Sum Mg# KD_{Fe-Mg} Run n Dorb-3 (1 atm, 1173°C, IW-0.57) 10 35.3 (6) 0.03 (3) 0.08 (3) 39.0 (5) 0.31 (5) 25.1 (5) 1.36 (4) 101.2 (4) 53.4 0.302 oliv plag Anorthite spinel 8 0.08 (5) 0.45 (16) 60.3 (1.9) 2.66 (1.67) 26.4 (6) 0.13 (3) 11.5 (3) 0.14 (5) 101.6 (1.4) 43.7 0.446 12.4 (1) 0.05 (3) 28.4 (2) 0.26 (3) 5.52 (13) 15.1 (1) 0.12 (3) 99.9 (4) 25.7 10 37.2 (2) 0.86 (5) glass Dorb-1 (1 atm, 1153°C, IW-0.59) 34.5 (4) 0.05 (3) oliv 8 0.08(1) 42.0 (4) 0.41 (5) 22.4 (3) 1.70 (9) 101.2 (6) 48.8 0.310 100.4 (1.6) 16.0 plag 6 43.1 (1.3) 35.6 (3) 1.26 (34) 0.13 (9) 20.3 (2) 0.13 9.46 0.00 100.2 34.9 0.552 0.22 57.3 0.66 spinel 1 0.81 31.5 0.16 9 37.0 (4) 1.01 (7) 11.2 (1) 0.02 (4) 29.0 (3) 0.29 (4) 4.81 (24) 15.9 (2) 0.19 (4) 99.4 (5) 22.8 glass Dorb-2 (1 atm, 1133°C, IW-0.61) 9 33.9 (6) 0.03 (4) 0.07 (11) 44.3 (3) 0.40 (6) 20.1 (4) 2.21 (36) 101.0 (7) 44.7 0.317 oliv plag 6 43.3 (7) 35.5 (6) 1.04 (36) 0.09 (2) 20.3 (2) 100.3 (1.3) 13.8 8 34.6 (1.0) 0.09 (8) 0.09 (11) 0.03 (3) 44.9 (2.1) 0.41 (3) 20.0 (2.4) 2.30 (64) 0.01 (4) 102.4 (1.3) 44.3 0.322 Ca-oliv 0.04 (4) 29.5 (2) 0.27 (3) 4.25 (5) 16.9 (1) 0.22 (3) 10 37.2 (3) 1.26 (9) 99.6 (5) 20.4 glass 9.8 (1) Dorb-4 (1 atm, 1113°C, IW-0.63) 100.9 (6) 41.3 0.289 8 33.3 (5) 0.05 (3) 0.04 (2) 46.2 (4) 0.44 (7) 18.3 (4) 2.58 (16) oliv 0.09 (2) 20.1 (2) plag 7 43.5 (3) 36.2 (3) 0.98 (19) 100.8 (7) 13.6 9 37.2 (7) 1.42 (7) 9.26 (18) 0.04 (3) 30.1 (3) 0.26 (3) 3.43 (37) 18.3 (6) 0.26 (4) 100.3 (6) 16.9 glass Dorb-11 (1 atm, 1094°C, IW-0.65) 10 33.4 (2) 0.06 (4) 0.04 (2) 0.03 (6) 47.6 (7) 0.40 (5) 15.1 (2) 3.90 (17) 0.01 (3) 100.6 (6) 36.2 0.299 oliv plag Anorthite 47.0 (9) 1.42 (32) 6.65 (1.51) 0.32 (19) 12.7 (9) 0.13 (3) 8.90 (53) 23.7 (2) 100.8 (1.1) 55.5 0.136 срх 8 36.6 (5) 1.79 (4) 8.64 (9) 0.02 (4) 30.2 (1) 0.24 (3) 2.87 (22) 19.3 (4) 99.7 (3) 14.5 glass 5 Dorb-9 (1 atm, 1136°C, IW+0.5) 35.2 (7) 0.06 (2) 0.04 (2) 38.8 (7) 0.46 (7) 24.3 (7) 1.53 (4) 100.4 (6) 52.7 0.336 oliv 8 4 43.1 (7) 34.8 (1.0) 1.12 (29) 0.13 (10) 19.5 (2) 98.7 (1.6) 17.4 plag 10 40.4 (6) 1.24 (4) 9.99 (15) 99.4 (8) 27.3 glass 0.06 (5) 25.0 (3) 0.30 (3) 5.27 (19) 17.1 (2) Dorb-10 (1 atm, 1120°C, IW+0.5) oliv 10 33.1 (6) 0.08 (4) 0.05 (2) 47.4 (8) 0.54 (9) 17.2 (7) 2.36 (9) 100.7 (7) 39.3 0.340 plag 5 42.5 (1.0) 35.5 (1.0) 1.53 (69) 0.08 (4) 19.9 (2) 99.6 (2.4) 8.6 10 48.7 (1.2) 0.94 (22) 5.32 (1.45) 0.28 (8) 12.5 (8) 0.15 (3) 9.86 (75) 23.6 (3) 101.3 (7) 58.5 0.156 срх 3 37.6 (1.1) 2.15 (20) 8.78 (16) 0.52 (5) 30.3 (1.2) 0.51 (2) 3.74 (7) 16.1 (1.1) 0.44 (7) 100.1 (8) 18.1 glass Dorb-8 (1 atm, 1106°C, IW+0.5) 7 32.8 (4) 0.06 (6) 0.09 (16) 50.2 (1.0) 0.53 (9) 13.9 (6) 3.17 (22) 100.8 (7) 33.0 0.368 oliv plag 3 43.1 (8) 35.3 (5) 1.21 (17) 0.06 (1) 19.8 (2) 99.5 (1.6) 8.0 6 46.2 (1.4) 1.59 (17) 6.80 (51) 0.22 (14) 13.3 (3) 0.11 (3) 8.56 (23) 23.6 (3) 100.5 (1.1) 53.4 0.158 срх glass 2 36.2 (2.5) 2.55 (98) 8.32 (79) 0.27 (74) 30.8 (1.1) 0.39 (36) 3.13 (41) 18.6 (5) 100.3 (4) 15.3 Dorb-6 (1 atm, 1163°C, IW+3.56) 7 36.3 (1.0) 0.02 (3) 0.07 (3) 100.8 (1.7) 63.1 0.313* oliv 32.2 (6) 0.35 (5) 30.9 (8) 1.02 (8) 100.0 (7) 24.0 plag 4 43.0 (4) 34.0 (1.7) 2.82 (2.24) 0.50 (46) 19.7 (4) 8 0.17 (17) 1.01 (13) 35.4 (1.9) 6.92 (1.96) 46.2 (1.2) 0.18 (4) 8.57 (52) 0.34 (11) 98.8 (8) 24.8 1.399 spinel glass 19 39.1 (4) 0.92 (5) 11.6 (2) 0.01 (2) 25.5 (1) 0.27 (4) 6.61 (17) 15.2 (2) 99.3 (5) 31.6 Dorb-7 (1 atm, 1151°C, IW+3.57) 7 35.0 (1.2) 0.03 (2) 0.10 (19) oliv 38.1 (7) 0.45 (5) 26.2 (6) 1.28 (18) 101.2 (1.3) 55.1 N/A 101.5 14.7 plag 43.9 35.8 1.64 0.16 20.0 1 6 47.6 (1.2) 0.53 (15) 6.4 (1.1) 0.04 (7) 12.5 (6) 0.13 (3) 10.7 (5) 22.6 (4) 100.4 (5) 60.5 N/A срх glass N/A (See Table 4 for details) Dorb-5 (1 atm, 1132°C, IW+3.59) oliv

7 34.8 (8) 0.04 (1) 0.05 (1) 39.3 (7) 0.48 (5) 24.5 (1.0) 1.30 (17) 100.5 (1.4) 52.6 0.328* 43.2 (3) 34.9 (0.6) 1.58 (34) 0.15 (5) 19.7 (3) 99.5 (8) 14.8 plag 4 19 47.6 (1.3) 0.51 (11) 5.46 (1.03) 0.05 (4) 12.1 (4) 0.13 (2) 11.1 (5) 22.3 (3) срх 99.2 (8) 62.1 0.188 9 0.30 (22) 5.87 (30) 10.3 (6) 0.56 (52) 73.4 (9) 0.21 (3) 2.93 (24) 0.31 (16) 93.9 (7) 6.6 4.339 spine 6 38.6 (6) 1.22 (7) 9.36 (26) 0.03 (5) 28.4 (1) 0.32 (3) 4.91 (20) 15.4 (1) 0.32 (8) 98.6 (7) 23.6 alass IHPV-1 (3 kbar, 1160°C, IW+1.81) 7 35.2 (2) 0.04 (3) 0.11 (18) 0.06 (4) 39.8 (6) 0.35 (6) 25.2 (3) 1.44 (16) 102.2 (7) 53.1 0.319 oliv plag Anorthite 10 38.3 (7) 1.08 (6) 11.2 (3) 0.003 (18) 26.3 (3) 0.28 (8) 5.33 (20) 16.1 (2) 0.17 (8) 98.8 (1.1) 26.5 glass IHPV-2 (5 kbar, 1190°C, IW+1.88) 6 36.0 (2) 0.04 (2) 0.03 (2) 0.02 (2) 36.1 (3) 0.28 (8) 27.4 (2) 1.13 (4) 0.03 (4) 101.0 (6) 57.5 0.325 oliv 101.3 (7) 49.2 0.452 0.18 (8) 0.23 (4) 61.1 (4) 2.38 (68) 24.0 (5) 0.14 (3) 13.1 (1) 0.23 (3) spinel 3 39.6 (1) 0.82 (4) 100.0 (4) 30.5 6 12.8 (1) 0.003 (11) 24.5 (3) 0.27 (3) 6.02 (8) 15.9 (1) 0.16 (3) glass B1412 (5 kbar, 1170°C, IW+0.5) 101.5 (3) 49.0 0.305 oliv 8 34.4 (3) 0.02 (2) 0.05 (2) 0.005 (12) 42.3 (3) 0.48 (9) 22.8 (3) 1.49 (6) Anorthite plag срх 15 47.2 (1.2) 0.70 (15) 7.73 (1.55) 0.36 (15) 10.6 (6) 0.13 (3) 10.9 (9) 23.0 (4) 100.7 (1.3) 64.6 0.160 glass 8 38.7 (1.3) 1.23 (6) 10.7 (4) 0.02 (4) 28.2 (5) 0.31 (3) 4.64 (20) 16.3 (2) 0.23 (4) 100.3 (1.9) 22.6 IHPV-3 (5 kbar, 1170°C, IW+1.94) 102.2 (6) 47.3 0.316 oliv 10 34.7 (9) 0.06 (7) 0.16 (49) 0.04 (4) 43.7 (4) 0.68 (11) 22.0 (8) 0.92 (4) plag Anorthite 9 48.2 (1.3) 0.82 (20) 6.73 (2.05) 0.06 (4) 12.5 (1.1) 0.21 (10) 10.6 (1.0) 21.5 (1.4) 100.7 (8) 60.2 0.188 срх 2 40.0 (7) 2.35 (3) 11.1 (5) 99.2 (1) 22.1 glass 27.8 (8) 0.59 (18) 4.44 (10) 12.4 (5) 0.52 (22) IHPV-4 (5 kbar, 1170°C, IW+1.94) 42.9 (1) 0.56 (10) 21.4 (6) 1.23 (17) 2 34.9 (1) 0.02 (5) 0.03 (1) 101.1 (8) 47.1 0.345 oliv plag Anorthite 6 46.5 (1.3) 0.76 (15) 9.89 (1.27) 0.16 (3) 10.8 (3) 0.13 (3) 10.0 (5) 22.5 (2) 100.8 (7) 62.3 0.186 срх 2 2.07 (58) 0.44 (12) 60.9 (4.1) 0.76 (94) 27.8 (3) 0.17 (6) 10.4 (4) 0.91 (37) 103.5 (1.4) 40.0 0.462 spinel glass 6 40.1 (3) 1.67 (4) 11.2 (1) 27.6 (2) 0.46 (6) 4.76 (27) 13.7 (3) 0.40 (4) 99.9 (5) 23.5 B1421 (7 kbar, 1190°C, IW+0.5) oliv 7 33.9 (3) 0.07 (3) 0.13 (20) 48.4 (4) 0.45 (4) 17.5 (1) 1.58 (9) 102.0 (4) 39.3 0.310 Anorthite plag срх 14 45.4 (6) 0.95 (19) 10.5 (9) 0.10 (6) 12.8 (4) 0.15 (3) 8.80 (52) 22.2 (3) 100.9 (4) 55.0 0.164 spinel 5 0.15 (11) 0.75 (13) 58.0 (4) 0.76 (45) 34.8 (1.3) 0.18 (5) 7.57 (56) 0.17 (21) 102.4 (1.0) 28.0 0.516 99.4 (7) 16.7 11 36.8 (5) 1.37 (7) 0.01 (3) 31.6 (7) 0.28 (6) 3.54 (23) 14.7 (2) 0.37 (15) glass 10.8 (6) B1402 (8 kbar, 1255°C, IW+0.5) 2.40 24.2 0.13 12.7 101.5 48.4 0.487 spinel 1 0.21 0.25 61.3 0.24 glass 10 38.9 (2) 0.86 (5) 12.3 (1) 0.01 (3) 25.9 (3) 0.25 (3) 6.65 (6) 14.9 (2) 0.15 (9) 99.9 (6) 31.4 B1403 (8 kbar, 1235°C, IW+0.5) 38.6 (6) 0.35 (5) 26.1 (5) 1.02 (1) 101.1 (5) 54.7 0.308 oliv 5 35.0 (4) 0.02 (1) 0.07 (2) 7 48.4 (8) 0.38 (6) 6.89 (95) 0.05 (3) 10.5 (3) 0.14 (2) 12.0 (6) 22.2 (4) 100.6 (9) 67.1 0.182 срх 0.27 (6) 60.3 (1.6) 1.22 (75) 26.3 (3) 0.14 (3) 11.6 (5) 0.29 (8) 100.3 (9) 44.0 0.474 spinel 9 0.16 (9) 12.3 (1) 0.03 (4) 26.8 (3) 0.28 (4) 5.60 (6) 14.8 (2) 0.18 (4) 8 38.8 (2) 0.92 (4) 99.7 (3) 27.1 glass B1400 (10 kbar, 1275°C, IW+0.5) spinel 4 0.23 (7) 0.21 (1) 61.5 (5) 2.18 (36) 24.4 (5) 0.12 (2) 12.3 (5) 0.17 (9) 101.1 (4) 47.4 0.523 38.6 (2) 0.84 (6) 11.9 (1) 0.01 (2) 25.5 (3) 0.24 (3) 6.73 (11) 15.0 (1) 98.8 (4) 32.0 glass 8 B1399 (10 kbar, 1245°C, IW+0.5) oliv 2 34.7 (1) 0.04 (6) 0.11 (4) 41.4 (1) 0.38 (13) 23.4 (2) 0.97 (2) 101.0 (5) 50.2 0.332 9 46.8 (1.2) 0.46 (9) 9.38 (1.51) 0.06 (4) 11.5 (4) 0.13 (2) 11.0 (9) 21.7 (3) 101.0 (7) 63.1 0.195 CDX spinel 8 0.34 (81) 0.29 (6) 59.2 (9) 0.44 (27) 28.7 (6) 0.15 (3) 10.6 (3) 0.35 (57) 100.1 (6) 39.6 0.508 10 37.5 (3) 1.01 (5) 11.5 (1) 0.04 (3) 29.5 (4) 0.31 (2) 5.53 (8) 14.0 (1) 99.4 (5) 25.0 glass B1398 (10 kbar, 1215°C, IW+0.5) 32.6 (6) 0.05 (4) 0.07 (2) 53.7 (9) 0.51 (6) 13.6 (7) 0.96 (9) 101.4 (5) 31.1 0.373 oliv 8 45.2 (5) 0.70 (8) 10.5 (9) 0.04 (3) 16.2 (5) 0.17 (3) 7.74 (28) 21.1 (3) 101.8 (8) 45.9 0.198 срх 10 101.3 (9) 22.2 0.590 spinel 8 0.25 (18) 0.74 (11) 56.9 (1.1) 0.26 (20) 36.7 (8) 0.19 (2) 5.87 (30) 0.29 (9) 37.5 (9) 1.66 (50) 11.3 (5) 0.19 (51) 33.4 (1.5) 0.44 (21) 3.15 (23) 12.1 (4) 99.7 (2.3) 14.4 8 alass B1401 (13 kbar, 1295°C, IW+0.5) 99.9 (5) 63.7 0.207 8 45.7 (7) 0.40 (6) 10.8 (1.4) 0.05 (5) 10.8 (5) 0.14 (2) 10.6 (5) 21.4 (4) срх spinel 8 0.16 (4) 0.26 (5) 59.1 (1.0) 0.57 (24) 27.8 (2) 0.14 (3) 10.8 (3) 0.20 (6) 99.0 (9) 40.9 0.527 36.9 (6) 0.98 (7) 28.2 (2) 0.28 (2) 5.76 (12) 13.8 (2) 97.2 (5) 26.7 glass 9 11.3 (1) B1404 (13 kbar, 1255°C, IW+0.5) 10 45.0 (6) 0.42 (7) 9.6 (0.9) 0.05 (5) 14.5 (1.1) 0.19 (4) 9.08 (29) 19.8 (4) 98.6 (8) 52.7 0.224 срх 98.7 (7) 29.8 0.587 spinel 10 0.28 (21) 0.48 (6) 55.9 (8) 0.31 (20) 33.4 (5) 0.17 (2) 7.97 (35) 0.19 (15) 10.3 (3) 0.00 (1) 32.3 (4) 0.32 (3) 4.51 (11) 11.9 (1) 0.28 (12) 9 36.3 (3) 1.16 (6) 97.1 (7) 19.9 glass B1407 (13 kbar, 1215°C, IW+0.5) 52.5 (6) 0.48 (10) 14.1 (4) 0.90 (10) oliv 10 32.5 (4) 0.02 (2) 0.09 (4) 100.6 (6) 32.4 0.335 0.05 (3) 16.7 (5) 0.22 (4) 7.75 (33) 19.6 (3) 11 44.9 (6) 0.57 (12) 9.83 (57) 99.6 (1.0) 45.3 0.193 срх 99.4 (6) 21.8 0.574 10 0.28 (25) 0.83 (6) 0.23 (9) 38.0 (4) 0.17 (3) 5.95 (19) 0.24 (9) spinel 53.7 (9) 10.2 (4) 0.03 (1) 35.8 (3) 0.36 (3) 3.22 (18) 11.4 (4) 2 36.9 (5) 1.53 (9) 99.5 (1.1) 13.8 glass

Number in parentheses is the 2SD of mean of replicate analyses. KD_{Fe-Mg} is for oliv/liq, cpx/liq and spinel/liq. * For the QFM experiments, the amount of Fe^{3+} in the liquid is non-negligible ($Fe^{3+}/Fe^{2+} \sim 14-15\%$, Kress & Carmichael 1991). The KD values, which are technically defined as (Fe^{2+}/Mg^{2+})_{liq}, were thus adjusted accordingly, and it is the corrected value which is

 Table 6

 Compilation of REEs concentrations in whole rock angrites (in ppm).

Sample Plutonic and	Mass (mg) grites	Ва	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Th	U	Ref.
AdoR	066	35	73	19		15.6	59	1 94		1.35	87				51	0.73	26	0.55	0.13	[1]
	52	36	6 14	10.2		16.3	5 76	1.54		1 30	0.7				4 82	0.70	2.0	0.60	0.10	[2]
	50.5	20 Q	62	18.5	3 00	17.2	59	1.70	73	1 30	92	2 03	56	0 83	5.02	0.00	2.75	0.04	0.20	[<u>~]</u>
Addit	00.0	20.5	0.2	0.0	0.03	0.2	0.1	0.07	1.5	0.05	0.2	0.00	0.0	0.00	0.1	0.72	0.07	0.74	0.20	[5]
	FF	0.3	0.2	10.3	0.04	0.5	0.1	0.07	0.2	0.05	0.5	0.00	0.2	0.03	0.1	0.01	0.07	0.05	0.01	[0]
	55	40	3.30	10.1		0.4	2.00	0.976		0.66					2.04	0.300	2.21	0.40	0.45	[2]
LEVV 86010	190	10 C	4.7	10.9		0.1 9.1	2.60	0.97		0 66	4.4				2.01	0.38	1.87	0.40	0.15	[1]
	avy	49.5	4.04	10.5		- 0.1	2.04	0.974		0.00	4.4				2.03	0.303	2.04	0.44	0.15	
NWA 2999	167	220	0.80	2.0		<1	0.67	0.236		0.177					0.77	0.120	0.58	<0.2	0.13	[4]
±		140	0.52	1.0			0.14	0.038		0.032					0.08	0.010	0.12		0.14	
NWA 2999	613.1		0.614	2.133	0.354	1.990	0.649	0.238	0.925	0.166	1.127	0.252	0.753	0.110	0.787	0.123				[5]
±			0.031	0.107	0.018	0.099	0.032	0.012	0.046	0.008	0.056	0.013	0.038	0.006	0.039	0.006				
NWA 3164	450	171	1.39	3.43	0.573	3.10	1.04	0.408	1.40	0.248	1.65	0.350	1.04		1.02	0.155	0.875	0.030	0.337	[6]
NWA 4931	50.8	72.5	0.522	1.72	0.299	1.89	0.69	0.39	0.93	0.183	1.26	0.284	0.82	0.132	0.88	0.141	0.72	0.028	0.032	[3]
±		0.2	0.003	0.01	0.006	0.01	0.01	0.01	0.02	0.004	0.03	0.007	0.02	0.002	0.03	0.003	0.02	0.002	0.002	
NWA 5167	500	160	0.48	1.59	0.290	1.71	0.652	0.290	0.956	0.170	1.18	0.267	0.80		0.87	0.135	0.697	0.028	0.019	[6]
NWA 6291	~33/645*		0.485	1.682	0.323	2.100	0.765	0.298	1.094	0.196	1.333	0.299	0.891	0.131	0.933	0.146		0.483	0.139	[7]
NWA 4590	50.3	81	3.19	8.8	1.35	7.42	2.61	1.06	3.51	0.70	4.9	1.14	3.32	0.52	3.31	0.50	2.2	0.325	0.096	[3]
±		2	0.04	0.1	0.01	0.09	0.05	0.03	0.07	0.02	0.1	0.02	0.07	0.01	0.07	0.01	0.5	0.009	0.004	• •
NWA 4590	~37/738*		2.044	6.230	1.092	5.950	2.212	0.896	3.402	0.616	4.312	0.966	3.066	0.462	3.290	0.504		0.364	0.126	[7]
NWA 4590	737.5		1.652	5.034	0.882	4.785	1.511	0.579	2.200	0.398	2.787	0.624	1.982	0.299	2.072	0.326				[5]
±			0.083	0.252	0.044	0.239	0.076	0.029	0.110	0.020	0.139	0.031	0.099	0.015	0.104	0.016				
NWA 4590 a	avg	81	2.295	6.688	1.108	6.052	2.111	0.845	3.037	0.571	4.000	0.910	2.789	0.427	2.891	0.443	2.2	0.345	0.111	[3,5,7]
NWA 4801	50.1	40.5	3.43	10.68	1.75	10.0	3.46	1.152	4.43	0.844	5.60	1.22	3.388	0.507	3.106	0.460	2.564	0.283	0.094	[3]
±		0.6	0.01	0.06	0.01	0.1	0.03	0.008	0.04	0.005	0.05	0.01	0.007	0.001	0.001	0.002	0.008	0.004	0.001	
NWA 4801	50.8	36.2	2.96	9.3	1.52	8.6	3.02	1.03	3.85	0.733	4.90	1.08	2.95	#####	2.72	0.404	2.24	0.242	0.081	[3]
±		0.8	0.07	0.1	0.03	0.2	0.08	0.01	0.05	0.009	0.05	0.01	0.01	#####	0.07	0.006	0.03	0.002	0.001	
NWA 4801	~31/611*		1.848	5.600	0.938	5.180	1.834	0.602	2.688	0.448	2.870	0.616	1.764	0.238	1.596	0.224		0.182	0.070	[7]
NWA 4801	611.2		2.199	6.664	1.116	6.131	2.233	0.716	2.682	0.533	3.416	0.733	2.099	0.283	1.883	0.267				[5]
±			0.110	0.333	0.056	0.307	0.112	0.036	0.134	0.027	0.171	0.037	0.105	0.014	0.094	0.013				
NWA 4801		38.35	3.195	9.990	1.635	9.300	3.240	1.091	4.140	0.789	5.250	1.150	3.169	0.475	2.913	0.432	2.402	0.263	0.088	[3]
Quenched a	Ingrites																			
Asuka 88137	71 50.3	23	2.50	6.3	0.99	4.9	1.58	0.63	2.09	0.38	2.60	0.57	1.66	0.243	1.60	0.24	1.24	0.33	0.082	[3]
±		1	0.06	0.1	0.03	0.1	0.06	0.02	0.04	0.01	0.08	0.02	0.06	0.009	0.06	0.01	0.09	0.02	0.005	
D'Orbigny	55.88/200*	47	3.56	8.78		nd	2.161	0.846		0.534					2.12	0.309	1.63	0.370	<0.21	C [8]
±		18	0.04	0.26			0.029	0.016		0.019					0.06	0.013	0.06	0.040		
D'Orbigny	53.34	52	3.76	9.18		5.4	2.23	0.876		0.511					2.13	0.308	1.48	0.434	0.116	[8]
±		7	0.04	0.24		2.6	0.03	0.017		0.018					0.04	0.007	0.05	0.029	0.022	
D'Orbigny	50.5	50.01	3.753	9.22	1.331	6.92	2.15	0.840	2.718	0.508	3.384	0.760	2.15	0.333	2.09	0.3156	1.58	0.454	0.082	[3]
±		0.02	0.002	0.04	0.009	0.01	0.02	0.007	0.004	0.002	0.009	0.004	0.01	0.000	0.02	1E-05	0.02	0.009	0.001	
D'Orbigny	65.8	49.35	3.425	8.943	1.301	6.953	2.169	0.858	2.756	0.499	3.479	0.752	2.178	0.321	2.120	0.307	1.552	0.451	0.077	[3]
D'Orbigny	~36/728"	49 70	3.727	##### 0 001	1.695	8.937 6 027	3.157	0.971	4.112	0.770	4.915	1.058	3.141 2 161	0.433	3.001	0.46	1 507	0.454	0.081	[/]
	y 10	40.79	3.579	0.901	1.310	0.937	2.100	0.640	2.131	0.514	3.432	0.750	2.104	0.327	2.110	0.311	1.307	0.425	0.000	[3,7,0]
	13	-60	2.32	0.2			1.40	0.530		0.30	2.1				1.52	0.239	1.17	0.22	-0.21	[∠] [1]
	21	<00	2.01	9.4 7 90			2.01 1 75	0.03		0.49	3.1 3.1				2.00	0.30	1.04	0.41	<0.21	[1]
	avy	10 70	2.31	0.007	1 205	7 070	1.75	0.00	2 00	0.43	3.1 2.695	0 901	2 217	0 244	1.70	0.27	1 502	0.52	0.067	[[].2]
NVVA 1290	03.3	40.70	3.333	9.097	1.295	6.44	2.222	0.045	2.00	0.527	3.000	0.001	2.317	0.344	2.23	0.325	1.095	0.451	0.007	
NVVA 1296	300	100	3.40	0.00	1.29	0.44	2.00	0.760	2.04	0.509	3.4Z	0.720	2.10	0 2 4 4	2.00	0.290	1.40	0.43	0.070	
NWA 1296 a	avg	47.0	3.367	8.874	1.293	6.760	2.141	0.813	2.86	0.518	3.553	0.764	2.239	0.344	2.15	0.311	1.527	0.441	0.069	[3,6]
INVVA 1670	250	47.3	2.59	6.70	0.97	4.88	1.56	0.629	2.08	0.377	2.53	0.538	1.61	0.01	1.54	0.220	1.12	0.33	0.075	[0] [0]
NVVA 7812		126	2.06	12.0***	0.88	4.92	1.39	0.58	1.88	0.33	2.26	0.49	1.49	0.21	1.37	0.21	1.5	0.000		[9]
Sahara 9955	5 28.89/522*	45.0	3.20	8.41		nd	2.107	0.829		0.512					2.12	0.319	1.80	0.360	<0.21	u [8]
±		17.0	0.04	0.24			0.028	0.018		0.023	-		_		0.04	0.009	0.06	0.040		
Sahara 9955	55 46.1	37.27	3.536	9.01	1.285	6.70	2.127	0.821	2.70	0.505	3.40	0.76	2.16	0.332	2.11	0.322	1.63	0.50	0.106	[3]
±		0.03	0.005	0.02	0.004	0.05	0.004	0.008	0.05	0.006	0.03	0.01	0.02	0.002	0.01	0.002	0.02	0.02	0.003	
Sahara 9955	5 290	31.7	3.54	9.16	1.34	6.74	2.16	0.860	2.87	0.519	3.49	0.748	2.23	0.000	2.11	0.305	1.51	0.45	0.097	[6]
Sanara 9955	oo avg	38.0	3.425	8.860	1.313	o./20	z.131	0.837	2.785	0.512	J.445	0.754	2.195	0.332	2.11	0.315	1.647	0.437	0.102	[3,6,8]
Luanasic an	OF IT AS																			

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NWA 12004	80.9	3.64	9.27	1.39	6.86	2.17	0.85	2.95	0.50	3.48	0.75	2.19	2.07 0.311	[10]
NWA 12320	83.1	3.31	8.45	1.26	6.20	1.98	0.78	2.67	0.46	3.18	0.69	2.02	1.92 0.287	[10]

References: [1] Warren & Kallemeyn (1990), INAA. [2] Mittlefehldt & Lindstrom (1990), INAA. [3] Riches et al. (2012), ICPMS. [4] Gellissen et al. (2007), INAA. [5] Sanborn & Wadhwa (2021), ICPMS. [6] Baghdadi et al. (2015), ICPMS. [7] Tissot et al. (2017), ICPMS. [8] Mittlefehldt et al. (2002), INAA. [9] Irving et al. (2013) ICPMS on wire-saw cutting dust. [10] Irving et al. (2019) ICPMS on wire-saw cutting dust.

*Post dissolution split (numerator) from a larger mass digested as a whole (denominator).

**Powder split (numerator) from an homogeneized mass (denominator).

***Anomaly requiring further work to be confirmed.

Table7 APB bulk composition best estimates (atomic ratios).

Method				APB mantle	APB core				
		Mg/Si	Al/Si	Ca/Si	Ti/Si	Fe/Si	Cr/Si	Fe/Si	(wt%)
Intercept nebular trend & OI-melt tie lines ^a		1.18-1.40	0.107-0.144	0.089-0.125	0.0031-0.0046	0.95-1.04	0.005-0.010	0.363-0.541	16-24
Two-component mixtures ^b		1.29-1.31	0.109-0.114	0.076-0.080	0.0031-0.0033	0.69-1.06	0-0.0052	0.400-0.404	12-24
OI-melt best fit to 2-component mixtures ^c		1.29-1.31	0.090-0.094	0.093-0.097	0.0037-0.0038	N/A	0.0024-0.0024	0.403-0.403	N/A
Recommended value ^d		1.29 ± 0.11	0.117 ± 0.027	0.101 ± 0.025	0.0039 ± 0.00080	0.875 ± 0.18	50.0062 ± 0.0038	0.452 ± 0.089	18 ± 6
Equivalent in oxide weight %	SiO ₂	MgO	AI_2O_3	CaO	TiO ₂	FeO	Cr_2O_3		
Recommended value APB ^d	32.07	27.76	3.18	3.01	0.16	33.56	0.25		
Recommended value bulk silicate angri	38.29	33.13	3.80	3.59	0.20		0.30	20.69	

^aAssumes the APB falls on the nebular trend defined by chondrites (grey envelop in Fig 10), except for Fe/Si and Cr/Si ratios, which are predicted by projecting the Mg/Si ratio of 1.18 to 1.40 onto the tie-line between the first (1400 K) and residual condensates (1400-830 K) from Morbidelli et al. (2020) (purple points in Fig 11). ^bAverage APB composition and core size derived from 2 end-member mixing calculations with $r^2 \ge 0.9997$ and residuals ≤ 1.1 (Table S4).

^bBest fit to the 2-component mixture produced by mixing the primitive angrite melt composition (LEW 87051) and its corresponding equilibrium olivine (Fo 80.5). ^dFull range from the three estimates, except for Cr/Si where the 0 value is omitted (as angrites clearly contain Cr).

Table 8

Oxygen fugacity estimates for the Angrite Parent Body

Meteorite	Туре	Method	ΔIW	Refs.
During magm	a crys	tallization		
AdoR	Plut.	Intrinsic fO2 measurements using the solid-electrolyte oxygen cell method.	0 to +1.2	[1]
AdoR	Plut.	Dynamic crystallization experiments.	~ 0 to >0	[2]
LEW 86010	Plut.	Comparison of experimental Eu/Gd partition coefficients in plagioclase and pyroxene with natural	~ +0.8	[3]
NWA 2999	Plut.	Comparison of experimental Eu/Gd partition coefficients in plagioclase and pyroxene with natural	+0.5 to +1.1	[4]
NWA 4590	Plut.	Comparison of experimental Eu/Gd partition coefficients in plagioclase and pyroxene with natural	+1.0 to +2.4	[4]
NWA 4801	Plut.	Comparison of experimental Eu/Gd partition coefficients in plagioclase and pyroxene with natural	+1.0 to +1.7	[4]
LEW 87051	Volc.	K-edge XANES determination of chromium valence (Cr ²⁺ /Cr tot) in olivine crystals.	~ 0 to +2 (core to rim)	[5]
D'Orbigny	Volc.	Partial melting experiments of CV chondrites to reproduce the bulk composition of D'Orbigny.	+1 to +2	[6-8]
D'Orbigny	Volc.	XANES determination of vanadium valence in clinopyroxene crystals.	-0.7 to +0.5 (core to rim	ı [9]
D'Orbigny	Volc.	Comparison of Mg# in cpx cores in 1 atm equilibrium experiments and natural D'Orbigny-like angr	+0.4 to +2.0	This work
During core-fe	ormatio	n		
Bulk silicate	APB	Comparison of experimentally determined metal-silicate partition coefficient of moderately	~ -1 ^a	[10]
Bulk silicate	APB	siderophile elements with values required to explain their depletion in the APB mantle relative to a	~ -1 ^b	[11]
Bulk silicate	APB	CV bulk composition. See set of elements used in table footnotes.	-1.40±0.45 ^c	[12]
References: [1] Bret	t et al., 1977; [2] Lofgren & Lanier, 1992; [3] McKay et al., 1994; [4] Sanborn & Wadhwa, 2021; [5]	Shearer et al., 2016; [6-	8]
Jurewicz et al	., 1991	I, 1993, 2004; [9] King et al., 2012; [10] Righter, 2008; [11] Shirai et al., 2009; [12] Steenstra et al.,	2017.	
^a Using Co, Ni	and W	l abundances, assuming equilibrium between a peridotite mantle and C-bearing FeNi metallic liquid	d core (8 mass %) at 21	73 K and 5 kba
^b Same as 'a' I	out witl	h the addition of Mo abundances, and at 2073 K and 1 kbar.		

^cUsing Co, Ni, Ga, Mo, and W abundances, for a range of core compositions, sizes, and temperatures, at 1 kbar.